

Muhammad Ali Kaleem

**Design and Development of Hybrid Tools
for Rotary Draw Bending Using Digital Twin
and Additive Manufacturing Processes**

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Univ.-Prof. Dr.-Ing. Bernd Engel (Hrsg.)

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Design and Development of Hybrid Tools for Rotary Draw Bending
Using Digital Twin and Additive Manufacturing Processes

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Siegen, 03.03.2026

Muhammad Ali Kaleem

Abstract

Rotary draw bending (RDB) process is a profile bending process mostly used in industrial practices for bending metal tubes. Presently, RDB process is conducted by using geometry specific bending tools. The fundamental tools used in RDB process are pressure-die, bend-die, clamp-dies, wiper-die, collet and mandrel. These tools have simplified geometries with a semi-circular tool surface which corresponds to only one specific tube diameter. This makes RDB process inflexible because different tube diameters cannot be used with a specific set of bending tools. In addition to process-flexibility, the modern production regime of present era needs bending tools to be cost effective and light weight. This doctoral thesis is aimed to utilize modern manufacturing techniques, i.e., 3D printing processes and digital twin of RDB process, to develop the geometric design of bending tools which should be cost effective, light weight and provides process-flexibility to RDB process. A digital twin of the RDB process is developed and the accuracy of the digital twin is verified by comparing the FE-simulation results with practically conducted experiments. The design factors which critically influence the tool design are identified through digital twin prototyping. The digital twin prototyping method encompasses systematic development and testing of 3D printed polymeric tools in RDB process. Topology optimization of a conventional tool geometry is conducted in order to identify minimum material required within the tool. The results obtained from digital twin prototyping and topology optimization envisioned the development of a hybrid tool. A hybrid tool consists of two different materials i.e., polymers and metals. The materials of a hybrid tool are selected from Ashby material charts on the basis of requirements resulting from process parameterization and topology optimization. A model of the hybrid tool is developed according to material properties of selected materials and identified tool design factors. The model is imported in digital twin of RDB process and tool performance is investigated by conducting process simulations with different tube diameters. After obtaining process feasibility through digital twin, the hybrid tool consisting of polymer - PLA and metal - stainless steel is practically 3D printed and experimentally tested in an actual RDB process. The experimental results demonstrates that a 3D printed hybrid tool is capable of conducting bending operations with different tube diameters while enabling significant material saving within the tool. A comparison is made between the novel 3D printed hybrid tools and conventional steel tools. A design formula is presented that determines the efficiency of bending tools through Tool Efficiency index (TEi). For practical applications, the geometry of 3D printed hybrid tools is standardized through aspect ratio and corresponding upscale size factors.

Keywords: Rotary Draw Bending, FE-Simulation, Digital Twin, Additive Manufacturing.

Kurzfassung

Das Rotationszugbiegen (RZB) ist ein Profilbiegeverfahren, welches vor allem in der Industrie zum Biegen von Metallrohren eingesetzt wird. Derzeit werden beim RZB-Verfahren geometriespezifische Biegewerkzeuge verwendet. Konventionell setzt sich ein solcher Werkzeugsatz aus den Einzelwerkzeugen Gegenhalter, Biegeform, Klemmbacken, Faltenglätter, Spannzange und Dorn zusammen. Diese Werkzeuge haben vereinfachte Geometrien mit einer halbkreisförmigen Werkzeugkavität, die nur einem spezifischen Rohrdurchmesser entspricht. Dies macht das RZB-Verfahren unflexibel, da mit einem bestimmten Satz von Biegewerkzeugen keine unterschiedlichen Rohrdurchmesser verwendet werden können. Neben der Prozessflexibilität erfordern moderne Produktionssysteme heutzutage, dass die Werkzeuge kostengünstig und leicht sind. Diese Doktorarbeit zielt darauf ab, moderne Fertigungstechniken, d. h. additive Fertigung und digitale Zwillinge des RZB-Prozesses, zu nutzen, um Biegewerkzeuge zu entwickeln, die sowohl kostengünstig und leicht sind als auch dem RZB-Prozess Prozessflexibilität verleihen. Ein digitaler Zwilling des RZB-Prozesses wird entwickelt, dessen Genauigkeit durch den Vergleich aus FE-Simulationsergebnissen und praktisch durchgeführten Experimenten verifiziert wird. Die Designfaktoren, die das Werkzeug entscheidend beeinflussen, werden durch Prototyping innerhalb des digitalen Zwillings identifiziert. Diese Methode umfasst die systematische Entwicklung und Prüfung von 3D-gedruckten Polymerwerkzeugen im RZB-Prozess. Zusätzlich wird an einer herkömmlichen Werkzeuggeometrie die Methode der Topologieoptimierung durchgeführt, um den minimalen Materialbedarf innerhalb des Werkzeugs zu ermitteln. Die Ergebnisse aus dem digitalen Zwillings-Prototyping und der Topologieoptimierung laufen schlussendlich in der Entwicklung eines Hybridwerkzeugs zusammen. Ein Hybridwerkzeug besteht aus zwei verschiedenen Materialien, in diesem Falle Polymer und Metall, die auf der Grundlage der Anforderungen, die sich aus der Prozessparametrisierung und der Topologieoptimierung ergeben, zielgerichtet entsprechend der Ashby-Materialtabellen ausgewählt werden. Ein Modell des Hybridwerkzeugs wird entsprechend der Eigenschaften der ausgewählten Materialien und den identifizierten Werkzeugkonstruktionsfaktoren entwickelt. Das Modell wird in den digitalen Zwilling des RZB-Prozesses importiert und das Werkzeugverhalten wird durch Prozesssimulationen mit verschiedenen Rohrdurchmessern untersucht. Nach der Ermittlung der Prozessdurchführbarkeit durch den digitalen Zwilling wird das aus Polymer und Metall bestehende Hybridwerkzeug real gefertigt und im RZB-Prozess experimentell getestet. Die experimentellen Ergebnisse zeigen, dass das hier vorgestellte Hybridwerkzeug Biegevorgänge mit unterschiedlichen Rohrdurchmessern durchführen kann und gleichzeitig eine erhebliche Materialeinsparung innerhalb des Werkzeugs ermöglicht. Hierfür wird ein Vergleich zwischen den neuartigen 3D-gedruckten Hybridwerkzeugen und herkömmlichen Stahlwerkzeugen durchgeführt. Es wird eine Rechenvorschrift vorgestellt, welche die Effizienz von Biegewerkzeugen anhand des Werkzeug-Effizienz-Index (TEi) bestimmt. Für praktische Anwendungen wird die Geometrie von 3D-gedruckten Hybridwerkzeugen durch das Seitenverhältnis und entsprechende Skalierungsfaktoren standardisiert.

Schlüsselwörter: Rotationsziehen, FE-Simulation, Digital Twin, additive Fertigung.

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List of Abbreviations & Symbols

Words	Abbreviation
Rotary draw bending	RDB
Fused deposition modelling	FDM
Fused Filament Fabrication	FFF
Laser Metal Deposition	LMD
Laser powder bed Fusion	L-PBF
Solid Isotropic Material Penalization	SIMP
Tool Efficiency Index	TEi
Computer Aided Design	CAD
Finite Element Modelling	FEM
Finite Element Analysis	FEA
Ultimate tensile strength	UTS
German institute of standardization	DIN
Three dimensional	3D
Association of German Engineers	VDI
Bending angle	α
Bending factor	B
Wall factor	W
Tube velocity	V_{tube}
Collet velocity	V_{collet}
Pressure die	Pd
Conventional polymeric pressure die	Pd _p
Conventional Metal pressure die	Pd _c
V-shaped geometry of the polymeric pressure die	Pd _{pV}
Topology optimization	TO
Topology optimized polymeric pressure die	TO-Pd _p
Poly lactide acid	PLA
Contact normal force	F _C
Contact normal pressure	P _{CN}
Von-Mises Stress	σ_{VM}
Coefficient of friction (COF)	μ
Base of radial curve of pressure die	b _R
Height of radial curve of pressure die	h _R
Length of conventional pressure die	l _{pd}

Length of topology optimized polymeric pressure die	l_{tpd}
Total surface area	A_{TOTAL}
Effective area on the surface	A_{EFF}
Process flexibility	f_R
Cost effectiveness	c_M
Lightweight of tools	w_L
Manufacturing time	t_N
Material composition factor	V_C
Volume composition of polymer-PLA	V_p
Volume composition of steel	V_s
Size factor	S_f
Average contact force per bending angle	F_{CN}/α°
Tube diameter	d
Radial angle	Θ
Tube ovality with hybrid tools	O_{HT}
Tube ovality with conventional tools	O_{CT}
Wrinkling factor in tube	Ω
Yield strength	Y_d
Contact force on conventional geometry of pressure die	F_{CP}
Contact force on conventional geometry of wiper die	F_{CW}
Contact force on conventional geometry of wiper die	F_{CM}
Tool surface displacement	δ

Chapter 1 : Introduction

1. Background and Scope

The world has witnessed a rapid change in technology in the last couple of decades [1]. The continuous advancement in manufacturing processes is bringing new trends in production processes [2]. Presently, the manufacturing regime is required to fulfil individual user requirements while achieving high standards of cost effectiveness and economic sustainability in production processes. The focus is therefore shifting from conventional production towards customized production [3]. Product customization according to the personalized requirements of individual users is presently considered as a megatrend in the manufacturing regime [4]. In order to achieve product customization, flexibility in manufacturing processes is considered as an essential requirement [5].

Rotary Draw Bending (RDB) is a profile bending process which is mostly used to bend metal tubes [6]. In the overall manufacturing regime, the Association of German Engineers (DIN) categorizes RDB process as a subclass of rotational forming processes according to 'DIN-8586' [7]. The RDB process is conducted on bending machines for producing profile bends to tubes using rotational kinematics. The process possesses the potential to bend metal tubes with wide range of outer diameters, wall thicknesses and tube materials [8]. In practical applications, the RDB process is widely used in aerospace, automotive, marine, sanitary and household industries. The bent tubes produced through RDB process possess high geometric accuracy as compared to the tubes produced through other tube bending processes (e.g., roll push bending etc.) [9]. A significant advantage of the RDB process is its potential to bend tight (or small) bends while maintaining the high standard of tube quality characteristics. The quality of bent tubes produced through the rotational forming process are determined according to the guidelines of Association of German Engineers 'VDI-3431' [10]. These guidelines provide 21 characteristics which are used to determine the physical quality of tubes. Amongst these tube characteristics, the fundamental quality aspects are wrinkling, tube ovality, springback and wall thickness deviation at intrados and extrados. These quality aspects can be minimized (or eliminated) by using correct procedures and methods used during the bending operation. The correct process procedures are already identified by the process experts through numerical and empirical techniques. These process procedures which control the process outcomes are called as process parameters. Fundamentally, two significant process parameters which determine feasibility of the bending process are Bending factor and Wall factor [11]. The Bending factor (B) is the ratio of bending radius of the tube to the tube outer diameter [12]. The Wall factor (W) is the ratio of tube outer diameter to the wall thickness of the tube [12]. In addition to these process related parameters, kinematic movement of tools also effect the process outcomes [11]. There are six fundamental bending tools used in the RDB process namely i) pressure-die, ii) bend-die, iii) wiper-die, iv) clamp-dies, v) mandrel and vi) collet. Recently, at the institute of forming technology (UTS) at Universität Siegen-Germany, it is identified that two tool based kinematic

parameters can be used to eliminate wrinkling in bent tubes [13]. These tool related kinematic parameters are i) ratio of tube and collet speed and ii) pressure die longitudinal kinematics and lateral clearance between the tube and the tool surface [13].

In addition to process parameters, the geometry and shape of bending tools have significant influence on the quality of finished products [6]. Conventionally, the bending tools have fixed geometry which correspond to only one tube diameter. Due to rigid geometry of tools, a particular tool set used in a RDB process is capable of bending only one specific tube diameter. For different tube diameters, a different tool set corresponding to the tube diameter is required. This makes the RDB process (with one specific tool set) inflexible for a large variety of tube diameters. On the other hand, other profile bending processes (e.g., roll push bending) which use generic tool sets are capable of conducting the bending operation for a larger range of tube diameters. However, these processes are commonly avoided in industrial practices due to low quality of finished products. Hence, amid the process in-flexibility, RDB process is preferred over other profile bending processes due to high quality of finished products. The tools used in the RDB process are presently manufactured from conventional subtractive techniques. Recent research conducted on the basis of FE-simulations have indicated that the tool surfaces do not experience uniform stress throughout the in-contact areas between the tube and the tool [14]. Rather only a portion of the tool surface experiences contact normal pressure due to which a pressure pattern is developed at the tool surface. This pressure pattern changes with the change in bending angle. These findings provide a window of opportunity to alter the geometry of a bending tool by reducing the tool design to include only those areas where contact pressure pattern develops. The reduced design of tool geometry is envisioned to provide substantial material saving while maintaining the desired quality of finished products. The identification of pressure pattern on tool surface not only indicates the possibility of tool's topology optimization but it also provides substantial basis to flexibilize the RDB process. Considering these aspects, a tool design capable of holding a wide range of tube diameters is envisaged which can transform the inflexible RDB process into a partially flexible process. This can be done by estimating the pressure applied by a wide range of tube diameters (and corresponding process parameters) and selecting a geometric design and tool materials which can withstand the applied pressure.

The increased demand of economic sustainability and product customization requires incorporation of modern manufacturing techniques in the primitive production practices. The digital twin of RDB process provides technological insights to utilize hybrid material combinations alongwith 3D printing techniques in order to design bending tools which will meet the requirements of modern production regimes.

Chapter 2 : Literature Review and State of the Art

2.1 Position of Rotary Draw Bending in overall manufacturing regime

The German Association of Engineers (DIN-8586) classifies the Rotary Draw Bending (RDB) process as a subclass of rotational and tensile forming process [7]. The position of a RDB process in the overall manufacturing regime is shown in Figure 2.1. A manufacturing process can be termed as an overall process in which raw material is developed into a desired product by the use of processes, machines, infrastructural equipment and accessories [15]. A forming process is a sub-class of the overall manufacturing regime in which material is changed into desired shape by the use of tools (dies, clamps, punches etc), processes and kinematic manipulations [16]. While forming processes are used for a wide variety of materials, yet in most of the industrial applications, the forming processes are established to produce parts mostly made from metals and alloys. Some of the examples of forming processes are forging, drawing, stamping, bending, casting, rolling, extrusion etc [17]. A tube bending process is a profile bending process in which semi-finished products are bent according to a preselected design. A tube bending process is influenced by various bending techniques. Two broad profile techniques used for tube bending applications are roll push bending and rotary draw bending. In industrial practices, a RDB process is preferred over roll push bending due to relatively high dimensional accuracy provided by a RDB process [9]. Previously, the bending operation conducted a RDB process was mainly conducted by the use of operator knowledge which operator had acquired from hit and trial methods. Recently, the use of FE-simulations have facilitated the formulation of process parameters which can be used to obtain high quality end products [13]. The identification of process parameters for a RDB process have greatly assisted the manufacturers in conducting the bending operations. However, in conducting complicated operations (particularly tight bends), the empirical knowledge of the machine operator still possesses fundamental importance because bending tools require specific adjustments, kinematics and force applications for desired process outcomes.

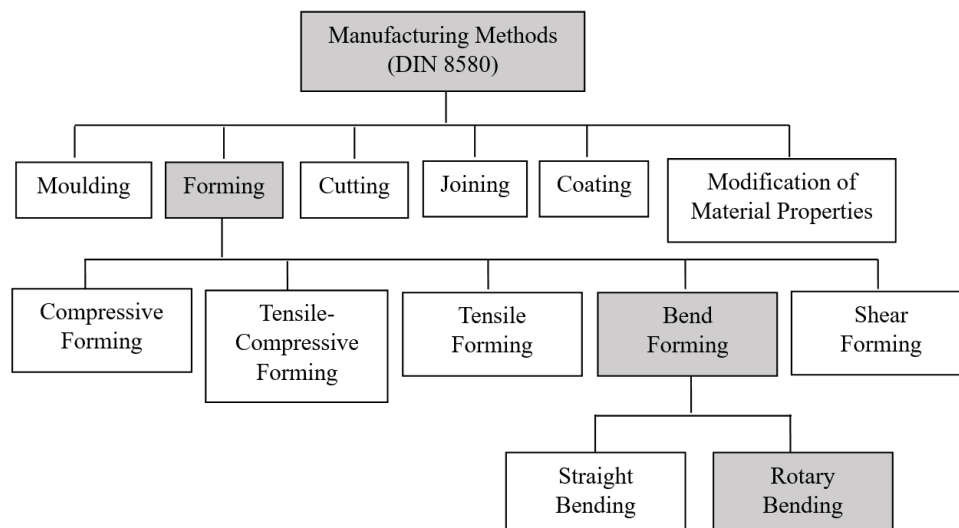


Figure 2.1: Forming processes in the overall manufacturing regime according to DIN 8580

2.2 Mechanics of RDB process

The process of RDB involves rotational bending of the tube along the tube axis [18]. The bending can be done along one plane or a combination of multiple planes. The process is carried out on a RDB machine which is installed with bending tools according to pre-designed fixtures. The tube is clamped by the clamp tools and a rotating band die rotates the tube according to a pre-calculated program which is coded and fed to the RDB machine. In conventional RDB machines used within the modern industrial setups, the process kinematics are fed to the machine using CNC coding. Over the years, computational and empirical research is conducted to investigate the process mechanics and corresponding effect on the tube quality. The quality of tubes bent from the RDB process are measured by German Association of Engineers VDI 3431 [10]. The standard VDI 3431 defines tube characteristics in twenty one quality aspects which can be used to determine the quality of bent tubes. Amongst these characteristics, wrinkling, ovality, springback and tube wall thickness are the fundamental quality aspects [19].

There are some fundamental parameters like process mechanics and tool kinematics which have significant effect on the tube quality. These procedures and methods are called as process parameters. The fundamental process parameters required to conduct a bending operation in the RDB process are bending factor (B) and wall factor (W) [11]. The B and W are calculated by following equations:

$$B = \frac{\text{Bending Radius}}{\text{Tube Outer Diameter}}$$

$$W = \frac{\text{Tube Outer Diameter}}{\text{Wall Thickness of Tube}}$$

These two process parameters form the basis of bent geometry of the tube. The process feasibility of the RDB process depends on the selected values of B and W. The values of B and W are mainly selected according to application requirements of the end user. Based on the selected values of B and W, the process parameters related to tool kinematics are employed to reduce or eliminate defects like wrinkling, ovality and springback [20].

2.2.1 Process parameterization in a RDB process

Process parameters encompassing tool kinematics play a significant role in reducing or eliminating tube quality defects [21]. There are mainly six fundamental tools in the RDB process. These are pressure die, bend die, wiper die, clamp dies, mandrel and collet [22]. The position of these tools during a bending operation is shown in Figure 2.2. Borchmann et al. demonstrated that the kinematics of bending tools significantly affect the tube quality [13]. She demonstrated that a lateral clearance between pressure die and tube can be used to reduce wrinkling and ovality in the tubes. In addition, the longitudinal movement of the pressure die contributes towards ovality reduction. The study also demonstrated that the collet can be used to withhold material flow within a tube surface. This resulted in a reduction in wrinkles however owing to low material flow, the strain at tube extrados (or the tube ovality) increased leading towards

enhanced risk of cracking. The two process parameters identified by Borchmann are (i) pressure die lateral clearance and (ii) ratio of tube and collet speed.

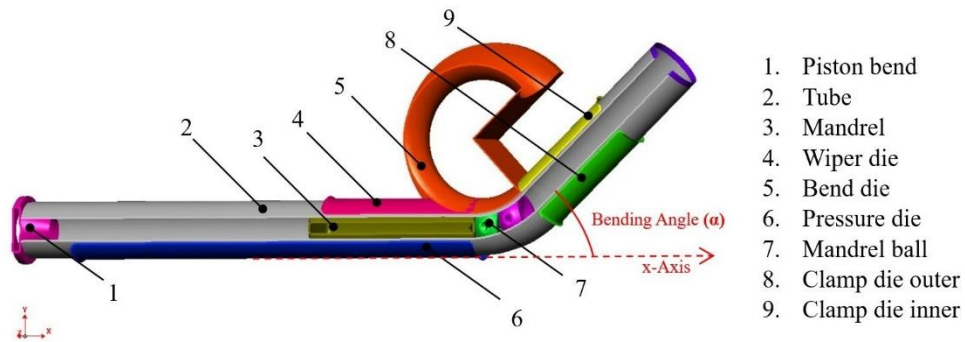


Figure 2.2: Position of fundamental tools in RDB process

The process parameters identified by Borchmann are shown in Figure 3. These process parameters were identified for a tube material of X5CrNi18-10 with $B = 1.875$ and $W = 20$. Although a change in B and W values will affect the tube quality in each respective case yet the values of two process parameters (pressure die clearance and tube-collet speed ratio) mentioned in Figure 2.3 can be used as a general yardstick to obtain wrinkle free tubes.

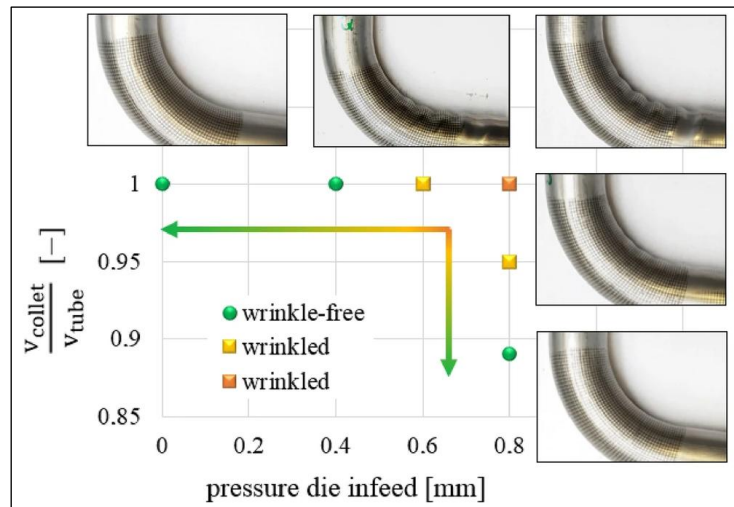


Figure 2.3: Identified tool based kinematic process parameters for obtaining wrinkle free tubes in RDB process. Process parameters are mentioned at X and Y axis respectively (Borchmann et al. [20], 2020)

In addition to above mentioned process parameters, tool design has a significant influence on the tube quality. Safdarian et al. [23] investigated the tube fracture in the RDB process. He investigated the tube fracture by using a mandrel with a different number of mandrel balls. He demonstrated the tube fractured when three mandrel balls were used alongwith the mandrel. However, at the same process parameters and tube material, the tube did not fracture with one and two mandrel balls. Subsequently, an ovality of 10% and 25% is obtained by using one and two mandrel balls respectively. Hence, it was concluded that two mandrel balls are optimum for the conduct of RDB process. Kajikawa demonstrated that the position of mandrel within the tube significantly affects the tube quality [24]. He highlighted

the requirement to push mandrel as forward as possible so that the tip of mandrel balls should conform to bending radius. It was shown that a backward position of the mandrel contributes towards wrinkle development. The coefficient of friction of the mating surfaces of the tools also have a significant effect on the tube quality. Hinkel et al. [25] investigated the influence of coefficient of friction of tool surfaces on the clamping behaviour of clamp tools. Kaleem et al. [26] (as part of this research project) demonstrated that a decrease in frictional values of pressure die surface results in improved tube ovality. Due to the frequent use of tools and subsequent cleaning and lubrication of mating surfaces, the surface roughness of the tools is decreased which results in slight reduction in coefficient of frictions. Kaleem used two models of coefficients of friction. In the Model-1, conventionally used values of the coefficients of friction were used whereas in the Model-2, slightly decreased values were used in the FE-simulation model of the RDB process. The process simulation yielded that a decrease in the values of the coefficient of friction resulted in a slight improvement in tube ovality. A practical experiment with the same process parameters was conducted and it was found out that the Model-2 matches with the practical results more than Model-1. The change in tube ovality as a result of slight change in coefficient of friction is shown in Figure 2.4.

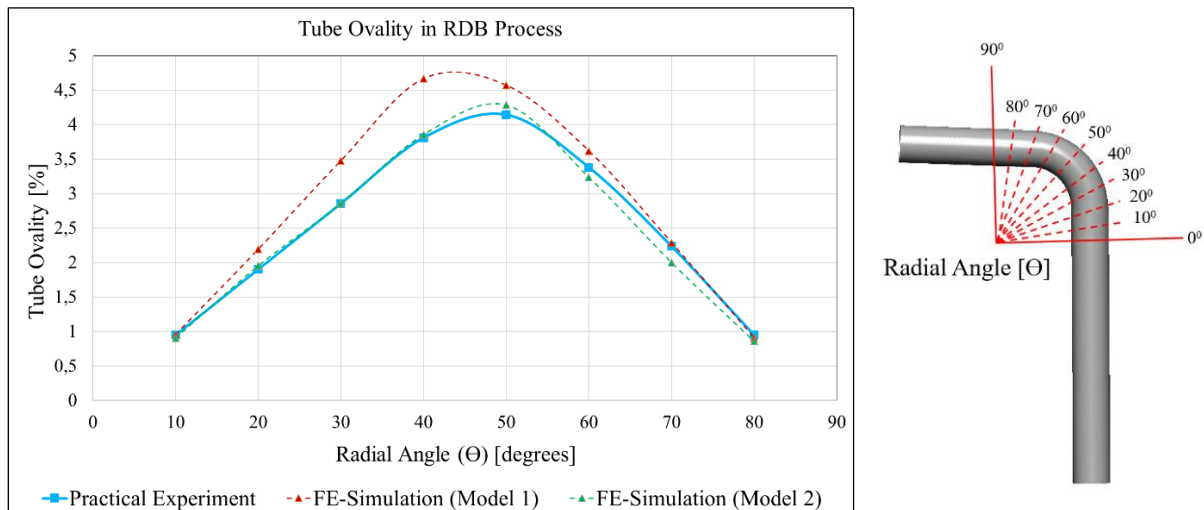


Figure 2.4. Effect of coefficients of friction (pressure die) on tube ovality (Kaleem et al. [26], 2024)

The RDB process is a cold form bending process. It is normally conducted at room temperature with standard temperatures and humidity conditions. Li et al. [27] conducted the RDB process by imparting cryogenic temperatures to bending tools. She found out that the coefficients of friction at the surface of bending tools vary with a decrease in temperature. She demonstrated that a considerable reduction in wrinkling and tube ovality can be obtained if the bending tools are cooled at a temperature of -60°C . Daxin et al. [28] investigated the influence of a gap between tools and tube. He identified that when a gap between the tools and tool increases more than 0.2 mm, a large increase in wrinkling is observed. Borchmann et al. [20] Identified that the machine stiffness has a profound influence on the process outcomes. A lower machine stiffness assists in wrinkle reduction and vice versa.

Kaleem et al. compiled a consolidated list of process parameters in RDB process [29]. The process parameters identified (and published) by process experts were compiled in tabular form and represented in green and red colours. The compiled list of process parameters in RDB process is shown in Table 1. The green colour represents desirable characteristics and red colour represents un-desirable characteristics.

Table 1: Compiled list of process parameters in RDB process (Kaleem et al. [29], 2023)

Process Parameters	Standard Value	Effect on Tubes Quality			Reference
		Wrinkling	Ovality	Strength against Cracking	
Pressure Die Speed (Relative to Tube)	1.0	Increase with speed	-	Increase with speed upto 1.7	7 & 8
Collet Speed (Relative to Tube)	1.05	Increase with speed	Increase with speed	Increase with speed upto 1.05	7 & 8
Pressure Die Clearance (Collet Speed of 1 relative to Tube)	0 to 0.4 mm	No Wrinkling	-	Decrease with clearance	19
Pressure Die Clearance (Collet Speed of 0.89 relative to Tube)	0.8 mm	No Wrinkling	-	Decrease at values less than or more than 0.8 mm	20
Friction Coefficient between Pressure Die and Tube	0.05 (Minimum Possible)	-	-	Increase with decrease in friction coefficient	21
Mandrel Position in Tube	As close to bending radius (15mm for 46mm bent radius)	No Wrinkling	Decrease when mandrels position is close to bending radius (upto certain limit – case based)	Increase when mandrels position is close to bending radius (upto certain limit – case based)	22
Mandrel Balls	Two	-	Decrease upto 2	Decrease with 3 onwards	24

Note: Green are desirable ; Red are undesirable. The references mentioned in the Table 1 are available at [29] (<https://doi.org/10.25819/ubsi/10365>).

2.2.2 Sensitivity analysis of quality characteristics

The manifestation of springback, wrinkles and tube ovality are considered as the three fundamental defects in bent tubes. The sensitivity analysis of these aspects has shown that each of these defects are influenced by relevant factors. Although there is no fixed solution to eliminate all of these defects yet an appropriate selection of process parameters and tool kinematics can significantly reduce or eliminate tube ovality and wrinkling. The state of the art on these defects is highlighted in following sections:

- (a) **Springback.** Research has shown that springback cannot be purely eliminated in a RDB process however such methods have been identified which can significantly reduce the springback by monitoring the bending process in real-time. Simonetto et al. [30] demonstrated the use of a springback compensation method in which in-process springback can be detected and a compensation method can be affected during the process. Liao et al. [31] formulated constitutive methods for measurement of springback of asymmetric tubes in a RDB process. Zhu et al. used plastic (polymeric) mandrels in RDB process [32]. He identified that rigid mandrel made from alloy steels are far better in overall performance as compared to plastic mandrels. The average springback provided by rigid mandrel was noticed to be 3.4° whereas average springback provided by plastic mandrels went upto 5.1° . The minimum springback provided by polymer mandrel was provided by PTFE mandrel having an average springback of 4.34° . Li et al. determined the springback of high strength titanium tubes (HSTT) [33]. He determined that the springback occurs due to elastic compensation of tube material. He showed that the occurrence of springback results in slight improvement of tube ovality. The springback cannot be completely eliminated due to the tendency of materials microstructure to attain its original position. Liu et al. mentioned that after bending operations, the non-linear residual stress within the material results in springback as shown in Figure 2.5 [34].

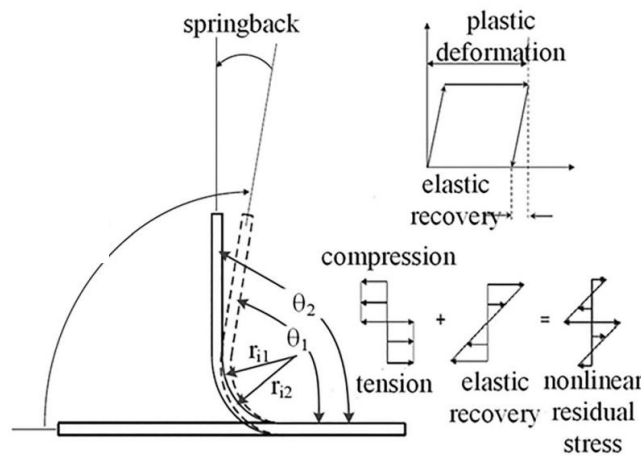


Figure 2.5. Non-linear residual stress in UHSS results in springback after bending operation (Liu et al. [34], 2020)

- (b) **Wrinkles.** Fundamental research is conducted at the institute of forming technology (UTS-Siegen) with specific focus on wrinkle detection and elimination in profile bending operations. Kuhnhen et al. [35] formulated a method of wrinkle detection in tubes used in a RDB process. He presented the concept of wrinkle evaluation factor based on numerical and practical investigations conducted on an industrial scale RDB machine. Borchmann et al. [36] used lasers to detect early development of wrinkles in the bent tubes. In another study, Borchmann investigated the influence of the machine axis stiffness on the development of wrinkles [20]. In

her PhD thesis [37], she identified two process parameters which can be used to eliminate wrinkling in the bent tubes. These process parameters are mentioned below:

- i. **Ratio of collet speed to tube speed = 1**: This ensures that the tube is firmly clamped by the collet from its base. A speed ratio of 1.0 between tube speed and collet speed ensures that tube material is neither over stretched nor gathered at a particular region (for example intrados). Hence, wrinkle development is prevented at the intrados. Since material is primarily restricted from flowing and gathering around the bending portions therefore possibility of crack development is slightly increased at the tube extrados [13].
- ii. **Pressure die clearance > 0.4 mm**: This ensures that the counter force of pressure die is transferred onto the tube which in turn transfers and balance the force of mandrel and wiper die. Due to the provision of effective counter force provided by the pressure die, the force exerted by wiper die is effectively transferred onto tube which restricts presence of gap between wiper die and the tube at the tube intrados. This prevents development of wrinkles at the tube intrados.

In the doctoral thesis of Borchmann, it was demonstrated that the pressure die clearance can be increased from 0.40 to 0.80 mm if the ratio of collet speed to tube speed is reduced from 1.00 to 0.89 [37]. An adroit adjustment of the above mentioned tool kinematics (mentioned at i and ii) produce wrinkle free tubes. The logical basis of her investigations show that the wrinkle free tubes are obtained due to the less material flow at the intrados of the tubes. The wiper die is compressed because of lateral force applied by pressure die and material flow is restricted [13]. The investigations also show that on one hand, wrinkling is eliminated by the use of aforementioned tool kinematics, however on the other hand, probability of cracking at the extrados is increased due to larger strains. Li et al. [38] used polymeric fillers within Aluminium tubes to reduce wrinkling. She demonstrated that the wrinkling can be significantly reduced by the use of fillers however, a careful selection of coefficients of friction is necessary to reduce wrinkling in the tubes.

- (c) **Ovality**. The ovality at the bent portion of the tubes fundamentally depends on the selected values of process parameters (particularly B and W) [13]. A lower value of B corresponds to a tight bend in which ovality changes sharply whereas in case of higher values of B, the change in tube ovality takes place relatively gradually [14]. In addition, tool kinematics also have a profound effect on the ovality [39]. As part of this research thesis, Kaleem et al. published a research article in which it was identified that the contact forces applied by the bending tools have a significant effect on tube ovality [40]. It was demonstrated that by changing the withdrawing time of mandrel, the contact forces of pressure die change and as a result tube ovality is altered. FE-simulations were used to identify the correct time of mandrel withdrawal in a RDB process. Safderian et al. [41] conducted an investigation on the ovality of tube for mild

steel (BS 3059). He demonstrated that the mandrel position during a bending operation significantly affects tube ovality. In addition to the correct mandrel position, the tube ovality significantly depends on tube material and process parameterization [29]. Heftrict et al. [14] conducted investigations on active surface area of bend die by considering tube ovality as the target criteria. He demonstrated that the active contact surfaces of bend die have a significant effect on the tube ovality.

2.2.3 Plasto-mechanical model of RDB process

Engel & Hassan et al. developed plasto-mechanical model of the RDB process. The model focus on accurate prediction of Neutral Axis Shifting (NAS) and wall thickness distribution of the tube during bending process [42]. The tube material has a profound influence on the NAS and wall thickness of the tube at bent portions. The strain hardening coefficient 'n' typically predicts the true stress strain relationship of materials [43]. In case of bent tubes, circular geometry of the tube effect the strain development in an un conventional manner. In the plasto-mechanical model, the material properties of the tube are taken into consideration by using an empirically determined formula C_T (Correction factor). The correction factor is used to determine the equations which can accurately predict NAS and wall thickness distribution in tubes. The correction factor is given by:

$$\text{Correction factor } (C_T) = \left| \ln \frac{n.R_b}{t_o.100} \right|$$

Due to shifting of neutral axis of the tube, the bending radius is also changed slightly. A change in the bending radius results in a slight change in Bending factor (B) and the overall process parameters are disturbed. Therefore, it is essentially important to accurately predict the NAS of the tube during a bending operation. The plasto-mechanical model of the RDB process demonstrated that the NAS in bent tubes decrease with an increase in Wall factor (W) and Bending factor (B).

2.3 Tool Geometric Design

The quality of products obtained from production processes are largely dependent on the performance of production tools. The geometry of tools significantly influences the conduct of production processes [44]. Substantial research has been conducted on the performance of various production processes however, the geometric design of tools and associated tool performances have not remained in specific focus. An in-depth analysis of various investigations which were primarily conducted for process methodologies indicate that the geometry of forming tools can significantly affect the process performance in production operations [45]. A review of the research conducted within the domain of a tool design is presented in following sections.

2.3.1 Geometric design of tools in forming processes

Presently, the metal forming processes are categorized in a significantly large variety of processes. Each forming process uses a unique type of forming tools. The geometry of tools used in forming processes fundamentally depends on the process requirements. Geueke et al. [46] conducted structural optimization of forming tools and proposed a lightweight geometry of stamping dies in rubber pad

forming. Azamirad et al. [47] developed a material economized design of a casting die with 37% volume reduction. Aitharaju et al. [48] highlighted the importance of using FE-simulations in improving the geometric design of stamping dies. Meng et al. [49] demonstrated that the product quality in forging operations can be significantly improved by altering the design of forging dies according to process requirements. The list of research conducted for improving the process performance of forging and stamping operations through the use of efficient designs of dies is almost inexhaustive. However, owing to the fact that profile bending operations require an in-depth specialization and only few specialized research platforms purely focus towards bending technology, the research in improving the tool designs in profile bending operations is relatively scarce.

2.3.1.1 Tool design factors

The tool design factors are considered before designing the tool for a specific process [50]. In forming processes, the geometric design of the tool critically influence the process outcomes [23]. It is essentially important that the factors which significantly affect the process outcomes are studied and these factors are used to design the geometry of the tools. In case of finish turning operations, the tool geometry significantly effects the final products [51]. It was demonstrated that the factors which contribute to appropriate tool approach angle, groove on rack face and side cutting edge are essentially important to in tool design. Mehalik et al. highlighted that design elements which effect the final product are essentially required to be consulted before fabricating tools [52]. He concluded that a process framework which produces most beneficial results is required for a good design. It was shown that 15 design elements are essentially sufficient to describe any process and these elements may be used to construct a good design. It was also mentioned in his study that the design factors which create high impact are required to be given more consideration and vice versa. The transition of investigations related to design elements into a geometric design require a skilful design strategy [52]. Anand et al. investigated the effect of tool geometry on friction stir welding [53]. It was highlighted that the rotational speed of the tool effects the process parameters of friction stir welding. It was concluded that the design factors which effect rotational tool speed and weld speed should be considered for finalizing the geometric design of tools for friction stir welding.

Nee et al. documented the fundamentals which are essentially required for a tool design [54]. It was highlighted that the geometric design of machine tools and fixtures should correspond to relevant process requirements. The process requirements are different for each respective process. For each process, the requirements should be studied in the form of influencing design factors and these factors should be given consideration while designing the tools and fixtures. In addition to influencing design factors, the material selection of the tools is required to be done in accordance with respective process requirements. The design methodology provided by Nee is shown in block diagram mentioned (Figure 2.6) below:

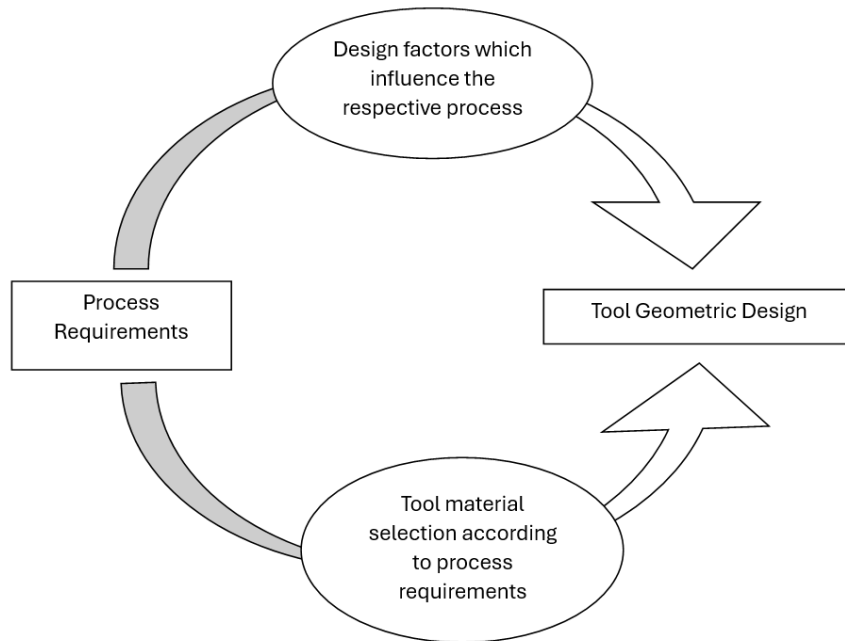


Figure 2.6. Design strategy for tools (punches and dies) in forming processes (Nee et al. [54], 2010)

2.3.1.2 Topology optimization of tools

Topology optimization and structural optimization are interchangeable terms used to describe an optimization process in which required material within a design space is reduced to bare minimum requirement [55]. The process is conducted by algorithms which predict the presence of material at places within the geometry where they it is essentially required [56]. Topology optimization of tool geometries can be conducted by using various computational approaches. Some of the fundamental approaches used for topology optimization are density approach (also called as SIMP: Solid Isotropic Material Penalization), level-set, topological derivative and evolutionary approach etc [55]. Each approach aims to place required material within a pre-set design in order to obtain best performance from the provided design constraints. For structural designs, a combination of these approaches known as ‘hybrid approaches’ provide best convergence criteria for topology optimization [26]. Presently, many commercially available FE-sofwares are equipped with an in-built module of topology optimization at the interface e.g., Autodesk Inventor uses a hybrid approach (combination of SIMP and level-set methods) to conduct topology optimization. In design of tools, topology optimization results in significant material saving and cost effectiveness.

Geueke et al. conducted structural optimization of stamping die [57]. It was demonstrated that the stamping dies can be reduced to 30% of the original tool volume through structural optimization. The tool performance of reduced stamping die was tested for small sized batch production using rubber pad forming operation. It was identified that stamping die executed cup drawing experiment with similar precision as the original die. A quarter section of the structurally optimized stamping die is shown in Figure 2.7. Kaleem et al. conducted topology optimization of bending tools in RDB process [26]. It was identified that the topology optimization of tools results in substantial material and cost savings. The

cost effectiveness of topology optimized tool is computed therefore material cost comparison model provided by Ashby. In the Ashby cost comparison model, the material costs are compared using cost performance index [58]. In addition to material costs, weight of the topology optimized tools is also significantly reduced due to removal of unwanted material from tool geometry.

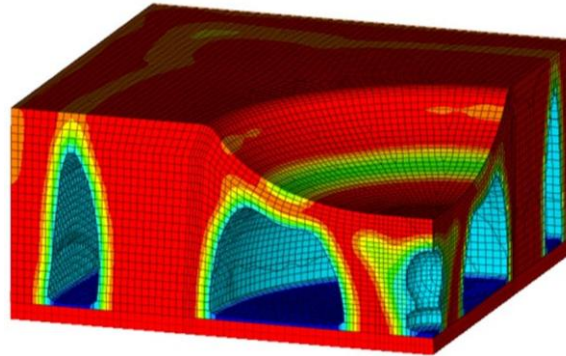


Figure 2.7. Structural optimization of stamping die with 30% material reduction within tool geometry (Geueke et al. [46], 2021)

2.3.2 Geometric design of tools in RDB process

The conventional bending tools used in a RDB process have fixed geometries [9]. This means that a RDB process can only be used to bend one specific tube diameter with a specific tool set. While not much research has been conducted on changing the geometric design of bending tools in a RDB process, yet there are considerable instances where researchers have pointed out that the tool geometries have a significant effect on the process outcomes. Xu et al. [59] highlighted that the tool geometries have significant effect on development of contact forces in a RDB process. The influence of tool geometries on the contact forces applied on tube surfaces indicate that a design change in the tool geometry can potentially change the process outcomes. Sun et al. [60] & [27] determined the fracture energy of the tubes in a RDB process. It was demonstrated that a change in the coefficient of friction of bending tools has a significant effect on the fracture energy of the tube. The tools were cooled at cryogenic temperature and the coefficient of friction of tools were changed in order to determine the effect of cryogenic temperatures on tube quality. The research related to tool geometry provides substantial evidence that the contact surface area of bending tools has a significant effect on the tube quality in a RDB process. An effective tool design should incorporate only required surface area of the bending tools. The surface area of the tools can be reduced to bare essential requirement by identification of contact pressure at the tool surface.

2.3.2.1 Effective design of tool

The effectiveness of a tool is determined on the basis of advantages obtained from tool performance [52]. These advantages can be observed in terms of cost effectiveness, process improvement, material savings, ease of manufacturing or any other measure relevant to efficient tool performance. Ozcan et al. demonstrated high efficiency of mandrel in RDB process by obtaining process improvement [61]. Bayramoglu et al. demonstrated tool effectiveness in terms of material savings [62]. He showed that

efficient tools in manufacturing processes can be developed with material savings upto 64%. Sufian et al. demonstrated process effectiveness in terms of cost savings [63]. Based on these perspectives, the effectiveness of a tool in RDB process can be categorized in terms of materials savings, process enhancement (e.g., process flexibilization) and process improvement. Mehalek et al. highlighted that any design of the dies and fixtures which contributes towards process or product improvement is categorized as an efficient design [52].

2.3.2.2 Contact pressure at the tool surface

In order to design an effective tool in RDB process, the contact pressure on tool surface is required to be identified. Heftrich et al. identified that the contact pressure at the tool surface is not distributed uniformly throughout the mated surface between tool and tube [14]. Rather, a pattern of contact pressure is developed at the tool surface. This contact pressure changes with the change in bending angle [40]. At some regions on the tool surface, a high pressure is manifested whereas at the other regions, a comparatively low pressure is observed. Heftrich conducted the investigations on bend die in RDB process and it was determined that only central portion and fringes of the bend die are mainly utilized during bending operation [14]. This was evaluated by considering the tube ovality during entire bending operation. The investigations showed that the results of reference geometry of bend die is closest to the test case geometry consisting of only central surface and fringes of the bend die. Kaleem et al. determined that the utilized area on pressure die surface (in static mode of RDB process) is significantly less than the total surface area of the pressure die. The pressure pattern changes with a change in bending angle, however at all bending angles from 0° to 90° the pressure pattern is evident only on the front portions of the pressure die, hence utilized area of pressure die is significantly lesser as compared to the total surface area of the pressure die. Figure 2.8 shows the utilized surface area of the pressure die at a bending angle of 45° . It can be seen that the contact normal pressure is acting only on the front portions of the tool. At the rear portion, only negligible contact is established.

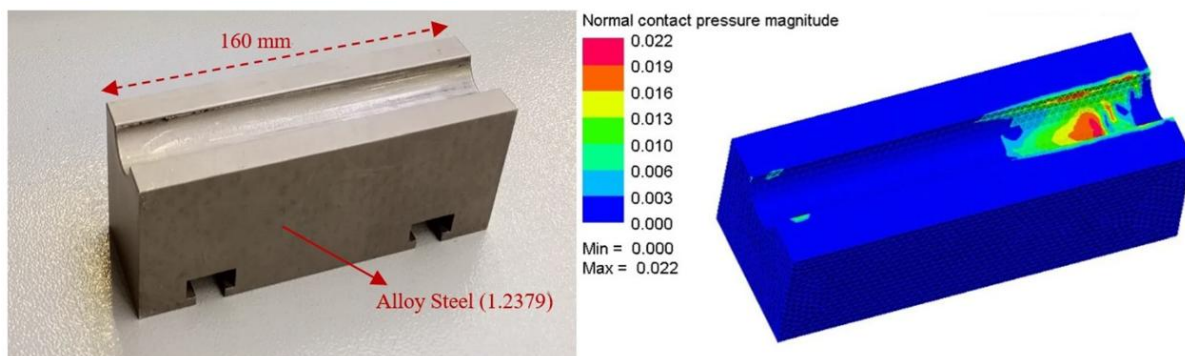


Figure 2.8. Contact pressure on tool surface of pressure die in static mode of RDB process. Only front portions of the pressure die experience contact pressure on the surface: Bending angle (α)= 45° , B=1.5, W=22 ; Tool material = EN 1.2379 or X155CrVMo12 (Kaleem et al. [26], 2024)

2.3.2.3 V-shaped tool design

Presently, RDB process is considered as an inflexible process i.e., the tool set used to bend tubes are specifically designed for respective tube diameter. These tools cannot be used with multiple tube diameters. This makes bending tools geometric specific to one tube size and incompatible for multiple tube sizes. In order to design tools which can hold multiple tube diameters, the surface of the bending tools is required to be developed in V-shaped geometry. Heftrich et al. suggested that the V-shaped tool surfaces can hold multiple tube diameters [14]. The concept emerging from his investigations show that the bending tools in RDB process can hold multiple tube diameters if the circular profile of the tube surface is transformed into V-shaped surface geometry. The concept of V-shaped tool geometry is depicted in Figure 2.9.

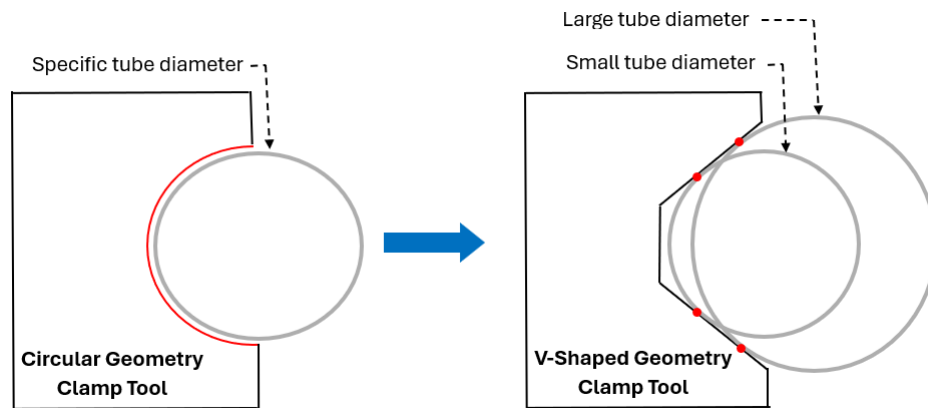


Figure 2.9. Concept of transforming circular tool surface into V-shaped tool surface for holding multiple tube diameters (Heftrich et al. [14], 2021)

2.3.3 Material Selection of Tools

Material selection is one of the fundamental requirements in tool design [64]. In metal forming processes, the tool material should possess requisite strength and capacity to withstand loads resulting during the process. The conventional tools used in RDB process are relatively hard and stiff [41]. Presently, the material used to manufacture bending tools in RDB process (for example pressure die and clamp dies) is D2 tool steel (X153CrMoV12 or EN 1.2379) [27]. In some case, a similar material EN 1.2363 or X100CrMoV5 is also used for manufacturing bending clamps and dies. EN 1.2363 is a subclass of alloy steel with almost 1% Carbon [65]. These conventionally used tool materials (alloy steels and tool steels) have high hardness and material stiffness. In comparison to these steels, polymers are less stiff but they are substantially cheaper in costs and carries significantly lesser weight [66]. Different polymeric materials have different stiffness. Frohn-Sörensen et al. conducted material testing of four commonly used 3D printed polymers namely PLA, PC, PETG and PA [67]. He identified that the material properties of PLA are comparatively higher than the other investigated polymer types. The 3D printed PLA exhibited higher yield strength and elastic modulus both in compression and stretching. The investigation results of Elastic modulus 'E' are shown in Figure 2.10.

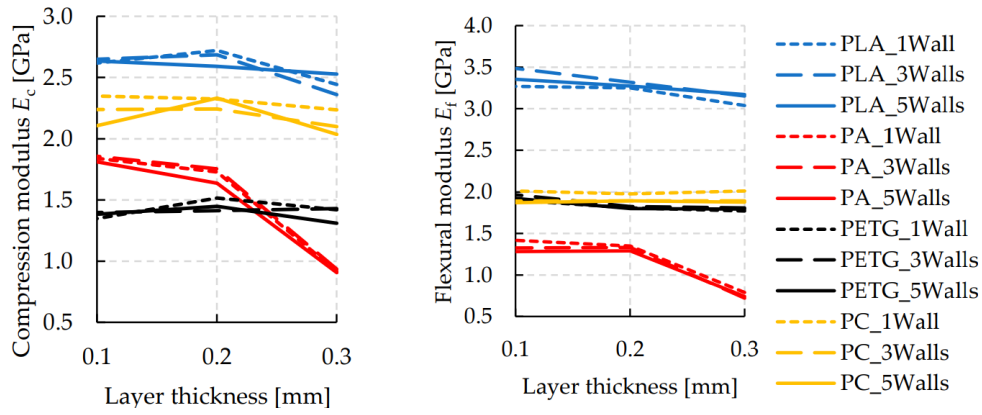


Figure 2.10. Elastic modulus of 3D printed polymeric materials. PLA demonstrated highest E both in compression and flexure (Frohn-Sørensen et al. [68], 2022)

For simpler geometries, the material stiffness is also referred to as material's Elastic modulus (E) or Young's modulus (Y) [69]. Due to process relatively higher loads in forming processes, the forming tools are required to possess comparatively higher material stiffness. In addition to material stiffness, the weight of tools has become critically important in forming processes [70]. This is because the lightweight tools can be easily handled and placed on production machines by collaborative robots (cobots). In future manufacturing industries, the cobots are foreseen to handle the production tools in digitally controlled setups [71]. These aspects of tool design directs that material stiffness and weight are critically important characteristics for tool design. Ashby presented a model of material selection for parts, products, tools and fixtures etc [72]. In the Ashby material selection model, the part material can be selected on the basis of stiffness to weight ratio of the materials. Ashby termed stiffness to weight ratio is called as the 'performance index' of the materials [73]. The performance index is a diagonal line which runs and passes through various material groups in Ashby chart. The stiffness to weight performance of all materials falling on the same performance index is equal. The diagonal slope of performance index depends on geometric shape of the part. In case of rectangular beams (for example tools with larger length as compared to width or height), the slope of performance index is calculated by $E^{1/2}/\rho$ [74]. The Ashby material selection chart is shown in Figure 2.11.

Based on the material performance of each material obtained through the performance index, Ashby highlighted that parts consisting of multi-materials of hybrid materials can also be designed [75]. It was highlighted that in case of parts made from hybrid materials, the values of stiffness and density are required to be calculated according to the design and composition of the different materials within the part geometry.

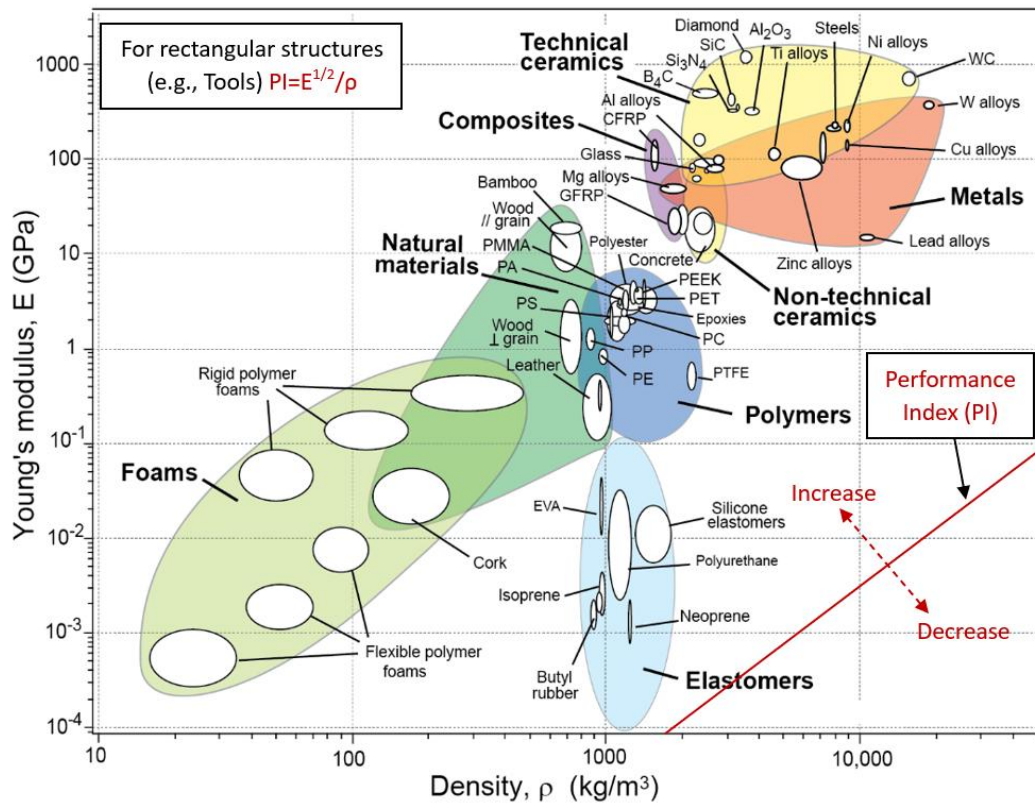


Figure 2.11. Material selection based on stiffness to weight ratio of designed parts. The stiffness to weight ratio of the materials are represented by a diagonal line (performance index). The performance of all materials falling on the same performance index is equal (Ashby et al. [74], 2018)

2.4 Additive Manufacturing

Additive Manufacturing commonly known as AM (or 3D printing processes) are manufacturing techniques in which an object is developed in the form of layers with each layer deposited over one another [76]. The three fundamental materials used in 3D printing processes are metals, plastics and ceramics. The ceramics are mostly used in construction industries whereas metals and polymers are largely used in manufacturing and production regimes [77]. Due to the possibility of developing complicated geometries with relatively faster rates of production for lower batch sizes, the 3D printing processes have entered in almost all manufacturing domains. In case of metal forming processes, the 3D printed tools are foreseen to deliver promising dividends. The reduction of a tool design from a simple geometry to a complicated geometry requires manufacturing through 3D printing (additive manufacturing) techniques. Presently, a wide range of 3D printing techniques exist in academia and industry. The techniques relevant to tool manufacturing are polymer based additive manufacturing and metal based additive manufacturing. One of the most commonly used polymer based additive manufacturing techniques is Fused Filament Fabrication (FFF) or commonly known as Fused Deposition Modelling (FDM). This technique uses relatively low cost 3D printing machines which are capable of printing only polymeric materials. In this technique, the speed of product development is significantly faster and post-processing treatments are generally not required for finished products. Due

to low cost of product development, this technique is mostly used in prototyping applications [78]. On the other hand, metal additive manufacturing process encompasses a wide range of techniques. Laser Powder Bed Fusion (L-PBF) is a commonly used metal 3D printing technique which predominantly uses Selective Laser Melting (SLM) technique in most of its applications. SLM technique involves sintering of metal powder on the application of heat from a laser. Presently, installation of SLM machines (with allied air circulation systems) is significantly expensive as compared to polymers. Moreover, the 3D printed products have relatively slower rate of production and produced parts generally require post-processing treatments owing to presence of porosity in the printed parts [79]. Laser Metal Deposition (LMD) is another metal additive manufacturing technique which is relatively simpler as compared to SLM. The LMD technique involves deposition of powder metals from a specialized deposition nozzle. The deposited metal powder is heated by laser application and a melt pool is created which sinters the deposited metal powder on substrate material. The LMD technique is mainly used to clad metal layers on various parts and components [80]. Presently, there is no industrially established 3D printing technique with which polymers and metals can be 3D printed together in a single machine. Hence, in order to 3D print a hybrid material comprising polymer and metal, two different 3D printing techniques are required to be used in tandem.

2.4.1 Advantages of additive manufacturing

The 3D printed forming tools are developed to explore the advantages offered by additive manufacturing techniques and use these advantages to bring improvement in process outcomes and product quality [81]. Recent research conducted in the domain of 3D printed forming tools have shown that 3D printing of forming tools is preceded by topology optimization and CAD modelling [82] & [26]. A significant benefit of 3D printing processes is the use of polymer made tools for prototyping purposes. In order to categorize the benefits offered by 3D printing processes, the research conducted in lieu of 3D printed forming tools can be segregated into distinct core areas. The literature review suggests that 3D printed forming tools are envisioned to deliver advantages in following core areas:

2.4.1.1 Manufacturing of complicated geometries through AM

Additive manufacturing possesses the potential to develop complicated geometries through layered fabrication of objects [83]. Colosimo demonstrated development of complicated geometries by Laser Powder Bed Fusion (L-PBF) technique [84]. He 3D printed metal lattice structures of A357 Al-Si-Mg Aluminium alloy. Olsson et al. [85] used 3D printing processes to develop complex part geometries from Boric Carbide. He demonstrated that fine structure like threads on nuts can be 3D printed with a fairly high level of accuracy. Gao highlighted the potential of obtaining design benefits from additive manufacturing. He highlighted the effective linkage provided by additive manufacturing in connecting design methodologies and topology optimizations with manufacturing processes [86]. The case studies of fabricating complicated designs through additive manufacturing in health care, aerospace and automotive industries were presented.

2.4.1.2 Material savings in AM built parts

In metal additive manufacturing, the use of powdered material contributes towards material savings as there is no scrap material from cutting, drilling or grinding. Ford et al. [87] highlighted the potential of additive manufacturing in material savings, lifecycle management of materials and improved sustainability of production processes. Despeisse et al. [88] conducted an assessment study and concluded that industrial practices incorporating AM processes result in almost 60% material savings through waste reduction. Kaleem et al. highlighted that the integration of AM processes in the context of industry 4.0 possesses the potential to incorporate material savings at factory level [76]. In addition to material savings through process methodology, the additive manufacturing processes bridge the gap between topology optimization and material economized production. The complex designs produced by topology optimization are generally not feasible for production through subtractive manufacturing processes. These designs are required to be manufactured by 3D printed techniques [26]. Saadlaoui et al. [89] demonstrated material savings through 3D printing of topology optimized designs of metal structures. Frohn-Sörensen et al. [68] demonstrated the polymer based 3D printing of tools. Geueke et al. [46] the development of structurally optimized stamping dies for rubber pad forming. He showed that substantial material savings can be incorporated in the die geometry through a topology optimized design and subsequent 3D printing by Fused Deposition Modelling process.

2.4.1.3 Lightweight of 3D printed parts

Due to material savings through DfAM (Design for Additive Manufacturing) and shape optimizations, the parts produced by additive manufacturing are significantly light in weight [90]. In addition to sneak geometries, the material selection in AM can prove to be significantly useful in manufacturing lightweight components. Cheng 3D printed lightweight components using Continuous Fiber Reinforced Composite Materials (CFRCs) [91]. He demonstrated that CFRCs can be used in production industries as they are substantially lightweight and cost effective as compared to many metals and alloys. Moon et al. [92] developed lightweight structures for unmanned aerial vehicles through 3D printing techniques. Zhu developed lightweight shell structures fabricated through polymer based 3D printing techniques [93]. He demonstrated that FDM technique can be effectively used to develop lightweight structures by creation of shells within the geometry and use of polymeric materials which are significantly light in weight as compared to metals.

2.4.1.4 Fast production of small batch sizes through AM

In comparison to bulk production processes, additive manufacturing processes have significantly high rate of production for low batch sizes [94]. This makes additive manufacturing processes significantly suitable for customized productions. Simons et al. [95] highlighted that L-PBF processes are cost intensive techniques however faster production of smaller components through L-PBF processes can offset the disadvantage of high costs. Gutowski et al. [96] highlighted that the speed of extrusion based 3D printing is relatively higher than the speed of metal 3D printing. He demonstrated that the process parameters can be adjusted to increase the rate of production in 3D printing processes. However, the

energy requirements of faster production rates are almost the same as compared to lower production rates. The rate of production of various 3D printing processes differ from each other due to differences in process methodologies. Nazir et al. [97] demonstrated that the rate of multijet extrusion processes is considerably faster than the rate of selective laser sintering technique. The batch size of production through 3D printing processes depends fundamentally on the compartment size of the 3D printing machine. Skora et al. [98] highlighted that the batch size of 3D printer machines can be tailored by formulating machine shifts within single production setup. The 3D printing machines have different print-bed sizes for example DMP Flex 350 from 3D systems is a metal 3D printing machine with a powder bed size of 275 x 275 x 420 mm (length x width x height) and Prusa MK-4 is a FDM 3D printer with print-bed size of 250 x 210 x 220 mm (length x width x height) [99] & [100]. The geometry of parts required to be produced therefore depends upon print-bed size of the installed 3D printers within a factory.

2.4.2 3D printed polymer made tools

‘Additive tooling’ is relatively a new term used to describe the 3D printed manufacturing tools in production setups [67]. Owing to comparatively lesser cost and weight of polymeric materials, the polymer made tools are considered to be useful in metal forming processes [101]. In comparison to metals, a significant limitation of the polymeric materials is their low strength and Young’s modulus. Different polymers manifest different material properties however in each case the elastic modulus of polymeric materials generally remains lesser than 5.0 GPa and the yield (in compression) generally less than 100 MPa. It has been observed that the material properties of 3D printed polymeric materials differ from the bulk material [101]. Frohn-Sörensen investigated that the print parameters selected in polymer 3D printing (FFF- Fused Filament Fabrication) have significant effect on the material properties of the 3D printed parts. The investigation conducted on four commonly used polymeric materials (PC, PLA, PA and PETG) is shown in Table 2:

Table 2: Mechanical properties of 3D printed polymers (Frohn-Sörensen et al. [68], 2022)

Material	PC			PLA			PA			PETG		
Layer [mm]	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3
E_f [GPa]	1.92	1.92	1.93	3.37	3.28	3.12	1.34	1.32	0.75	1.93	1.81	1.79
σ_f [MPa]	92	93	92	111	105	98	82	79	49	82	79	76
E_c [GPa]	2.23	2.30	2.12	2.63	2.67	2.44	1.84	1.71	0.92	1.38	1.46	1.39
σ_c [MPa]	79	78	79	90	78	71	79	72	44	56	54	48
R_z [μ m]	26	60	125	14	26	26	13	23	63	15	26	30
Hardness (Shore-D)	82	82	82	84	80	81	79	77	71	79	78	78
ρ [kg/m^3]	1186	1178	1172	1228	1202	1166	1114	1095	1002	1252	1239	1213

The investigations conducted by Frohn-Sörensen show that in comparison to other polymeric materials, PLA demonstrates enhanced mechanical properties. The layer thickness in FFF based 3D printing processes is a fundamental print parameter which affects the mechanical properties of 3D printed parts. From Table 1 (highlighted columns) it is also noticed that a layer thickness of 0.1 and 0.2 are ideally suitable for developing 3D printed parts through FFF technique.

2.5 Digital Twin in forming processes

The digital twin of a production process is the virtual representation of the real process [102]. It uses real process constraints, kinematics, material properties, environmental conditions and FE-simulations to compute the process outcomes in virtual domain [103]. In case of production processes, the digital twin is used to obtain an in-depth process performance, tool behaviours, material performance and process results [104]. Polini et al. developed the digital twin of composite assembly manufacturing process [105]. Link et al. developed a digital twin of the deep drawing process [106]. He demonstrated the possibility of linking Machine Learning (ML) with the process simulations of digital twin. The real time data was fed by ML into process simulations and friction of the parts was adjusted during in the process. The adjustment of friction was used to avoid predicted defects in the parts. Turan et al. highlighted that the development of digital twin in production processes require FE-simulation and input process parameters which can be obtained by sensors or already established process data [107]. Turan demonstrated that a digital twin can be used as enablers of production optimization which can result in process sustainability. Zhou et al. developed digital twin for stamping system for incremental bending [108]. He named digital twin stamping system as DTSS. In incremental bending, the process data is at each incremental step is required for enhanced process understanding. It was demonstrated that the information related to loading path and punch speed can be obtained with the help of DTSS. This information was compared with practically measured data and substantial accuracy is ascertained. The concept of developing digital twin for manufacturing process is shown in Figure 2.12.

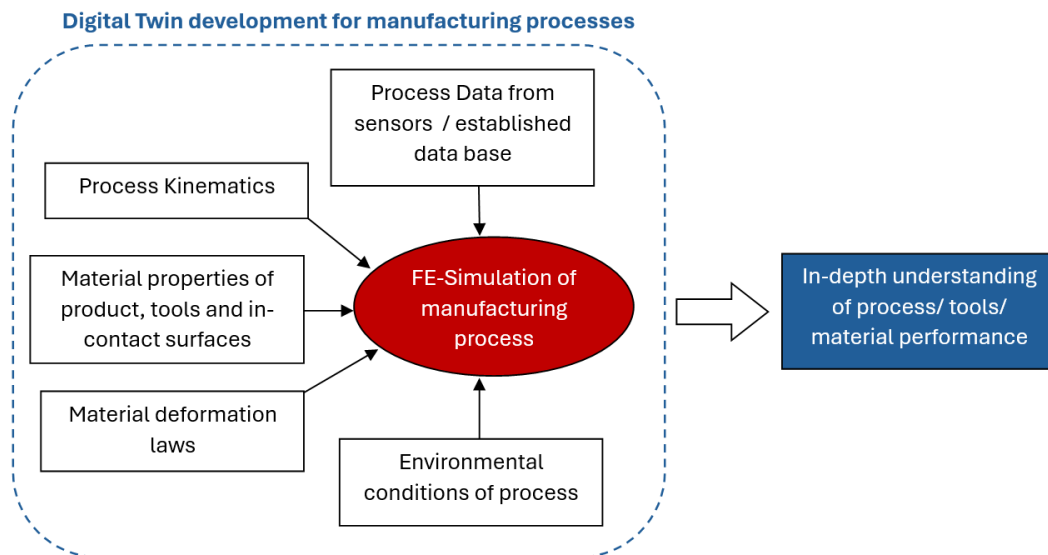


Figure 2.12. Development of digital twin of manufacturing process (Tao et al. [103], 2019)

Kim et al. demonstrated the integration of prototypes in digital twin of large buildings [109]. The term ‘Digital Twin Prototyping’ is presently considered as a new concept in which prototypes can be used to develop digital twins of large structures or processes. Barbie et al. highlighted that digital twin prototyping can be used for large industrial applications in which actual development of prototypes is not economically viable [110]. The use of prototypes in digital twin is related to process design and requirements. Callisto et al. used digital twin prototyping in IoT based saving system [111].

2.6 Summary from literature review and identification of research gap

The summary of literature review identifies the research gap for future investigations. RDB is a cold form bending process mostly used for profile bending of metal tubes. The process performance of a RDB process can be enhanced by accurate process parameterization which mainly includes pre-selected tool kinematics. The quality of bent tubes produced from a RDB process is characterized according to "Verein Deutscher Ingenieure" (Association of German Engineers) - VDI 3431. The fundamental tube quality characteristics in VDI 3431 are wrinkling, tube ovality and springback. The wrinkling can be eliminated by selecting correct pressure die clearance and appropriate ratio of tube speed to collet speed. The springback and tube ovality cannot be completely eliminated. However, correct process parameterization can significantly reduce springback and tube ovality while ensuring no wrinkling at intrados and tube cracking at extrados. The process parameterization fundamentally depends on tool kinematics therefore tool geometries can only be modified after correct assessment of tool performance. On one hand, conventional tools used in RDB process are capable of conducting the process amicably yet on the other hand, the enhanced demands of product customization and economic sustainability require these tools to be more cost effective, lightweight and readily available. In addition, a RDB process is presently considered an inflexible tube bending process which means that the tool set used in the bending operation can only be used to bend one specific tube diameter. Hence, the cost effectiveness of tools, lightweight tool performance, faster rate of tool production and incorporation of process flexibility through effective tool geometry are seen as the future challenges in a RDB process.

Additive manufacturing (AM or 3D printing) offers significant advantages which can be utilized to overcome the identified challenges in a RDB process. A fundamental advantage provided by all AM techniques is the possibility to manufacture complicated geometric designs which are otherwise very difficult to be constructed by conventional manufacturing processes. A significant advantage offered by polymer based AM processes is the prototyping of objects. The prototypes made from inexpensive polymeric materials can be used to determine physical process effects. Fused Deposition Modelling (FDM) is the most commonly used polymeric based AM technique. The polymers are light weight and low cost materials in comparison to metals. The objects made from FDM technique are considered to be significantly cost effective and lightweight as compared to their metallic counterparts. However, due to relatively lesser material stiffness, polymer made objects can withstand less loads as compared to metals and therefore their practical applications are limited. On the other hand, metal 3D printing techniques for example Laser Metal Deposition (LMD) or Selective Laser Melting (SLM) are relatively expensive till to date. In this backdrop, tools made from hybrid materials and using multiple additive manufacturing process are possible to be designed and developed. The metal 3D printing techniques can be used in addition to polymer based 3D printing techniques so as to develop hybrid tools which are cost effective, lightweight and considerably as stiff as metallic objects. The geometric design of these hybrid tools should be able to allow bending of multiple tube diameters from a single tool set. The design of such a tool geometry requires FE-simulation of the RDB process. A digital twin of the RDB process can

provide tool response within the process. Hence, it is possible to develop CAD of the bending tools while considering the offered advantages of additive manufacturing processes. The CAD can be tested in digital twin of the RDB process. On availability of satisfactory results from digital twin (FE-simulation) the tools can be practically fabricated and tested in actual RDB process.

The potential advantages offered by the envisioned 3D printed hybrid tools are cost effectiveness, lightweight, enhanced process flexibility and faster rate of production for customized productions. Fundamentally, the envisaged 3D printed hybrid tools are foreseen to transform an inflexible RDB process into partially flexible process. In addition, these hybrid tools will be significantly cost effective and light in weight as compared to currently used conventional bending tools made from alloy steels.

Chapter 3 : Aim and Objective(s)

Due to the enhanced requirements of product customization in present era [112], the production processes are required to be flexible and cost effective. The **overarching aim** of this doctoral thesis is to design bending tools which provides tool effectiveness through flexibilization of RDB process while meeting the requirements of customized production. This is achieved through development of a digital twin of the RDB process and utilize the advantages offered by digital twin and additive manufacturing (AM) techniques.

The mega-trend of product customization is directly associated with economic sustainability in production processes [5]. In profile bending processes (for example RDB process), the prognostic challenges developed as a result of enhanced production requirements can be addressed by effective tool performance [20]. Therefore, hybrid forming tools consisting of a combination of polymers and metals are envisioned which can enhance tool effectiveness in a RDB process. The hybrid tools are foreseen to be 3D printed by using multiple AM techniques. This research thesis is focused to investigate the process outcomes obtained from the use of digital twin and 3D printed tools in RDB process. The findings obtained from these investigations will be used to develop an effective design of a hybrid tool in which material properties of polymer-PLA and steel are utilized to maximum extent. The envisioned design of 3D printed hybrid tools is primarily aimed to meet following principal objectives:

- **Process flexibilization.** Presently, the tool set used in a RDB process can only be used to bend one specific tube diameter. This makes a RDB process inflexible for different tube diameters. This research thesis will present a geometric design of a 3D printed hybrid tool that will allow the use of a wide range of tube diameters while ensuring the high quality of bent tubes. Hence, the geometric design of 3D printed hybrid tools will transform the inflexible RDB process into a partially flexible process.
- **Material reduction and cost-effectiveness.** Economic sustainability has acquired a pivotal position in the production processes. The material cost of polymers is significantly less than alloy steels. Therefore polymer made forming tools are considerably cost effective as compared to tools made from alloy steels. A hybrid tool consisting of substantial polymeric material is foreseen to be significantly cost effective as compared to a metallic tool. The scientific investigations conducted in this research thesis are used to develop a hybrid tool which will be cost effective for customized productions.
- **Lightweight.** Collaborative robots (cobots) have entered into automation and manufacturing setups. The future factories are expected to be completely automated where cobots will install and position the forming tools on production machines. In these futuristic automated setups, weight of the forming tools is critically important as lightweight tools can be easily handled by cobots.

A hybrid tool made from a combination of polymers and metals is foreseen to be considerably lightweight due to the large presence of polymeric material within the tools geometry. The investigations conducted in this research thesis will identify the material composition which is suitable for the development of lightweight hybrid tools without affecting tool performance.

- **Faster production of tools for customized requirements.** The increased trend of product customization requires individualized or low batch productions. For low batch and customized products, 3D printing techniques provide a higher rate of production as compared to conventional manufacturing processes. Due to higher speed of production and possible development of complicated geometries, the envisioned hybrid tools will be 3D printed by using additive manufacturing techniques. For low batch sizes, the speed of production of 3D printed hybrid tools will be significantly greater as compared to metal tools made from conventional subtractive manufacturing processes.

Keeping in view the in-depth insights provided by digital twin of the RDB process, a **sub-aim** of this doctoral dissertation is to standardize the design of hybrid tools for different tube diameters. The design of hybrid tools will be standardized on the basis of tool's geometric aspect ratio. In order to compare the tool performance of hybrid tools with conventional tools, a tool comparison criterion is aimed to be formulated. This criterion should compare the efficiency of the bending tools in RDB process.

Chapter 4 : Method of Research

4.1 Research method

This research thesis utilizes the in-depth understanding of tools and process performance provided by the digital twin of RDB process. Based on the investigations related to tool performance, a novel design of hybrid tools is presented. The hybrid tools are 3D printed and practically tested in the actual process. Tool performance of hybrid tools is compared with the conventional tools. The chapter wise block diagram showing the overview of research methodology used in this doctoral thesis is shown in Figure 4.1 below:

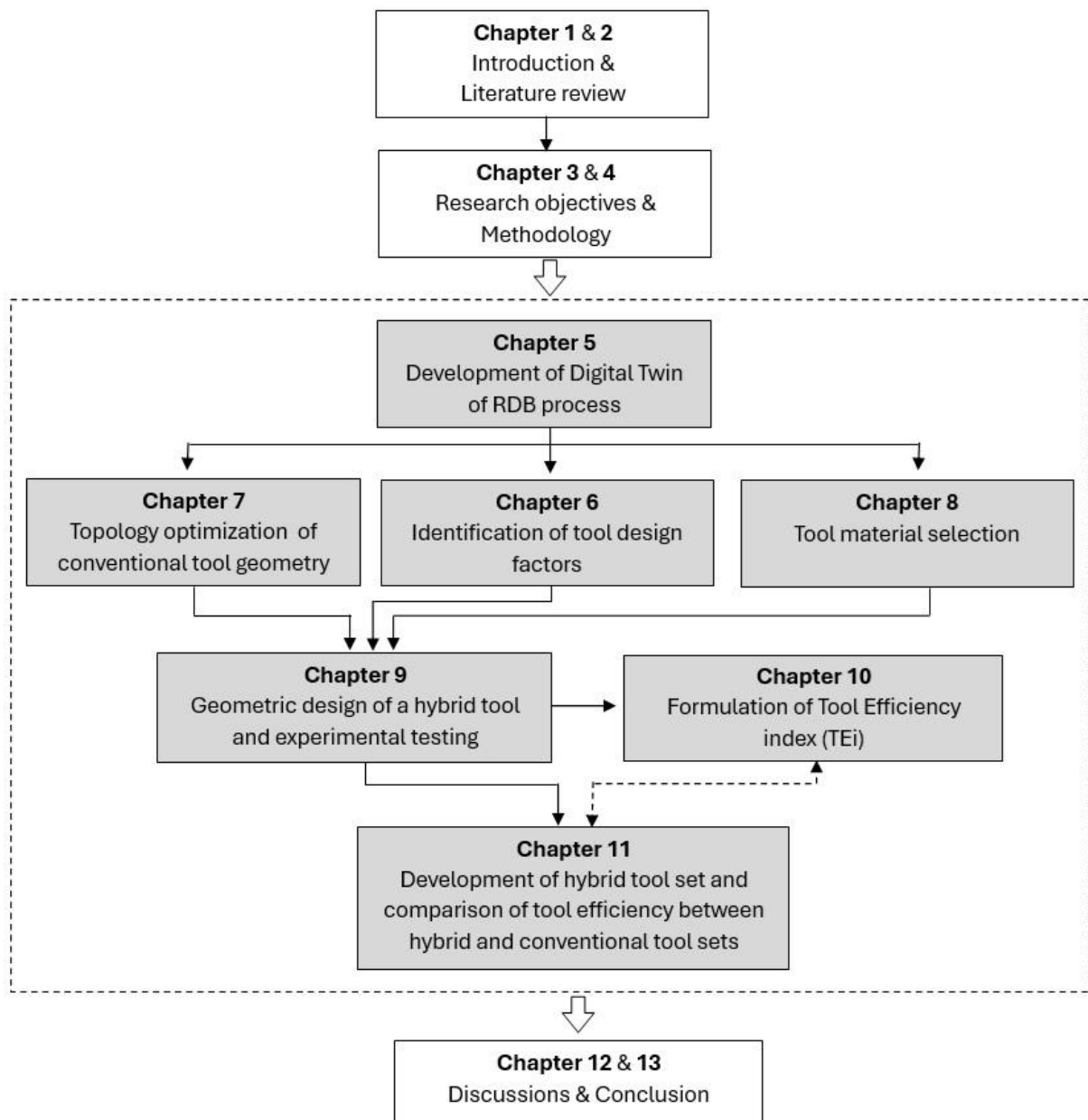


Figure 4.1: Block diagram of the methodology used in this doctoral thesis

After conducting literature review, a digital twin of the RDB process is developed using actual process kinematics, environmental conditions, positional constraints, CAD modelling and FE-simulations. The relevant mechanical properties and material deformation laws of the tube and bending tools are fed to the FE-simulation software. The accuracy of the digital twin is accessed by conducting the RDB process practically and agreement of results obtained through FE-simulations and practical experiments [113]. The initial phase of this research encompasses practical development of 3D printed polymeric tools using FDM technique. The geometric design and corresponding tool performance obtained from the geometric design of a fundamental forming tool (pressure die) is investigated. Due to relatively less Young's modulus of polymeric materials, a 3D printed polymeric tool (3D printed pressure die) is found to be suitable for only small bending operations applying low stresses on tool surfaces. On one hand, the 3D printed polymeric tools are considered in-effective for high stress bending operations yet on the other hand, these tools can be used effectively for tool prototyping. By using a digital twin prototyping method, the circular and V-shaped geometric designs of 3D printed polymeric tools are fabricated and tested in the actual RDB process in order to identify the design factors which are required to design a tool capable of withstanding high stresses resulting from a wide range of process parameters. Topology optimization is used to generate the tool geometries with material savings within the tool. The identified design factors required for tool development are studied in the light of material reduction criterion developed from topology optimization of conventional tool geometry. The tool design factors and material reduction criterion envisioned a tool made from a combination of two different materials called here as a hybrid tool. A hybrid tool (hybrid pressure die) is made from a combination of polymers and metals. The contact surfaces of a hybrid pressure die consists of metallic sheets with relatively high Young's modulus hence allowing the tool to withstand high contact stress during a bending operation. The base structure of a hybrid pressure die is 3D printed from an inexpensive and lightweight polymeric material. A commonly used polymeric material (PLA) is used as the base material and stainless steel (EN 1.4301) slabs are used as the surface material of the hybrid pressure die. The CAD of the hybrid pressured die is developed and imported in the parameterized FE-simulation model of the RDB process and the process range is identified (*here, process range means the range of tube diameters which can be used with the hybrid pressure die*). After identifying the process range, the hybrid pressure die is physically 3D printed and tested in a practical setup with same process parameters. Tool evaluation is conducted by comparing the 3D printed hybrid tool with conventional metallic tool in terms of tool performance and cost comparison index. Tool performance is determined by identifying contact forces, von-Mises stress, contact normal pressure and elastic or plastic deformations within the hybrid tool. The target variables of the tool performance are tube ovality and tool failure (tube wrinkling is not considered as the target variable of tool performance because the accurate process parameterization ensures wrinkle free bent tube). The cost comparison is conducted on the basis of the Ashby cost comparison index [114]. The findings obtained from tool performance are used to formulate a mathematical formula called here as Tool Evaluation index (TEi). The mathematical formula of TEi serves to compare the efficiency of

hybrid tools with conventional tools. For practical applications, the geometric design of a 3D printed hybrid tool is standardized for a wide range of tube diameters using tool aspect ratio and upscale size factors.

4.2 Description of research methods

In order to develop 3D printed hybrid tools and subsequently test their efficiency in a RDB process, the investigations conducted in this research thesis are structured serially in such a way that the findings obtained from one investigation serves as the basis to conduct subsequent investigation. There are six fundamental forming tools used in a RDB process [40]. Initially, a hybrid design of a fundamental forming tool ‘pressure die’ is geometrically developed, tested and analysed. The results obtained from tool performance of hybrid pressure die are used to formulate design instructions which can be used to design, develop and evaluate other forming tools (for example bend die, clamp die etc.) in a RDB process as shown in Figure 4.2.

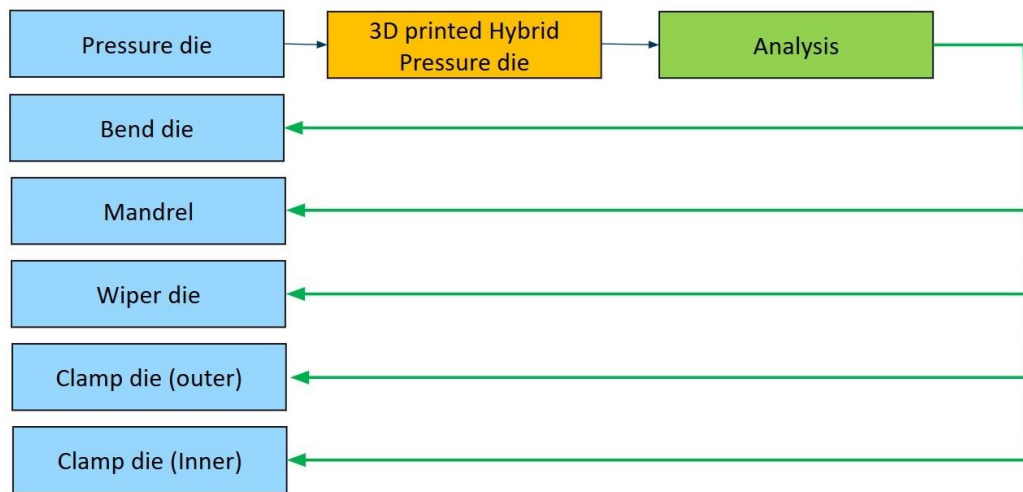


Figure 4.2: Development strategy of hybrid bending tools in RDB process

The development of an effective tool geometry requires identification of design factors which influence the tool performance [115]. The polymer based 3D printing techniques are mostly used for prototyping purposes because polymers are inexpensive and readily available in local markets for 3D printing using FFF techniques [116]. In a prototyping process, a 3D printed prototype is made and tested under practical conditions so that performance analysis of the actual object can be extracted from the prototype [117]. In this research thesis, a digital twin prototyping method is used in which polymer made prototypes of a forming tool (pressure die) are 3D printed and tested in the actual RDB process. In the digital twin prototyping method, the material of the pressure die is changed from alloy steel (1.2363) to polymer (PLA) and two different geometric designs (circular design and V-shaped design) are 3D printed. Both geometric designs are practically employed in a parameterized RDB process and the effect of tool geometry on process performance is noted. The geometries of prototypes are modelled in CAD modelling software and imported in the 3-dimensional parametrized FE-simulation model. The results of process simulation are compared with the practical results. This verified that the digital twin model

is substantially accurate and the tool performance obtained from digital twin can be used for investigations. The digital twin prototyping method is used to identify the design factors that are required to design an effective tool geometry with high process performance. The block diagram of the digital twin prototyping method is shown in Figure 4.3.

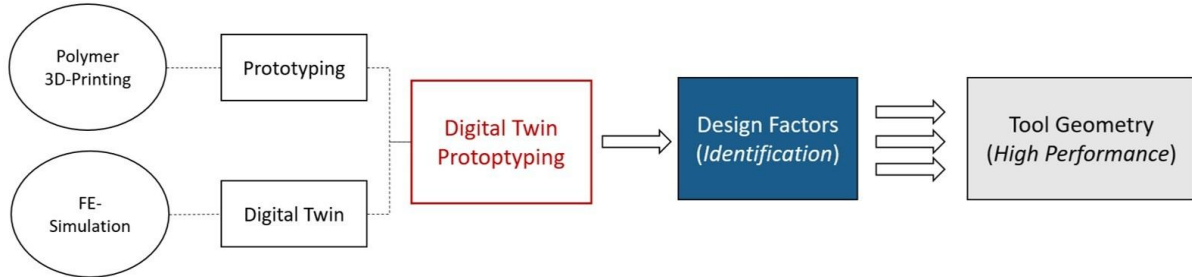


Figure 4.3: Methodology of digital twin prototyping

In order to flexibilize the tool to hold different tube diameters, it is essential that the geometry of the tool surface be changed from circular profile to V-shape profile [14]. The suitability of low cost materials for customized production require tools to be made from polymers [81]. The transition from circular geometry of the conventional steel tool towards V-shape polymer tool involves two steps: (i) change of material and (ii) change of geometry. There are two possibilities to follow these two steps. In the 1st possibility, initially the material of the tool is changed (steel to polymer) and subsequently the geometry of the tool is changed (circular to V-shape). In the second possibility, initially the geometry of the tool is changed (circular to V-shape) and subsequently the material of the tool is changed (steel to polymer). The two possibilities are highlighted in Figure 4.4. The tool performance during the transition from circular (steel) tool towards V-shape (polymer) tool will be used to identify the critically important design factors. These design factors will be used for the development of effective tools in RDB process. From technical perspective of RDB process, the 2nd possibility cannot be adopted because it does not involve tool performance with circular surface profile and the critically important design factors are foreseen to be pronounced when the tool performance is determined through circular profile of tool surface. Moreover, the design factors which are envisioned in 2nd possibility (for example process flexibility and surface wear etc.) will already be covered in the 1st possibility. Hence, this research thesis adopts 1st possibility to identify the tool design factors. Figure 4.5 shows the block diagram of the methodology in which digital twin prototyping is used to explore the tool design factors through 1st possibility.

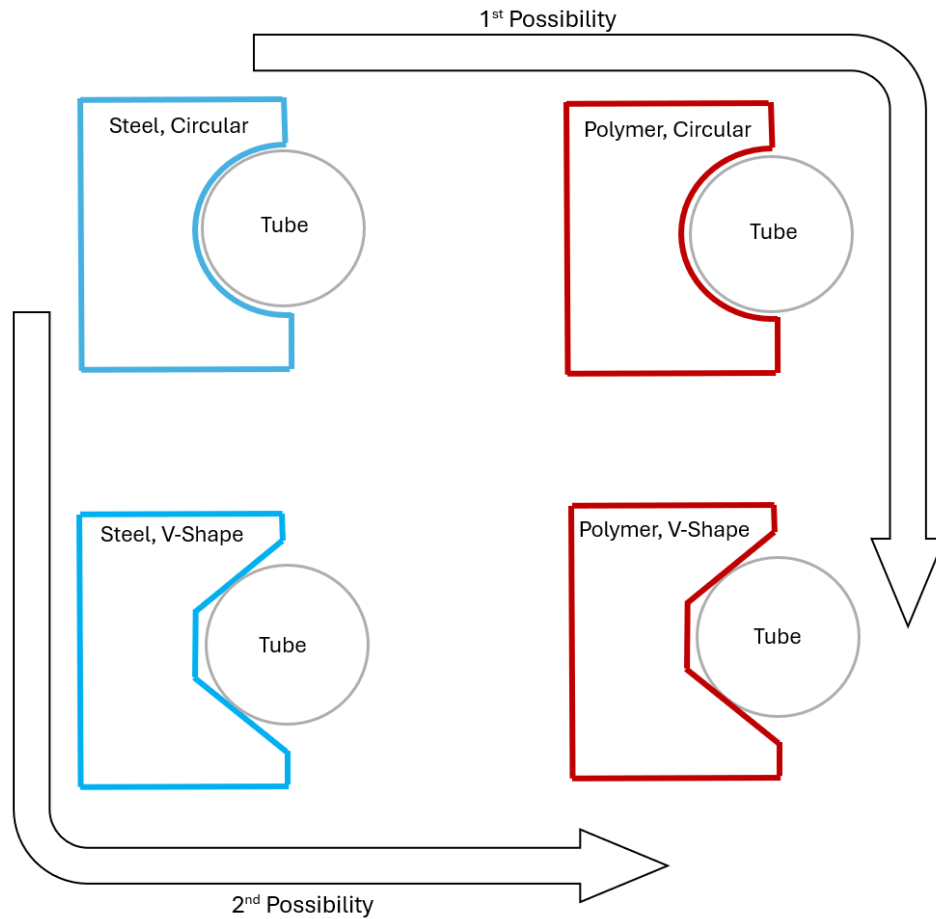


Figure 4.4: Two possibilities to identify tool design factors during transition from circular (steel) tool to V-shape (polymer) tool

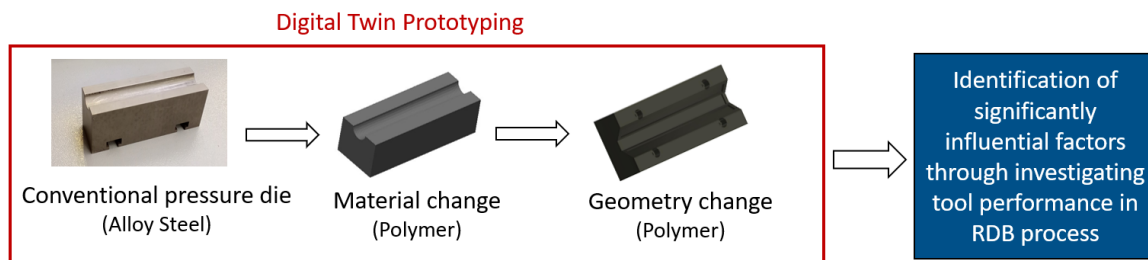


Figure 4.5: Methodology to identify tool design factors through digital twin prototyping

Topology optimization of a tool's geometry provides information about the minimum volume of material required (within the tool) to conduct the process without any failure [26]. The topology optimization is conducted through a FE-simulation software on the basis of conventional tool geometry and pre-processing boundary conditions resulting from process requirements [118]. Through topology optimization, a material reduction criterion can be developed which provides information about the minimum possible material required within the tool. The material reduction criterion also forms the basis of materials selection [119]. The materials used in the hybrid tool are selected on the basis of 'Ashby-material selection model' [120]. The selected materials are studied in relation to identified tool design

factors and a model of the hybrid tool is developed. The block diagram representing the development method of the geometric design of a hybrid tool is shown in Figure 4.6.

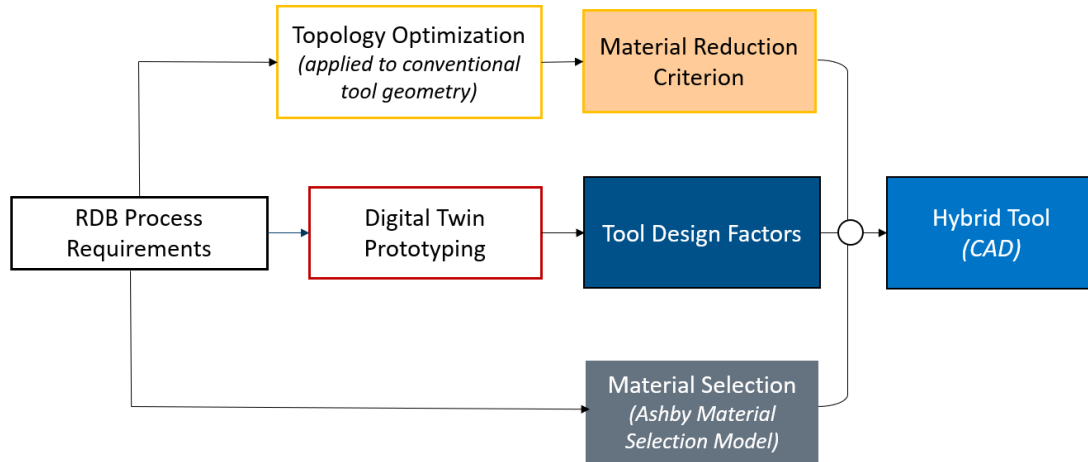


Figure 4.6: Design process for development of the model of hybrid tools

The model of the hybrid tool is imported in FE-simulation model (digital twin) and tool performance is investigated on the basis of tool failure, tube wrinkling and tube ovality. The desirable quality characteristics are (i) ‘no wrinkling’ at tube intrados, (ii) tube ovality from hybrid tool should be less than the tube ovality from conventional tool and (iii) von-Mises stress in hybrid tool is lesser than the yield strength of the tool material. Amongst these three quality characteristics, the wrinkling at tube intrados is eliminated by selecting accurate process parameters [13]. If the other two characteristics (i.e., ii and iii) are satisfied, the hybrid tool is practically 3D printed and tested in a practical RDB process. Based on the results obtained from practical experiments, a comparison of tool performance is made between the novel design of a hybrid tool and the conventional design of the metallic tool. The block diagram of tool performance is shown in Figure 4.7.

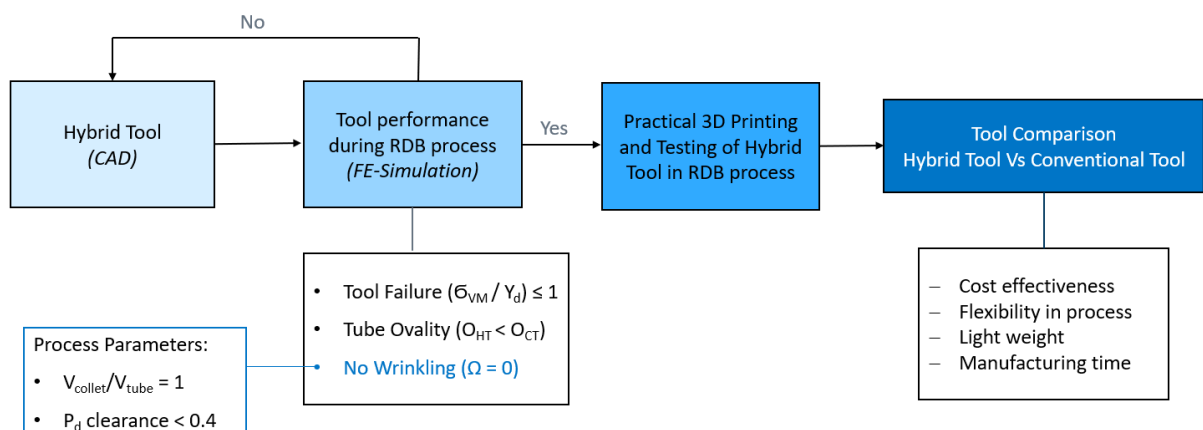


Figure 4.7: Method of hybrid tool testing in RDB process

The comparison of tool performance between the hybrid tool and conventional metallic tool is conducted on the basis of cost effectiveness, process flexibility provided by the tool, lightweight of the tool and manufacturing time required for customized productions (low batch productions). Based on the

influence of each of the aforementioned criteria of tool effectiveness, a mathematical formula is formulated which can be used to determine tool effectiveness in a RDB process. This mathematical formula is termed here as the ‘Tool Efficiency index (TEi)’. The TEi is used as the design instruction to compare bending tools in RDB process. The range of process flexibility provided by hybrid tools is used for tool standardization. In order to demonstrate the method of tool standardization for practical applications, the geometry of a hybrid tool is standardized through aspect ratio and corresponding upscale size factors.

4.3 Brief structure of this research thesis

The method of investigation in each sub-structures of this doctoral thesis is presented in section 4.2. These sub-structures are conducted systematically and they serve to form an overall structure of this research work. The overall structure diagram showing the methodology of research used in this doctoral thesis is shown in Figure 4.8 below:

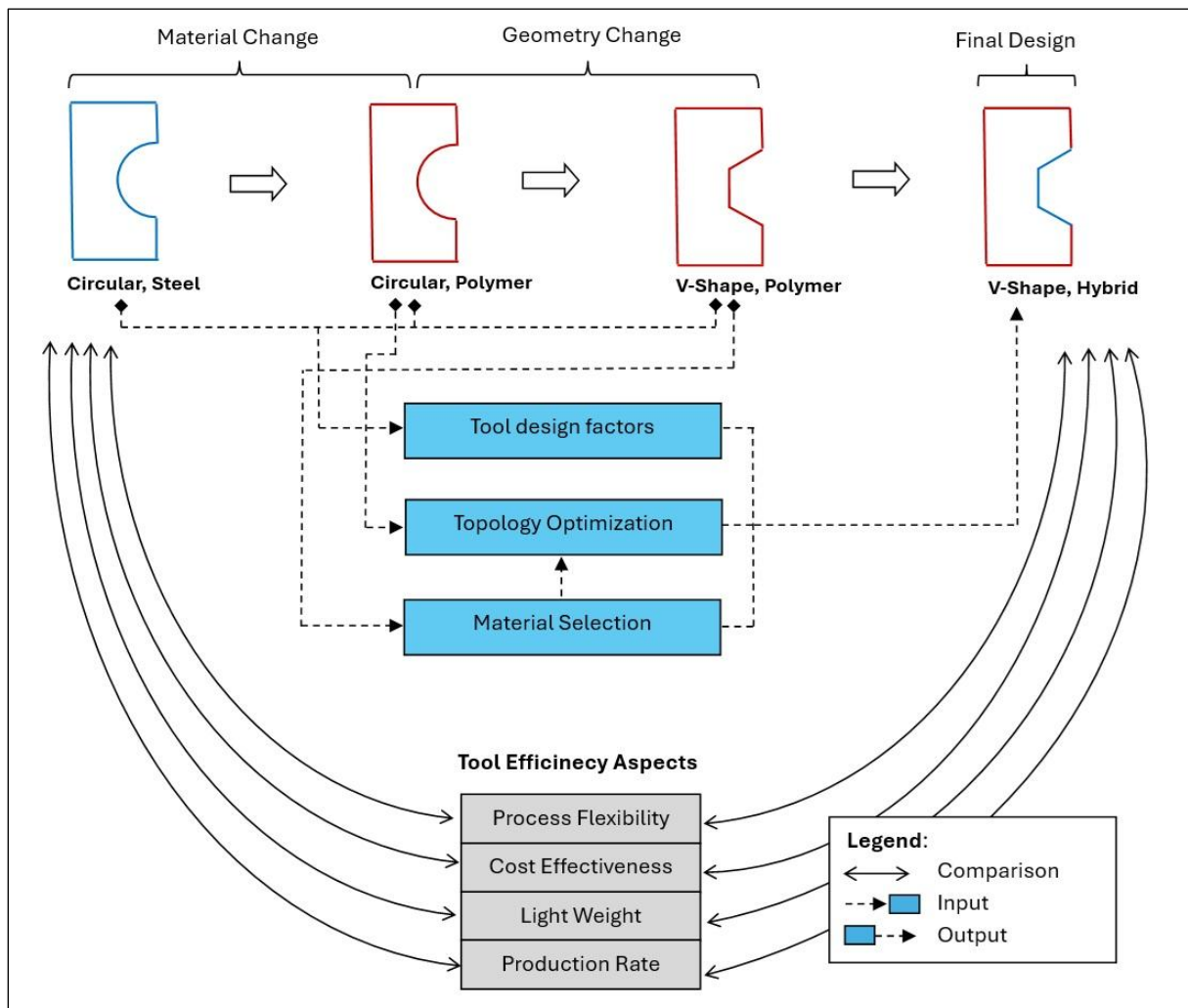


Figure 4.8: Overall structural diagram showing brief development methodology of hybrid tools for RDB process

Chapter 5 : Digital Twin of RDB process

5.1 Development of digital twin (FE-simulation model) of a RDB process

A digital twin is a virtual representation of an object or a system designed to predict the physical behaviour of that object or the system [121]. In case of a metal forming process, digital twins are developed by using CAD modelling and specialized FE-simulation softwares [122]. The actual process conditions, material properties, equipment response and operation methodologies are fed to the virtual process environment of FE-simulation and the process is conducted by using mathematical computations performed by the software. The results obtained from process simulation are used for performance prediction of components used within the process and corresponding process outcomes [123]. In order to accurately predict the process outcomes, it is vitally important to verify the accuracy of a digital twin by comparing the results of FE-simulation results with the practical results [124]. A verification criterion is required to be formulated which confirms the accuracy of the digital twin. In this research doctoral research, a digital twin of the RDB process is developed by feeding process parameters, process operating conditions, machine response and material properties of tools and the tube to the FE-simulation software PMASTAMP. In order to conduct the process simulation with volume elements, the bending tools are required to be developed as CAD models, the CAD models should be meshed and later imported in the process simulation environment as meshed files. Therefore, the fundamental tools used in a RDB process are modelled in the CAD Modelling software 'Autodesk INVENTOR'. In order to mesh the tools, an appropriate mesh size of volume elements is required to be selected. Literature review suggests that the results of RDB process simulations converge at mesh size of 1.00 mm [14] & [113]. In this research thesis, the precise identification of mesh size is obtained by conducting a mesh convergence study. The mesh convergence study is conducted on a conventional pressure die geometry in the software 'Autodesk INVENTOR'. The results obtained from the mesh convergence study are shown in figure 5.1.

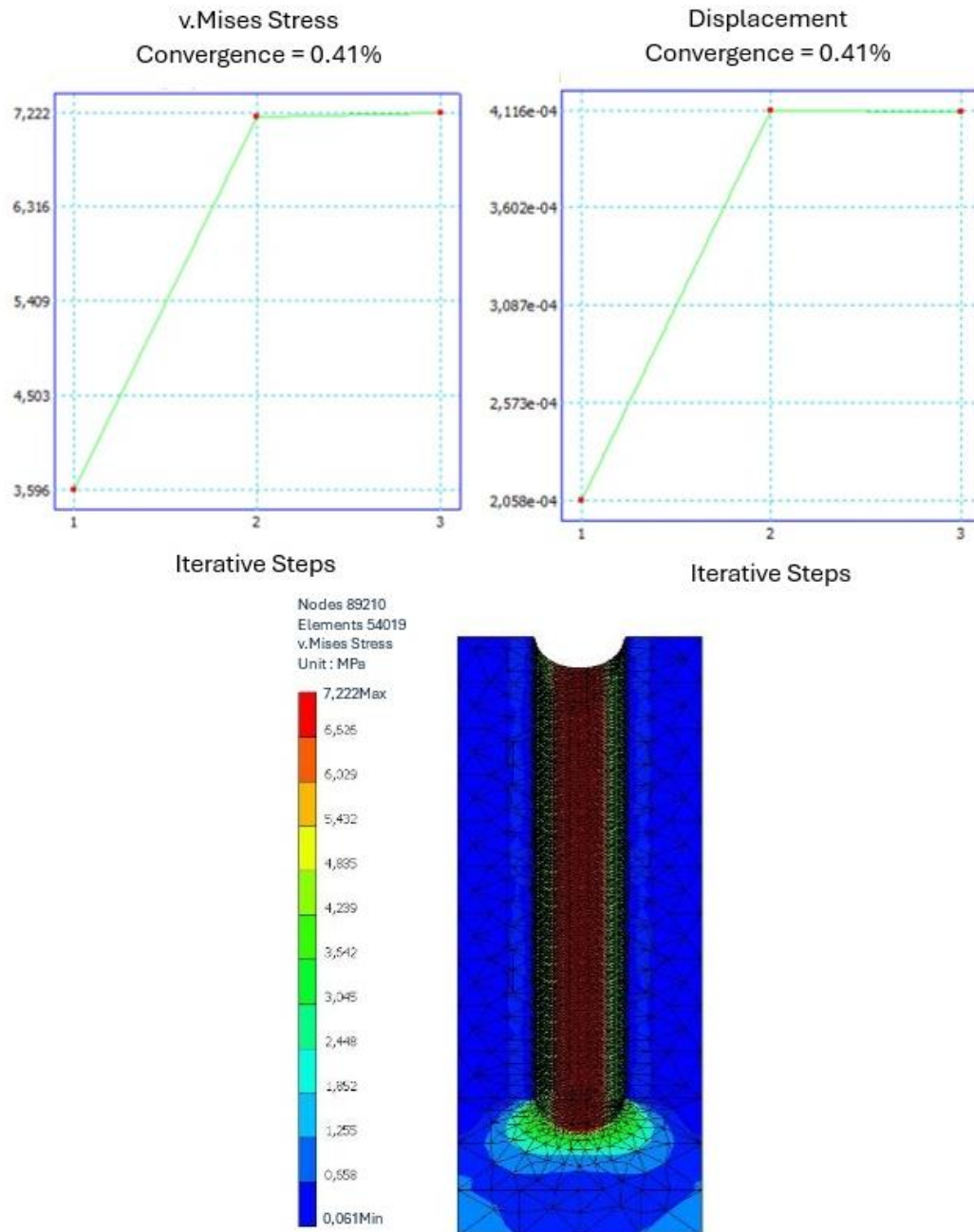


Figure 5.1: Mesh convergence study conducted in the software Autodesk INVENTOR in order to identify the mesh size at which results of von-Mises stress and tool displacement converges

The results of von Mises stress and tool displacement shows a convergence of less than 1.00% at a mesh size of 1.28 mm. In order to reduce the total number of meshed elements for faster computation of simulations, a localized meshing strategy is adopted. This means that the potentially high stress areas in tool geometry (for example mated tool surfaces or geometric areas under direct application of loads) are meshed at a mesh size of 1.00 mm whereas the less influenced or un-used areas in tool geometry are meshed at progressively bigger mesh sizes (upto a maximum mesh size of 8.00 mm in un-used areas). By using the localized meshing strategy, the total number of finite volume elements of the digital twin model are reduced from 1.24 Million to 0.28 Million. This reduced our simulation computation time

from 88 hours (3.6 days) to 25 hours (1.1 days). The CAD models of bending tool are developed in Autodesk INVENTOR. In order to carry out localized meshing of bending tools, the CAD models are brought into the specialized meshing environment of the software 'HYPERMESH'. A localized mesh size of 1.00 mm is applied at in-contact tool surfaces and the geometric areas where high stress is anticipated. The meshed tool geometries are imported as Nastran (.nas) files in the process simulation software PAMSTAMP. The input values related to actual process conditions, material properties, material deformation laws, equipment kinematics, environmental conditions and process methods are fed to PAMSTAMP and the process is simulated as a digital twin of the RDB process. The three softwares used in the development of a digital twin of a RDB process are shown in Figure 5.2.

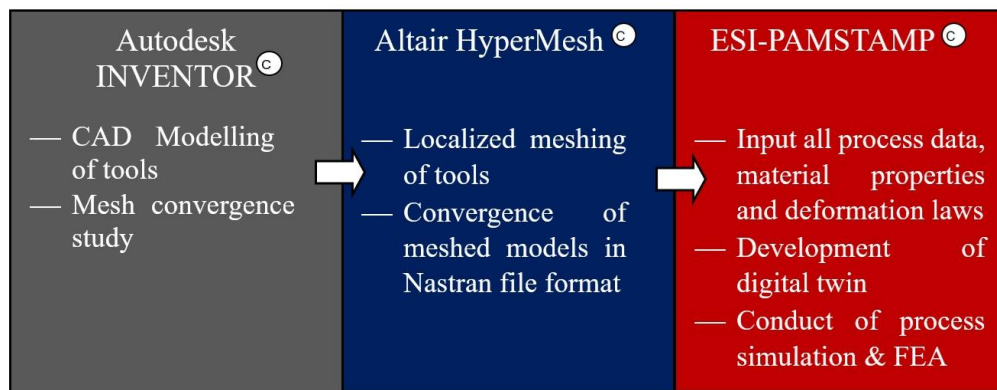


Figure 5.2. FEM and FEA softwares used in the development of digital twin of the RDB process

5.2 Accuracy of digital twin

In order to use the physical response of tools from the digital twin, it is essential that the accuracy of the digital twin may be verified by conducting the experiment practically. The accuracy of digital twin is ascertained by comparing physical measurements with simulation results. Literature review suggests that physical measurements of bending tool during the process kinematics are not substantially accurate [37]. Borchmann et al. demonstrated that the tool deformations in steel tools are so less that they cannot be captured with high level of accuracy through physical measurements [20]. Moreover, the machine axis stiffness also restricts the accuracy of physical measurements methodologies. Kersten et al. highlighted that significant inaccuracies may arise during physical measurement of the kinematic motion of tools in roll push bending of tubes [125]. Keeping in view the potential inaccuracies arising from physical measurements of bending tools, the accuracy of the digital twin is required to be verified by physical measurements of the tube profile. In this doctoral thesis, the accuracy of the digital twin is verified by considering the key quality aspects of bent tubes according to VDI-3431 [10]. The key quality aspects considered for verification of the digital twin of the RDB process are tube ovality, wrinkling, springback, wall thicknesses at bent tube's intrados and extrados [113]. The practically measured values of these physical quality aspects are compared with the simulation results. The agreement /substantial closeness of results obtained from practical experiments and FE-simulation verifies the accuracy of the digital twin. The process parameters selected for practical experiments and

FE-simulation are shown in Table 5.1. The FE-simulation model of the digital twin along with quality aspects considered for accuracy verification of the digital twin are shown in Figure 5.3.

Table 5.1: Process parameters of the RDB process

Process Parameters / Process Conditions		Coefficients of Friction (COFs)	
Bending Factor (B)	1.5	Tools	Value
Wall Factor (W)	22	Pressure Die	0.1
Tube thickness (mm)	1.00	Bend Die	0.1
Bending Angle (α)	0 - 90 ⁰	Wiper Die	0.1
Pd Mode	Static	Mandrel	0.08
Tube velocity	$V_{\text{tube}}/V_{\text{collet}}=1$	Clamp Die Outer	0.3
Pd clearance	< 0.4 mm	Clamp Die Inner	0.3

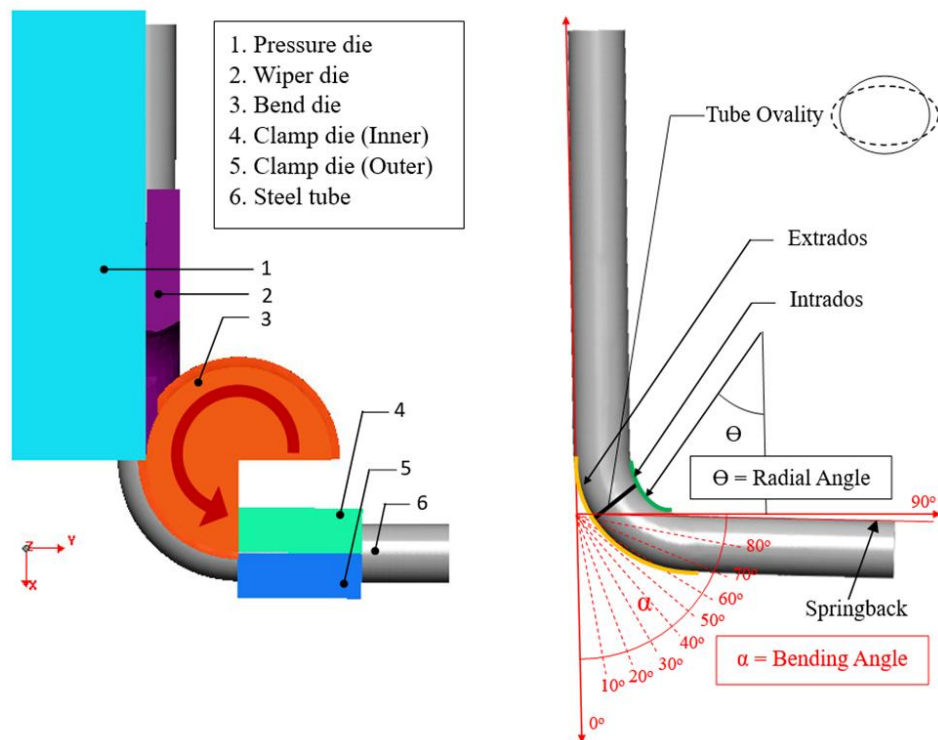


Figure 5.3: Digital twin of the RDB process (left) and quality aspects considered to determine the accuracy of digital twin (right)

The practical experiment is conducted on a RDB machine (RBV-35) by WAFIOS Umformtechnik GmbH. The process parameters and operating conditions used in the FE-simulation and practical experiments are kept identical. The physical measurements of bent tubes obtained from practical experiments are measured by using precise measurement instruments. The tube ovality and wall thicknesses at intrados and extrados are measured by using Mitutoyo Digital Indicator having a resolution of 0.01mm [22]. The measurement is conducted at a radial angle of 45 degrees. The accurate process parameters used to produce wrinkle free tubes are applied [13]. The process parameters rendered

wrinkle free tubes at the end of practical bending operation. The measurement method of practically bent tubes is shown in Figure 5.4 (a-c).

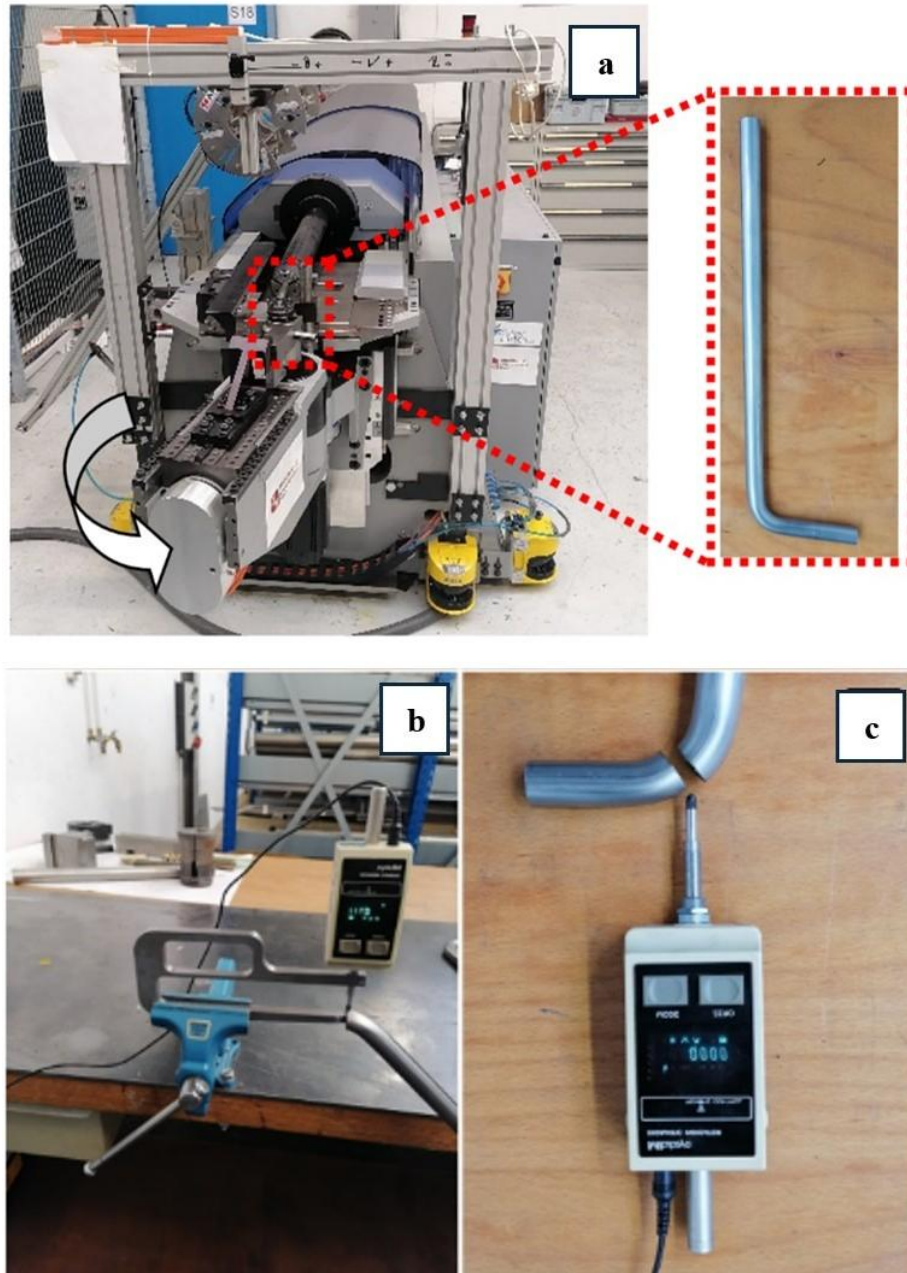


Figure 5.4 (a) Practical experiment of RDB process and (b-c) physical measurement of tube wall thickness and ovality

After conducting the practical process, the practical results are compared with the simulation results. The comparison of results is presented in the form of a spider diagram as shown in Figure 5.5 (a-b). Here, the simulation and practical experiment provided a wrinkle free tube with identical tube ovality. The wall thickness at intrados and extrados is significantly identical. A slight variation of 0.5° in springback is noticed. The variation of springback in FE-simulation and practical results can be attributed to heterogeneous microstructural variations present within the tube. The substantial agreement

of tube ovality, wrinkling and wall thicknesses between FE-simulation and practical experiment verify the accuracy of the digital twin. Therefore, the tool response provided by the digital twin is used for further investigations.

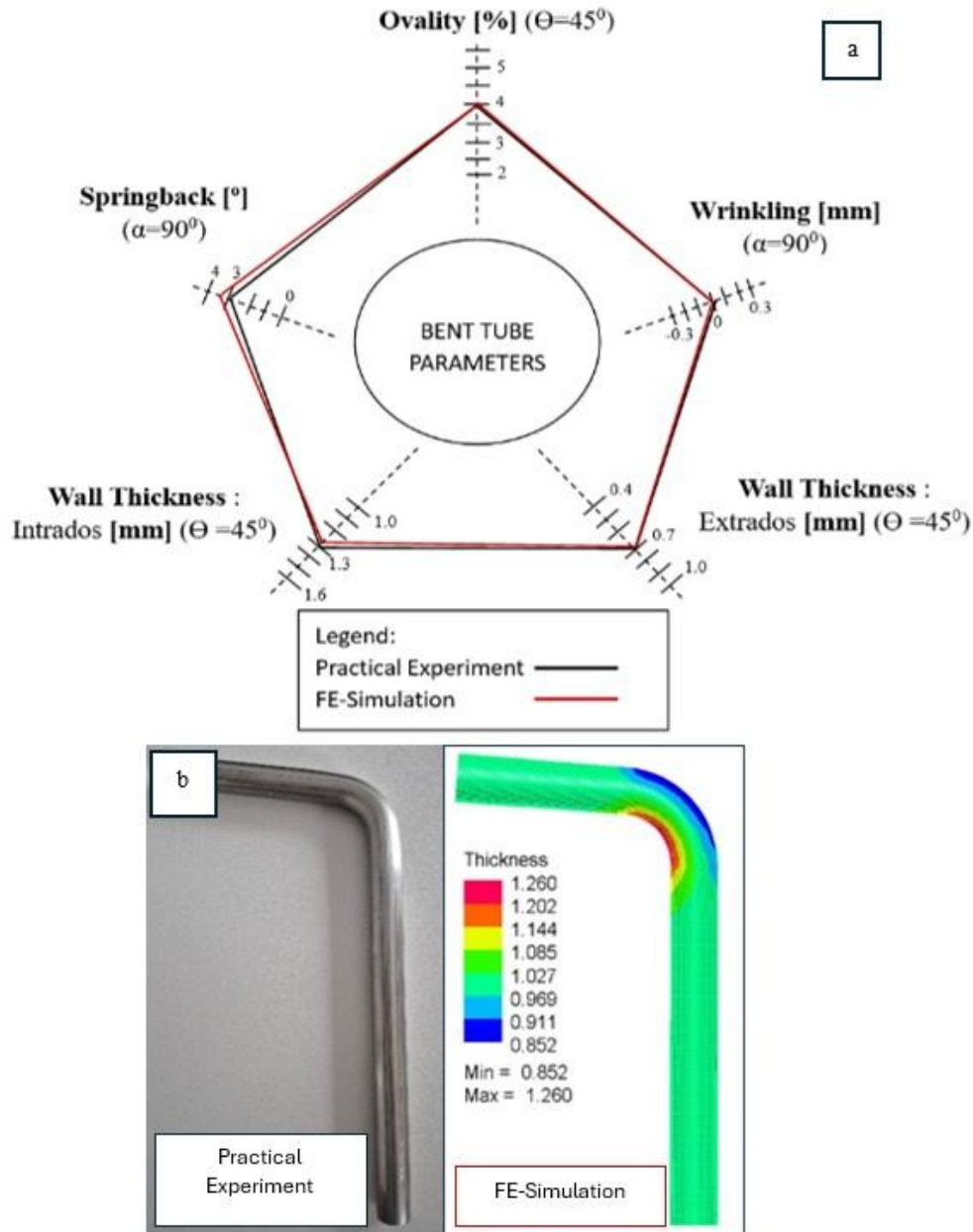


Figure 5.5 (a) Accuracy of digital twin by comparison between practical experiment and FE-simulation (b) bent tube obtained from practical bending experiment and FE-simulation

Chapter 6 : Identification of tool design factors

6.1 Identification of tool design factors through digital twin prototyping

In order to develop a geometric design of a high performance tool in RDB process, the design factors which influence the tool performance are required to be identified [54]. In this research thesis, the tool design factors are identified through digital twin prototyping method. A digital twin prototyping method encompasses the use of a digital twin consisting of a polymer tool used as a prototype in the RDB process. Prototyping means development of an object with an in-expensive material (like polymer) and use the object in actual process conditions to predict the response of that object in the actual process [126]. In case of a RDB process, the tool prototyping is conducted by development of bending tools with polymeric materials using polymer based 3D printing techniques and subsequent investigation of polymeric tool response in a RDB process [113]. A digital twin of the RDB process with a polymeric tool is developed and the process response obtained as a result of the use of a polymeric tool in a RDB process is investigated. This process is repeated by testing various tool geometries and the influence of each tool geometry on the process outcome is noted. These influences manifest in the form of design factors required for an effective tool geometry (*block diagram of digital twin prototyping method is mentioned in Figure 4.3*). Literature review suggests that in addition to a circular tool surface, a V-shaped tool surface can also be used to hold the tubes [14]. A V-shaped tool surface allows a tool to flexibilize the process by holding different tube diameters [113]. In the digital twin prototyping method, a polymer made tool (polymeric pressure die) is separately developed in geometric designs with circular and V-shaped surfaces and subsequently tested in a RDB process. In the beginning, only CAD geometries are developed and tested in the digital twin (FE-simulation model). The verification of digital twin requires practical process results. Therefore, the polymeric pressure die is physically 3D printed and tested in the actual RDB process. The operating conditions, tool materials and process parametrization of the actual process and digital twin are kept identical.

The development of a digital twin requires feeding of accurate material deformation laws to the FE-simulation software. In case of metallic materials (for example stainless steel tube made from EN 1.4301), the Swift Krupkowsky law is used to predict material deformation [127]. In case of polymeric materials, no single law is yet formulated which can predict material response of general polymeric materials in a FE-simulation. This is because each polymeric material possesses different material properties for example material stiffness, yield strength, position's ratio etc. To simulate the response of polymeric material in a FE-simulation, a practically obtained stress-strain curve of the specific polymeric material is required to be fed to the software. Therefore, stress-strain curve of 3D printed polymeric material (PLA) is obtained by conducting practical material characterization using already established material standards [128]. In RDB process, the tools experience compression stress through force applied by the. Hence, instead of tensile strength, the compressive strength of tools is required to be identified. In order to identify compressive strength, a compression test of 3D printed PLA cylinders

is conducted according to DIN-604. Three circular cylinders each 20 x 30 mm (width x length) are 3D printed by using FFF technique. The PRUSA MK-4 3D-printer from PRUSA Corporation is used. The 3D print parameters used for fabrication of samples are mentioned in Table 6.1.

Table 6.1: Print parameters of Fused Filament Fabrication (FFF)

Print Parameter	Value
Print material	ecoPLA
Layer height	0.2 mm
Material type	Filament
Line width	0.4 mm
Print Temperature	210 °C
Print direction	In vertical plane

The 3D printed polymeric (PLA) samples are fabricated in both horizontal and vertical directions. Three samples are individually placed in the universal tensile testing machine (Zwick Roell Z-250) both in vertical and directions and a compressive force is applied. The gradual increase in compressive stress applied by the machine (true stress) is noted against the engineering strain and a stress-strain curve is obtained. The stress-strain curves of both horizontal and vertical samples are noted. In addition to isotropic behaviour of the PLA, the investigation also served to provide accurate yield strength of PLA. A high level of precision is noticed within the three samples. The average value of the samples is considered for the stress strain curve. The 3D printed PLA samples and their corresponding yield strength are shown in Figure 6.1. It can be noted that both horizontal and vertical samples showed substantial closeness in yield strength (Y_d) and deformation behaviour within the elastic region, therefore 3D printed PLA is considered here as an isotropic material. The literature review highlights that the yield strength of 3D PLA is 75 MPa [68]. However, the characteristic investigation conducted here exhibits a minimum value of 72.5 MPa. Therefore, in order to maintain tool safety, a yield strength 72 MPa is considered in this research work. The identified values of the stress-strain curve shown in Figure 6.1 are fed to the software PAMSTAMP. The software simulates the behaviour of polymeric materials used within the digital twin model according to this curve.

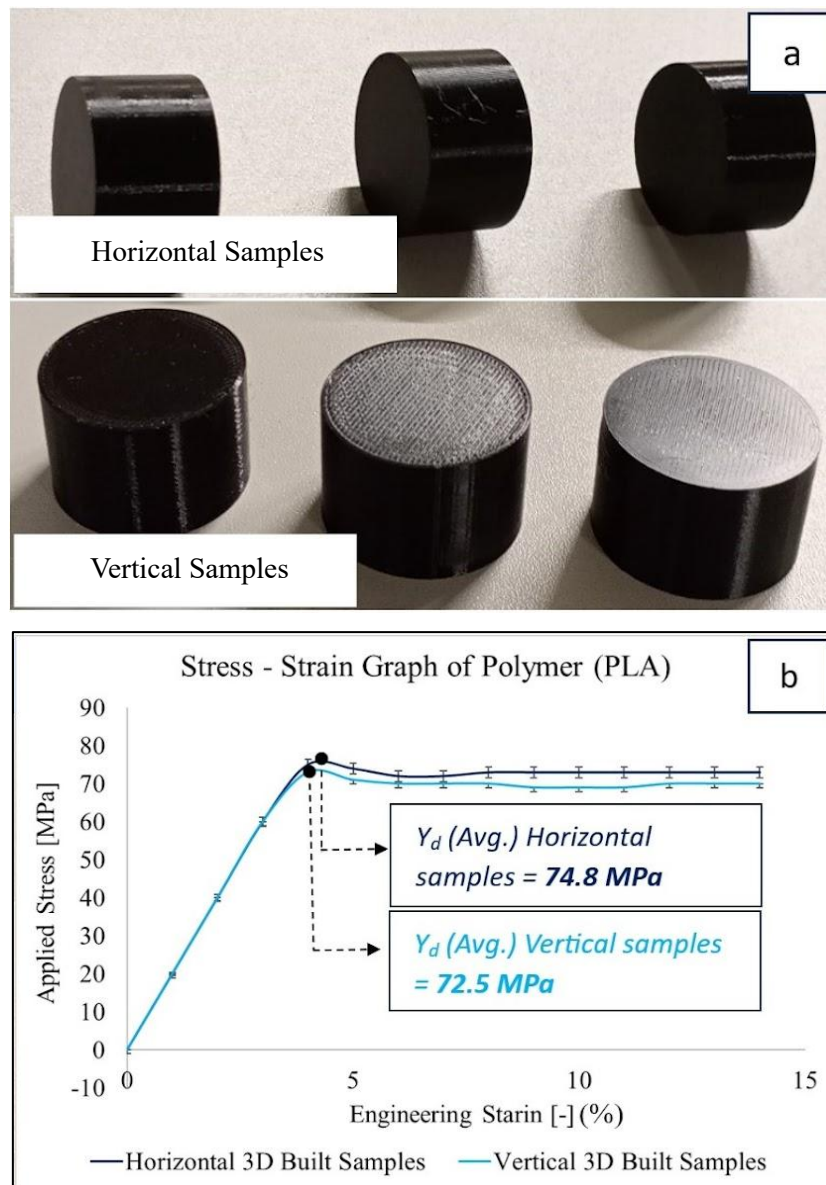


Figure 6.1: Material characterization of 3D Printed PLA obtained from compression test conducted according to DIN 604. An accurate value of the yield strength of 3D Printed PLA is required for FE-simulation of polymeric tools

In the subsequent sections, a fundamental forming tool (pressure die) used in the RDB process is geometrically designed with circular and V-shaped surfaces and each geometry is subsequently tested in the RDB process. Using the method of digital twin prototyping, the CAD of each geometric design is constructed and the material properties of polymeric material (PLA) is assigned to the respective CAD. It is pertinent to highlight that the surface geometry and tool material of the pressure die is only changed to identify some design factors which significantly affect the process outcomes. These design factors will be form the basis to develop the final design of flexible bending tools envisaged in this doctoral thesis. The CAD is brought into the digital twin model of the RDB process and a FE-simulation of the bending process is conducted. After the conduct of process simulation, a practical process with identical 3D printed geometry is conducted. The accuracy of process simulation is verified by comparing the

simulation results with the results of practical process. The accuracy of simulation is determined on the basis of tube quality characteristics (*mentioned in section 5.2*). After confirmation of the accuracy of process simulation, the tool response of polymeric prototypes used in the digital twin is analysed. The analysis of tool performance is used for identification of tool design factors.

6.2 Identification of tool design factors through circular tool surface

A pressure die with a geometrically circular tool surface identified following design factors. These design factors are used to develop the geometric design of an effective tool in a RDB process.

6.2.1 Influence of Young's Modulus of tool material on contact forces

A model (CAD) of the conventional geometry of the pressure die is created. The material properties of alloy steel (EN 1.2363) are assigned to the conventional pressure die. The conventional pressure die made from an alloy steel is called here as Pd_C. Another model is created with the same geometrical dimensions and material properties of the polymeric material (PLA) is assigned to the model. This geometry with polymeric material properties is called here as Pd_P. To investigate the effect of tool material in a RDB process, the process simulation is conducted with both tools (Pd_C and Pd_P) and respective tool performance is compared. The tool performance of bending tools in RDB process is the ability of the tools to withstand stresses during a bending operation and thereby produce bent tubes without any significant plastic deformation in tool geometry [113]. In order to obtain tool performances, the material properties of tool steel (EN 1.2363 or X100CrMoV5 used for conventional pressure die Pd_C) and polymeric material (PLA used for polymeric pressure die Pd_P) are fed to the software. The details of materials properties are shown in Table 6.2.

Table 6.2: Material properties of the tools used in RDB process

Tools and Tube	Material	Element type	Elastic modulus (GPa)	Yield strength (MPa)	Poisson ratio	Density (g/cm ³)	Material deformation law
Metallic pressure die (Conventional)	Alloy steel (EN - 1.2362)	Volume Element	205	950	0.3	7.85	Swift Krupkowsky law
Bend die	Alloy steel	Volume Element	205	950	0.3	7.85	
Clamp dies	Alloy steel	Volume Element	205	950	0.3	7.85	
Mandrel	Hard chrome plated steel	Volume Element	210	520	0.3	7.96	
Wiper die	Hard chrome plated steel	Volume Element	210	520	0.3	7.96	
Bend die	Alloy steel	Volume Element	205	950	0.3	7.85	

Tube	Stainless steel	Blank (thickness = 1 mm)	210	550	0.3	7.70	
FFF-pressure die (polymer)	PLA	Volume Element	3.2	70	0.35	1.24	Experimentally obtained stress-strain curve (DIN-604)

The bending operation is conducted from 0° to 90° . During the bending operation, the tool surface experiences contact pressure resulting from process kinematics. The contact pressure experienced by the tool surface of Pd_C (alloy steel pressure die) and Pd_P (polymeric pressure die) are shown in Figure 6.2. It can be seen from Figure 6.2, that the contact surface pressure of Pd_P increases gradually whereas the contact surface pressure of Pd_C remains almost at one particular level. Moreover, the magnitude of maximum pressure exerted at the surface of Pd_C is significantly larger than the magnitude of maximum pressure obtained at the surface of Pd_P . The colour code representing the range of pressure experienced by respective tools (Pd_C and Pd_P) is kept the same. This shows that the pattern of contact pressure on the surface of Pd_C is significantly more intense than the pressure pattern at the surface of Pd_P . This investigation shows that there is possibility of deflection/ displacement in tool surface of Pd_P . The base of both tools is static therefore surface displacement is captured in terms of lateral strain in tool geometry. However, before investigating deflection at tool surfaces, the von-Mises stress in tool geometry is determined.

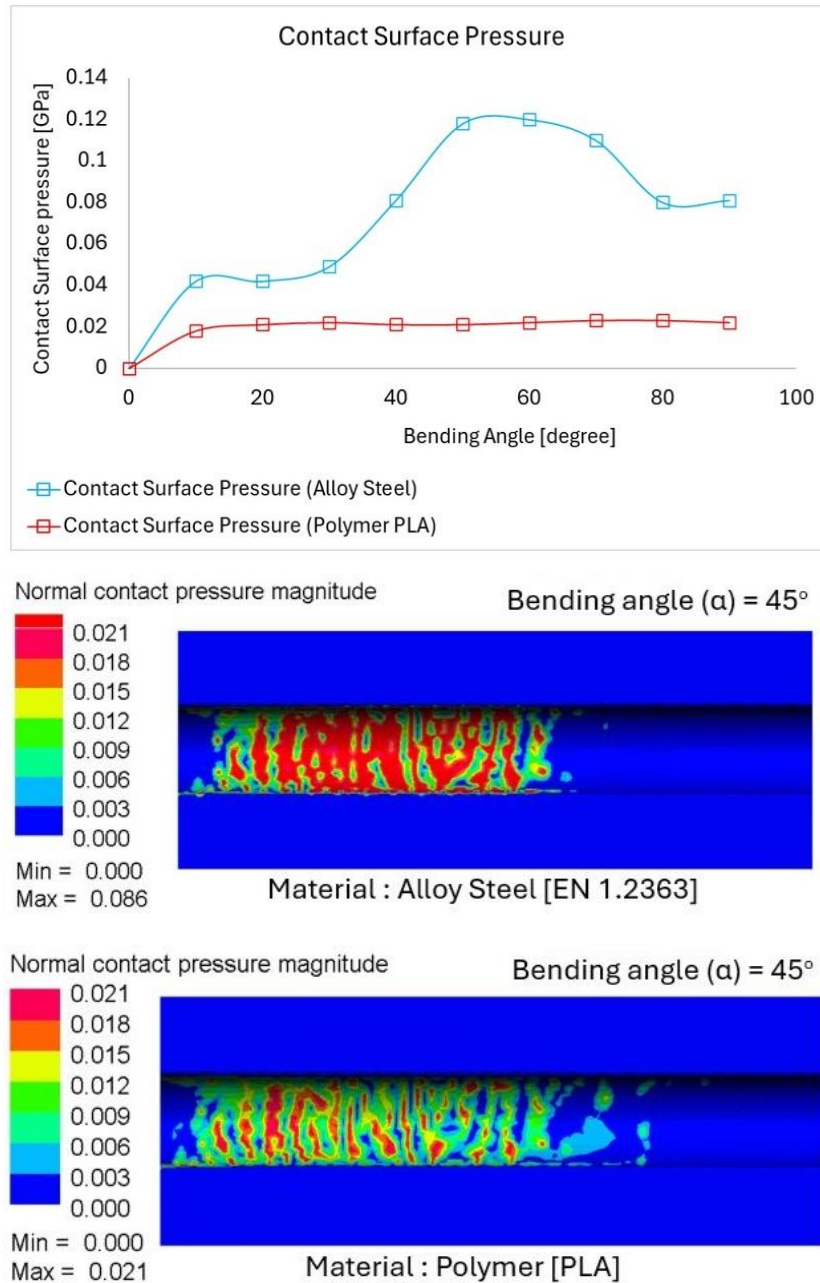


Figure 6.2 : Contact pressure (max.) at the surface of conventional geometry of pressure die with Pd_C made from alloy steel and Pd_P made from polymer.

The von-Mises stress within the tool geometry represents the equivalent stress experienced by the tool material [129]. Figure 6.3 shows the variation in von-Mises stress with an increase in bending angle. It can be seen that the pressure die made from an alloy steel (Pd_C) experiences substantially high von-Mises stress as compared to the pressure die made from the polymer (PLA). In case of Pd_P , the maximum von-Mises is substantially less as compared to Pd_C . It can be noticed that the stress travels from the circular centre towards tool edges as seen in case of Pd_C . On the other hand, lower stress development in Pd_P indicates that the polymeric material of Pd_P is elastically deformed and as a result experienced relatively less von-Mises stress as compared to pressure die made from alloy steel (Pd_C).

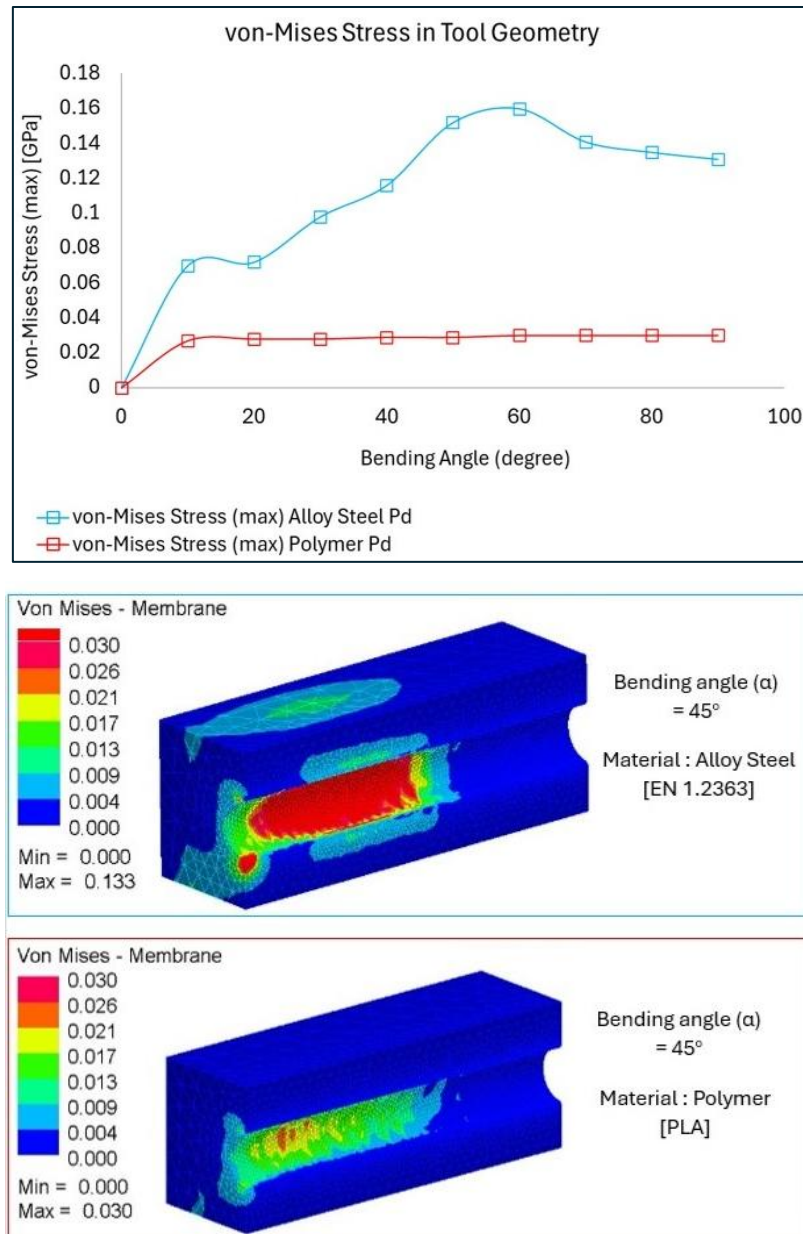


Figure 6.3: Von-Mises stress (max.) developed within the conventional geometry of pressure die: Pd_C (made from alloy steel) and Pd_P (made from polymer)

In order to investigate the elastic deformation within the tool geometry and associated deflection/displacement at tool surfaces, the directional strain in tools is required to be determined. The directional strain in lateral direction (Y-axis) within tool geometry is the major strain. The lateral strain within tool geometries is shown in Figure 6.4. It is seen that Pd_P is substantially deformed (laterally strained) whereas the Pd_C is almost undeformed at all bending angle (α) between 0° to 90°. From the above mentioned curves of von-Mises stress (Figure 6.3), it can be noticed that the maximum von-Mises stress remained less than the material yield of polymer (i.e., PLA $Y_d = 72$ MPa) and therefore the geometry of Pd_P is elastically deformed and tend to return back to its original geometric dimensions at the end of bending operation. Hence, in case of Pd_P , the strain is only witnessed during the bending operation and

as soon as bending operation is finished (at $\alpha=90^\circ$), the strain tends to reach a value equal to zero. Figure 6.4 shows that a maximum strain of 0.003 is observed in Pd_P during the bending operation at $\alpha=45^\circ$.

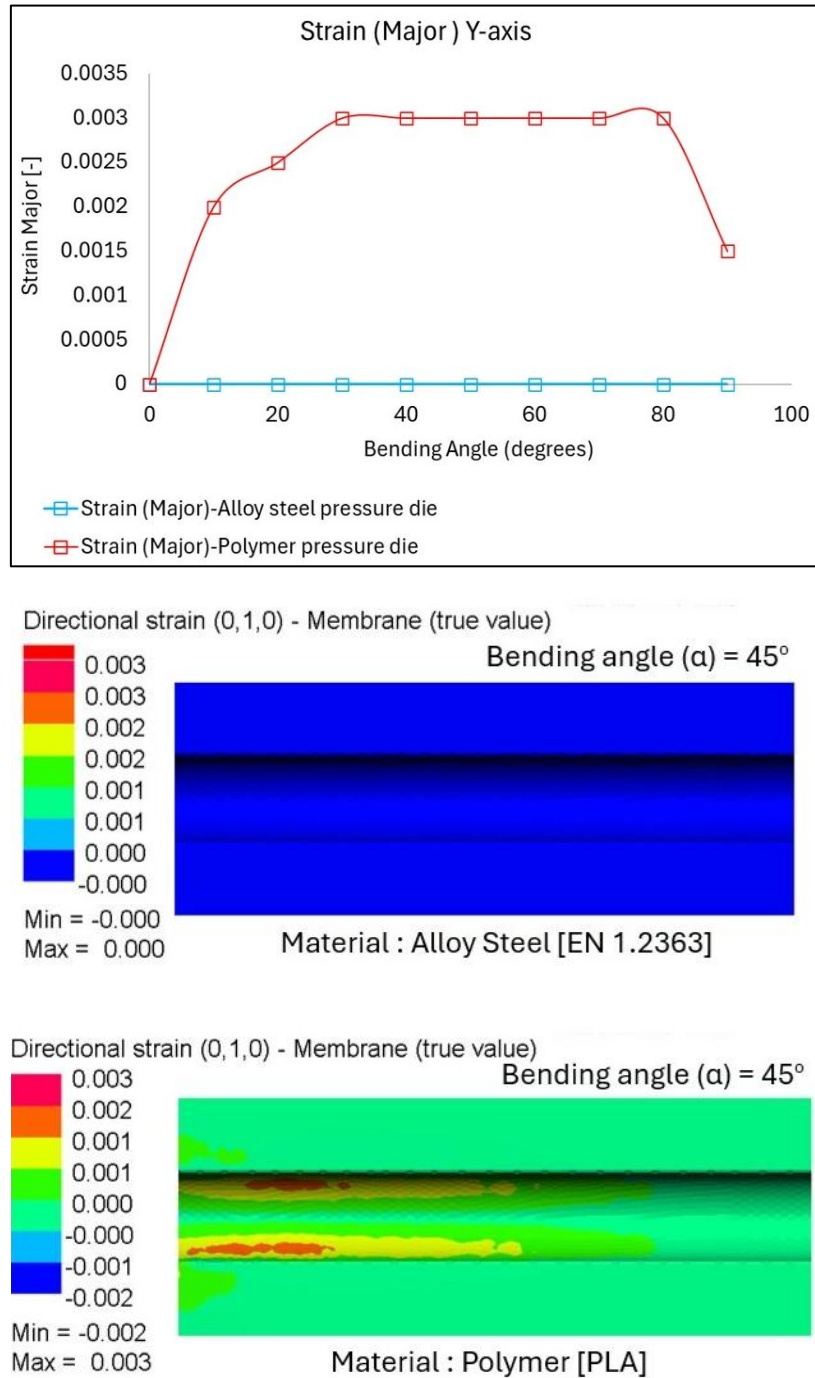


Figure 6.4: Strain-major (max.) in the conventional geometry of pressure die: Pd_C (made from alloy steel) and Pd_P (made from polymer)

The contact forces experienced at the surface of Pd_P and Pd_C are investigated. The contact forces developed at tool surfaces during the bending process are obtained by FE-simulation. Figure 6.5 shows the comparison of contact forces experienced by Pd_C and Pd_P . It is seen that the Pd_P experiences substantially less contact forces as compared to Pd_C . This finding is supported by the earlier investigation

regarding strain development in which it is shown that Pd_P is elastically deformed whereas Pd_C is undeformed. This means that the surface of Pd_P is displaced from its original position due to elastic deformation and the intensity of the contact is decreased which resulted in decreased contact forces. A less intense tube contact between the tube and polymeric material exerts less contact force as compared to the contact between the tube and alloy steel. The maximum contact force applied by the tube on the surface of Pd_C is 44 kN whereas the maximum contact force experienced by Pd_P is almost 25 kN. A significant decrease in contact force shows that the development of contact forces on the tool surface during a bending operation depends on the tool material. A highly stiff material (e.g., alloy steel 'EN 1.2363' with Young's Modulus = 210 GPa) experiences significantly high contact force as compared to a relatively less stiff material (e.g., Polymer PLA with Young's Modulus = 2.75 GPa).

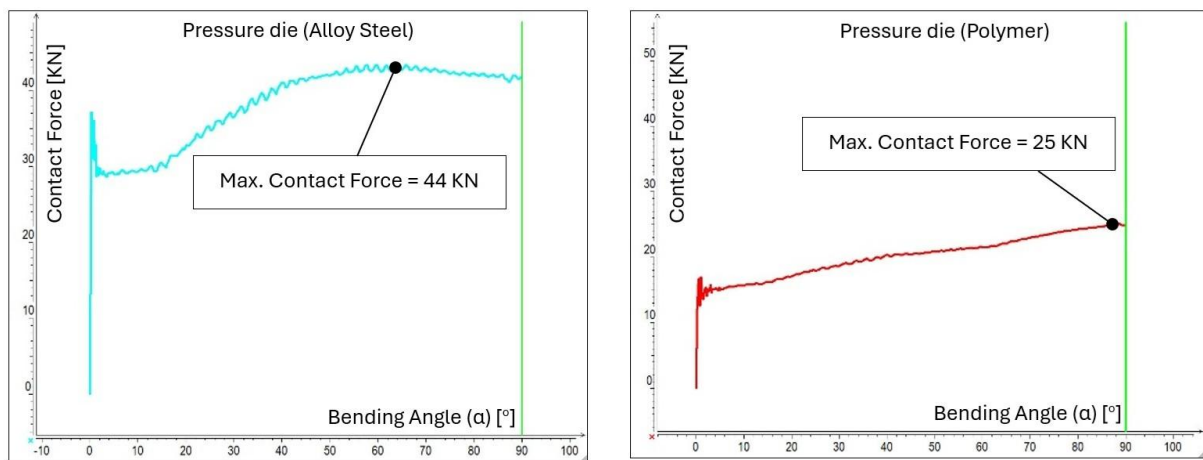


Figure 6.5: Contact force developed at the surface of conventional geometry of pressure die: Pd_C (made from alloy steel) and Pd_P (made from polymer)

The investigations conducted in this section determined that the development of contact forces on a tool surface depends on the Young's Modulus (stiffness) of tool material. The geometric design of a tool fundamentally depends on the development of contact forces which a tool can withstand. Therefore the geometry of a tool should be selected according to a tool material which is capable of withstanding the contact forces applied by the tube during a bending operation.

6.2.2 Effective area on tool surface

The simulation results obtained from the digital twin shows that the conventional geometry of a pressure die do not utilize the complete surface area of the tool during the bending process. Only one side of the surface of a pressure die experienced the contact pressure (P_{CN}) during the process. A considerable surface area remained un-used on the other side of the pressure die where no contact pressure acted during the entire bending operation. The surface area of the pressure die where a contact pressure is experienced is called here as an active or effective area. The results obtained from the digital twin showed that the effective area of the pressure die is significantly less than the total surface area of the pressure die. This finding was also identified by Heftrich et al. [14] during the investigations conducted on a bend die. He identified that the complete surface area of bend die is not utilized during a bending

operation and the effective surface area is considerably less than the total surface area of the bend die. Here, in case of pressure die, the P_{CN} pattern at the surface of a pressure die at various bending angles is shown in Figure 6.6. It can be seen from Figure 6.6 that the magnitude and pattern of P_{CN} changes with the change in bending angle (α).

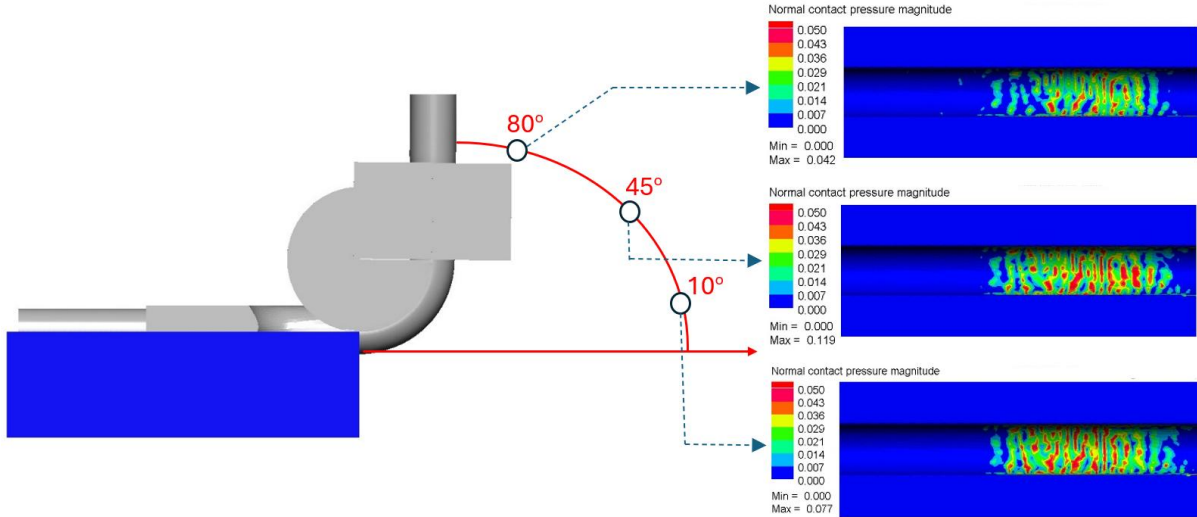


Figure 6.6: The contact pressure P_{CN} pattern at the surface of pressure die during a bending operation. The figure shows that a different P_{CN} pattern manifests at different bending angle (α). Moreover the surface area of the pressure die is not utilized completely during the static mode operation of pressure die in RDB process

The average P_{CN} acting on the surface of the pressure die (P_{dC}) is shown in Figure 6.7(a). The contact force (F_{CN}) applied by the tube on the surface of a pressure die (P_{dC}) during the entire bending operation (from 0° to 90°) is shown in Figure 6.7(b).

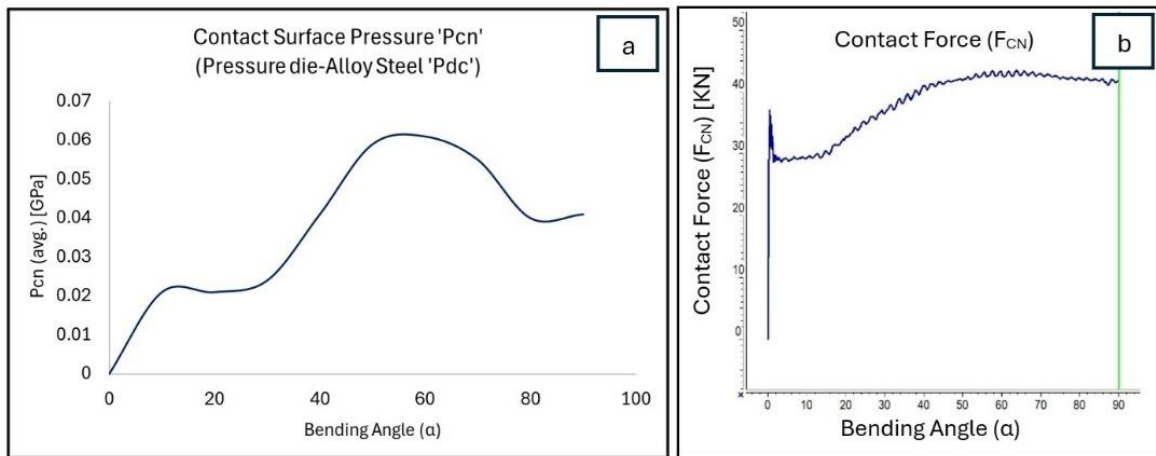


Figure 6.7(a-b). (a) Contact pressure P_{CN} on the surface of alloy steel pressure die (P_{dC}), (b) Contact force F_{CN} applied at the surface of alloy steel pressure die (P_{dC})

The effective area (A_{EFF}) at the surface of a pressure die can be calculated by using the equation (6.1) below:

$$\text{Pressure } P_{CN} = \frac{\text{Force } (F_{CN})}{\text{Effective area } (A_{EFF})} \dots\dots\dots(6.1)$$

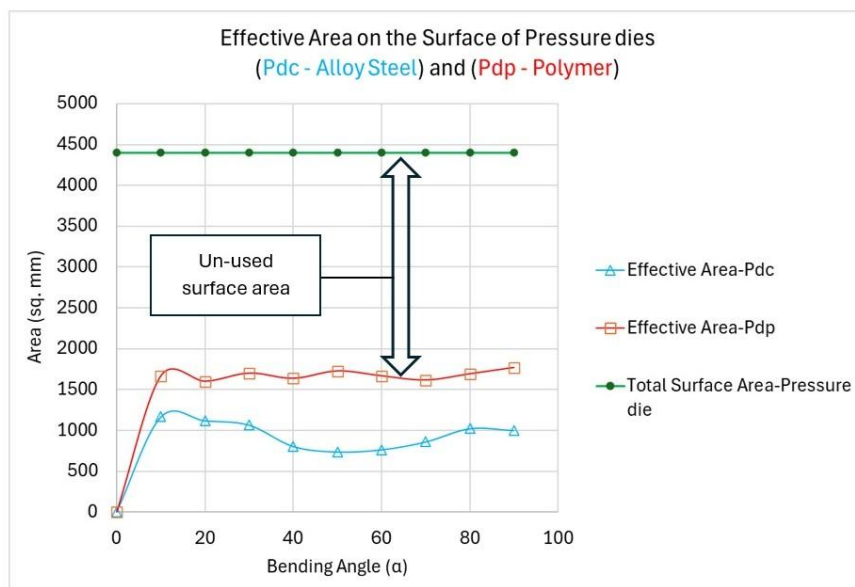
The equation (6.1) is rearranged in the form of equation (6.2) below:

$$A_{EFF} = \frac{F_{CN}}{P_{CN}} \dots\dots\dots(6.2)$$

The total surface area of the pressure die is calculated by the equation (6.3) below:

$$\text{Total surface area } (A_{TOTAL}) = \frac{1}{2} [(2\pi r) \cdot l] \dots\dots\dots(6.3)$$

The effective area on the surface of pressure die during a bending operation (0° to 90°) is calculated from equation (ii) and the total surface area is calculated by equation (iii). The effective area and the total surface area of Pd_C are shown in Figure 6.8. In case of pressure die made from polymeric material (Pd_P), the total surface area of Pd_P is same as that of Pd_C . The effective surface area of the polymeric pressure die (Pd_P) is however different and as computed by using equation (ii) and shown in Figure 6.8. In both pressure dies, it can be seen that a substantial surface area has remained unused during the entire bending operation. However, the effective surface of Pd_P is considerably larger than the effective surface area of Pd_C . In an ideal tool design, the surface area of the tool should be utilized completely and the unused surface area should ideally be zero (i.e., for ideal tool geometry: $A_{EFF} = A_{TOTAL}$). Hence, in order to design a tool, the geometry of the tool should allow maximum utilization of the surface area. In practical applications, it has been observed that the effective area on the tool surface change continuously with an increase in bending angle. This happens due to the fluctuations of P_{CN} at the tool surface. Due to continuously changing effective area, the unused surface area also change. Therefore the unused tool surface should remain restricted to bare minimum value.



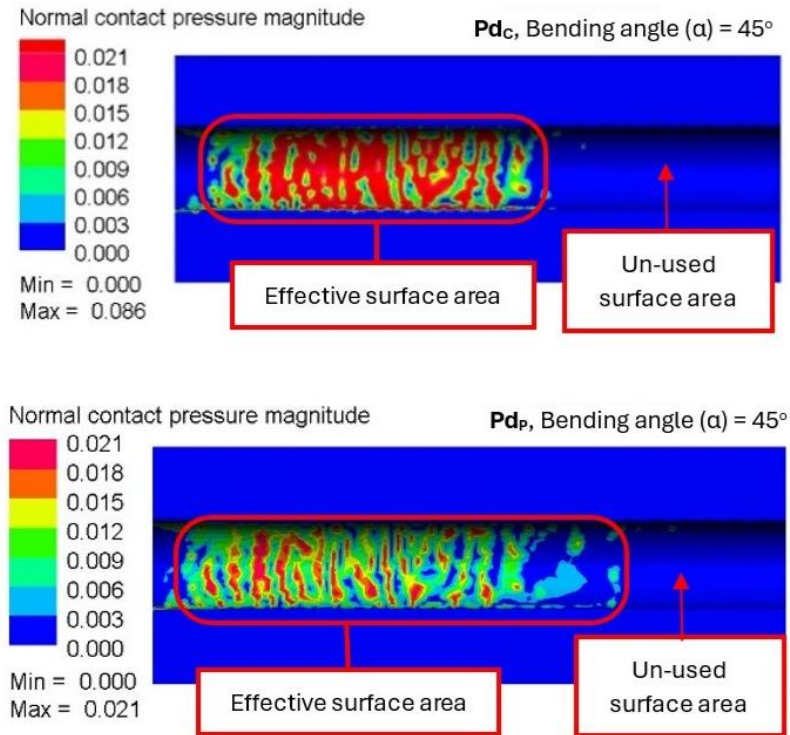


Figure 6.8: Effective areas and unused areas on pressure dies: Pd_C (made from alloy steel) and Pd_P (made from polymer). The effective surface area of Pd_P is greater than the effective surface area of Pd_C

6.2.3 Friction coefficients of tool surface

This section investigates the influence of coefficients of friction of tool surfaces on the process results. In order to find the exact influence of coefficients of friction on the process outcome, it is essential to consider the role of each bending tool in a RDB process and investigate the process results in relation to the role of the bending tool. Pressure die performs following two fundamental roles in a RDB process:

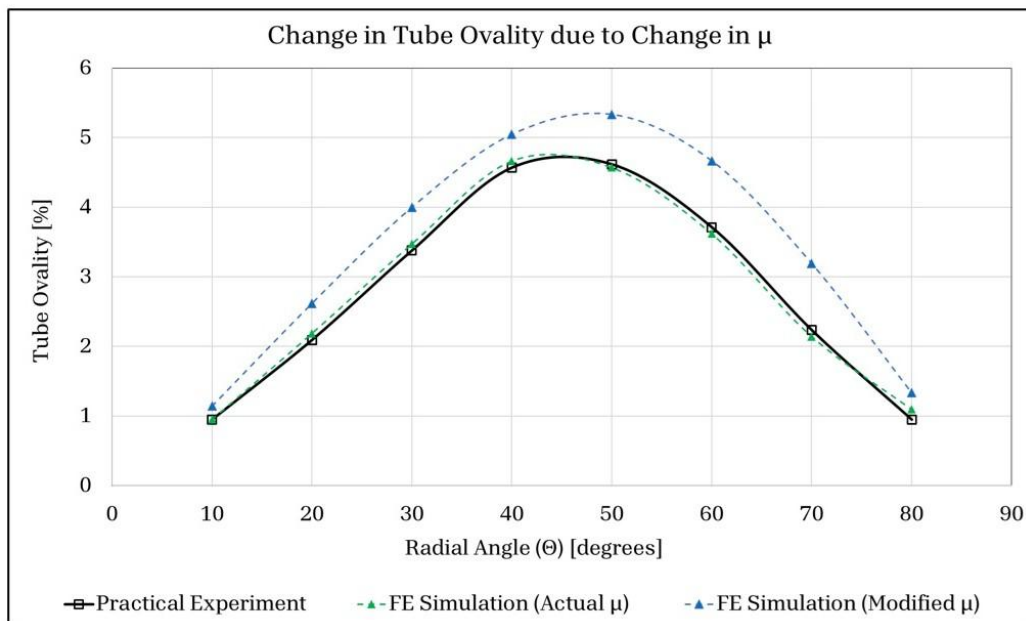
- (i) Support and counter-act the bending moments applied by the bent tube during the execution of a bending operation.
- (ii) Allow material flow at tube surface in order to reduce the tube ovality and decrease the chances of cracking at tube extrados.

The frictional behaviour of the pressure die surface controls the material flow in the tube extrados. The material flow provided by the frictional behaviour of the pressure die is therefore critically important for the tube ovality and cracking [13]. In order to determine the influence of coefficients of friction on the material flow and corresponding tube ovality, the optimum value of the coefficient of friction of pressure die is changed in the digital twin (FE-simulation model) of the RDB process. The change in tube ovality due to change in coefficient of friction is noted. The changed values of the coefficients of friction are shown in Table 6.3.

Table 6.3: Coefficients of friction used in the digital twin of RDB process

Coefficient(s) of Friction (μ)		
Tools	Actual μ	Modified μ
Pressure Die	0.1	0.3
Bend Die	0.1	0.1(no change)
Wiper Die	0.1	0.1(no change)
Mandrel	0.08	0.08 (no change)
Clamp Die Outer	0.3	0.3 (no change)
Clamp Die Inner	0.3	0.3 (no change)
Tube	0.1	0.1 (no change)

The change in tube ovality resulting due to change in coefficient of friction of pressure die is noted. Subsequently, a practical experiment of a RDB process is conducted and the tube ovality obtained from the practical experiment is measured by using Mitutoyo Digital Indicator [40]. The tube ovalities obtained from digital twin (FE-simulation) and the practical experiment are compared as shown in Figure 6.9.



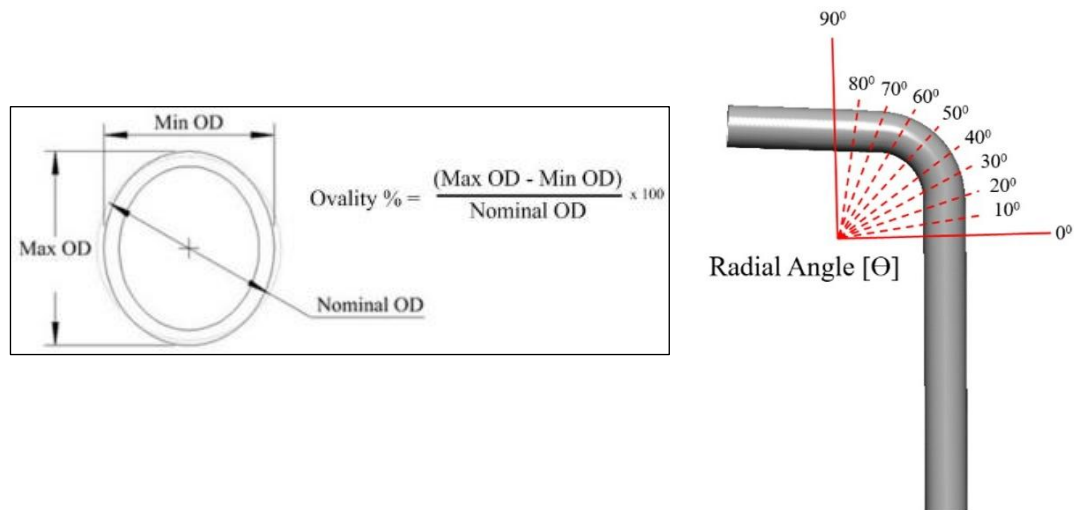


Figure 6.9: Change in tube ovality due to change of coefficient of friction (μ) at pressure die surface.

The tube ovality is increased when μ is changed from $\mu = 0.1$ to $\mu = 0.3$.

It can be seen from Figure 6.9 that the dimensions of tube ovality obtained from the practical experiment and digital twin (with actual μ) agrees substantially with each other. On the other hand, when the coefficient of friction of pressure is increased from $\mu=0.1$ to $\mu=0.3$ in the modified μ model, the tube ovality is increased to a considerable extent. A considerable enhancement in the tube ovality due to a change in the coefficient of friction of a pressure die indicates that the values of coefficients of friction controls the material flow within the tube which in turn affects the tube ovality. Hence, the design of a tool should incorporate tool surfaces with appropriate/desired values of coefficients of friction. Here, the geometric design of a pressure die is investigated therefore a lesser coefficient of friction is desired. In case of other bending tools (e.g. clamp dies), a higher coefficient of friction is desired. Therefore the geometric design of each bending tool is required to be seen in the context of the role that specific tool exhibits during a bending operation.

6.2.4 Inter-dependence of contact force of tools

In a RDB process, the bending tools exert contact force on the tube. The tube in turn reciprocates the same contact force in the opposite direction. The analysis of the contact forces has shown that the contact force applied by one tool is countered by the contact forces applied by other tools positioned in opposite direction. In case of a pressure die, the contact force applied by the pressure die is countered by the contact forces applied by the wiper die and mandrel. For a stable RDB process, the contact force applied by the pressure die must be greater than the sum of contact forces applied by the mandrel and the wiper die. The contact forces of bending tools obtained from the digital twin of the RDB process are shown in Figure 6.10 (a & b).

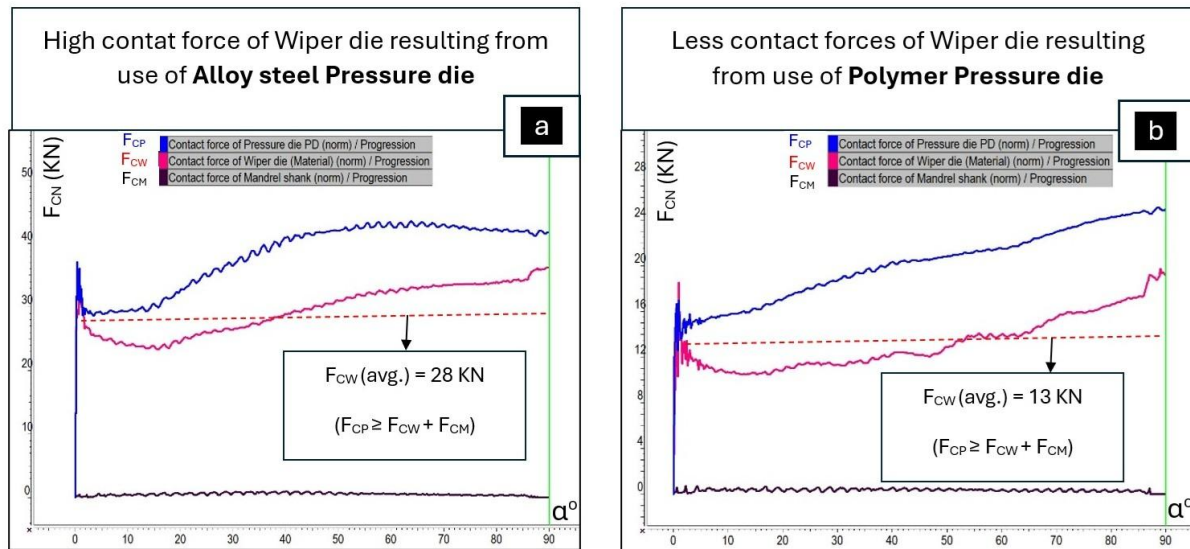


Figure 6.10 (a-b): Interdependence of contact forces of bending tools. (a) increased contact force of wiper die due to use of alloy steel pressure die Pd_c , (b) reduced contact force of wiper die due to use of polymeric pressure die Pd_p

It is seen that the contact forces applied by a conventional pressure die made from an alloy steel (Pd_c) are significantly high as compared to contact force applied by a pressure die made from polymer PLA (Pd_p). The corresponding contact forces applied by wiper die in Figure 6.10(a) are also significantly higher as compared to respective contact forces of wiper die in Figure 6.10(b). It is highlighted that in Figure 6.10(b), only the material of the pressure die is changed from alloy steel to polymer (PLA). The material of the wiper die and mandrel has not been changed. Hence, the change in contact forces of wiper die resulted from the change in contact force of pressure die. A polymeric pressure die (Pd_p) applied relatively less contact force on the tube and as a result, the wiper die and mandrel counteracted with relatively less reactionary force. This investigation reveals that the contact forces of bending tools are interdependent on each other. Hence, in order to design an efficient geometry of a pressure die, the contact forces of wiper die and mandrel should also be considered during the design phase.

6.2.5 Fatigue Strength of tool material

The fatigue strength of forming tools is an considered as a fundamental criteria in tool design [130]. Therefore, it is essential that the influence of a material change (from steel to polymer) on the fatigue strength of a tool should be investigated. Miner's rule provides the fatigue strength of parts based on the number of cycles a part can withstand before failure. These number of cycles are computed through SN-curve (Stress to Number of cycles curve) of the material [131]. Over the years, SN-curves of various materials are developed by product manufacturers and material researchers by conducting the experiments practically at a wide range of cyclic loading. In order to determine the fatigue strength of a part using Miner's rule, a load history of the part is required to be determined [132]. This load history tells the maximum stress which is applied on the part. The applied stress is compared with the graph of

SN-curve. The number of cycles are obtained from the x-axis of the curve. This number of cycles is the maximum limit of cycles at which part undergoes fatigue [131].

In RDB process, the maximum pressure applied on the surface of a pressure die change with the change in bending angle (α) [81]. A comparison of the max. pressure experienced by a pressure die made from alloy steel and a pressure die made from polymer PLA is shown in Figure 6.11.

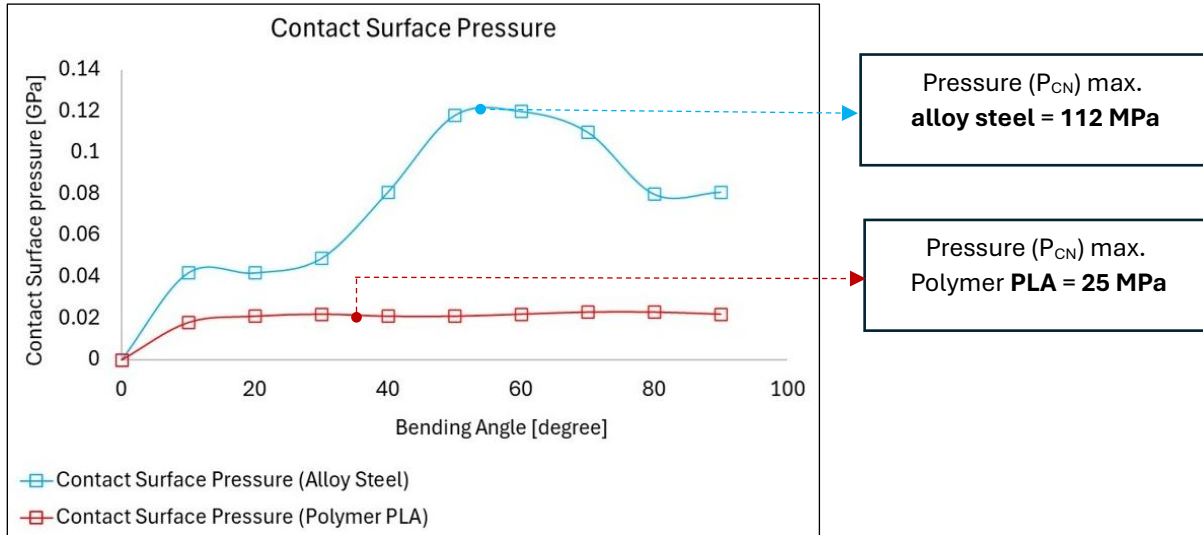


Figure 6.11: Maximum contact pressure applied on the surface of the pressure die in RDB process (RDB process parameters: $B = 1.5$; $W = 22$; R (bending radius) = 33mm, α (bending angle) = 0° to 90°)

From Figure 6.11, the maximum contact pressure experienced by pressure dies are obtained and plotted on the respective SN-curves of polymer PLA and alloy steel. The SN-curves of alloy steel and PLA are obtained from literature review [133] & [134]. Since, alloy steel and polymer PLA are commonly used industrial materials therefore substantial research is available related to SN-curves of these materials. The SN-curves of alloy steel and polymer-PLA are shown in Figure 6.12 (a & b). The maximum contact surface pressure experienced by the pressure dies in RDB process are plotted on these curves and corresponding number of cycles before material fatigue are obtained.

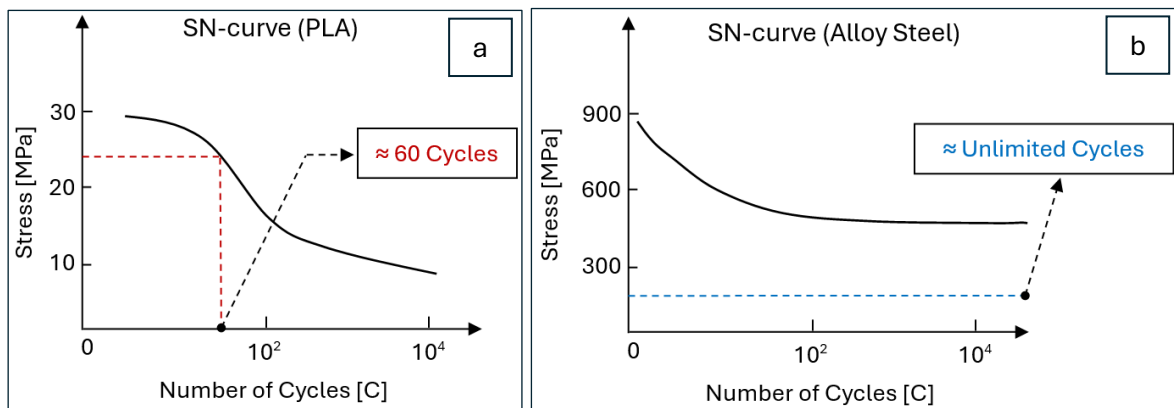


Figure 6.12 (a & b): SN curves of (a) 3D printed PLA obtained from Afrose et al. [133] (b) alloy steel obtained from et al. Wei [134]. The curves show that the pressure die made from PLA can perform a

maximum of 60 bending operations whereas the pressure die made from alloy steel can perform unlimited bending operations (The investigation is valid for RDB with process parameters: $B = 1.5$; $W = 22$; $R = 33\text{mm}$, $\alpha = 0^\circ$ to 90°).

It can be seen from Figure 6.12 that the pressure die made from PLA can be used upto 60 bending operations whereas the pressure die made from alloy steel can be used for unlimited bending operations. The SN-curves are made after practical testing of the materials, however owing to differences in process loadings arrangements and variation in material properties, a slight variation in the fatigue strength provided by SN-curves is expected [134].

The investigations conducted in this section shows that the fatigue strength of polymer made tools is significantly shorter than the fatigue strength of corresponding tool made from alloy steel. This points out that polymer made tools may be used for customized (or individualized) productions in which batch size of required products is small. Hence, during the process of material selection and geometric design of tools in RDB process, the fatigue strength of tool material should be given significant consideration. Therefore, fatigue strength is considered as a fundamental design factor for the geometric design of hybrid tools.

6.3 Identification of design factors through V-shaped tool surface

In order to enhance process flexibility of the RDB process, it is essential that the circular geometry of a tool surface is changed into a V-shaped geometrical surface. This allows the pressure die to hold a wide range of tube diameters. A V-shaped geometrical design of the pressure die is created with the polymeric material 'PLA' and the tool response resulting from a V-shaped surface is investigated. In the preceding section (section 6.2.1: Figure 6.4) of this thesis, it has been shown that a polymeric tool deforms elastically during a bending process and therefore induces a springiness effect. It is critically important to investigate that whether a spring-like tool surface with V-shaped geometric design can successfully conduct a bending operation or otherwise. Therefore, hollow spaces are created within the geometric design of the V-shaped pressure die (called here as Pd_{PV}) and the bridge legs of the Pd_{PV} are made considerably thicker so that a spring-like response is obtained from the tool surface. In addition to spring-like effect, the hollow spaces reduce the material usage within the tool geometry and makes it considerably lightweight. The geometric design of the V-shaped pressure die along with tool design considerations is shown in Figure 6.13.

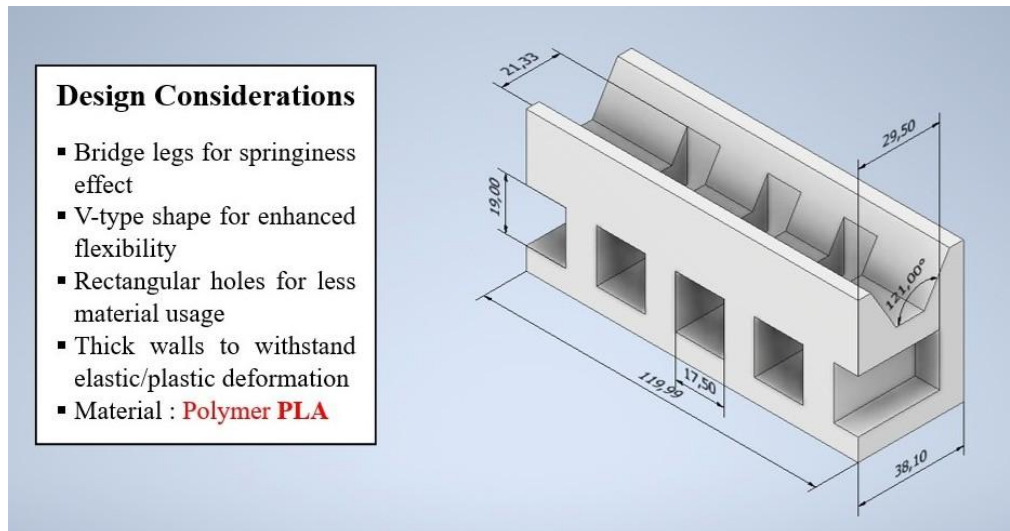


Figure 6.13: CAD of the V-shaped pressure die (Pd_{PV}) [81]

(Figure already published as part of this research thesis. DOI:

<https://link.springer.com/article/10.1007/s00170-024-14221-3>)

In order to investigate that V-shaped geometry of the polymeric pressure die (Pd_{PV}) will be able to conduct the RDB process successfully, a static analysis of the pressure die is conducted in the software Autodesk INVENTOR. The static analysis of the pressure die is conducted because the complete simulation of the RDB process (as a digital twin model) takes almost 88 hours to complete whereas a static analysis provides the approximate results in less than 40 minutes. Although the results of static analysis are not completely accurate yet they are used as an interim measure to find out the feasibility of using V-shaped pressure die in a RDB process. The static analysis is conducted by feeding the software with prognostic process loads being applied on the tool surface and feeding the material properties of PLA (Young's Modulus, Yield strength, Poisson's ratio and density). The distortion energy theory (DET) commonly known as von-Mises criterion states that a tool material will fail (crack or plastically deform) if the von-Mises stress surpasses the yield strength of the tool material. Keeping in view the failure criterion of DET, the post processing results of the static analysis show that the value of maximum von-Mises stress developed within Pd_{PV} remained significantly less than the yield strength of the polymeric material PLA (i.e., 46 MPa < 72 MPa). The result of static stress analysis is shown in Figure 6.14. The static stress analysis shows that Pd_{PV} can be safely used in a RDB process.

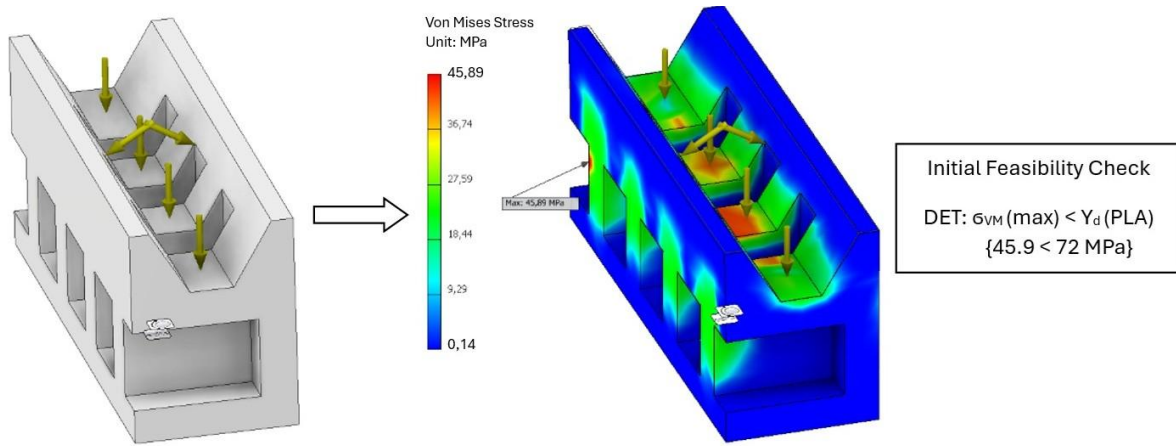


Figure 6.14: Initial feasibility of Pd_{PV} for use in a RDB process [81]

(Figure already published as part of this research thesis. DOI: <https://link.springer.com/article/10.1007/s00170-024-14221-3>)

After obtaining feasibility that the CAD of Pd_{PV} will execute the tube bending operation safely, the CAD is imported in the digital twin model of the RDB process and complete process simulation is conducted. The complete process simulation with digital twin took almost 88 hours to complete. The digital twin model of the RDB process consisting of Pd_{PV} is shown in Figure 6.15. The tool performance of Pd_{PV} is investigated and the tool response is used to identify tool design factors.

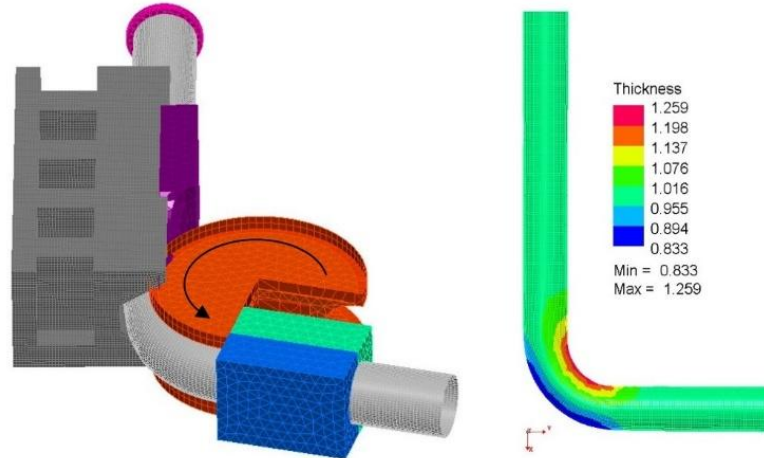


Figure 6.15 : Digital twin of the RDB process consisting of V-shaped pressure die (Pd_{PV})

6.3.1 Process flexibility range

In the digital twin simulation, the maximum von-Mises stress remained less than the yield strength of PLA. Based on the von-Mises criterion (DTE), it was verified that the Pd_{PV} conducts the understudy RDB process without any failure. Moreover, the digital twin model did not show any crack or plastic deformation within the tool geometry. Therefore, it is possible to test the flexibility range of Pd_{PV} using digital twin. Hence, the RDB process is conducted with smaller and larger tube diameters while using the same geometry of Pd_{PV}. From Table 5.1, it can be noticed that the fundamental process parameters i.e., Bending factor 'B' and Wall factor 'W' have values of B=1.5 and W=22.00. In order to keep these

process parameters (B and W) identical, the wall thickness and bending radius of larger and smaller tubes are modified in the digital twin model. This ensures that the process parameters are identical for process simulations conducted with larger and smaller tube diameters. First, the tube diameter is reduced from 22 mm to 16 mm and the process simulation is conducted. The tool geometry of Pd_{PV} remained the same. The process results showed that the process can be executed safely at a tube diameter of 16 mm as wrinkle free bent tube is obtained without any crack development at the extrados. Second, the tube diameter is increased from 22 mm to 28 mm and the process simulation is conducted. The process results showed that the Pd_{PV} cannot be used to conduct the process at a tube diameter of 28 mm as wrinkles are seen at the tube intrados. Moreover, a crack development is also witnessed at extrados. The process results provided by Pd_{PV} are shown in Figure 6.16.

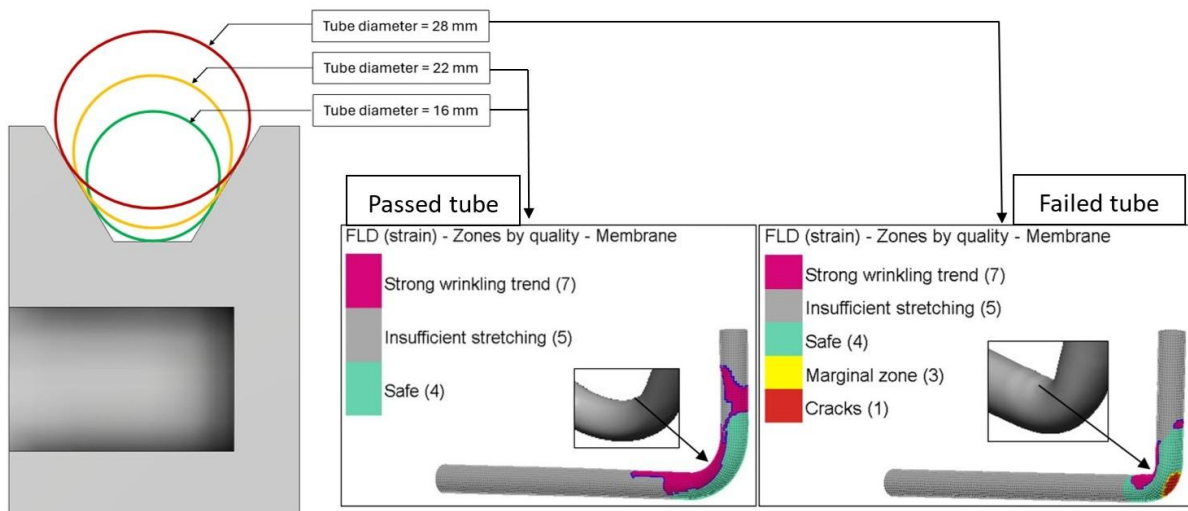


Figure 6.16: Identification of range of tube diameters with V-shaped pressure die (Pd_{PV}) [81]

(Figure already published as part of this research thesis. DOI:
<https://link.springer.com/article/10.1007/s00170-024-14221-3>)

Figure 6.16 shows that there is a certain range of tube diameters which can be used with V-shaped tool geometry. Hence, not all the tube diameters which fit in the V-shaped surface can be used in the RDB process. This investigation shows that the range of tube diameters (or process flexibility range) supported by a V-shaped tool surface should be considered in the tool design process.

6.3.2 Contact pressure enhancement due to line contact (Localization of P_{CN})

The maximum contact pressure (P_{CN}) on the tool surface of a V-shaped geometry is compared with the contact pressure on a circular geometry. In both cases, the material of the tool (pressure die) is polymer PLA. The maximum contact pressure (P_{CN}) developed due to line contact in a V-shaped geometry and full contact in a circular geometry is shown in Figure 6.17. It can be seen that the maximum surface pressure experienced by the line contact is substantially larger as compared to the circular contact. The maximum contact pressure per degree (P_{CN}/α°) of V-shaped tool surface is significantly greater than the circular tool surface.

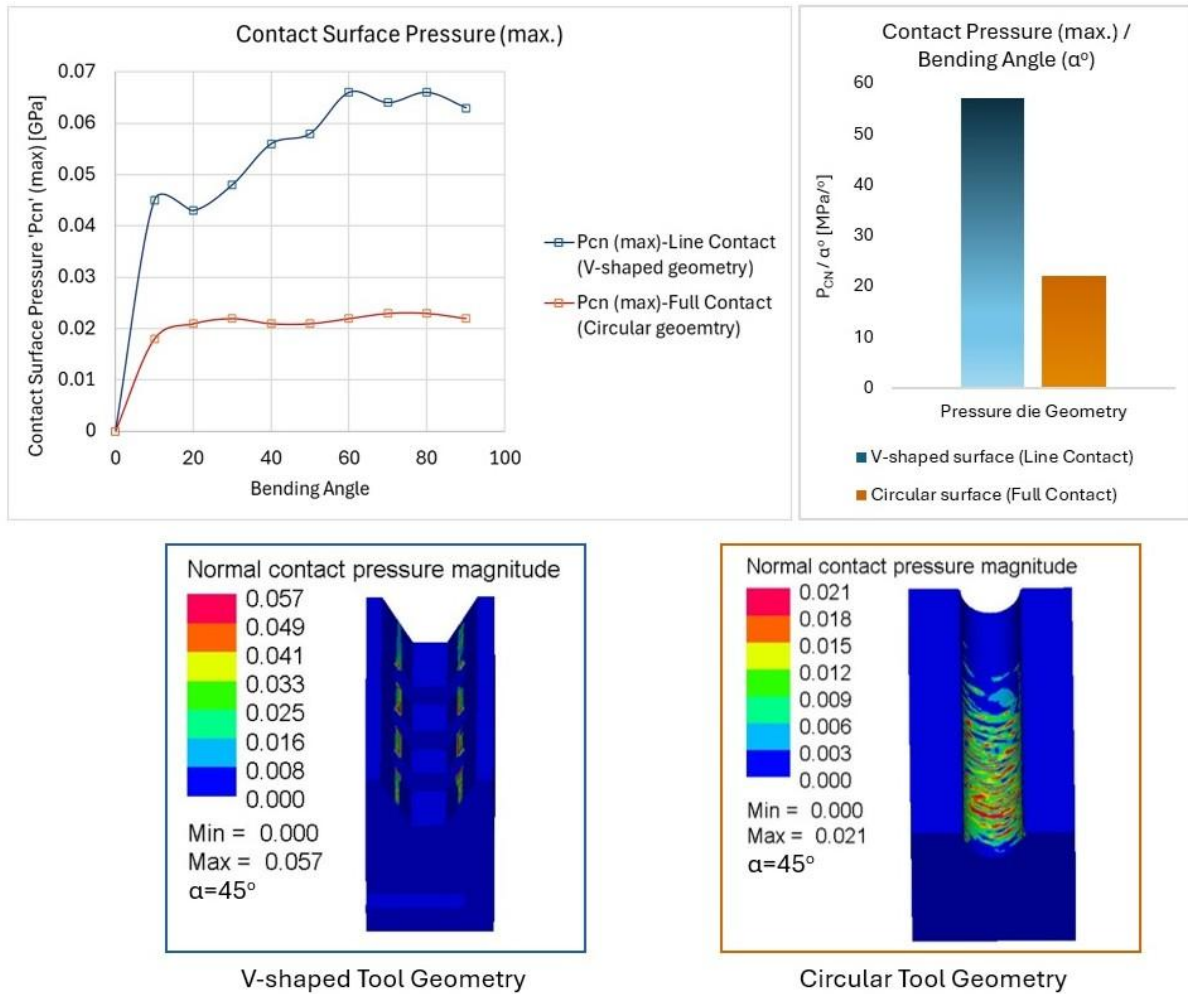


Figure 6.17. Increase in contact surface pressure (P_{CN}) in V-shaped tool surface as compared to the circular tool surface

The contact force F_{CN} acting on the surfaces of V-shaped pressure die (Pd_{PV}) and circular pressure die (Pd_P) is shown in Figure 6.18. It can be seen that F_{CN} increases steadily in case of Pd_P whereas fluctuations are observed in case of Pd_{PV} . The fluctuations of F_{CN} in case of Pd_{PV} are attributed to the V-shaped geometry. The tool sides in case of V-shaped geometry are prone to enhanced elastic deformations hence resulting in fluctuation of contact forces [135]. Moreover, the F_{CN} (max.) of the circular tool surface is considerably larger than the F_{CN} (max.) of the V-shaped surface.

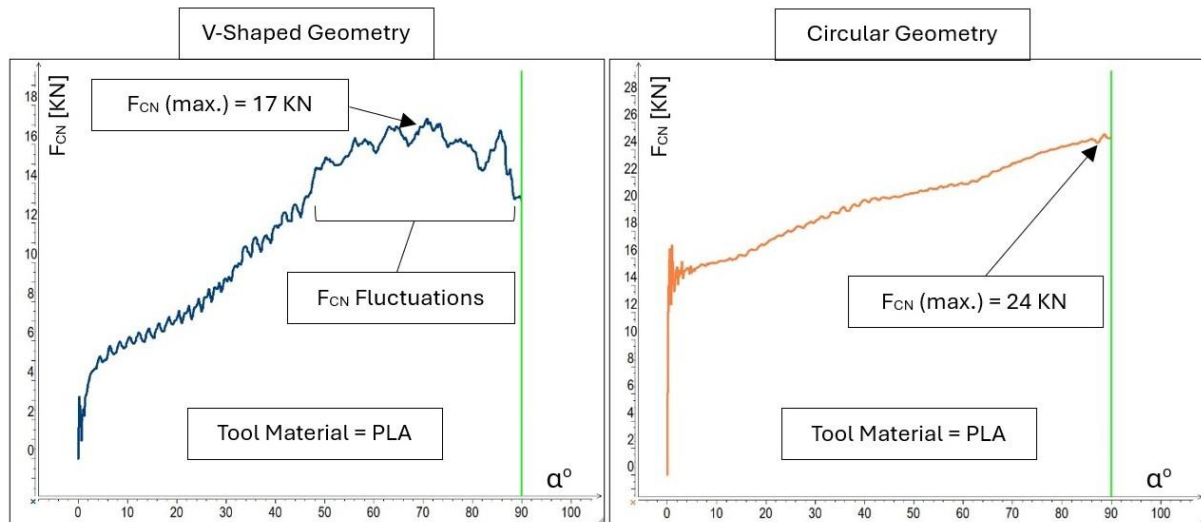


Figure 6.18: Contact force (F_{CN}) on surface of V-shaped and circular tool geometry.

It can be seen from Figure 6.17 (previous figure) that the effective area on the surface of circular geometry is significantly greater than the effective area on V-shaped geometry. Hence, in case of V-shaped geometry the contact pressure is squeezed in a smaller effective area. The squeezing of contact pressure to a smaller effective area (in the form of a line contact) is termed as the localization of contact pressure [136]. The localization of contact pressure on the tool surface is an important tool design factor since an increase in contact pressure directly influences the von-Mises stress which increases the chances of tool failure [137]. Therefore, localization of contact pressure resulting from a line contact should be given an important consideration during the tool design process.

6.3.3 Wear resistance of tool material

Wear resistance of tool material plays a significant role in the design of production tools [138]. In order to determine the wear resistance, the wear rate of tool material is required to be determined [139]. For large scale productions, a material with comparatively lesser wear rate is required at the surfaces of tool geometry [140]. Literature review suggests that polymeric materials have significantly higher wear rate as compared to steels [141]. In this section, our focus is to determine the influence of changing tool material (from steel to polymer) and tool geometry (from circular to V-shape) on the tool wear. The wear in a material is numerically calculated by Archard wear equation mentioned in equation 6.4 [139]:

$$W = \frac{K \cdot F \cdot L}{H} \dots\dots\dots(6.4)$$

Here, W is the wear volume [mm^3], K is the wear coefficient [-], F is the applied force [N], L is the sliding length [mm] and H is the hardness of material [MPa] which experiences wear.

To quantify the wear within a tool material, it is essential to determine the wear rate (W'). In order to determine the wear rate, the length (L) of the sliding surface can be replaced with the velocity (V) of slide i.e., length of slide per unit time [142]. Therefore, equation 6.4 becomes equation 6.5 as shown below:

$$W' = \frac{K \cdot F \cdot V}{H} \dots\dots\dots(6.5)$$

Here, W' is wear rate [mm^3/sec] and V is the velocity of slide [mm/sec]. In case of RDB process, the contact between tube and tool develops linear wear. Hence, instead of F (force), the contact pressure can be exerted on the area of tool surface [143]. By replacing F with P (pressure), equation 6.5 becomes equation 6.6 as shown below:

$$W' = \frac{K \cdot P \cdot V}{H} \dots\dots\dots(6.6)$$

The production processes are normally characterized by high number of cycles. Therefore, another factor ' n ' (number of cycles) is introduced in equation 6.6. The equation 6.6 takes the form of equation 6.7 as shown below:

$$W' = \frac{K \cdot P \cdot V \cdot n}{H} \dots\dots\dots(6.7)$$

Equation 6.7 is used to calculate the wear rate (W') of circular tool geometry and V-shaped tool geometry. The tool materials are alloy steel and polymer-PLA. It is pertinent to mention that the Wear is calculated for one surface i.e., the surface which slides over the other surface. Hence, one surface is considered reference and the other surface is considered sliding. In case of RDB process, tool surface is considered as sliding surface and the wear at tool surface is computed by Archard law mentioned in equation 6.7. The list of parameters required for calculation of wear for steel and polymers are shown in Table 6.4. Here, the parameter values of steel (alloy steel) and polymer (PLA) are presented.

Table 6.4: Parameters required for calculation of wear in tool materials according to Archard wear law

Ser	Parameter required for Archard Wear law	Steel (alloy steel)	Polymer (PLA)	Units
1.	Pressure (P) applied on the sliding surface	OPC	OPC	MPa
2.	Hardness of tool material (H)	2000	240	MPa
3.	Velocity (V) of slide [Tube velocity]	OPC	OPC	mm/sec
4.	Wear coefficient of tool material (K)	7.0×10^{-6}	1.67×10^{-4}	(mm^3/Nm)

OPC: Obtained from Process Conduct. In RDB process, the applied pressure on tool surface and the velocity of tube on tool surface depends on the process parameters.

The values of surface pressure (P) and slide velocity of tube (V) are taken according to parameterized RDB process [process parameters: B (bending factor)=1.5; W (wall factor)=22; R (bending radius)=33mm and α (bending angle)=90°] as shown in Table 6.5. The value of K (wear coefficient) depends on surface quality, surface behaviour related to heat transfer and chemical compatibility between rubbing surfaces [139]. K can be obtained experimentally [143]. Literature

review shows that the value of K for steels and polymers are 7.0×10^{-3} and 1.67×10^{-4} respectively [144] & [145].

Table 6.5: Wear rate [mm^3/sec] at too surfaces in RDB process according to Archard wear law
[The values of P (contact pressure-max.) and V (tube linear velocity) are obtained from process parameters: B =1.5; W =22; R (bending radius)=33mm and α (bending angle)= 90°]

Pressure die geometry in RDB process		K (mm^3/Nm)	P (MPa)	V (mm/sec)	H (MPa)	W' [n=1] [one cycle] (mm^3/sec)	W' [n=100] [100 cycles] (mm^3/sec)
1.	Circular conventional tool geometry (alloy steel)	7.0×10^{-6}	112	5.7	2000	2.23×10^{-6}	2.23×10^{-4}
2.	Circular conventional tool geometry (polymer PLA)	1.67×10^{-4}	24	5.7	240	9.12×10^{-5}	9.12×10^{-3}
3.	V-shape tool geometry (polymer PLA)	1.67×10^{-4}	67	5.7	240	2.54×10^{-4}	0.0254

The numerical calculations of wear rate (W') shown in Table 6.5 shows that polymer made tools have significantly higher tendency of wear development. On the other hand, alloy steel show substantially less wear rate (and high wear resistance) as compared to polymers. Moreover, when the geometric design of tool is changed from circular geometry to V-shaped geometry (line contact), the tendency of wear development is significantly enhanced. The increase in wear rate between circular geometry (polymer) and V-shaped geometry (polymer) occurred due to the decrease in contact area between tube and tool and corresponding increase in contact pressure.

The investigations conducted in this section showed that the wear rate at tool surface is significantly increased due to change in tool material (from steel to polymer) and change in geometric design (from circular geometry to V-shaped geometry). A higher wear rate means less wear resistance and vice versa [139]. Hence, polymers have significantly less wear resistance as compared to steels. Wear resistance significantly effects the design of a tool. Therefore, tool wear is an important aspect which should be considered while designing a tool for RDB process.

6.4 Summary of the identified tool design factors

In order to design the geometry of a bending tool, it is essential to identify the design factors which influence the tool performance during RDB process. This research thesis used the digital twin model of a RDB process in which polymer made tools provided essential information related to tool performance within the process. The tool performance of a fundamental bending tool 'pressure die' is investigated and the influencing factors related to tool design are identified. The tool design factors are the fundamental aspects which significantly influence the process outcomes due variation in tool geometry

or tool material. These aspects will assist in the development of envisioned hybrid tools. The objective of this research thesis is to develop the tool geometry which should render process flexibility to RDB process and enhance tool effectiveness by using advantages offered by additive manufacturing techniques. Therefore, the tool design factors identified in this chapter will be used to develop a geometric design which delivers tool effectiveness in terms of process flexibility, material economization and suitability for customized productions. The identified tool design factors are mentioned below:

- a. Young's Modulus of tool material (M_Y).
- b. Friction coefficient of the tool surface (F_S).
- c. Effective (or active) area on tool surface (A_E).
- d. Contact force of other tools (F_T).
- e. Fatigue strength of tool material (S_F).
- f. Process flexibility range (R_F).
- g. Localization of surface pressure (P_L).
- h. Wear resistance of tool material (W_R).

Chapter 7 : Topology Optimization of the Tool Geometry

7.1 Topology Optimization process

A Topology Optimization (TO) is a structural shape change process in which the topographical features of the structure are optimized by using algorithms and mathematical models so as to adjust material layout within a pre-defined space [146]. It is conducted by using inputs like loads, process conditions and constraints. The algorithms and mathematical models used in the TO process are substantially elaborate and complex therefore the computations of algorithms are nowadays carried out with specially designed FE-simulation softwares [147]. There are numerous approaches to conduct TO. Few commonly used approaches to conduct TO are density, evolutionary, level-set, phase field, derivative etc [148]. Every approach uses a specific mathematical model which is capable of computing the structural response based on provided input values [149]. SIMP (Solid Isotropic Material Penalization) is the most recent form of a density approach in which material properties are considered to achieve process convergence by using a penalization factor decided on the basis of input values [150]. On the other hand, the level-set approach is another commonly used mathematical model which is primarily based on the geometry of the topology optimized structure [151]. Level-set method uses shape sensitivity of pre-defined geometries to achieve convergence through mathematically computed level-set functions [152]. Significant research conducted in the domain of TO has shown that a combination of these two approaches called as the hybrid approach is best suited to obtain precise results [153] & [26]. The computations conducted in the realm of a hybrid approach are substantially complex and complicated [154]. These computations are nowadays conducted by using FE-simulation softwares. Autodesk INVENTOR uses the hybrid approach for conducting the TO of input geometries [155]. The hybrid approach used by the INVENTOR uses a combination of SIMP and level-sets methods [26]. The software uses both the geometrical aspects and material properties of the input geometry in order to obtain convergence of the desired optimization. The material properties, geometric constraints and other pre-processing boundary conditions are fed to the software. The meshing of the input geometry is conducted by the auto-mesh module and input loads and constraints are manually applied on the input geometry according to the actual process conditions. The processing time taken by the software depends on the number of input constraints, geometric complexity of input geometries, meshing parameters and speed of the computing system [156].

7.2 Topology Optimization of Pressure die in a RDB process

The topology optimization of bending tools used in a RDB process is conducted by applying input loads on tool surfaces, kinematic constraints, material properties and other process related pre-processing conditions [26]. In this research thesis, the topology optimization of a fundamental bending tool 'pressure die' used in a RDB process is conducted in the FE-simulation software Autodesk INVENTOR. The conventional tool geometry of the pressure die is shown in Figure 7.1 alongwith pattern of P_{CN} on the tool surface.

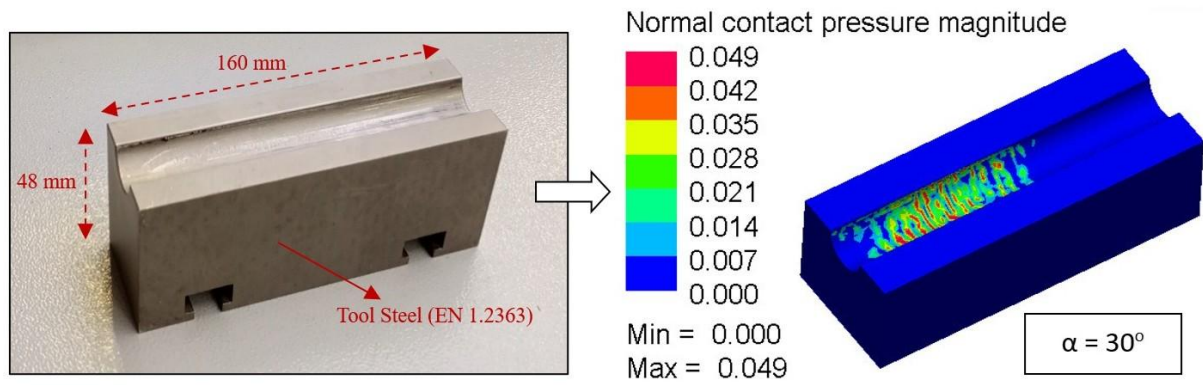


Figure 7.1: P_{CN} pattern on the conventional geometry of the pressure die made from alloy steel [26].

(Figure already published as part of this research thesis. DOI:

<https://link.springer.com/article/10.1007/s12008-024-01932-w>)

The topology optimization process produces complicated geometries which often require practical development by using 3D printing techniques [157]. In comparison to steels, polymeric materials offer significant advantages. Polymers are light weight, low cost and easy to manufacture through FDM technique [158]. The FDM (Fused Deposition Modelling) is a polymer based 3D printing process that is inexpensive and substantially fast in terms of production speed [159]. Practical experience has shown that a small size polymeric part (e.g. with dimensions less than 200 x 100 x 50 mm) can be produced within 30 minutes depending upon machine speed and print conditions. In order to practically 3D print a complex geometry produced by a TO process, the material of the conventional pressure die is changed from the alloy steel to a polymer 'PLA' while the geometric dimensions are kept the same. This measure will allow the comparison of polymer made topology optimized geometry with the original geometry of the pressure die. The PLA made conventional geometry of the pressure die is called here as Pd_p . The CAD of Pd_p is developed and imported in the FE-simulation model and the process simulation is conducted. The results of FE-simulation shows that the surface of Pd_p experiences a different pattern of PCN as shown in Figure 7.2.

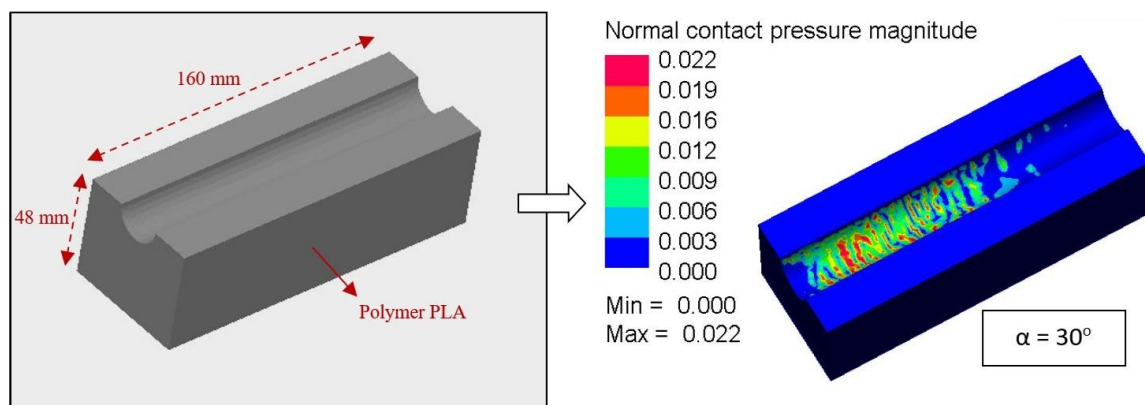


Figure 7.2: P_{CN} pattern on the conventional geometry of the pressure die made from polymer PLA

[26]. (Figure already published as part of this research thesis. DOI:

<https://link.springer.com/article/10.1007/s12008-024-01932-w>)

The P_{CN} is used as the input variable to conduct the TO of Pd_p . The kinematic constraints are fed to the software according to the actual process conditions. The length of the tool surface is reduced according to the maximum effective area on tool surface. The process parameters are applied as the pre-processing boundary conditions. The complete development process of topology optimized pressure die is shown in Figure 7.3 alongwith respective process steps mentioned in Table 7.1.

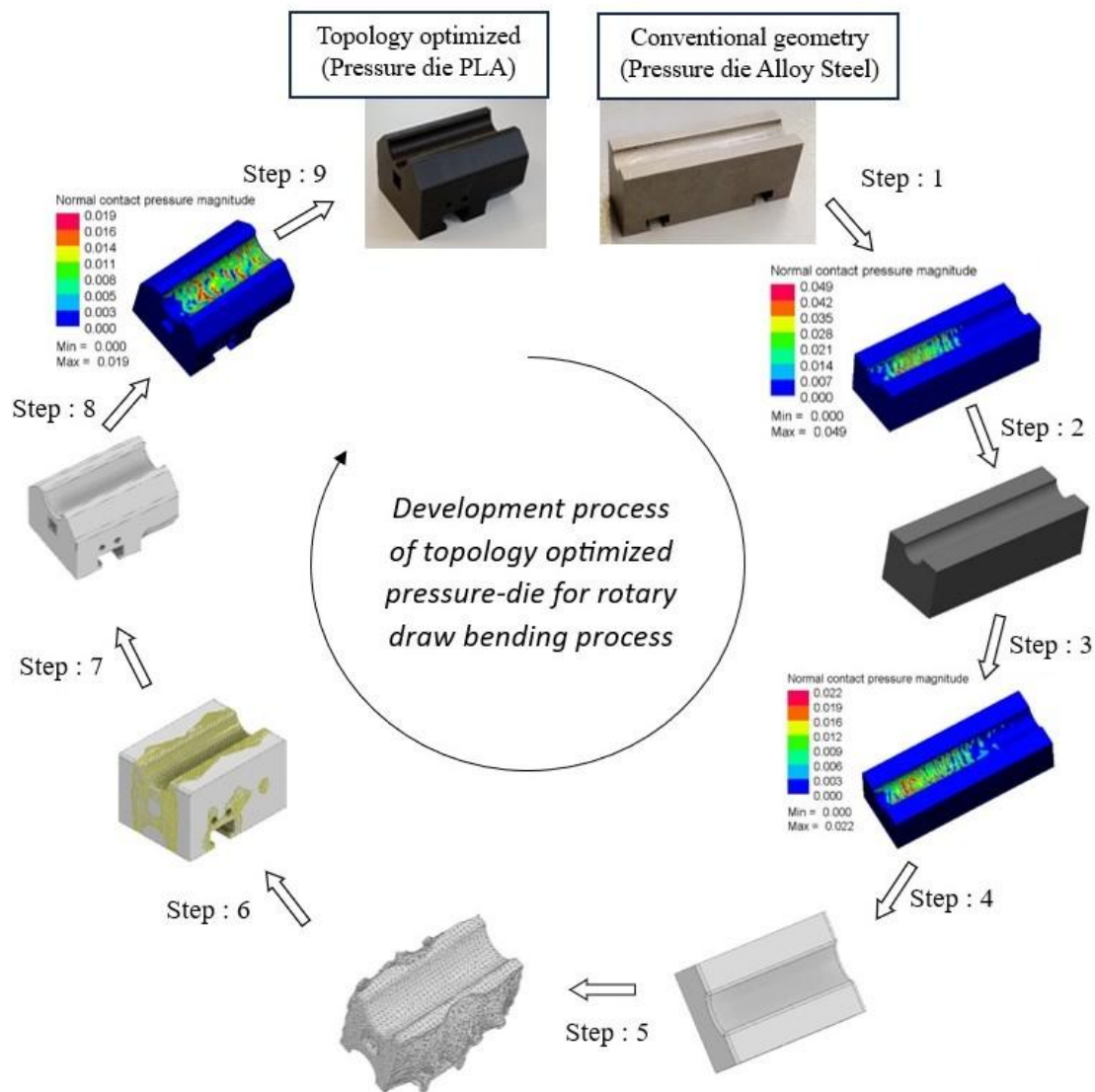


Figure 7.3: Topology optimization of pressure die in a RDB process [26].

(Figure already published as part of this research thesis. DOI: <https://link.springer.com/article/10.1007/s12008-024-01932-w>)

Table 7.1: Steps of Topology Optimization from Figure 6.3

Step 1	Obtaining contact normal pressure distribution on the surface of conventional pressure die (Pd_{metal}) using FE-simulation
Step 2	Making CAD model of Pd_p with identical geometrical dimensions. Change of material of pressure die from alloy steel (EN 1.2363) to polymer polymer (PLA)

Step 3	Obtaining contact normal pressure distribution on the surface of Pd _p using FE-simulation
Step 4	Shortening the length of Pd _p from 160 mm to 80 mm so that the tool length with unused tool surface is omitted
Step 5	Topology optimization using combination of SIMP (Solid Isotropic Material Penalization) and Level-Set methods in the software Autodesk INVENTOR
Step 6	Shape comparison of topology optimized Pressure die with shortened Pressure die
Step 7	Modifying the dimensions of shortened Pd _p according to the dictates of topology optimization results while leaving the safety margins. The final model is called TO-Pd _p
Step 8	Testing the CAD model of TO-Pd _p in RDB process using FE-simulation in PAMSTAMP and obtaining the contact pressure distribution pattern on the tool surface
Step 9	Fabrication of TO-Pd _p by additive manufacturing (Fused Deposition Modelling) for subsequent experimental tests

7.3 Practical conduct of the RDB process with topology optimized tool

The CAD of the topology optimized pressure die (TO-Pd_p) is physically 3D printed using PRUSA MK4 3D printer. The print parameters used for 3D printing are kept the same as mentioned in Table 5.2. In order to ascertain the tool performance, the CAD of TO-Pd_p is imported in the FE-simulation model and the complete bending process is simulated. To investigate the accuracy of the FE-simulation model (digital twin with TO-Pd_p), a practical RDB process is conducted by using physically 3D printed TO-Pd_p in the RDB process. The conduct of RDB process is shown in Figure 7.4.

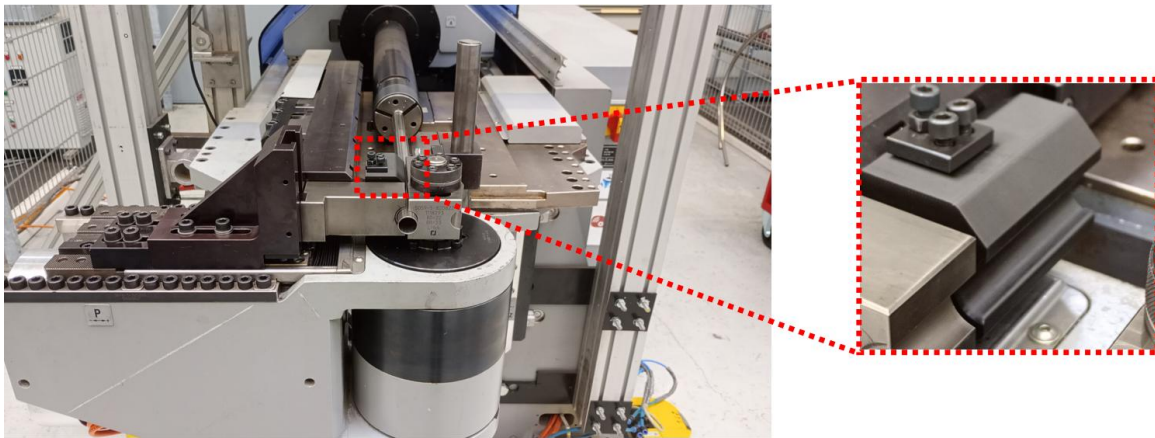


Figure 7.4: Practical conduct of the RDB process with TO-Pd_p

The TO-Pd_p conducted the RDB without tool failure and the sample tubes were bent successfully. The significant tube quality characteristics of practically bent tubes are compared with the respective tube characteristics obtained from the FE-simulation model. A substantial agreement is noticed between the results obtained from FE-simulation and practically conducted experiment. The comparison of results obtained from FE-simulation and practical experiment are shown in Figure 7.5.

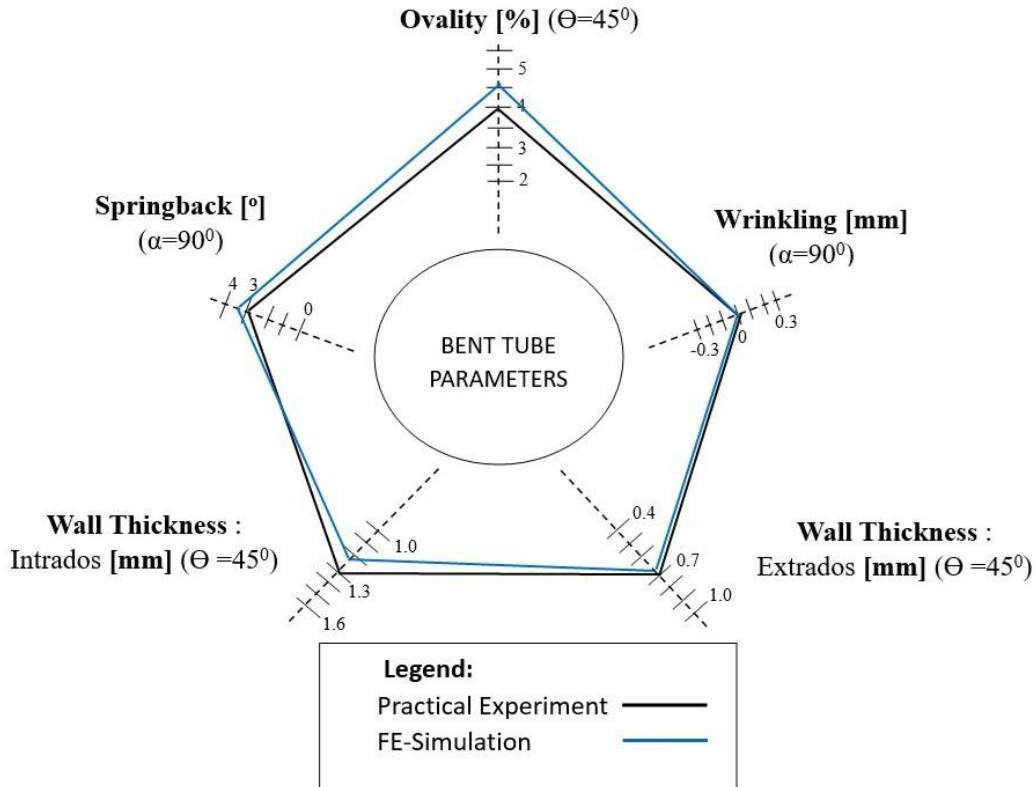


Figure 7.5: Development of digital twin of RDB process with TO-PdP. Comparison of tube quality characteristics obtained from FE-simulation (blue) and practical experiment (black).

The significant agreement between the simulation and practical experiment allows the use of FE-simulation model for investigating the tool performance of TO-PdP. The tool performance is investigated in terms of contact pressure (P_{CN}) on tool surface, contact forces (F_{CN}) acting on tool surface, von-Mises stress developed within tool geometry, effective area on tool surface and elastic deformation within tool geometry. The tool performance of TO-PdP is compared with the tool performance of PdP. The comparison of tool performances of both tool geometries identifies the influence of topology optimization on the tool performance.

7.4 Comparison of tool performance (Topology optimized tool geometry Vs Conventional tool geometry)

The practical conduct of the RDB process with TO-PdP showed that there is no noticeable plastic deformation or crack development in the geometry of the TO-PdP. In order to investigate the stress withstanding capability of TO-PdP, the development of von-Mises stress within the tools geometry at each bending angle (α) is investigated. The comparison of von-Mises stress between TO-PdP and PdP at each bending angle (α) is shown in Figure 7.6(a). It can be seen that a relatively larger von-Mises stresses appeared within the TO-PdP as compared to PdP. The value of maximum von-Mises stress remained substantially less than the yield strength of the polymeric material PLA. This verifies that the 3D printed TO-PdP is capable of withstanding the stresses applied during the bending operation. It can be seen from Figure 7.6(b) that the P_{CN} (max.) acting on the surface of TO-PdP is considerably larger as compared to

P_{dP} . However, larger fluctuation in P_{CN} are noticed. The fluctuation of P_{CN} in TO- P_{dP} generally takes the shape of a sinusoidal wave which increases and decreases continuously.

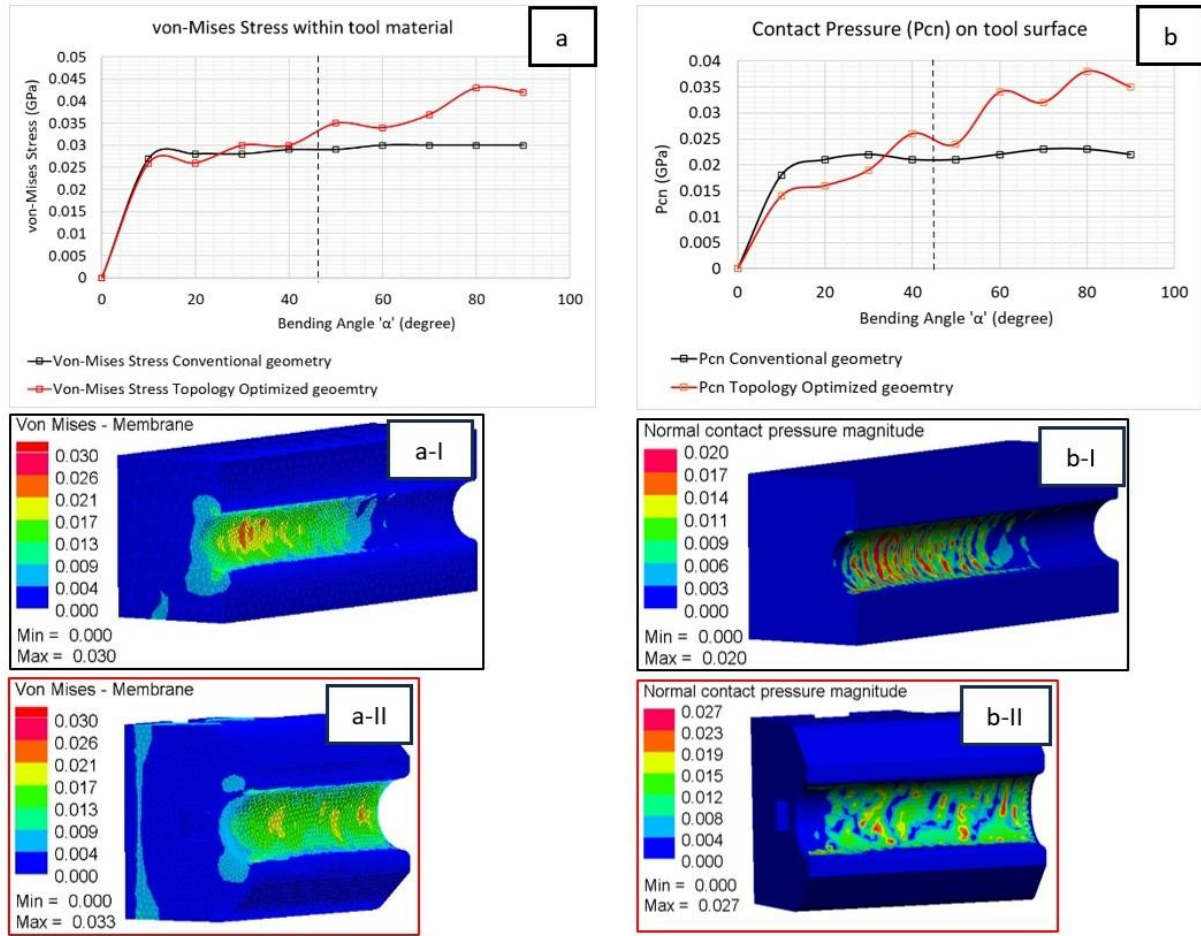


Figure 7.6 (a) von-Mises stress within tool geometries: a-I. von-Mises stress in P_{dP} at $\alpha=45^\circ$ and a-II. von-Mises stress in TO- P_{dP} at $\alpha=45^\circ$ (b) Contact Surface Pressure [P_{CN}] (max.) at tool surface: b-I. P_{CN} in P_{dP} at $\alpha=45^\circ$ and b-II. P_{CN} in TO- P_{dP} at $\alpha=45^\circ$

The fatigue strength of the topology optimized tool is obtained by comparing P_{CN} (applied stress at tool surface) with the number of cycles on SN-curve of PLA [133] (details related to computation of fatigue strength are mentioned in section 6.2.5). The maximum number of cycles (bending operations) a topology optimized tool (TO- P_{dP}) can withstand before failure is shown in Figure 7.7. It is pertinent to mention that SN-curves should be considered as a general yard stick to obtain tool failure or fatigue limit. The exact number of bending operations a tool can conduct before tool failure is ideally obtained by practical bending operations.

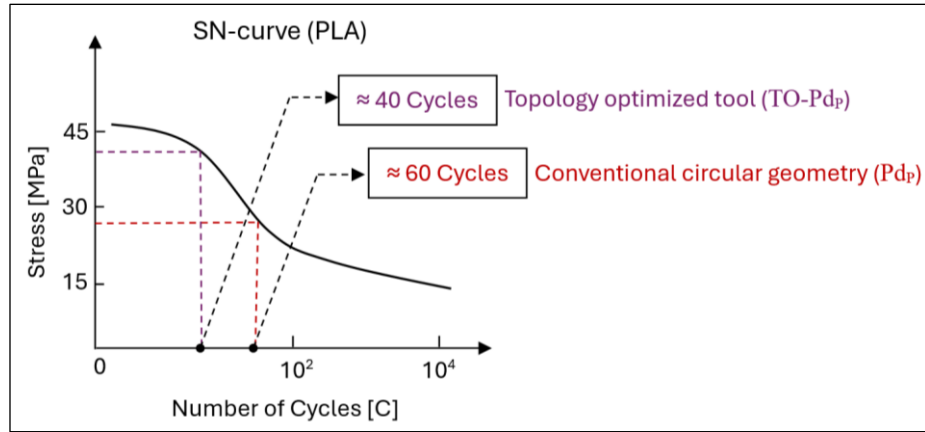


Figure 7.7: SN-curve shows the fatigue strength of the tools. The number of cycles a topology optimized tool (TO-Pd_P) is less than the number of cycles a conventional tool geometry (Pd_P) can conduct. The investigation shows that fatigue strength of TO-Pd_P is less than the fatigue strength of Pd_P.

Due to relatively high P_{CN} , the maximum vertical displacement at the surface of TO-Pd_P is considerably larger as compared to Pd_P. At the end of the bending operation, the surface of TO-Pd_P regains its original position. This shows that the surface of the TO-Pd_P is only elastically deformed during the bending operation. As soon as the loads acting on the tool surfaces are removed, the tool surface of Pd_P and TO-Pd_P regains their original position. The comparison of surface displacement between the surfaces of TO-Pd_P and Pd_P is shown in Figure 7.8.

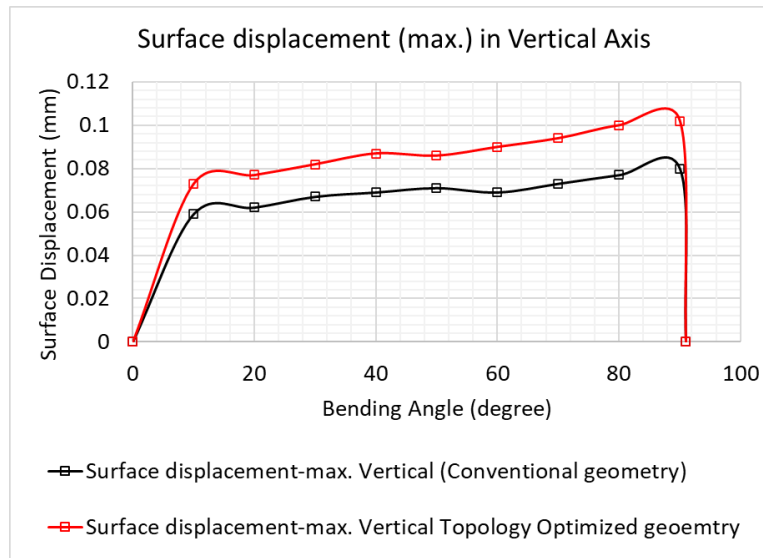


Figure 7.8. Surface displacement on tool surface of polymeric pressure die: Conventional pressure die geometry 'Pd_P' (in black colour) and Topology Optimized pressure die 'TO-Pd_P' (in red colour). The return of tool surfaces to their original position after end of bending process.

The contact forces F_{CN} on the surface of the Pd_P and TO-Pd_P are shown in Figure 7.9. It is seen that the contact force of TO-Pd_P is considerably less than the contact force on tool surface of Pd_P. Usually, it is seen that a higher contact force results in higher P_{CN} and higher surface displacement. However, in this case, a lesser contact force on TO-Pd_P results in higher P_{CN} and higher tool surface displacement. In

order to determine the reason which contribute to this unusual behaviour, it is essential to determine the effective surface area on the tool surface.

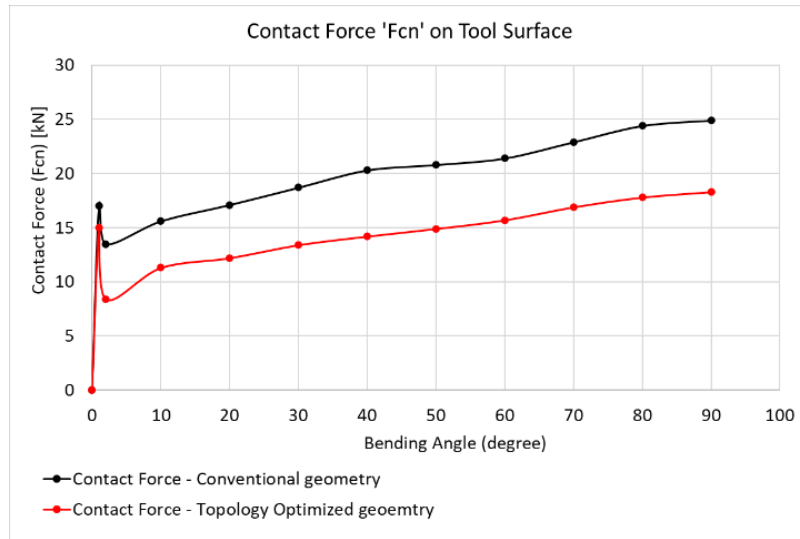


Figure 7.9. Contact force (F_{CN}) on tool surface of Pd_p and TO- Pd_p

Keeping in view the respective value of contact pressure (P_{CN}) and contact force (F_{CN}) at each bending angle (α), the effective area on the tool surface is calculated by using equation (6.2) [Chapter 6, section 6.2.2] i.e.,

$$A_{EFF} = \frac{F_{CN}}{P_{CN}} \dots\dots\dots (7.1)$$

The total surface area of the pressure die is calculated by the equation (7.2) below:

$$\text{Total surface area } (A_{TOTAL}) = \frac{1}{2} [(2\pi r) \cdot l] \dots\dots\dots (7.2)$$

The effective area and the total area of the tool surface of both tools (Pd_p and TO- Pd_p) are shown in Figure 7.10. It can be seen that the unused area on the tool surface of TO- Pd_p is significantly smaller than the unused area on the tool surface of Pd_p . Hence, for the under investigated parameterized RDB process, the topology optimized geometry of the pressure die uses the surface area of the tool with substantially high effectiveness as compared to the conventional geometry of the pressure die.

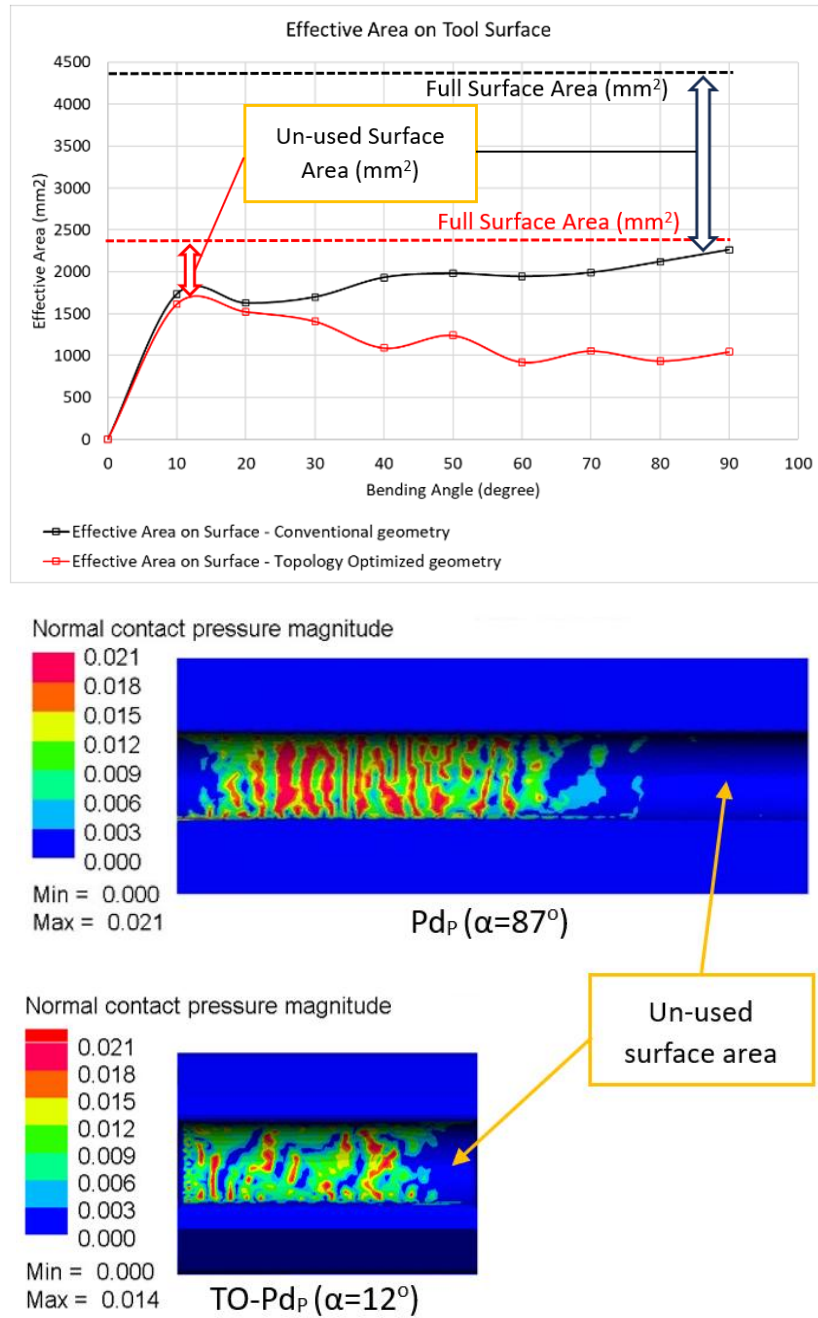


Figure 7.10: Effective Area and Un-used areas on tool surfaces (Pd_P and TO-Pd_P). The investigation shows that the un-used surface on tool surface of TO-Pd_P is significantly lesser than the un-used surface area of conventional geometry of Pd_P. The material of both pressure dies is polymer (PLA)

The investigation conducted in this section showed that a topology optimized geometry of the pressure die can safely conduct a bending operation without any failure. The tool performance of the topology optimized geometry is analysed in terms of P_{CN} , F_{CN} , von-Mises stress, tool surface displacement and effective area on tool surface. The effectiveness of the topology optimized tool is primarily delivered in terms of lesser un-used area of the tool surface. It is also noted that the volume of material used in the topology optimized geometry of TO-Pd_P is significantly lesser as compared to the volume of material used in the conventional geometry. A significant decrease in the volume of the tool

materials made TO-Pd_p significantly light in weight as compared to Pd_p. The geometric dimensions and weights of TO-Pd_p and Pd_p are shown in Table 7.2.

Table 7.2: Geometric dimensions and weight of TO-Pd_p and Pd_p

	Pd_p (Conventional Geometry)					TO-Pd_p (Topology Optimized Geometry)				
	Length (mm)	Width (mm)	Height (mm)	Volume (cm ³)	Weight (kg)	Length (mm)	Width (mm)	Height (mm)	Volume (cm ³)	Weight (kg)
Max	160	60	48	430	0.64	80	60	48	197	0.21
Min	same	same	37			50	41	37		

7.5 Development of material reduction criterion

Tool performance of the topology optimized geometry of a tool has shown that it is possible to conduct a RDB process by employing minimum material within the tool geometry. A reduction in tool material contributes towards efficient utilization of tool surface and decreases tool weight and cost [160]. In order to discretely identify the minimum material required within the tool geometry, a digital study is conducted which uses the topology optimization process. A half cross-section of the tool geometry is cut from the CAD of the conventional tool geometry. The thickness of the half cross section is reduced to 10 mm. The CAD of the cross-sectional part is shown in Figure 7.11(a). The part is assigned the material properties of polymer (PLA). The maximum P_{CN} obtained on the surface of the conventional geometry of Pd_p is applied at the surface of the cross-sectional part as shown in Figure 7.11(b). The relevant kinematic constraints are applied according to the actual tool position in a RDB process and TO process is conducted. The TO process is conducted with a material reduction (volume decrease) of 15%, 30%, 45% and 60% in the cross-sectional part. The results of the study are shown in Figure 7.11 (a-g).

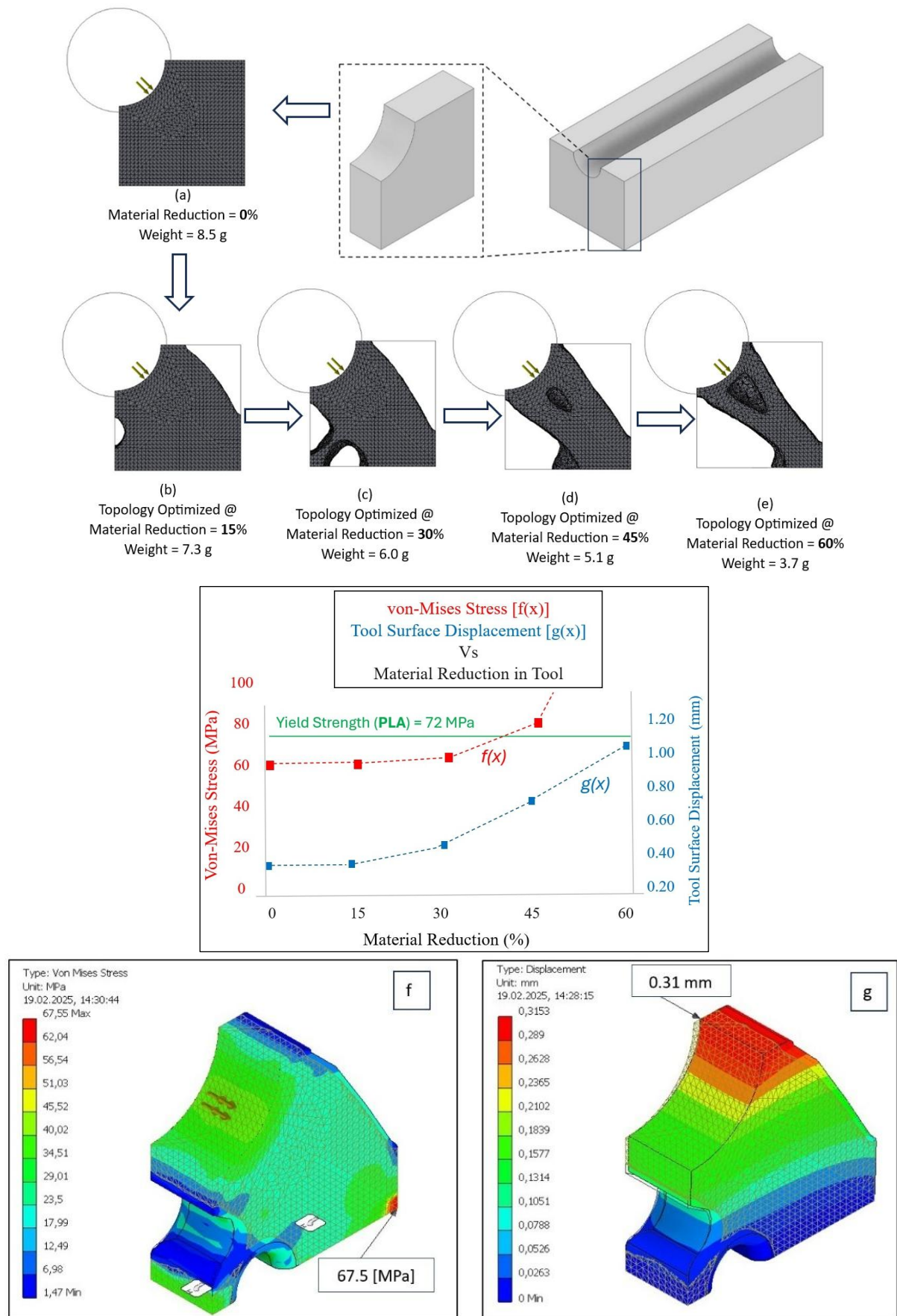


Figure 7.11 (a-g): Material reduction criterion developed by topology optimization of cross sectional structure of polymer (PLA). The criterion shows that material can be reduced to 30% of its original

volume by conducting topology optimization with actual process constraints. The results are shown in the form of curves (red: von-Mises stress and blue: tool surface displacement):

- (a). Cross sectional part of PLA
- (b-e). Topology Optimization of the cross sectional part with actual process constraints
- (f & g). The cross sectional part with 30% reduced material can execute the RDB process safely
- (f). Max. von-Mises stress at 30% material reduction in geometry
- (g). Max. tool surface displacement with 30% material reduction in geometry

The material response of the tool material is investigated in terms of von-Mises stress and surface displacement at the tool surface. Here, it is highlighted that the scope of this thesis encompasses the use of polymers with 100% infill. This is because the infill percentage and infill pattern has substantial effect on the material yield and Young's modulus [161]. In order to avoid the influence of material infill, the infill percentage is kept at standard value of 100% throughout the course of investigations. From Figure 7.11(f) it can be seen that for actual process conditions, the von-Mises stress developed within the cross sectional geometry (@ material reduction of 30%) remained less than the yield strength of the material (PLA). When the material reduction is increased beyond 30%, the von-Mises stress surpassed the yield strength. Hence, the maximum possible material reduction is 30%. Similarly, the process parameters of RDB process identified by Borchmann et al. [13] have shown that a tool surface displacement of upto 0.40mm is permissible for obtaining wrinkle free tubes. Although this study was conducted for steel based tools, yet keeping in view the development of lesser contact forces (F_{CN}) in polymer made tools, the maximum allowable tool displacement for polymer made tools is also considered to be 0.40mm. In this study, the maximum surface displacement of the polymer tool surface is 0.31mm (remained significantly less than 0.40mm) at 30% reduction of tool material. This study identified a material reduction criterion which is used as a general yard stick to design topology optimized polymeric tools in RDB process. It demonstrates that the conventional tool geometry can be reduced to 30% of its original volume in case of tool made from polymeric material (PLA). The material reduction criterion developed in this section is used to develop the polymeric base structure of the hybrid tool. It is highlighted that the computed material reduction criteria is only valid for the under investigation RDB process with specific process parameters (Table 5.1). For other process parameters, the P_{CN} and F_{CN} on the tool surface will change and therefore the material reduction criterion will change accordingly.

Chapter 8 : Material selection and development of hybrid tool design

8.1 Material selection and performance index of a hybrid material

The 3D printed polymeric materials can withstand the contact surface pressure upto a certain limit. If the contact pressure produces von-Mises stress equal to the yield strength of the material, then the polymeric material is expected to fail and crack or plastic deformations are expected to be seen at the tool surface [162]. Therefore the tool surface of a hybrid tool should consist of a material having high yield strength and elastic modulus. A commercially available grade of steel (austenitic chromium-nickel stainless steel AISI-304 or EN 1.4301 or X5CrNi18-10), commonly used in sheet metal applications, is selected as the material for tool surface. A commonly used polymeric material PLA (thermoplastic polylactic acid) is selected as the base material of the hybrid tool [163]. A combination of steel and polymer makes the hybrid material. The hybrid material is termed here as ‘polymer-steel hybrid’. In order to identify the material performance delivered by the hybrid material, the Ashby material performance index is computed individually for steels, polymer and polymer-steel hybrid [164].

The Ashby material charts are widely used to design geometrical structures and parts consisting of lightweight and stiff materials [165]. The Ashby material performance chart is a bubble chart in which various materials are grouped into different categories with each group representing a separate class of a material as shown in Figure 7.1. The material performance of a particulate material is computed by considering the stiffness and respective density of the material [166]. The logarithmic scale of the chart allows visualization of larger changes in material stiffnesses in respect to small variations in respective material densities. The performance of a material is computed by locating the material on a straight line known as ‘performance index (PI)’. The PI is plotted diagonally between the perpendicular axis of the chart. The computation of PI depends upon structural geometry of the material [167]. For rectangular structures in which length is significantly larger than the width and the height, PI is calculated by equation (8.1) below:

$$\text{Performance Index (PI)} = \frac{\text{Elastic Modulus 'E'}^{1/2}}{\text{Density '}\rho\text{'}} \dots\dots\dots (8.1)$$

The PI determines the material performance in terms of its stiffness to weight ratio [166]. The PI is represented by a line which passes through a group of materials and every material present on the line shows the same material performance (i.e., same stiffness to weight ratio). A higher value of the PI represents higher stiffness to weight performance and vice versa. From equation (iv), the value of PI is calculated for steels, polymers and hybrid materials as shown in Table 8.1. The computed PI is then plotted on the Ashby material selection chart as shown in Figure 8.1. Here, the volume ratio of polymer-steel hybrid is [9:1] which means that the 90% volume of hybrid pressure die consists of polymeric material and 10% volume consists of steel. The stiffness of a hybrid material equals the stiffness of a steel because the in-contact surface of the hybrid tool consists of steel sheets. The density of hybrid

material consists of a combination of the densities of polymer and steel at a ratio of 90% polymer and 10% steel. Keeping in view the material composition by volume, the polymer-steel hybrid used in this research thesis is called as hybrid [9:1]. Table 8.1 shows that the material performance of the hybrid [9:1] is significantly higher as compared to the material performance of steels and polymers. The material performance of a hybrid material will decrease when the composition of a hybrid material includes higher volume of steel e.g. the PI of a hybrid tool [7:3] will be relatively less than the PI of a hybrid [9:1]. The PI of a hybrid material will be higher than the PI of stand-alone steels and polymers.

Table 8.1: Performance indexes of alloy steel, polymer (PLA) and hybrid material [9:1]

Ser	Material	Stiffness (GPa)	Density ' ρ ' (g/cm ³)	Performance Index (PI) = $E^{1/2} / \rho$
a.	Steel (EN 1.2363)	210	7.78	1.86
b.	Polymer (PLA)	3.25	1.24	1.49
c.	Hybrid (9:1)	210	(0.9 x 1.24 + 0.1 x 7.78) = 1.90	8.05

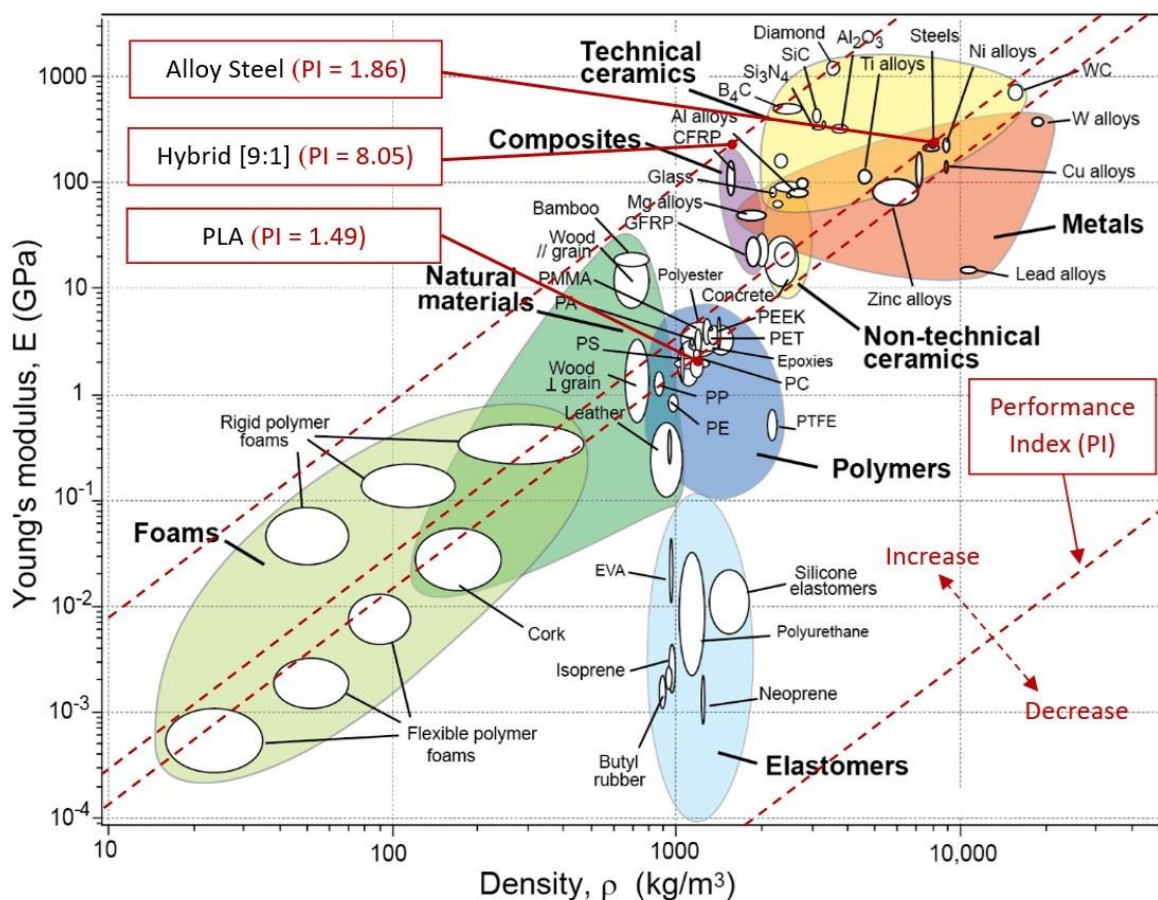


Figure 8.1: Ashby material selection chart and computation of performance index (PI) of alloy steel, polymer (PLA) and hybrid [9:1]

8.2 Numerical Modelling of a tool with hybrid material

In simple geometries like cubes and rectangular bars, the material stiffness is expressed in terms of its Young's Modulus (or Elastic Modulus 'E') [168]. In order to develop the design of a hybrid tool, it is essential to calculate the minimum stiffness of the tool surfaces which are in-contact with the tube during a bending operation. The minimum stiffness limit ensures that the tool surfaces are capable of withstanding the stresses resulting from a bending operation [169]. This minimum stiffness limit required by the tool is called here as the threshold stiffness. The threshold stiffness of a tool can be calculated numerically by investigating the permissible displacement at the tool surface. BORCHMANN et al. [20] identified that the permissible displacement of tool surface of the pressure die in a RDB process is ≤ 0.4 mm (i.e., $\delta_{\max} < 0.4$).

The surface displacement of a pressure die can be calculated by equation (8.2) [73] mentioned below:

$$\delta_{\max} = \frac{FL^3}{48 EI} \quad \dots\dots\dots (8.2)$$

Substituting the value of moment of inertia (i.e., $I = bh^3 / 12$) the equation (8.2) can be written as:

$$\delta_{\max} = \frac{FL^3}{4 Ebh^3} \quad \dots\dots\dots (8.3)$$

By rearranging equation (8.3), the stiffness ('E' or Elastic modulus) can be calculated by using equation (8.4):

$$E = \frac{FL^3}{4\delta_{\max} bh^3} \quad \dots\dots\dots (8.4)$$

or, equation (8.4) can be written as equation (8.5) below:

$$E = \frac{F}{\delta_{\max}} * \frac{L^3}{4bh^3} \quad \dots\dots\dots (8.5)$$

From equation (8.5), it can be noted that all quantities expressed in $(L^3 / 4bh^3)$ have fixed values as they represent the geometric dimensions of the tool geometry. The combined fixed geometric quantities $(L^3 / 4bh^3)$ have a constant value therefore they are categorized here as a constant 'C'. On the other and, the quantities $(F / \delta_{\max})$ are variable as Force (F) and Surface displacement ($\delta_{\max}$) change with an increase in bending angle (α°). The permissible displacement at the surface of the pressure die varies from 0.1 to 0.4 mm. The maximum permissible surface displacement is $\delta_{\max} = 0.4$ mm and the minimum surface displacement (or safe displacement) $\delta_{\text{safe}} = 0.1$ mm. The value of F at the tool surface varies at each bending angle (α°) and reaches a maximum value of $F_{\max} = 45$ kN in case of conventional tool geometry. By substituting the values of $F_{\max}$ and C in equation (vii), the minimum and safe threshold limits of tool stiffness are obtained at each value of surface displacement as shown in Table 8.2.

Table 8.2: Stiffness threshold limits of hybrid pressure die

Stiffness (GPa)	Permissible surface displacement (mm)			
	$\delta_{\min} = 0.1$	$\delta = 0.2$	$\delta = 0.3$	$\delta_{\max} = 0.4$
	16.2 (safe limit)	8.0	5.4	4.1 (minimum limit)

The stiffness threshold limits (minimum limit and safe limit) of the pressure die are plotted on the Ashby material selection chart as shown in Figure 8.2 [166]. From Figure 8.2, it can be noticed that very few polymers from the group of polymeric materials are above the line of minimum threshold limit. Hence, very few polymeric materials are capable of conducting a RDB process. In case of metals, a substantial number of metals and alloys belonging to the group of metals are safe for use as a tool material in a RDB process. The position of the novel hybrid material (hybrid [9:1]) is located well above the safe threshold limit. Hence, a tool developed with hybrid (9:1) can safely conduct a RDB process. Numerical calculations have shown that a hybrid tool consisting of 90% polymer (at the base of the tool geometry) and 10% steel (at the tool surface) possess significantly high stiffness to weight tool performance as compared to a tool made completely from an alloy steel.

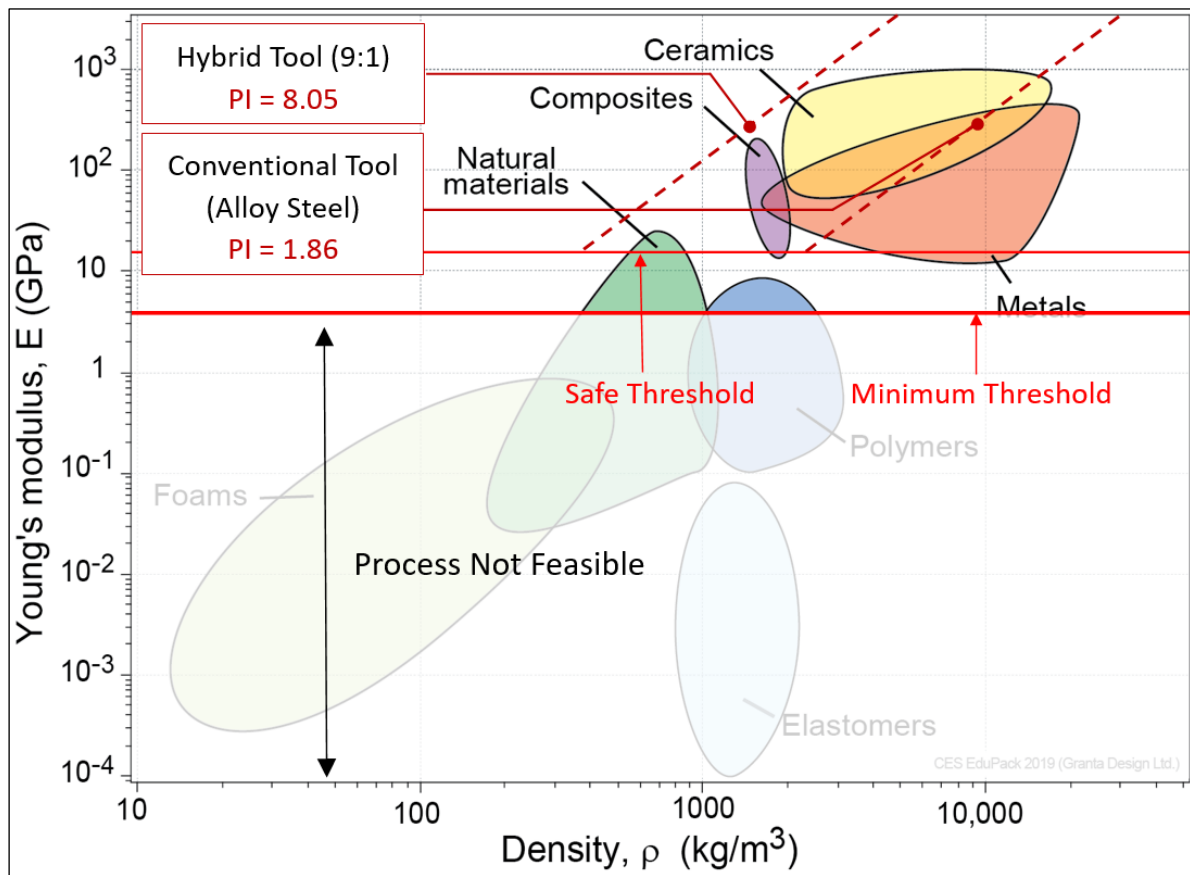


Figure 8.2: Minimum and safe stiffness limits required by pressure die to conduct bending operation in RDB process

8.3 Construction of hybrid pressure die-CAD

The CAD of a hybrid pressure die is constructed on the basis of identified tool design factors (section 6.2) and minimum material criterion (section 7.5). The tool design factors are used to formulate the geometric design of the hybrid tool. The input values of the design factors are selected according to the process parameterization and material selection of the hybrid material. The minimum material criterion developed through the use of topology optimization is used to determine the quantification of base material volume within the tool. The development strategy used for the creation of the CAD of the hybrid pressure die is shown in Figure 8.3.

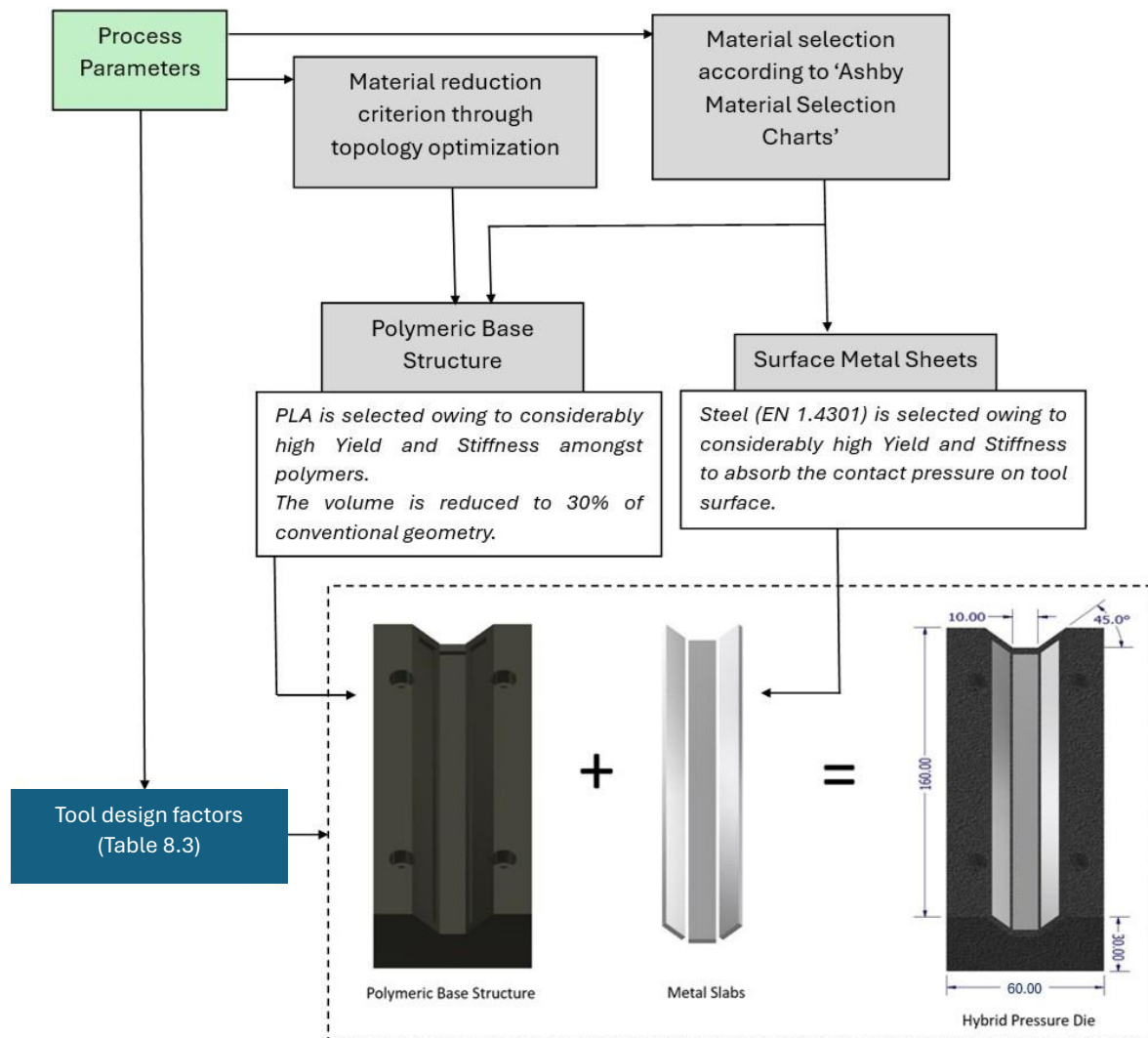


Figure 8.3: Development strategy of hybrid pressure die-CAD

Table 8.3: Engineered values of tool design factors

Tool design factors	Selected value for hybrid pressure die
Stiffness (Young's Modulus)	210 GPa for steel slabs (Yield strength = 550 MPa) 2.75 GPa for polymer PLA (Yield Strength = 72 MPa)
Friction Coefficient 'μ'	Steel (EN 1.4301) with μ = 0.1 (Minimum μ from pressure die surface is desired for lesser tube ovality)

Effective contact Area	Line contact between tube and metal surface sheets
	Full contact between metal sheets and polymeric base structure
F_{CN} of other tools	Contact force (F_{CN}) of pressure die is greater than the combined contact force of wiper die and mandrel
Fatigue Strength	An unlimited fatigue strength demonstrated by steel
	Maximum 60 bending operations before material fatigue of polymer PLA
Process flexibility range	22 to 30 mm
P_{CN} localization	Contact surface pressure (P_{CN}) enhancement due to transformation from full contact to line contact is at a factor of 1:3 for alloy steel : polymer PLA
Wear resistance	High wear resistance of steels as compared to polymer PLA

The geometric dimensions of hybrid pressure die-CAD are shown in Figure 8.3. From Figure 8.3, it can be seen that the CAD of hybrid pressure die is created in which three rectangular steel sheets serve as the tool surface and a polymeric base is designed to hold the steel sheets. The polymeric base structure also serves as a fixture for RDB machine. Each rectangular steel sheet has a dimension of 152mm x 10mm x 2mm (length x width x height). One rectangular steel sheet lies in the centre and the other two steel sheets are inclined at an angle of 45° with the central sheet. The base structure of the pressure die is made from the polymer (PLA). The hollow rectangular spaces are created at the top of the base structure. These hollow spaces allow fixing of steel sheets at the top surface of the base structure. The steel sheets remain in contact with the tube during a bending operation and withstands the stresses applied during the bending operation.

Chapter 9 : Experimental testing and results

9.1 FE-Simulation of RDB process with hybrid tool

In this research thesis, the design process for developing an effective tool geometry consists of simulating the RDB process with a hybrid pressure die and subsequent evaluation of the tool performance. The digital twin of the RDB process with conventional tool geometries has already been developed by using CAD modelling and FE-simulations (section 5.2). The CAD of the newly created design of the hybrid pressure die is imported in the digital twin model and complete bending process is simulated. The accuracy of the process simulation is verified by comparing the tube characteristics obtained from process simulation and practical results. After determining the process accuracy, the tool performance of the hybrid pressure die is investigated by determining von-Mises stresses, contact forces and elastic deformations at the tool surface. The tool performance of hybrid pressure die is compared with the performance of conventional pressure die made from an alloy steel. The performance comparison is used to formulate a numerical formula. This numerical formula will determine the foreseeable effectiveness of bending tools in a RDB process.

The mesh convergence study conducted in section 5.1 has shown that the process results converge at a mesh size of 1.28 mm. The CAD of the hybrid pressure die is meshed in a global mesh domain with a mesh size of 1.00 mm. The total number of volume elements of the hybrid pressure die are 1.2 Million tetrahedral elements. The higher number of meshed elements increase the simulation time however it provides accurate quantification of stresses at every part of the tool geometry. To simulate the RDB process with hybrid pressure die, relevant material properties and deformation laws are fed to the software PAMSTAMP as shown in Table 9.1.

Table 9.1: Material properties of tools fed to the software PAMSTAMP

Tools and Tube	Material Type	Element type	Elastic modulus (GPa)	Yield strength (MPa)	Poisson ratio	Density (g/cm ³)	Material deformation law
Bend die	Alloy steel	Volume	205	950	0.3	7.85	Elastic region: Young's modulus Transition from elasticity to plasticity of tube: Hill-48 law Plasticity: Swift Krupkowsky strain hardening law
Clamp dies	Alloy steel	Volume	205	950	0.3	7.85	
Mandrel	Hard chrome plated steel	Volume	210	950	0.3	7.96	
Wiper die	Hard chrome plated steel	Volume	210	950	0.3	7.96	
Bend die	Alloy steel	Volume	205	950	0.3	7.85	
Tube	Stainless steel (1.4301)	Shell	210	550	0.3	7.70	

Hybrid pressure die (9:1)	PLA	Volume	2.75	72	0.35	1.24	Experimentally obtained stress-strain curve (DIN-604)
	Stainless steel (1.4301)	Volume	210	550	0.3	7.78	Elastic region: Young's modulus No plastic region

The elastic deformation of the metallic materials (particularly steels) can be predicted with substantial accuracy by using Young's modulus of the material [170]. The transition from elastic region to plastic region and the plastic deformation behaviour of the steels is computed by Hill-48 and Swift Krupkowsky law [171]. In case of polymers, the experimentally obtained stress-strain curve of the 3D printed polymeric material (PLA) is fed to the software PAMSTAMP [113]. Hence, the FE-simulation of a hybrid material requires the assignment of different deformation laws to the respective materials. The FE-simulation is conducted and the tool performance is investigated in terms of surface deformation, contact forces, surface pressure, von-Mises stress and major strains within the tool geometry. The FE-simulation model of the RDB process with hybrid pressure die is shown in Figure 9.1.

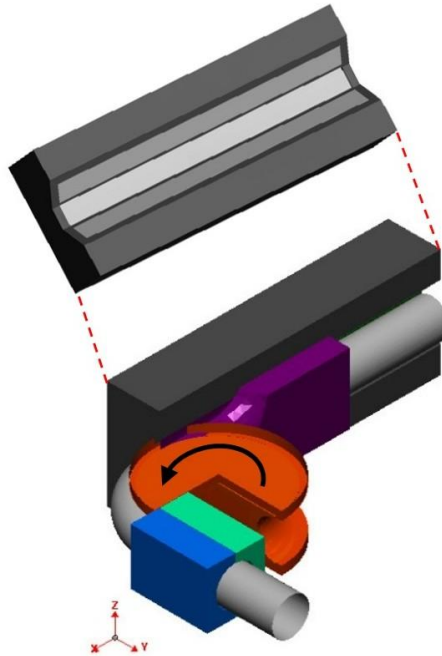
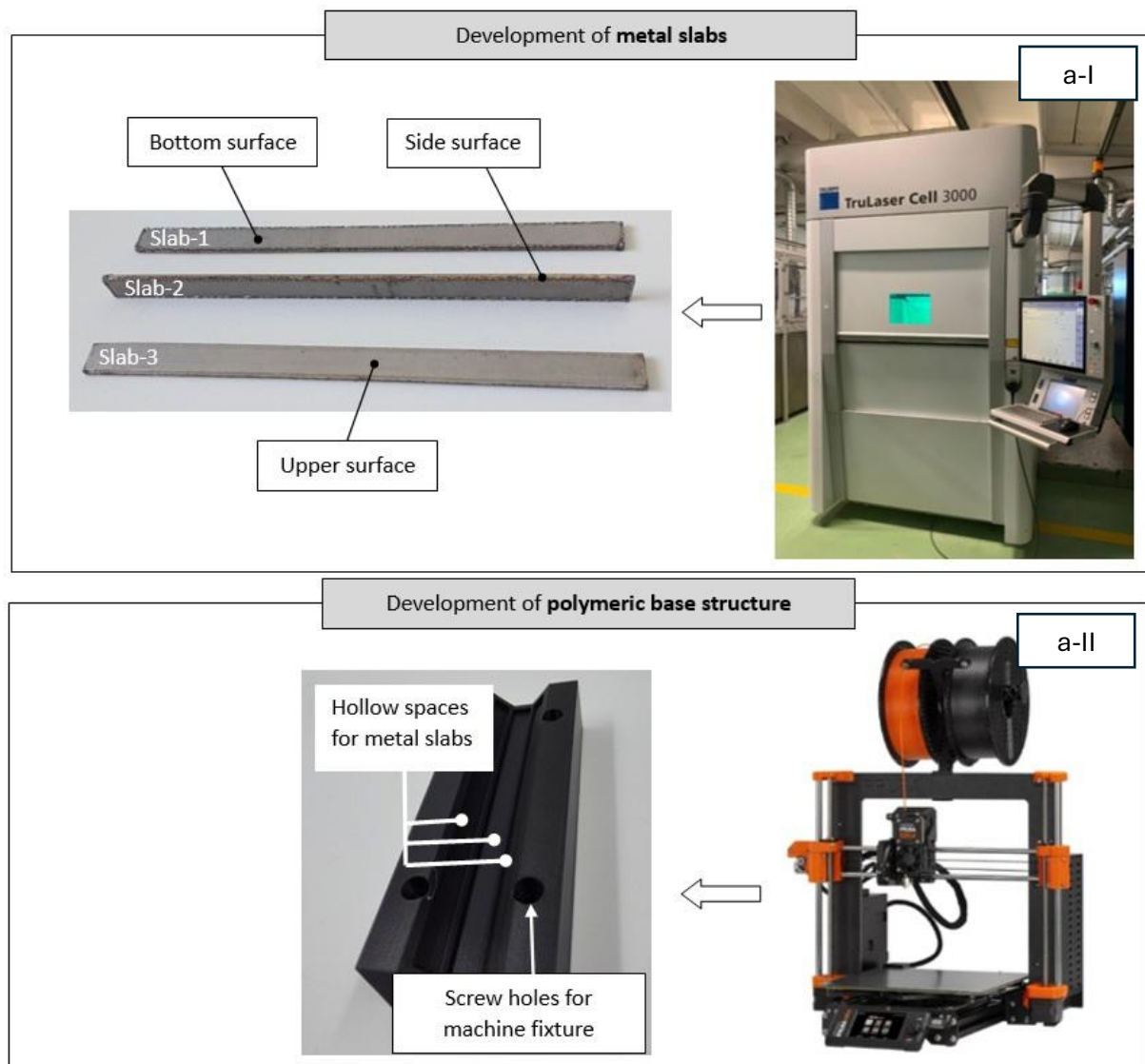


Figure 9.1: Digital twin /FE-simulation model of RDB process with hybrid pressure die

9.2 Practical experimentation with 3D printed hybrid tool

Two different manufacturing techniques are used to physically fabricate the hybrid pressure die. The Fused Filament Fabrication (FFF) method is used to 3D print the polymer base structure and Laser Metal Deposition (LMD) is used to cut rectangular metal slabs. In the case of FFF method, a PRUSA (MK4)

3D printer is used and in the case of LMD, the Trumpf LASER 300 is used for fabrication. The laser cutting is used to obtain precise metal cutting of a 2.00mm thick steel sheet. The cut dimensions are 152mm x 10mm. This makes the dimension of each metal slab equal to 152mm x 10mm x 2mm (length x width x height). A precise cutting of edges ensures that the CAD models of steel slabs with uniform corners resemble the practically cut steel slabs. The rectangular steel slabs are fixed on the 3D printed polymeric base structure. The physical fabricating the hybrid pressure die is shown in Figure 9.2 (a-I, a-II & a-III). The next step is to practically test the physically 3D printed hybrid pressure die in a RDB process and compare the characteristics of practically bent tubes with the FE-simulation results. The hybrid pressure die is installed on an industrial scale RDB machine RBV-35 by WAFIOs. The process is practically conducted on the basis of same process parameters that are used in the FE-simulation model (Table 5.1). The position of the hybrid pressure die on the RDB machine is shown in Figure 9.2 (b).



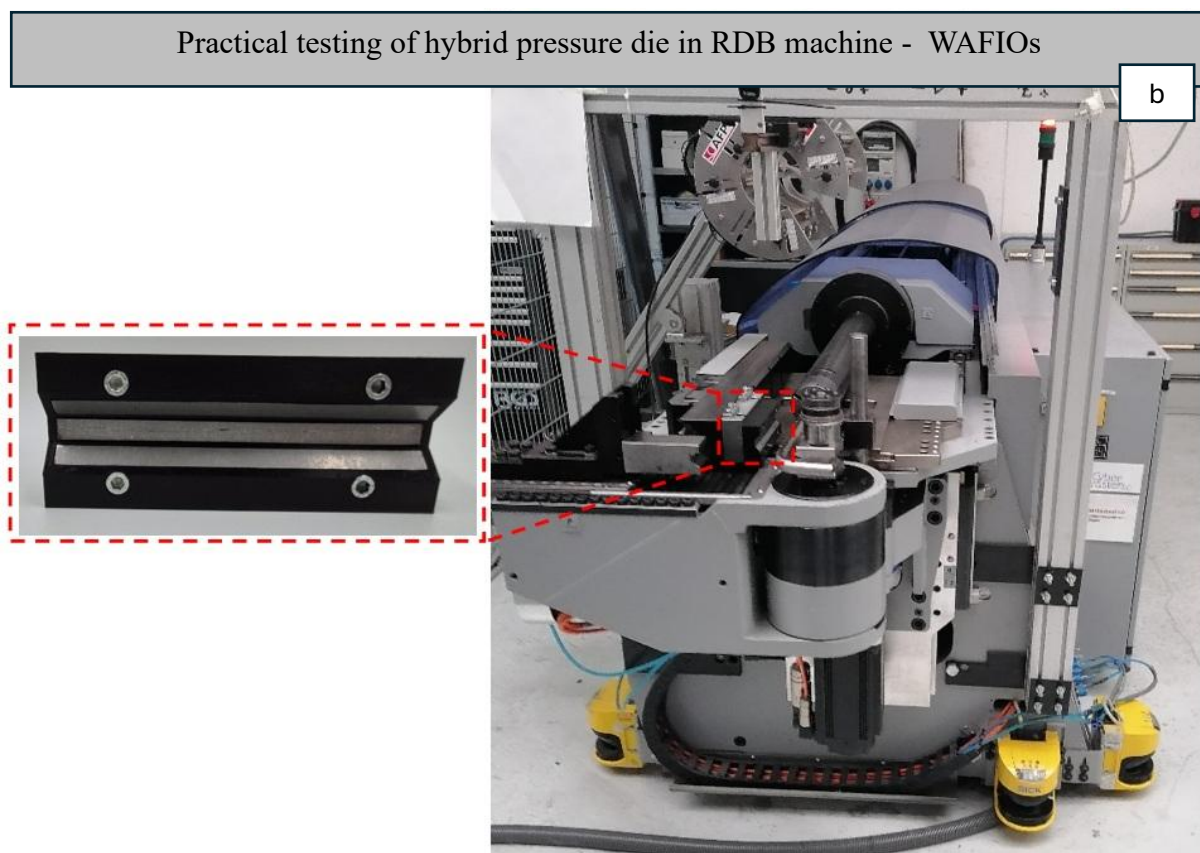
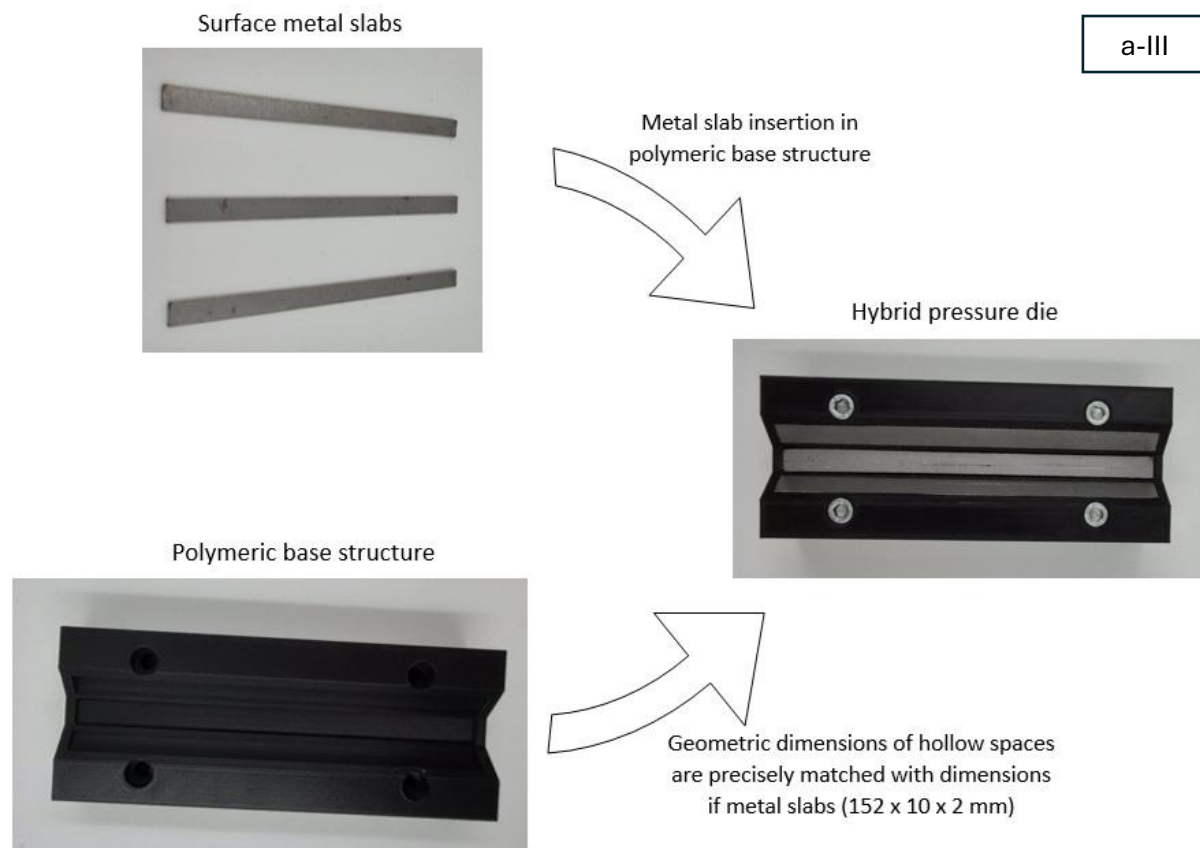
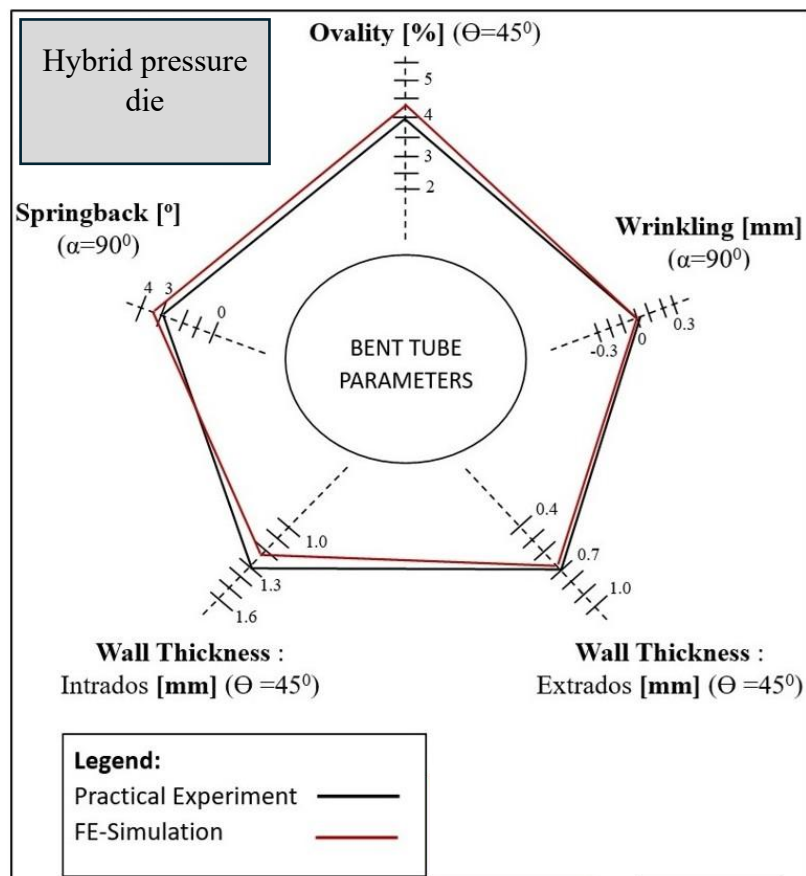


Figure 9.2 (a & b): (a-I to a-III) Fabrication process of hybrid pressure die (b) practical testing of hybrid pressure die on industrial RDB machine by WAFIOs

9.3 Comparison between hybrid tool and conventional tool

9.3.1 Accuracy of Digital Twin with hybrid tools

Before analysing the results of tool performance obtained through digital twin (FE-simulations), it is essential that the accuracy of the digital twin with hybrid tools is verified. The accuracy of digital twin consisting of the conventional tool geometry of pressure die is already verified in section 5.1. In this section, the simulation and practical results obtained from the newly developed geometry of the hybrid pressure die are compared with each other. The comparison showed that the digital twin consisting of a hybrid pressure die is substantially accurate. The comparison between FE-simulation and practical experiments of the conventional pressure die and hybrid pressure is shown in Figure 9.3. It can be seen that a slight difference in tube ovality and wall thickness exist however this difference is identical in both tools. This verifies that the digital twin is accurate and FE-simulation results can be used to compare the tool performances.



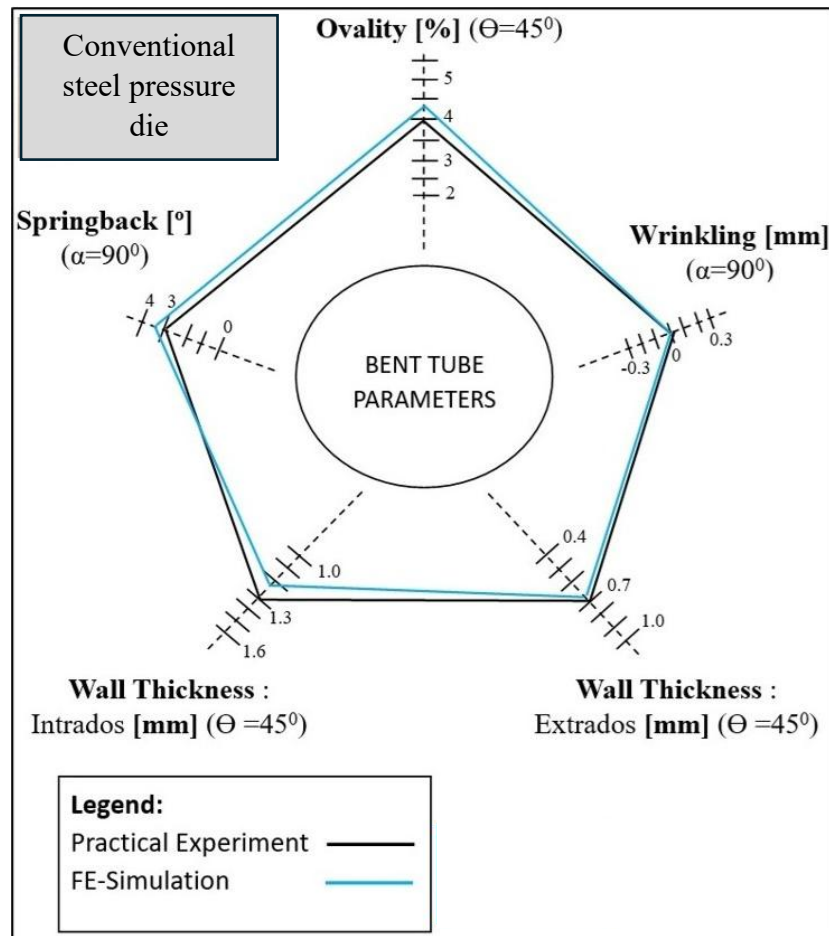


Figure 9.3. Comparison of FE-simulation and practical experiments on *Accuracy-Meter* diagram ^[23].

The comparison shows identical results of tube quality with hybrid pressure die (left) and metal pressure die (right)

9.3.2 Tool performance comparison

9.3.2.1 Von-Mises stresses within the tool geometry

The investigation of stresses within the tool geometry is fundamentally important to determine the tool performance in a RDB process [172]. The stresses developed within the tool geometry change with a change in bending angle. The maximum von-Mises stress experienced by a hybrid pressure die is compared with the corresponding values experienced by a conventional pressure die. The comparison results are shown in Figure 9.4 (a-b). Figure 9.4 (a) shows the comparison between overall values of hybrid pressure die and conventional pressure die. The hybrid pressured die consists of a polymeric base structure and three stainless steel metal slabs. The von Mises stress (max.) experienced by each sub-component in the hybrid pressure die i.e., polymer base structure and metal sheets (1-3) are shown in Figure 9.4 (b). From Figure 9.4 (b), it can be seen that the polymeric base structure (consisting of PLA) experienced substantially less von-Mises stress as compared to the metal slabs. This happened because the stresses are largely withstood by the metal slabs and substantially lesser stresses are transmitted to the polymeric base structure. The stresses developed within the polymeric base structure remained well below the yield limit of the polymeric material (PLA). This prevents the polymeric base structure from

undergoing plastic deformation and allows the hybrid tool to withstand large stresses generated during a bending operation.

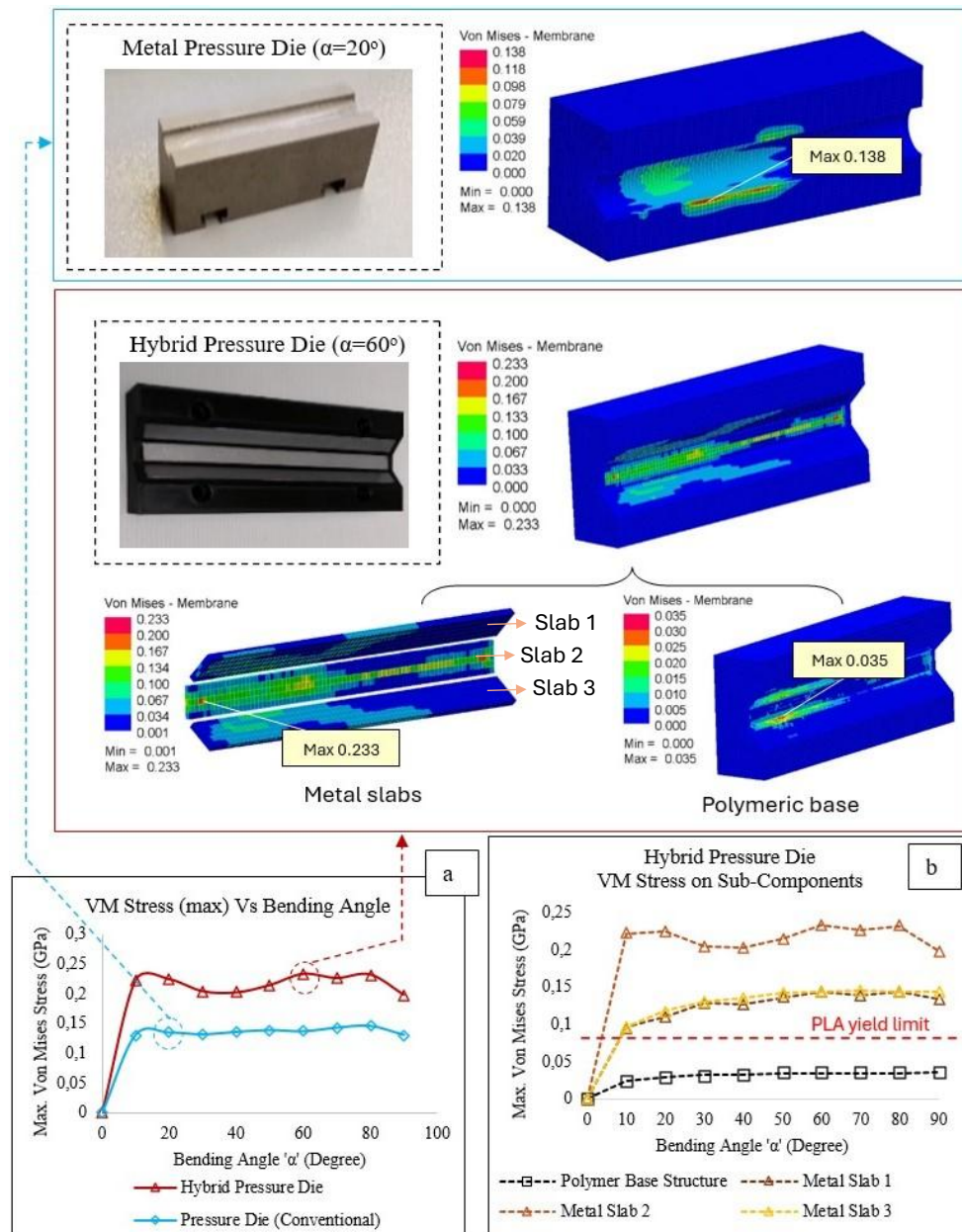


Figure 9.4 (a & b): Comparison of von-Mises stress between hybrid pressure die and conventional metallic pressure die (a). overall von-Mises stress in hybrid pressure die and conventional metallic pressure die (b). von-Mises stress developed in each sub-component of the hybrid pressure die. The von-Mises stress developed in the polymeric base structure is less than the yield strength of the polymer PLA.

9.3.2.2 Contact forces on tool surface

The magnitude of the contact forces acting on the tool surface change with the change in bending angle (α). The comparison of the contact forces acting on the surfaces of the hybrid pressure die and the conventional pressure die are shown in Figure 9.5 (a & b). The hybrid pressure die consists of metal slabs that are only in-contact with the tube therefore no contact force is experienced by the polymeric

base structure. It can be seen that the contact force experienced by the central metal slab is considerably greater than the contact forces acting on the side slabs as shown in Figure 9.5 (a). The contact force acting on the circular surface of the conventional metallic pressure die is shown in Figure 9.5 (b). From Figure 9.5 (b), it can be seen that the contact force on the surface of metallic pressure die initially decreases and then increases. On the other hand, the contact forces acting on hybrid pressure die (metal slabs) remain almost at the same level.

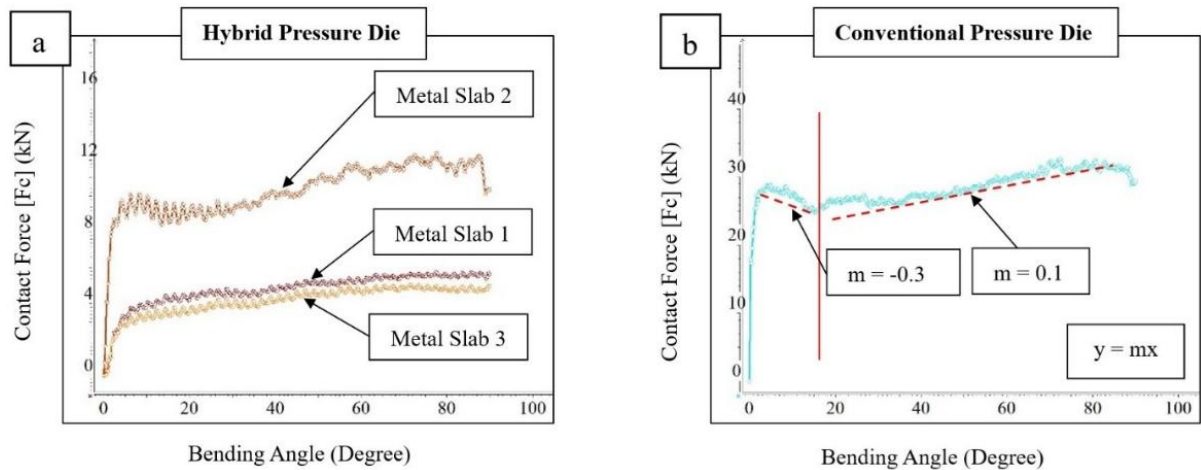
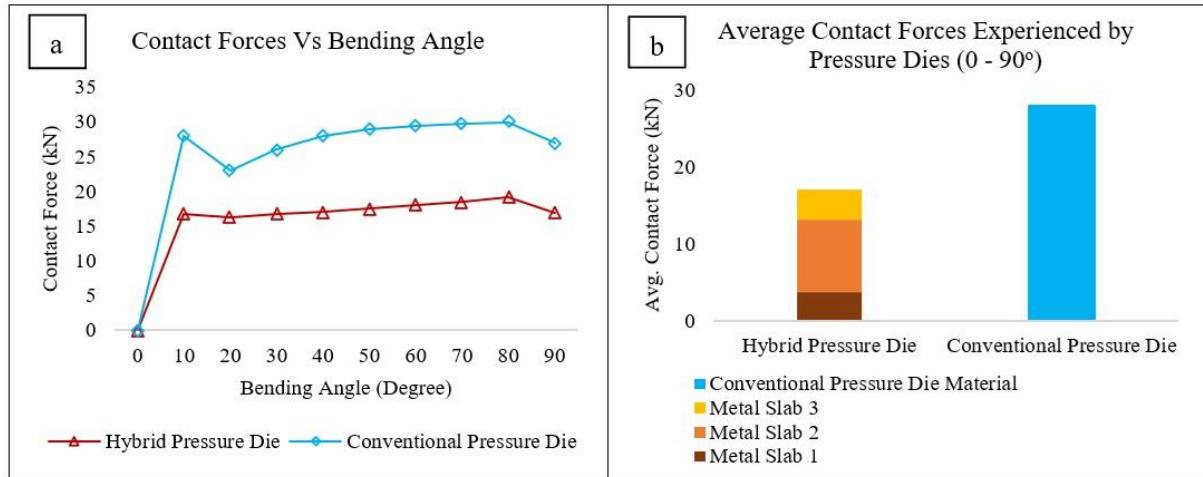


Figure 9.5 (a & b). Contact forces on tool surfaces of (a) metal slabs of hybrid pressure die (b) semi-circular surface of conventional metallic pressure die

In order to compare the contact forces acting on the surfaces of both tools, the contact forces acting on the metal slabs are added and presented in a single graph which is then compared with the contact forces acting on the conventional pressure die as shown in Figure 9.6 (a). From Figure 9.6 (a), the average contact force acting at each bending angle (α) during a bending operation is computed and shown in Figure 9.6 (b). This investigation shows that the contact force acting on the surface of the hybrid pressure die is significantly less as compared to the contact force acting on the surface of the conventional (metallic) pressure die. The decrease in contact forces on the surface of the hybrid pressure die indicates that the surfaces of the hybrid pressure die undergo surface displacement which remains within the elastic domain. In order to further investigate the tool behaviour, the surface displacements of hybrid pressure die are computed and compared with conventional pressure die.



9.6 (a-b): Comparison of contact forces on the surface of hybrid pressure die and conventional pressure die (a). Contact forces experienced by hybrid pressure die and conventional pressure die (b). Average contact force per bending angle (F_{CN}/α°) of hybrid pressure die and conventional pressure die

9.3.2.3 Displacement of tool surfaces

Due to the application of contact forces during a bending operation, the surfaces of the hybrid pressure die are displaced from their original position. As soon as the bending operation ends, the contact forces are lifted and the surfaces regain their original position. The displacement of the tool surface is predicted to be extremely small therefore the measurements are preferred to be determined by a process simulation. The practical measurement methods cannot be accurately employed due to closed profiles of the tool surface and the unavailability of direct visual access till the tool surface [173]. FE-simulation shows that the surface displacement manifested by the hybrid pressure die is quite small as the maximum surface displacement is noticed to be less than 0.15 mm. On the other hand, the surface displacement of the metallic pressure die is noted to be extremely small i.e., 1.05×10^{-3} (almost no displacement). Figure 9.7 shows the surface displacement of the hybrid pressure die and the conventional (metallic) pressure die at bending angle (α) from 0° to 90° .

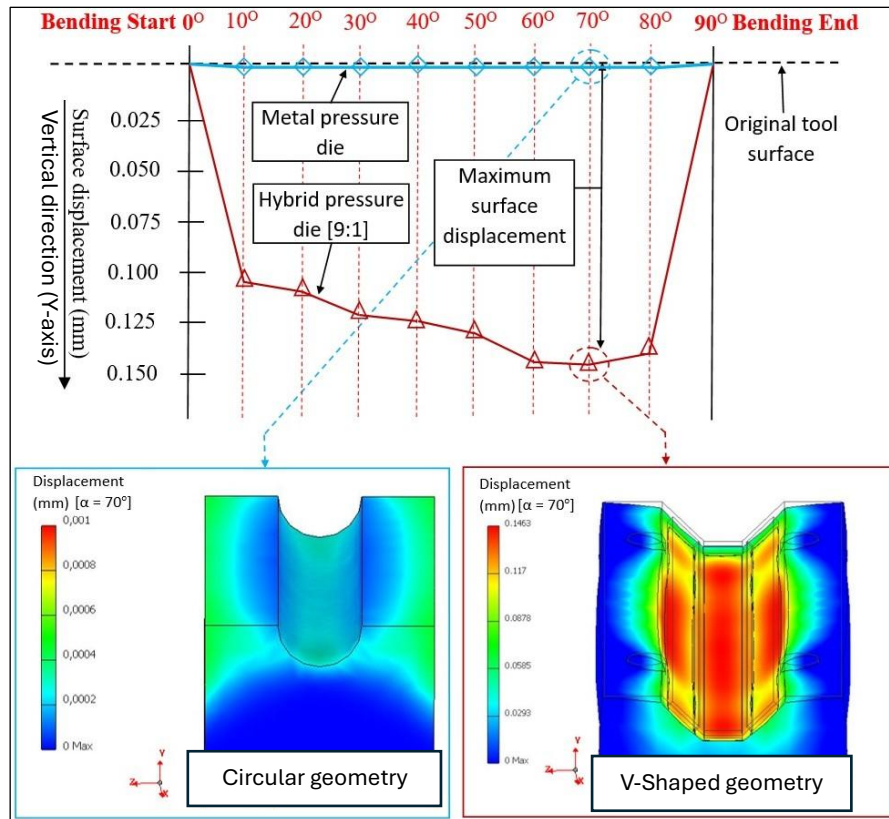


Figure 9.7: Negligible (or almost zero) surface displacement in metal pressure die (shown at left), and surface displacement (max.)=0.14 mm in hybrid pressure die at $\alpha=70^\circ$ (shown at right).

The surface displacement seen in case of the hybrid pressure die is manifested due to the elastic springiness effect provided by the polymeric base structure [174]. The polymeric base structure experiences the applied stress and as a result the material is compressed. Since the applied stress is less than the yield strength of the material (PLA), therefore the polymeric material remains within the elastic region and regains its original position on the removal of stress. Hence, a spring-like effect is created in which the polymeric material continuously compresses and regains its original geometry on the removal of stresses. The displacement of metal slabs is seen due to this elastic deformation within the polymeric base structure. The elastic deformation within the polymeric base structure reaches a maximum value of 0.14 mm. There is a negligible elastic deformation (almost no deformation) within the metal slabs and conventional metallic pressure die. The maximum elastic deformation in the polymeric material PLA (polymeric base structure) is compared with the deformation in metal slabs and conventional metallic pressure die in Figure 9.8. Due to the deformation in the polymeric base the metal slabs fitted at the surface of the hybrid pressure die displace to a maximum value of 0.14 mm. The displacement at the tool surface is found to be a beneficial aspect in the RDB process since bent tube characteristics provided by the hybrid pressure die have remained un-changed (tube ovality, wall thickness and springback essentially remained the same as provided by the conventional pressure die). A considerably less contact force is experienced on the surface of the hybrid pressure die due to the surface displacement. Here, the

maximum surface displacement is 0.14 mm which is less than the maximum surface displacement required for obtaining wrinkle free tubes [20].

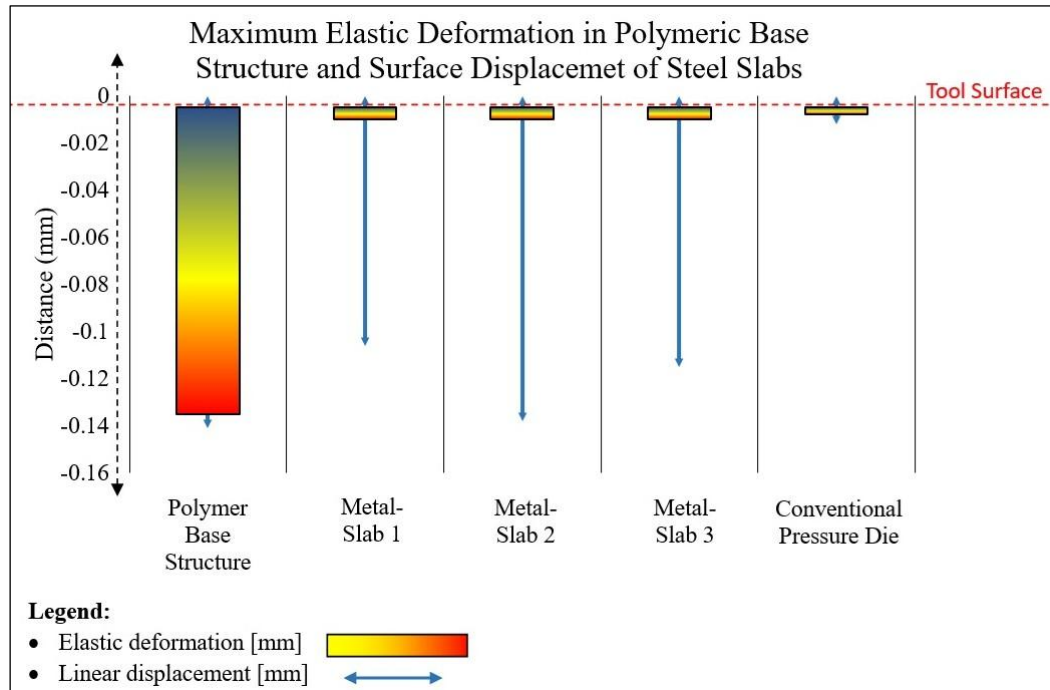


Figure 9.8: Elastic deformation (shown in colour code) and surface displacement (shown with arrows) in hybrid pressure die. The metallic slabs show a surface displacement of 0.14 mm due to elastic deformation in polymeric base structure.

The engineered design of the hybrid tool must be made after careful investigation of the material yield strength and the prospective stress developed within the material. In all circumstances, the developed von-Mises stress within the material should remain less than the yield strength of the material. In the presented model of the hybrid pressure die, the design is engineered in such a way that the applied stresses are primarily withstood by the steel slabs (steel has relatively high yield strength as compared to the polymer PLA) and significantly less stresses are passed on to the polymeric base structure. The stresses passed on to the polymeric base are easily withstood by PLA because these stresses are considerably less than the yield strength of PLA.

9.3.3 Geometric comparison

The geometric dimensions and the weight of the hybrid pressure die and a conventional metallic pressure die are shown in Table 9.2. The hybrid pressure die consists of 90% polymer (PLA) and 10% metal (steel) therefore the polymeric material contributes mainly towards the overall weight of the tool. In case, the material composition is changed i.e., the composition of steel is increased and the composition of the polymer is decreased, the overall weight of the hybrid tool will increase proportionally. The light weight tools are considered essentially important for future manufacturing regimes in which cobots are foreseen to handle and place the tools on manufacturing machines.

Table 9.2: Geometric dimensions and weight of hybrid pressure die and conventional metal pressure die

	Hybrid pressure die					Conventional (metallic) pressure die				
	Length (mm)	Width (mm)	Height (mm)	Volume (cm ³)	Weight (kg)	Length (mm)	Width (mm)	Height (mm)	Volume (cm ³)	Weight (kg)
Max	160	62	30	265	0.41	160	60	48	430	3.32
Min	same	same	19			same	same	37		

9.3.4 Cost comparison

The Ashby cost comparison index is a cost comparison model for comparing the costs of structural components being manufactured from different materials [175]. In Ashby cost comparison index, the comparison is made on the basis of material performance index [176]. After comparing the tool performance and geometry of the two tools, a cost comparison is conducted between the hybrid pressure die and conventional metallic pressure die by using the Ashby cost comparison index. The cost comparison is presented in Table 9.3. Here, the cost per part is calculated by multiplying the cost/kg with respective weight of the tool. A higher value of cost performance index shows better cost effectiveness and vice versa [177]. The cost comparison index is based only on the material costs.

Table 9.3. Cost performance index of hybrid pressure die and metal pressure die

Tool material	Elastic modulus 'E' (GPa)	Density 'ρ' (g/cm ³)	Performance index (PI) = $E^{1/2} / \rho$	Approx cost per kg* (€)		Approx cost per part [€'] (Wt. x €)	Cost Performance Index (CPI) = PI / €'
Conventional Pressure Die	210	7.78	1.86	2.74		9.07	0.206
Hybrid Pressure Die	210	1.9	8.05	2.11 (PLA)	(0.1 x 4.19) +	0.95	8.47
				4.19 (SS)	(0.9 x 2.11) = 2.32		

* Costs per kg are obtained in February 2025.

9.3.5 Comparison of wear at tool surface

It has been demonstrated in Chapter 6 (section 6.3.3) that the wear at tool surface is calculated by Archard wear law. Equation 6.7 is used to calculate the wear rate (W') at the tool surface of hybrid tool and conventional (steel) tool. A higher wear rate (W') represents low wear resistance and vice-versa [144]. The wear rate is computed for one bending operation therefore the value of $n=1$ is placed in equation 6.7. The comparison of wear resistance (W') at the surface of hybrid pressure die and conventional pressure die is shown in Table 9.4. It can be seen from Table 9.4 that the wear rate of hybrid tool (consisting of polymer and steel) is relatively higher as compared to conventional circular steel tool. However, the wear rate is comparable and a significant difference of wear does not exist between the two tools. This relative difference is manifested due to the difference in contact pressure and material hardness of the tool materials. The contact pressure at the tool surfaces is obtained from the digital twin and the hardness is computed on the basis of material composition. In case of hybrid pressure die, the material composition is [9:1]. This means that 90% hardness value of polymer and 10% hardness value of steel is considered for the computation of wear according to equation 6.7. The higher wear rate shows lesser wear resistance and vice versa [144] therefore, hybrid tool is considered to be less wear resistant as compared to conventional steel tool.

Table 9.4: Wear rate at the tool surfaces (computed to Archard wear law, Chapter 6: Equation 6.7)

Ser	Parameters required for computation of wear	Hybrid Tool (Hybrid Pressure die)	Conventional Tool (Circular Steel Pressure die)
1.	Wear coefficient (K) [mm ³ /Nm]	7.0×10^{-6}	7.0×10^{-6}
2.	Pressure (P) on tool surface [MPa]	40	112
3.	Tube velocity (V) [mm/sec]	5.7	5.7
4.	Hardness of tool material (H) [MPa]	315	2000
Wear rate (W')		5.06×10^{-6}	2.23×10^{-6}
Comparison of wear resistance		Relatively low	Relatively high

9.4 Process flexibilization with hybrid tool

In this chapter, it has been demonstrated that a tube bending operation with tube diameter = 22 mm can be conducted successfully by using hybrid pressure die. The surfaces of the hybrid pressure die constitutes a V-shaped geometric design which opens the possibility to use different tube diameters with the same tool. Therefore, a tube having a diameter of 30 mm is tested in the process simulation. The digital twin (parameterized FE-Simulation model) is upscaled to 1.36 times with respect to its original geometric size. This increases the tube diameter from 22 mm to 30 mm while values of bending factor and wall thickness remains the same at $B=1.5$ and $W=22$. The size of the hybrid pressure die is not upscaled hence same hybrid tool is used to conduct process simulation of the RDB process with tube diameter = 30mm. The results of tool performance obtained from process simulations of RDB process with both tube diameters is shown in Figure 9.9. The RDB process was conducted successfully with a tube diameter of 30 mm and there was no tool failure (cracking or wrinkling) in the bent tube. The tool material also withstood the stresses applied during the bending process. It can be seen that the maximum von-Mises stress applied by the tube during the bending operation is 43 MPa (0.043 GPa) which is considerably less than the yield strength of PLA ($Y_{PLA}=72$ MPa). However, it is also noticed that the von-Mises stress increases in case of 30mm tube in comparison to 22mm tube. This shows that an increase in tube diameter increases the chances of tool failure. A tool failure is expected to happen when the von-Mises stress surpasses the yield strength of the material. The tool failure means a possible development of crack or plastic deformation at the surface of the tool. Since, no failure manifested from simulation results and the stress values remained less than the material yield hence the hybrid pressure die safely conduct the bending operation for tube diameters ranging between 22mm to 30mm. In other words, hybrid pressure die manifested that the RDB process can be safely conducted for tube diameters ranging between 22-30mm and a hybrid tool partially flexibilized the RDB process.

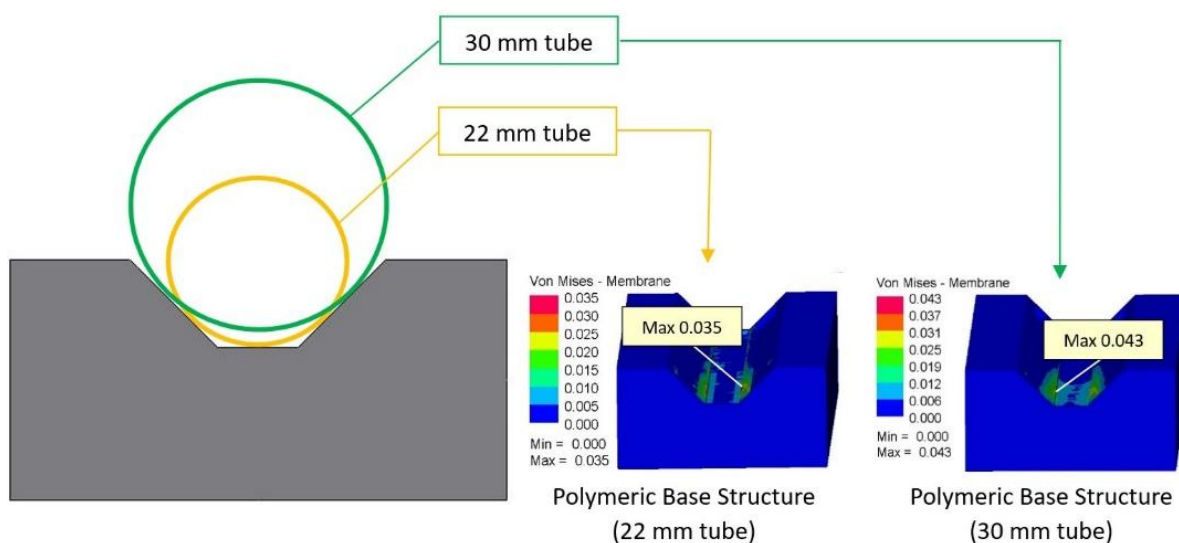


Figure 9.9. von-Mises stress in polymeric base structure of hybrid pressure die. The stress increases when larger tube diameter is used with the same geometry of hybrid pressure die.

Chapter 10 : Evaluation of Results

10.1 Tool Efficiency index (TEi)

To determine the efficiency delivered by a tool, the characteristic performance of the tool in each category is required to be evaluated in the form of a grading scale or index. In this research thesis, the tool performance is focused in the context of customized production which translates into tool effectiveness provided in terms of process flexibility, cost effectiveness, lightweight performance and rate of production of tools. These effectiveness criteria are analysed by comparing the tool performance of hybrid pressured die and conventional pressure die. The analysis results are used to formulate a design formula which determines the overall tool effectiveness in the form of an index. This index can be used to compare the effectiveness of bending tools in a RDB process. The comparison of tool performance between hybrid pressure die and conventional metallic pressure die is highlighted in terms of following effectivity criteria:

10.1.1 Process Flexibility (f_R)

From section 9.4, it is demonstrated that the hybrid pressure die can be used to conduct the RDB process with tube diameters ranging between 22 mm to 30 mm. Hence the process flexibility represented in terms of different tube diameters that can be used with the same tool is given by:

$$\text{Range of tube diameters (hybrid pressure die)} = \Delta d = d_2 - d_1 = 30 - 22 = 8 \quad \dots\dots\dots (10.1)$$

It can be noted that the conventional metallic pressure die is capable of conducting a RDB process with only one tube diameter i.e.,

$$\text{Process range (conventional circular pressure die)} = d=1 \quad \dots\dots\dots (10.2)$$

Since, $d=1$ is considered as the minimum range of the tube diameters which can be used in a RDB process therefore equation (10.1) take the form of equation (10.3):

$$\text{Process range of (hybrid pressure die)} = \Delta d + 1 = 8 + 1 = 9 \quad \dots\dots\dots (10.3)$$

The increase in process flexibility range directly contributes towards enhanced efficiency of the tool. A higher process flexibility represents higher tool performance and vice versa. Hence, the relationship of the tool efficiency and process flexibility is given by:

$$\text{Tool effectiveness} \propto \text{process flexibility } (f_R) \quad \dots\dots\dots (a)$$

10.1.2 Cost effectiveness (c_M)

The cost effectiveness of tools can be computed according to the Ashby cost performance index [120]. The Ashby cost comparison index does not compare the base costs of materials, rather only a comparison between two (or more) parts is made on the basis of present time market price of the material. Considering the market price of steel and polymer PLA in February 2025 (from section 9.3.4), the cost performance index (C_{Pi}) of the hybrid pressure is C_{Pi} = 8.47 and conventional metallic pressure

die is $C_{Pi} = 0.21$. The comparison of C_{Pi} shows that the material cost of one conventional metallic pressure die is equal to the material cost of 9.5 hybrid pressure dies. The increase in C_{Pi} indicates higher cost effectiveness of the hybrid pressure die and vice versa. Hence, the tool effectiveness is directly proportional to the cost performance index:

$$\text{Tool effectiveness} \propto C_{Pi} \text{ (or } c_M) \dots\dots\dots (b)$$

10.1.3 Lightweight of tools (w_L)

The weight of the conventional geometry of the pressure die made from an alloy steel (EN 1.2363) is 3.32 kg. The weight of the hybrid pressure die [9:1] consisting of 90% volume of PLA (polymer) and 10% volume of steel (EN 1.4301) is 0.41kg. The substantial difference in the weight of the tools is attributed to the light weight of the polymeric materials. If the composition of the tool is changed to incorporate a lesser volume of polymeric material (for example hybrid tool [7:3] consisting of 70% polymer and 30% steel), the weight of the hybrid tool will increase proportionately. The lightweight tools are considered to be significantly effective as lesser energy is required to handle the tool and place the tools on the bending machines. In modern production factories, the handling and position of tools is foreseen to be done entirely by cobots. In such production setups, the requirement of lightweight tools will be significantly pronounced. Hence, a decrease in the weight of the tools is considered to increase the tool effectiveness as shown below:

$$\text{Tool effectiveness} \propto \frac{1}{\text{weight of the tool } (w_L)} \dots\dots\dots (c)$$

10.1.5 Manufacturing time (t_N)

The Additive Manufacturing (AM) processes are particularly faster when considering customized productions which entail low batch and individualized productions. However, the speed of production depends on the type of AM process and the size of the print bed of the 3D printing machine. The modern FFF-3D printers generally have a print bed size of almost 250 x 200 x 200mm (for example PRUSA MK-4 3D printer has a print bed size of 250 x 210 x 220mm) [100]. Similarly, metal 3D printers have similar or relatively larger bed sizes (for example DMP 350 Flex by 3D Systems have a bed size of 275 x 275 x 420mm) [99]. Therefore, considering a print bed size of 250 x 200 x 200mm and a standard fabrication time of one hour, almost 4 pressure dies can be built with FFF-3D printer. The laser cutting of 3 metal sheets of the size of 152 x 10 x 2 mm carried out through a LMD process takes less than half hour (10 minutes each metal strip). Therefore a total number of 4 hybrid pressure dies can be manufactured through additive manufacturing processes in one hour. On the contrary, conventional metallic tools are fabricated by a vast range of conventional production processes. Here, a common conventional fabrication technique is considered in which the geometric shape of the conventional pressure die is milled and the surface of the tool is polished by nitriding. The experience has shown that a total number of 3 conventional geometries of the metallic pressure dies are produced in one hour. A

higher number of products produced per hour represents the capability of the tool to be produced faster. Hence, the tool effectiveness is also measured in terms of rate of production. A total number of 4 hybrid tools can be produced in one hour whereas a total of 3 conventional tools can be produced in one hour. A higher number of parts represents a higher rate of production and vice versa.

$$\text{Tool effectiveness} \propto \text{rate of production } (t_N) \dots\dots\dots (d)$$

10.1.6 Material composition of tools

The material composition affects the tool performance and hence effectiveness of the tool. The higher volume percentage of steel within the tool should makes a tool more robust and stable. On the other hand, a lighter weight polymer made tool is more vulnerable to vibrations and movements. The hybrid tools have lesser weight as compared to conventional tools therefore they are more prone to vibrations. A material composition factor is therefore required to be introduced which should accommodate the material's volume composition in computation of tool efficiency. The material composition of steel and polymer within a tool geometry is presented below:

$$\text{Material composition factor 'V}_C\text{' [volume \%]} = \frac{(V_s + V_p)}{(1 + V_s.V_p)} \dots\dots\dots (e)$$

Here, V_s is the volume percentage of steel and V_p is the volume percentage of polymers. In case of a hybrid pressure die [9:1] the volume percentage of steel (V_s) = 0.1 and the volume percentage of polymer PLA (V_p) = 0.9. In case of conventional pressure die, the whole tool is made from steel therefore volume percentage of steel is $V_s = 1.00$. Therefore, from formula presented in (e), the V_C values are calculated to be V_C (conventional pressure die) = 1.0 and V_C (hybrid pressure die) = 0.91.

10.1.7 Wear resistance

It has been demonstrated in section 6.3.3 (Table 6.4) that the tool made from alloy steel has significantly high wear resistance as compared to the tool (with same geometry) made from polymer PLA. In other words, steels show high wear resistance as compared to polymers. This phenomenon is critically important as it restricts the use of polymer made tools for large scale productions. The design of hybrid tools encompasses the use of steel slabs at the tool surfaces therefore effect of wear in hybrid tools and conventional metallic tools will almost remain the same. On the other hand, owing to the use of polymer in base structure of the hybrid tool, wear in polymeric base will take place at the interface of metal slabs and polymeric base. However, this wear is expected to be relatively less as compared to the wear at tool surfaces. Moreover, this doctoral thesis aims to develop hybrid tools for customized production (individualized or small scale productions), therefore the influence of wear at the interfaces is not pronounced in therefore not considered in computation of tool efficiency.

10.1.8 Formula of Tool Efficiency Index

The influences of tool effectiveness criteria are combined together to formulate a single design formula which incorporates the influences of each effectiveness criterion. The design formula computes the

influence of each criterion and computes a numeric number which shows the overall effectiveness of the tool. This calculated numeric number is called here as the Tool Efficiency index (TEi). From the relationships obtained in (a), (b), (c), (d) and (e) the TEi is formulated as:

$$TEi = \frac{V_s + V_p}{1 + (V_s \cdot V_p)} \left[\frac{f_R + t_N + C_M}{W_L} \right] \dots\dots\dots(10.4)$$

The numerical formula of TEi is specifically developed to assist practical tool manufacturers working in the industrial setups. By using TEi, the manufacturers can assess the tool effectiveness before physically manufacturing the tool. A higher value of TEi represents higher tool effectiveness in terms of process flexibility, cost effectiveness, lightweight performance and tool production time. The TEi can be used to compare and evaluate the effectiveness of all bending tools used in a RDB process. For the research conducted within this doctoral thesis, the TEi of the newly developed design of the hybrid pressure die is compared with the presently used conventional design of metallic pressure die. The brief computation is shown in Table 10.1.

Table 10.1: Tool Efficiency index (TEi) of conventional circular (steel) tool, interim circular and V-shape designs made with polymer-PLA and the final design of hybrid tool

Target Feature	Relationship between target feature and TEi	Conventional tool (Circular, steel)	Interim tool design (Circular, polymer)	Interim tool design (V-shape, polymer)	Final tool design (V-shape, Hybrid)
Cost Effectiveness (C_M) [CPI]	$TEi \propto C_M$	0.206	1.04	1.67	8.47
Flexibility range ' f_R ' (d2-d1) [mm]	$TEi \propto f_R$	1	1	8	8
Light weight performance ' W_L ' [kg]	$TEi \propto 1/W_L$	3.32	0.65	0.38	0.41
Manufacturing time ' t_N ' [number]	$TEi \propto t_N$	3	4	4	4
Volume %	-	$V_s=100\%$ $V_p=0\%$	$V_s=0\%$ $V_p=100\%$	$V_s=0\%$ $V_p=100\%$	$V_s=10\%$ $V_p=90\%$
Tool Efficiency index (TEi)		1.28	9.29	35.97	49.92

A significant advantage delivered by the hybrid tool is the provision of partial flexibility to the RDB process. This means that the geometric design of hybrid tools allows bending of a range of tube diameters. To determine the range of tube diameters which can be used with hybrid tools, it is important to standardize the geometry of hybrid tools according to tube diameters.

10.2 Standardization of hybrid tools for different ranges of tube diameters

In order to standardize the hybrid tools for a wide range of tube diameters, the geometric dimensions of the tool are required to be categorized according to a discrete standard. This standard will assist the manufacturers working in the industrial setups to choose a particular tool for their desired process. To demonstrate the process of standardization, the geometric design of the hybrid pressure die is categorized based on its aspect ratio.

The aspect ratio is a pre-computed single entity that describes the geometric dimensions of a hybrid tool in the form of a ratio of length x width x height. To change the tool size, the aspect ratio of a tool is multiplied by a size factor ' S_f '. The S_f determines the range of tube diameters which can be used with the hybrid tool. The standardization process of the newly developed design of the hybrid pressure die is presented below:

The basic aspect ratio of the hybrid pressure die = 8 : 3 : 1 (length x width x height).

The standardization factor is classified into four discrete levels namely $S_f=10$, $S_f=20$, $S_f=30$ and $S_f=40$. The geometric dimensions of the hybrid pressure die obtained from each S_f are:

- $S_f 10 = 10 \times \text{aspect ratio} = 10 \times (8 : 3 : 1) = 80 : 30 : 10$ [80 (length) : 30 (width) : 10 (height)]
- $S_f 20 = 20 \times \text{aspect ratio} = 20 \times (8 : 3 : 1) = 160 : 60 : 20$ [160 (length) : 60 (width) : 20 (height)]
- $S_f 30 = 30 \times \text{aspect ratio} = 30 \times (8 : 3 : 1) = 240 : 90 : 30$ [240 (length) : 90 (width) : 30 (height)]
- $S_f 40 = 40 \times \text{aspect ratio} = 40 \times (8 : 3 : 1) = 320 : 120 : 40$ [320 (length) : 120 (width) : 40 (height)]

The hybrid pressure die developed and tested in this research thesis has a $S_f=20$. Hence, the dimensions of size 2 hybrid pressure die are 160 x 60 x 20 mm as shown in Figure 10.1.

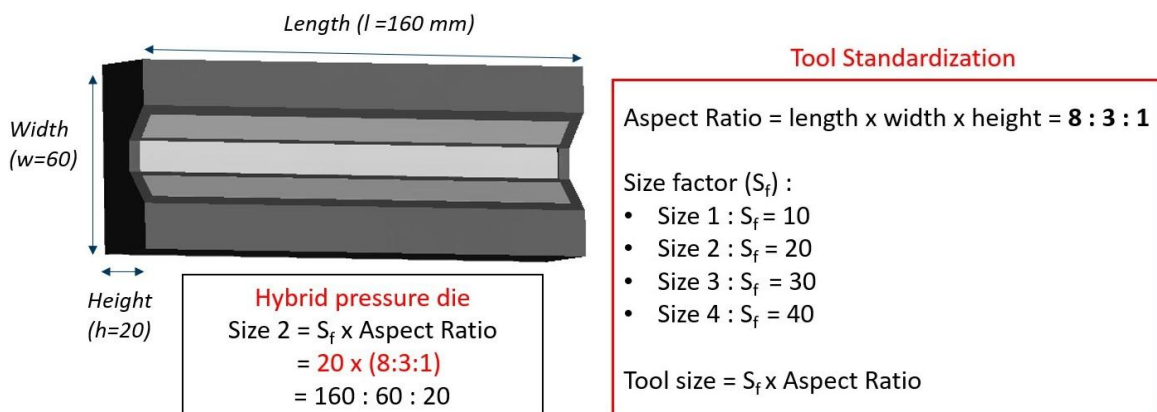




Figure 10.1 : Standardization of hybrid tools according to the aspect ratio and size factor (S_f)

It has already been demonstrated in section 9.4 that the range of tube diameters which can be used in bending operation with hybrid pressure die ($S_f=20$) is 22-30mm. It is important to remember that this range is identified at $B=1.5$ and $W=22$ (detailed process parameters are mentioned in Table 5.1). Hence, for different tube diameters, the selection of bending radius and tube wall thickness should be done in such a way that the values of B and W are equal or close to $B=1.5$ and $W=22$ respectively. In this research thesis, FE-simulations are conducted to identify the tube diameters which can be bent by employing $S_f = 10$, $S_f = 20$, $S_f = 30$ and $S_f = 40$. The ranges of the tube diameters that can be safely used in RDB process for each size factor of the hybrid pressure die are shown in Figure 10.2.

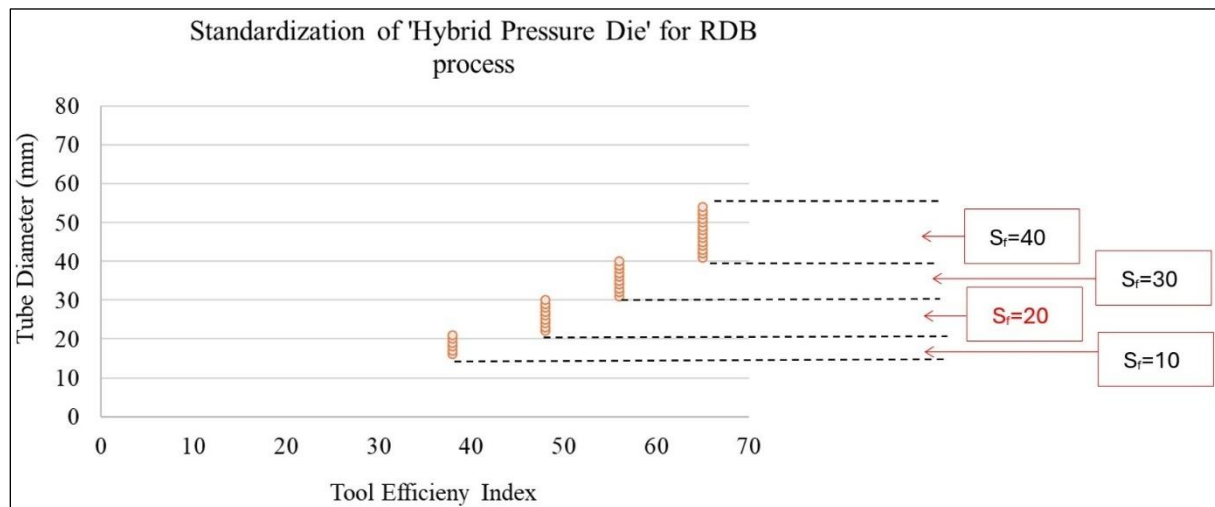


Figure 10.2. Standardization of hybrid pressure die according to different tube diameters and tool efficiency index (TEi). The hybrid pressure die (shown in Figure 10.1) can be used with a tube diameter range of 22mm to 30mm and therefore standardized with a size factor of $S_f=20$. The size factor $S_f=20$ delivers a tool efficiency index ≈ 49 .

It can be seen from Figure 10.2 that the tool efficiency increases with an increase in S_f . Thus, higher the size of the tool, the higher is the tool efficiency and vice versa. The increase in TEi with an increase in the S_f is attributed to the increase in geometric volume of the hybrid pressure die which in turn increases the volume of polymeric material within the tool geometry. Increased polymeric material reduces the cost and weight of the hybrid tool.

Section 10.2 demonstrated the standardization procedure of hybrid pressure die in RDB process. For other bending tools (e.g., hybrid bend die, hybrid clamp dies and hybrid wiper die) the tool standardization is required to be carried out after identification of the respective aspect ratio of the tool. The size factor ' S_f ' will identify the range of tube diameters which can be employed with hybrid tools in RDB process.

Chapter 11 : Development of hybrid tool set for RDB process

11.1 Fundamental role of the bending tools in a RDB process

Each bending tool used in a RDB process executes a specific role [178]. The tool design factors (identified in chapter 5) provide general influences of various factors which assist the development of an efficient tool geometry. A specific value is required to be assigned to each tool design factor. This value depends on the specific role of each bending tool in RDB process. Therefore, in order to determine the specific numerical value of each tool design factor, the role of respective bending tools in a RDB process is investigated. The basic role of each bending tool in a RDB process is shown in Figure 11.1.

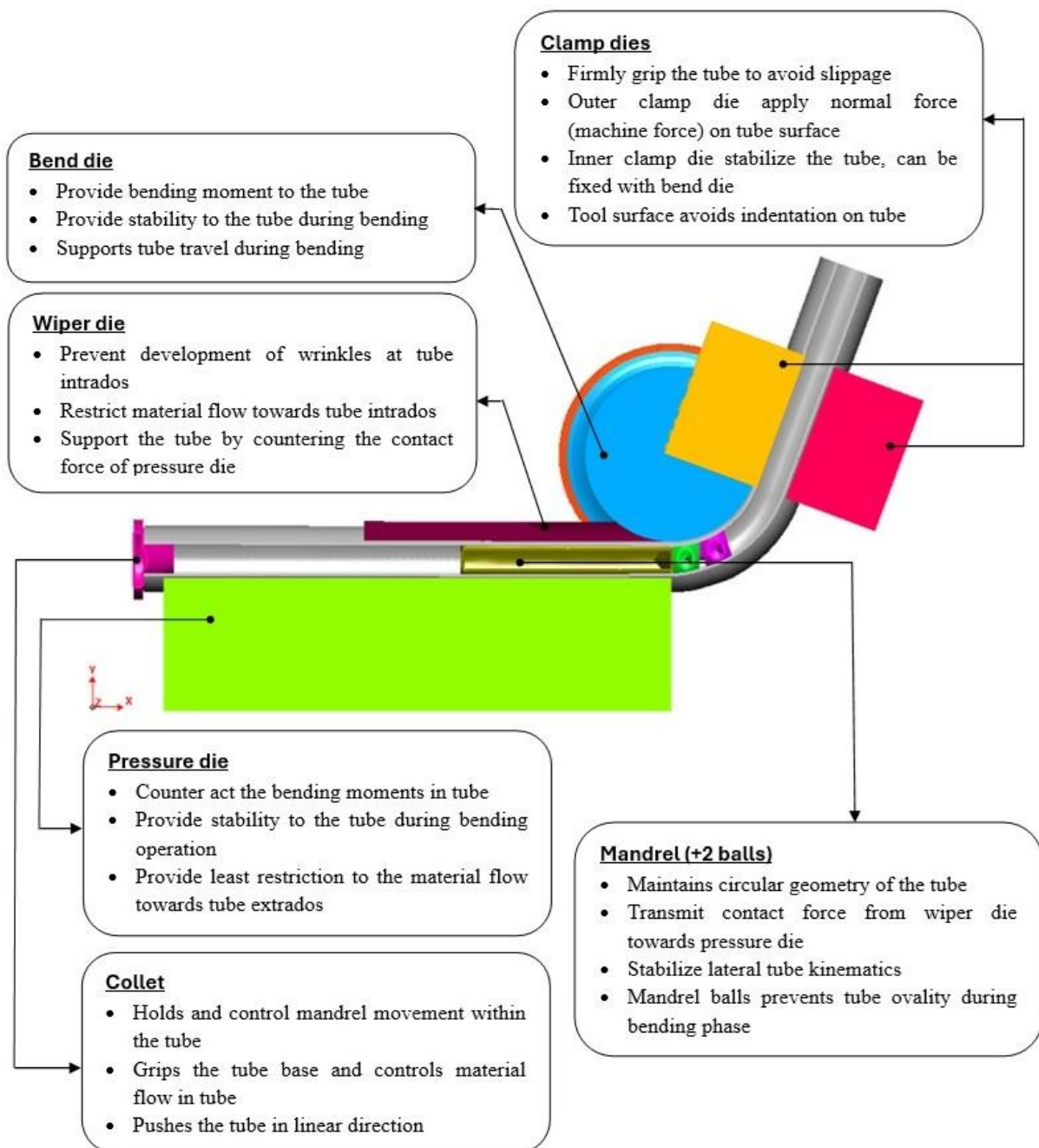


Figure 11.1: Specific role of each bending tool used in RDB process

The numerical values of tool design factors are assigned according to the role of each bending tool. The assigned numerical values are selected on the basis of favourable process outcomes which is identified by the digital twin (FE-simulation) of the RDB process. In some cases where numerical values of the tool design factors cannot be determined, the empirical knowledge of the process experts, which they acquired after substantial years of experience, has been taken into consideration. The desirability and selected numerical value of the tool design factors for each hybrid tool in a RDB process is shown in Table 11.1.

Table 11.1: Numerical values for tool design factors
(selected on the basis of the specific role of each bending tool in RDB process)

Ser	Tool design factors	Pressure die		Wiper die		Bend die		Clamp dies		Mandrel	
		Desirability	Numeric value	Desirability	Numeric value	Desirability	Numeric value	Desirability	Numeric value	Desirability	Numeric value
1.	Young’s Modulus ‘GPa’ (tool surface)	High	210	High	210	High	210	High	210	High	210
2.	Coefficient of friction ‘μ’ (tool surface)	Low	0.1	High	0.25	High	0.25	High	0.25	Low	0.1
3.	Dependence of Contact forces on other tools	Wiper die Mandrel		Pressure die Mandrel		Mandrel balls		Inner clamp die on outer clamp die and vice versa		Pressure die Wiper die	
4.	Effective / Active Area on tool surface	Maximum effective surface is desirable. Minimum two line contact throughout the surface length is envisioned									
5.	Fatigue Strength	Maximum fatigue strength is desirable. Steels produce unlimited fatigue strength with under-investigated RDB process therefore steels should be used at tool surfaces									
6.	Process flexibility range*	8 mm									
7.	Surface pressure enhancement due to area localization**	Increase Factor = 2.5									
8.	Wear resistance	Steels have comparatively high wear resistance as compared to polymers therefore steels are desirable at tool surfaces									

* Identified for V-shaped geometry of the hybrid tool. Flexibility range represents range of tube diameters which can be bent by the use of hybrid tools.

** Surface pressure increases by a factor of 2.5 when circular contact reduces to line contact for V-shaped geometries. The factor is identified for PLA. Different materials will manifest different increase factor.

11.2 Development of hybrid tool set

The development methodology of a hybrid pressure die is explained in chapter 8 (Figure 8.3). The same methodology is used to construct the geometric designs of the other hybrid tools. The values of the tool design factors for each hybrid tool are obtained from Table 11.1. Due to the peculiar role of mandrel and

collet, the geometric design of these tools is not changed. Hence, mandrel and collet are suggested to remain in conventional geometries made from metals or alloys. The geometric design and material of pressure die, bend die, clamp dies and wiper die are transformed into hybrid tools. The surfaces of hybrid tools consist of metallic materials and the base structure consists of polymeric material. The geometric design of the pressure die is already presented in chapter 8. The geometric designs of other hybrid tools are shown in proceeding sections.

11.2.1 Hybrid Bend die

In case of bend die, the steel surfaces are constructed in circular geometries which are fixed on the 3D printed polymeric base structure. The geometric design of the hybrid bend die is shown in Figure 11.2.

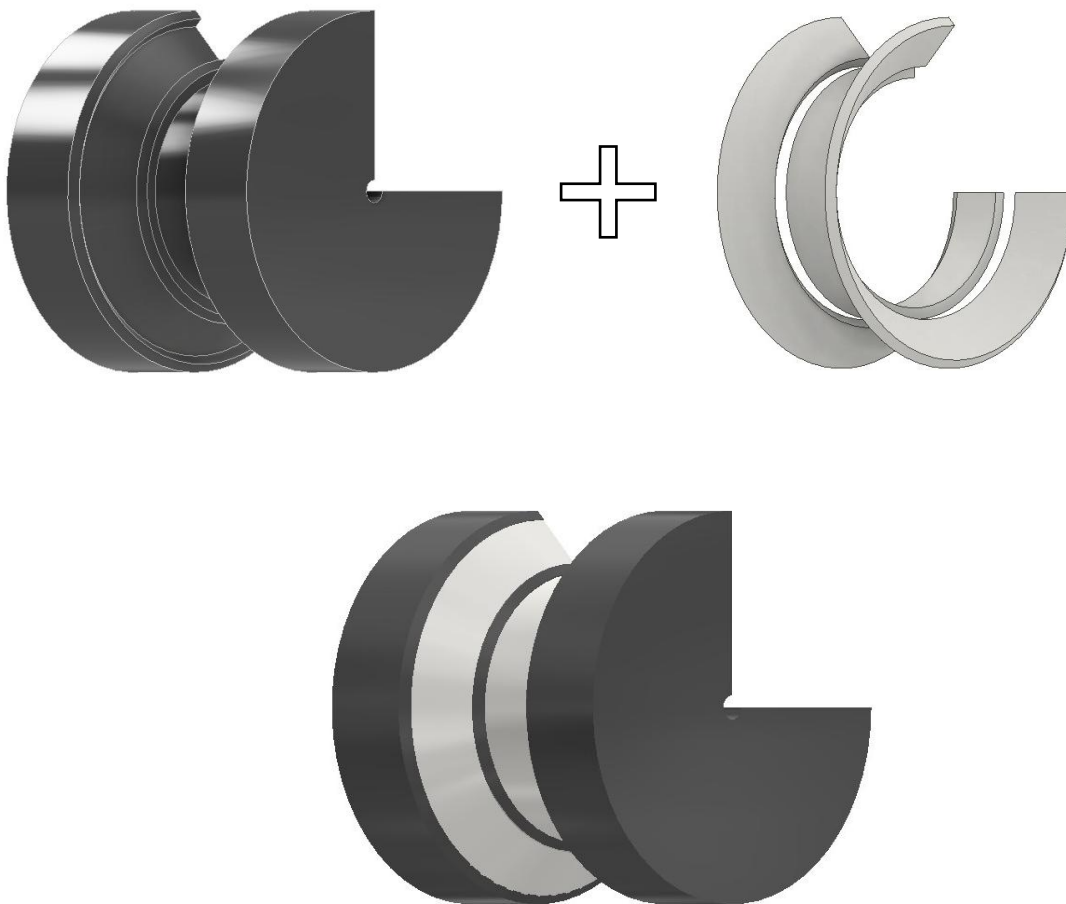


Figure 11.2. Hybrid bend die consisting of polymeric base structure and surface metal slabs

The hybrid bend die is a circular geometry therefore its length is calculated by equation (11.1) below:

$$\text{length 'l'} = 2 \cdot \pi \cdot R \dots\dots (11.1)$$

The aspect ratio of the bend die is calculated by equation (11.2):

$$\text{Aspect ratio (A}_R\text{)} = \text{length : width : height} = 2 \cdot \pi \cdot R : \text{width : height} \dots\dots (11.2)$$

In order to particularly design the bend die for customized productions, the length of bend die can be adjusted according to the product requirement. In this case, the tube is bent from 0° to 90° , therefore

the circular geometry of the bend die can be reduced from 270° to 95° as shown in Figure 11.3. The unused surface of the hybrid pressure die is omitted from the geometric design. The used and unused surfaces of the hybrid pressure die are identified through digital twin as shown in Figure 11.3.

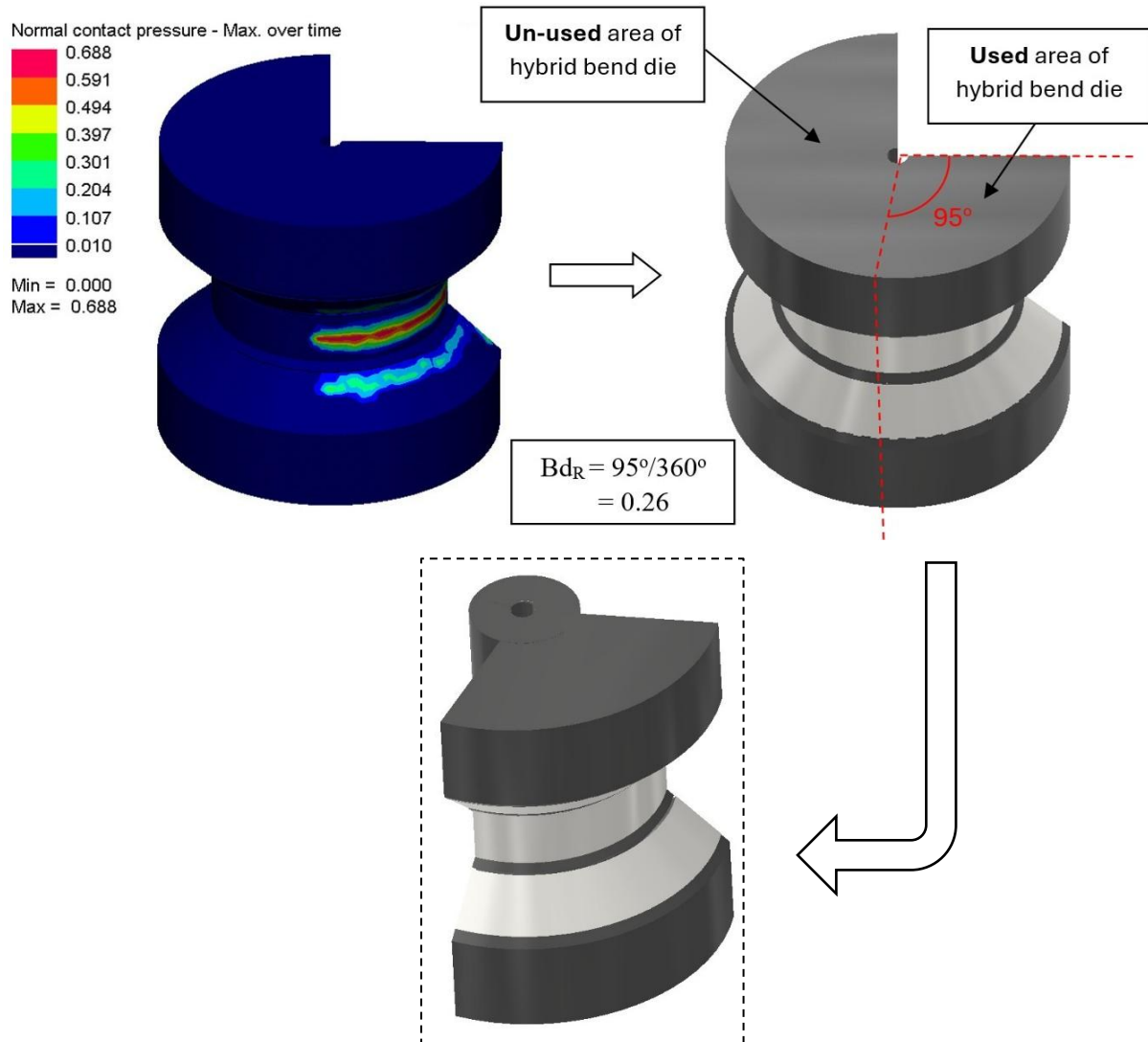


Figure 11.3: Un-used and used area in hybrid bend die. The bend die reduction factor (Bd_R) can be used to reduce the geometry of the hybrid bend die.

It can be seen from Figure 11.3 that only 95° of the circular geometry is used during the bending process. This means that a bend die reduction factor can be used while designing the hybrid bend die. The bend die reduction factor (Bd_R) depends on the total angle (α) at which the tube is bent. It can be calculated by the following equation:

$$\text{Bend die reduction factor } (Bd_R) = \text{surface area used during bending} / 360^\circ \dots\dots (11.3)$$

The Bd_R of the under investigated parameterized RDB process is $95^\circ / 360^\circ = 0.26$. The Bd_R is incorporated in equation (11.2) and the aspect ratio of the reduced hybrid bend die can be obtained as shown in equation (11.4):

$$\text{Aspect ratio } (A_R) = B_{dR} \times \text{total aspect ratio} \dots\dots\dots (11.4)$$

$$\text{Aspect ratio } (A_R) = 0.26 (2 \pi R) : \text{width} : \text{height} = 0.26 (69) : \text{width} : \text{height}$$

$$\text{Aspect ratio } (A_R) = 54 : 60 : 20 = S_f 20 (2.7 : 3 : 1)$$

The geometric design of the reduced hybrid bend die is shown in Figure 11.3. The aspect ratio (A_R) of the hybrid bend die is used for standardization of the geometric design for practical applications. The tool manufacturers working in the tube bending industries can select the aspect ratio according to the tube diameters (Figure 10.2) and corresponding size factor (S_f). In the under investigated RDB process, the tube diameter is 22 mm therefore the $S_f = 20$ is used for development of hybrid bend die. It may be noted that if the tube is required to be bent to lesser value (or more value) than 90° then the bend die factor reduction mentioned in equation (11.3) will decrease (or increase) and the aspect ratio will also change accordingly. In this section, it is shown that the geometry of hybrid bend die can be reduced according to utilized or effective surface area of the hybrid bend die. However, owing to circular bending moments originated during process kinematics, the reduced geometry of the hybrid bend die is not recommended to be used in a RDB process. Instead, a complete circular geometry as shown in Figure 11.2 is recommended to be used in RDB process.

11.2.2 Hybrid Clamp dies

The geometric design of the hybrid clamp dies is similar to the design of the pressure die except for the length of the tool. In case of hybrid clamp dies, the length of the tools (outer and inner clamp die) is 44mm whereas the width and the height of the tools remains identical as that of hybrid pressure die. The geometric dimensions of the hybrid clamp dies are shown in Figure 11.4. The aspect ratio of the hybrid clamp dies is:

$$\text{Aspect ratio} = 44 : 60 : 20 = S_f 20 (2.2 : 3 : 1)$$

In this research thesis, the hybrid tools are designed while keeping in view the tube outer diameter of 22mm. Therefore, the outer and inner clamp dies make 6 point contact with the tube. For higher tube diameters, the same geometry of the hybrid clamp tools will make 4 point contact with the tube as shown in Figure 11.5. The tool performance results have shown that both 6 point contact and 4 point contact manifest similar efficiency. This is because the contact forces experienced by the tube are equal and opposite in directions.

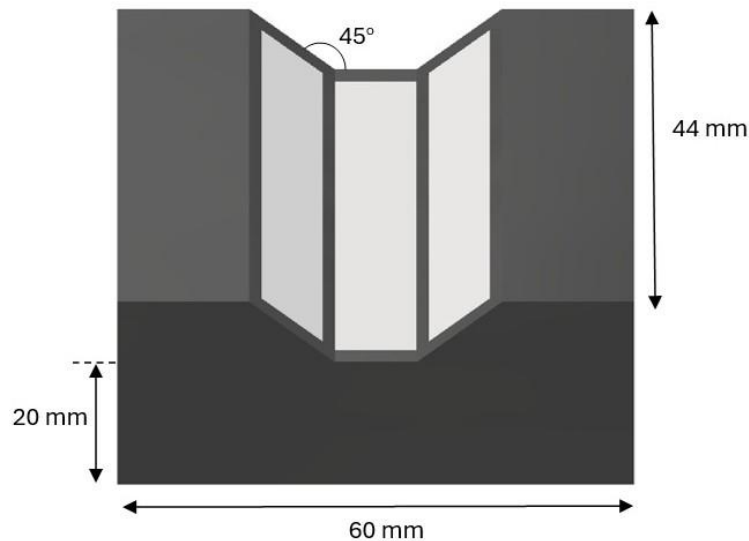


Figure 11.4. Hybrid clamp die (Outer and Inner clamp dies have the same geometrical dimensions)

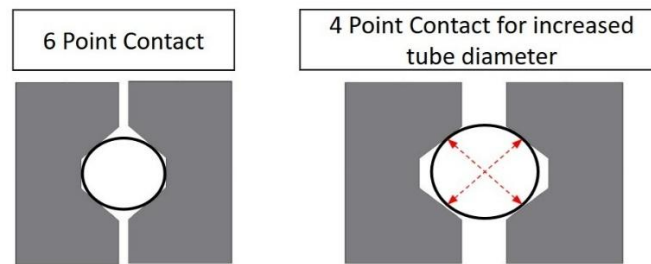


Figure 11.5. (Side view) Hybrid clamp dies making line contact with the tube. 6 point contact with standard tube at which tools are designed and 6 point contact for increased tube diameters.

11.2.3 Hybrid wiper die

The wiper die has a peculiar role of wrinkle elimination in addition to tube support and stabilization. Therefore, the geometric design of the wiper die is divided into two different parts as shown in Figure 11.6. The first part is a hybrid part in which tool geometry is developed by using the same design methodology by which the other bending tools are developed. The second part is the plug-in part which consists of a sharp edged metal/alloy sheet. The curvature of the plug-in part corresponds to the tube diameter. Hence, for each tube diameter, a separate geometry of the second part (plug-in) is required to be fabricated. This is done because the elimination of wrinkles requires precise contact between the tip of the plug-in and potential development of wrinkles in the tube. The hard tip of the plug-in restricts the development of wrinkles in the tube. The aspect ratio of hybrid tools is used to standardise the tools for practical manufacturers working in the tube bending industries. Therefore only the first part of the hybrid tool can be standardised according to aspect ratio and corresponding standardisation factors. In the under investigated RDB process the aspect ratio of the first part of the hybrid wiper die is:

$$\text{Aspect ratio (first part)} = 80 : 60 : 20 = S_f 20 (4 : 3 : 1)$$

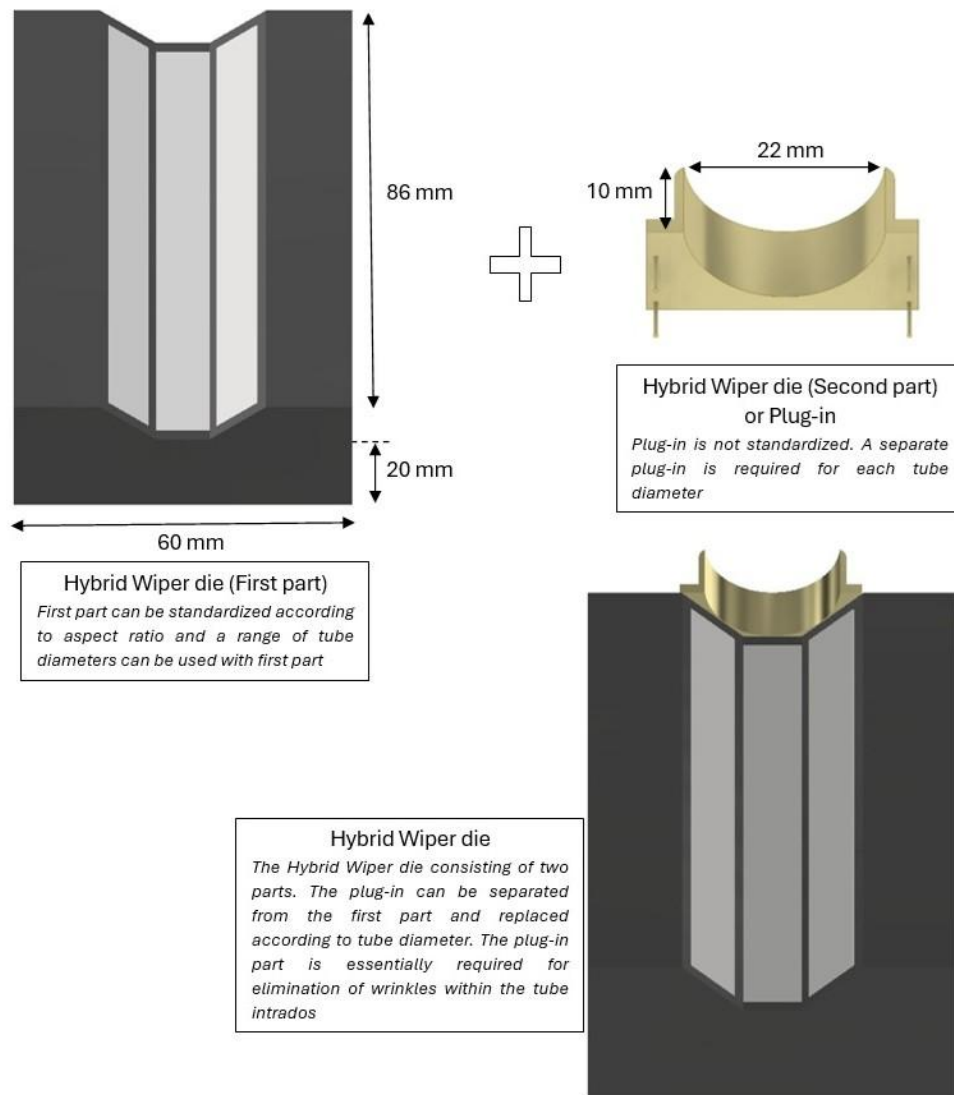


Figure 11.6. Hybrid Wiper die consisting of *First* and *Second* part. The *Second* part is called ‘plug-in’.
A separate plug-in is required for each tube diameter.

11.3 Tool performance with hybrid tool set

The hybrid tools shown in the previous sections are incorporated in the digital twin setup. A complete process simulation of the RDB process is conducted with hybrid tools. The digital twin setup of the RDB process with hybrid tool set is shown in Figure 11.7 (a-2). The hybrid tools conducted the RDB process without any failure. The von-Mises stress obtained within the tool geometries of the hybrid pressure tool set remained significantly less than the yield strength of the respective tool materials. The maximum von-Mises stress developed within each material of the hybrid tools (with respective yield strength of the tool material) is shown in Figure 11.7 (b).

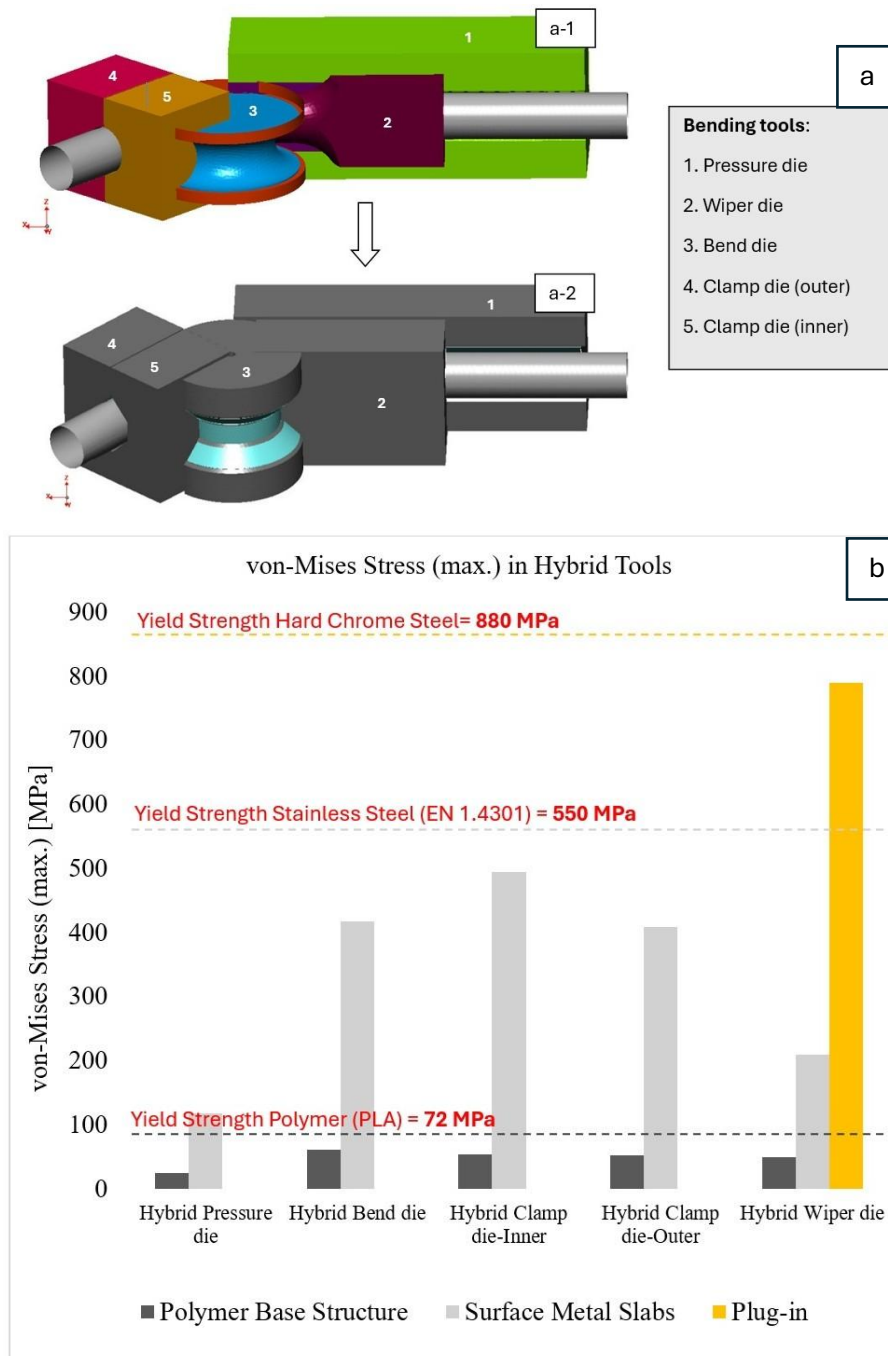


Figure 11.7 (a & b): (a). The digital twin model of the RDB process with conventional tool set (a-1) and hybrid tool set (a-2). (b). The max. von-Mises stress developed in hybrid tools during bending process. The yield limit of each tool material is shown in red colour.

In order to investigate an in-depth tool performance of the hybrid tools, the mechanical response of the hybrid tools is analysed. It is noticed that the surfaces of the hybrid tools are displaced from their original position due to the elastic cushion provided by the polymeric base. The surface displacement occurs due to the elastic deformation within the polymeric base. The metallic surfaces slabs fixed at the top of the base structure remained almost undeformed however these slabs are displaced from their original position during bending process. The surface displacement does not affect the tube kinematics

since equal and opposite contact forces are applied by the hybrid tools surrounding the tube (Figure 11.5). The surface displacement of hybrid tool set is shown in Figure 11.8.

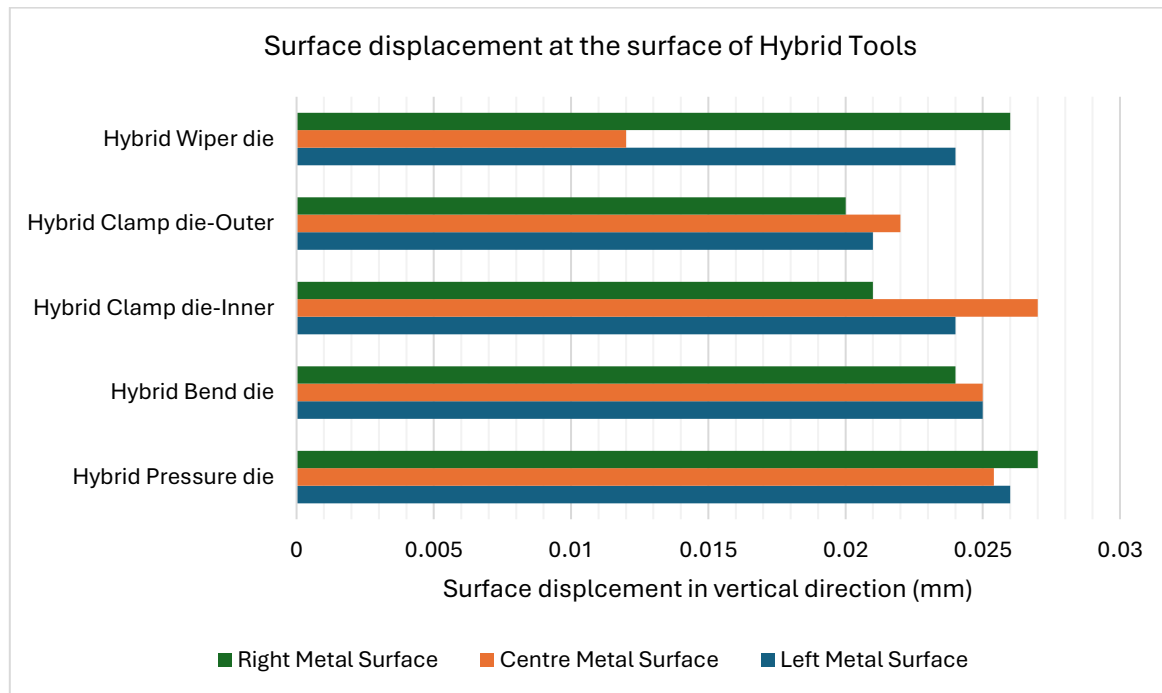


Figure 11.8: Surface displacement in hybrid tools (displacement measured only in vertical direction)

It is highlighted that the surface displacement manifested by the hybrid tools did not affect the tube quality. On the other hand, tool surface displacement resulted in development of lesser contact forces as compared to conventional tools. During the process, only the steel slabs at the surfaces of the hybrid tools are in-contact with the tube. The polymeric base structure did not make any contact with the tube. Therefore, the combined contact force of a hybrid tool is obtained by adding the contact force on each metal slab of a respective tools. The maximum contact forces developed in the hybrid tool set are compared with the maximum contact forces developed in conventional tools ($\alpha = 0^\circ$ to 90°). The comparison of maximum contact forces between the two tool set is shown in Figure 11.9.

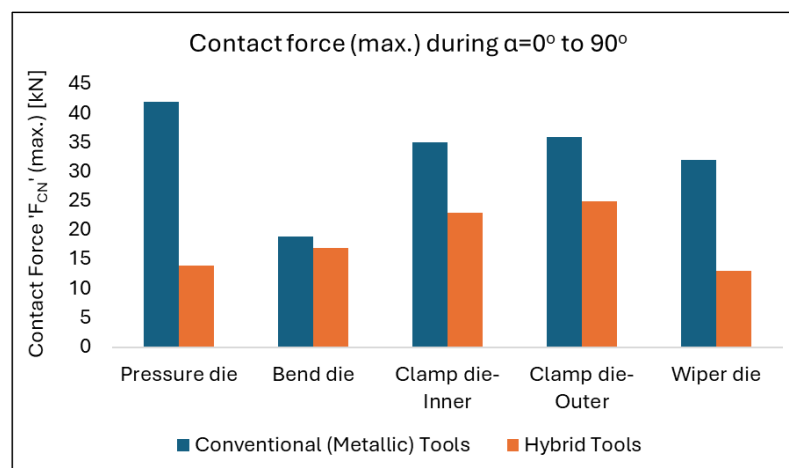


Figure 11.9: Maximum contact forces ' F_{CN} ' experienced by tools during bending operation between $\alpha=0^\circ$ to 90°

The surface displacement at the surface of hybrid tools result in development of lesser contact forces between tube and hybrid tool surfaces. The contact forces developed at the surfaces of each bending tool in a RDB process is shown in Figure 11.10 (a-e). It can be seen that the contact force of hybrid tool is less than the corresponding conventional metallic tool. This investigation has shown that the surface displacement in hybrid tools results in the development of lesser contact forces at the tool surfaces.

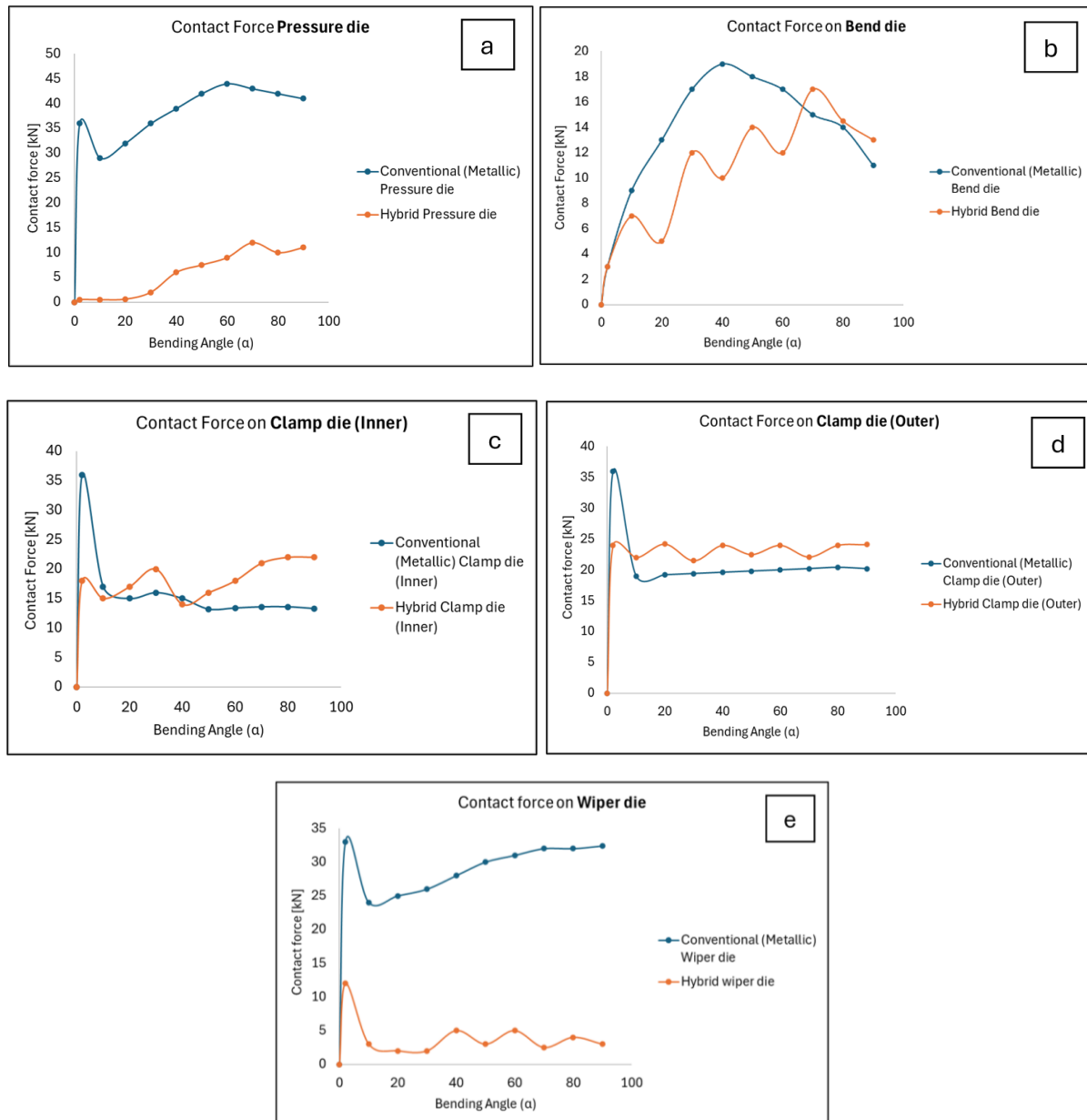


Figure 11.10 (a-e): Contact forces on bending tools from $\alpha = 0^\circ$ to 90° (a) Pressure die (b) Bend die (c) Clamp die-Inner (d) Clamp die-Outer (e) Wiper die. The mandrel's geometric dimensions and tool material remains in conventional circular design.

It can be seen from Figure 11.10 that a large difference of contact forces exist in pressure die and wiper die i.e., in case of pressure die: the contact force of hybrid pressure die is significantly lesser than the contact force of conventional design of pressure die and in case of wiper die, the contact forces of

hybrid wiper die is substantially less than the contact force of conventional wiper die. It is highlighted that the circular geometry of the mandrel is kept the same in both cases. Here, two cases regarding same geometry of mandrel are present:

Case 1: Conventional circular geometry of mandrel (+2 balls) when used with conventional metallic tool set.

Case 2: Conventional circular geometry of mandrel (+2 balls) when used with hybrid tool set.

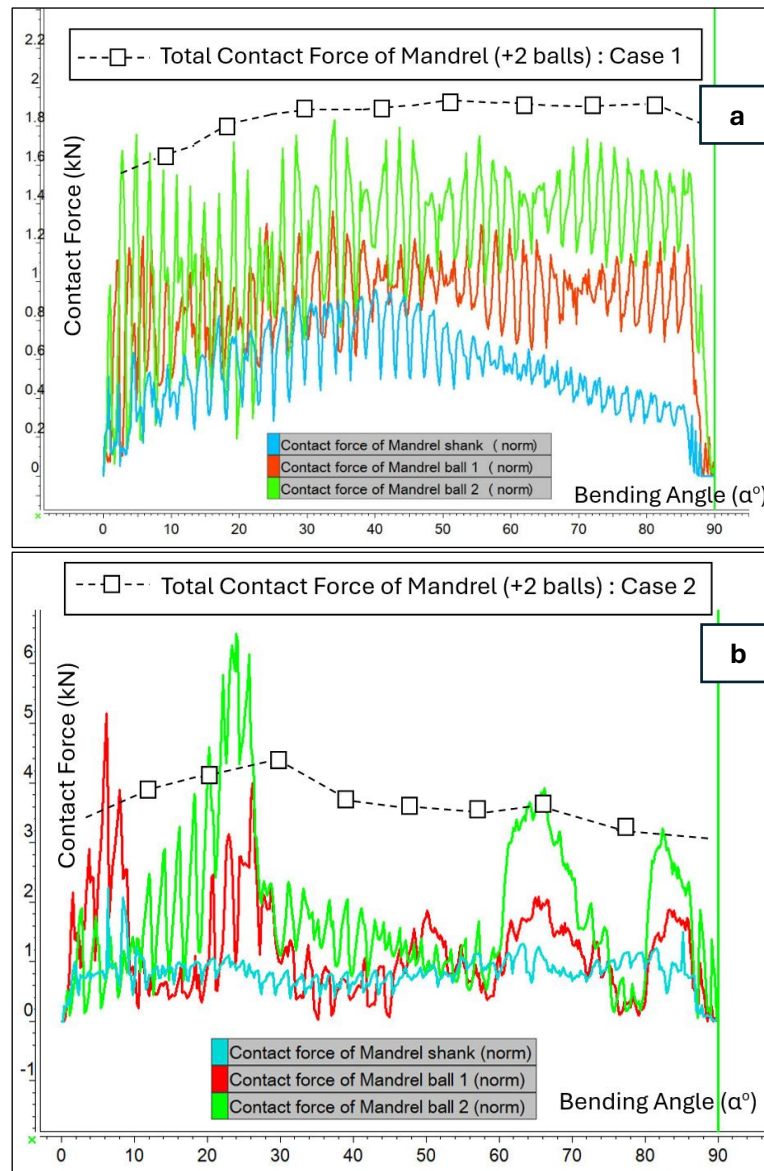


Figure 11.11 (a & b). Contact Forces on Mandrel (+2 balls) (Case 1 & Case 2): (a). In case 1: Mandrel (+2 balls) received less contact force. The total contact force remained between 1.6 to 2 kN (b). In case 2: Mandrel (+2 balls) received relatively high contact force. The total contact force remained between 3.2 to 4.1 kN

The contact force in case 1 is considerably lesser as compared to case 2 as shown in Figure 11.11 (a & b). Figure 11.11 explains the reason of larger difference of contact forces in 11.10 (a & e). In other words, in case of hybrid tool set, the contact forces on the circular mandrel are high (as shown in Case

2) whereas, in case of conventional tool set, the circular mandrel experienced relatively less contact force (as shown in Case 1).

The contact surface pressure (P_{CN}) on the tool surface is investigated. The comparison of P_{CN} on the tool surfaces of hybrid tools and conventional metallic tools is shown in Figure 11.12 (a-e). The decrease in contact force in case of hybrid pressure die should lead to a decrease in P_{CN} at the tool surface. However, in Figure 11.12 (a-e), it can be seen that hybrid tools experience high P_{CN} as compared to conventional tools.

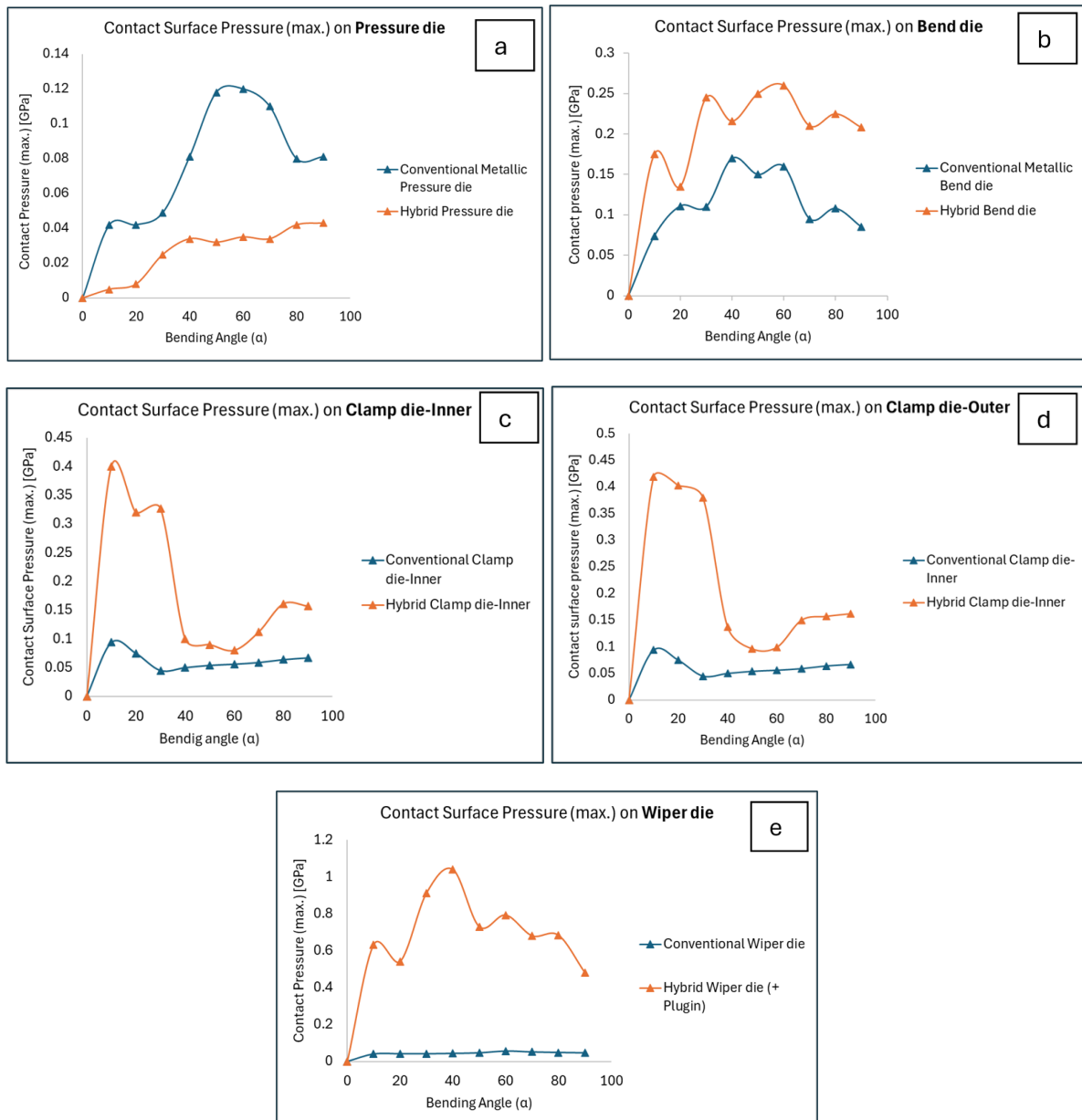


Figure 11.12 (a-e): Contact pressure ' P_{CN} ' on surface of bending tools from $\alpha = 0^\circ$ to 90° (a) Pressure die (b) Bend die (c) Clamp die-Inner (d) Clamp die-Outer (e) Wiper die.

The contact pressure P_{CN} at the tool surface develops von-Mises stress within the tool geometry. The von-Mises stress developed in the tool geometries of the bending tools is shown in Figure 11.13 (a-

e). It can be seen from Figure 11.13 that, in all hybrid tools (except wiper die), the von-Mises stress remained less than the yield strength of stainless steel (EN 1.4301) metal slabs (yield strength of EN 1.4301 = 550 MPa). Thus, the surface slabs made from stainless steel withstood the stresses developed during the bending process.

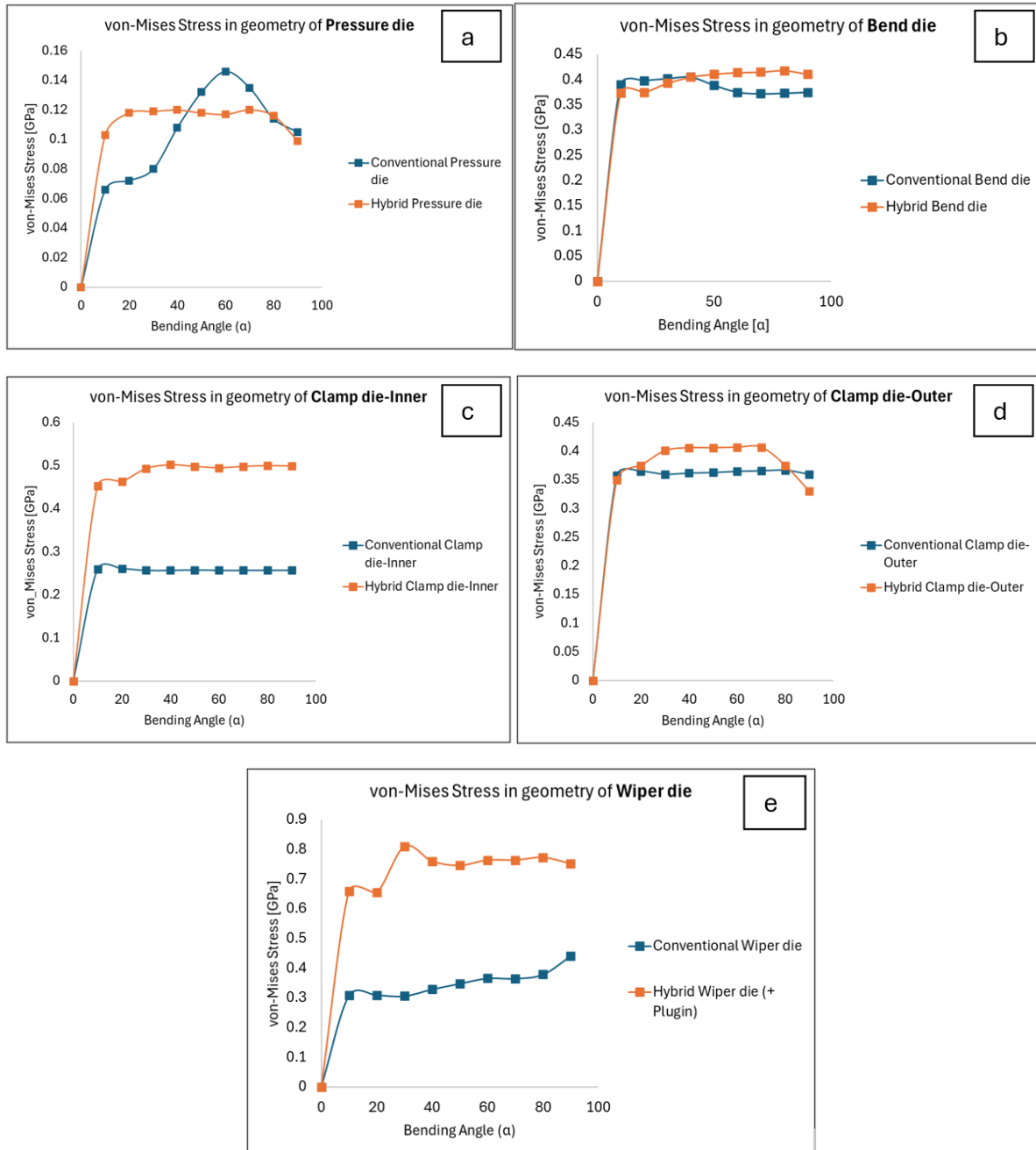


Figure 11.13 (a-e): von-Mises Stress in tool geometry from $\alpha = 0^\circ$ to 90° (a) Pressure die (b) Bend die (c) Clamp die-Inner (d) Clamp die-Outer (e) Wiper die.

The steel slabs withstood the stress primarily and transmitted very few stress towards the polymeric base structures. It is important to remember that the polymeric base structure of hybrid tools is made from PLA having a yield strength of only 72 MPa. Hence, the stresses transmitted to the polymeric base structure must be lesser than the 72 MPa. In all hybrid bending tools, the stress

transmitted to the polymeric base structure remained less than its yield strength (Figure 11.7). The transmission of stress in hybrid bend die and hybrid clamp die (outer) is shown in Figure 11.14 (a & b) at $\alpha = 89^\circ$.

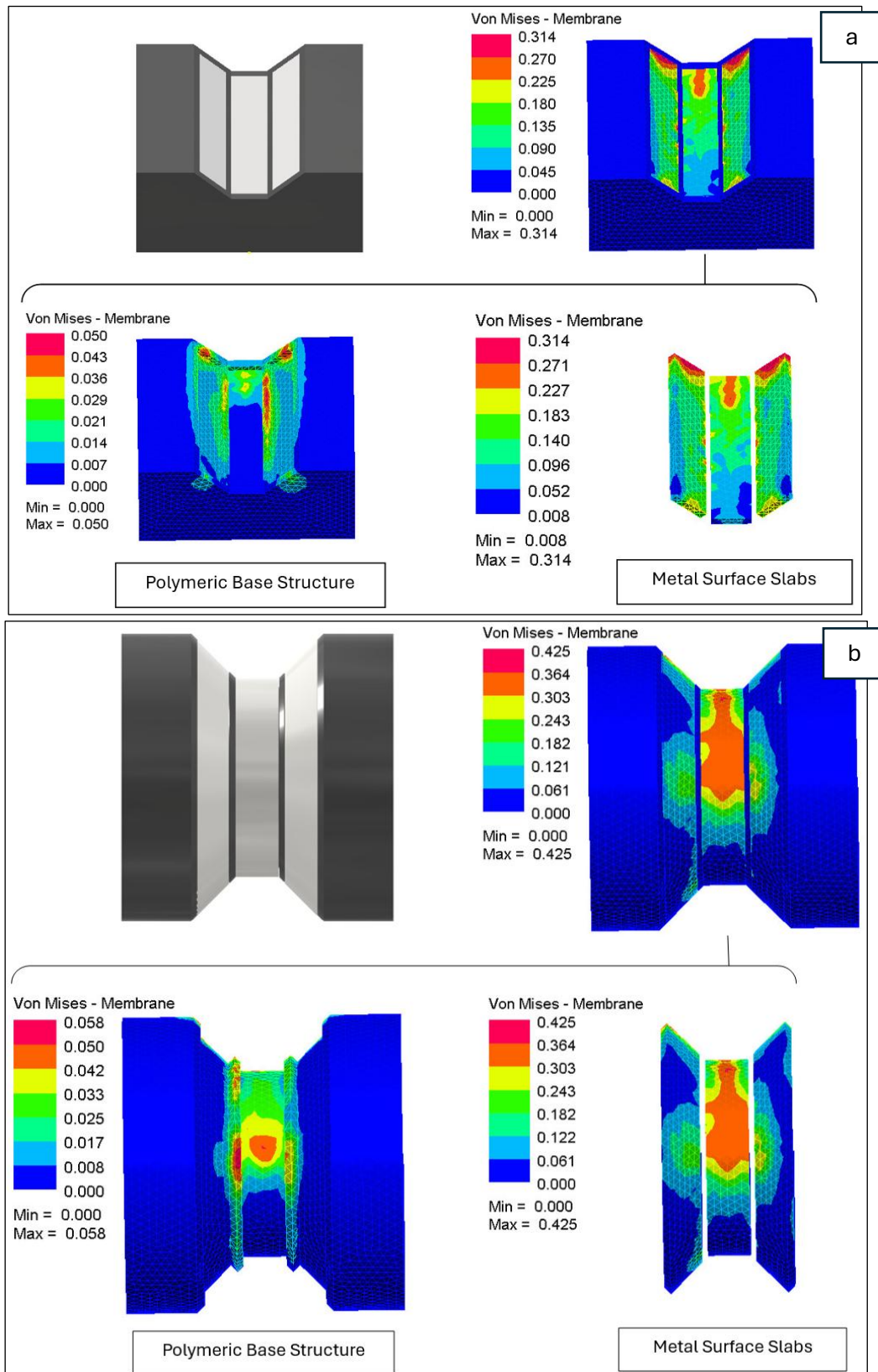


Figure 11.14. (a) von-Mises stress developed in hybrid clamp die (outer) at $\alpha = 89^\circ$. The total stress in the tool is 314 MPa. The stress is mainly withstood by surface metal slabs. The stress developed in polymeric base structure is only 50 MPa (b). von-Mises stress developed in hybrid bend die at $\alpha = 89^\circ$. The total stress in the tool is 425 MPa. The stress is mainly withstood by surface metal slabs. The stress developed in polymeric base structure is only 58 MPa.

In case of hybrid wiper die, the stresses are mainly withstood by Plugin. The development of stresses in hybrid wiper die is shown in Figure 11.15. It can be seen that the complete surface of the Plugin experienced a high stress and the maximum stress developed in the Plugin reached to value of 755 MPa at $\alpha = 89^\circ$. The metal slabs also experienced considerably high stress but a lesser surface area of the metal slabs experienced the stresses. The stress is mainly withstood by Plugin and metal slabs. The stress transmitted to the polymeric base structure is only 54 MPa. It is highlighted that the material of the Plugin is hard chrome steel with a yield strength of almost 880 MPa. Hence, in the under investigated RDB process, the plugin successfully withstood the applied high stresses. During a bending process, the Plugin restricts the development of wrinkles at the tube extrados.

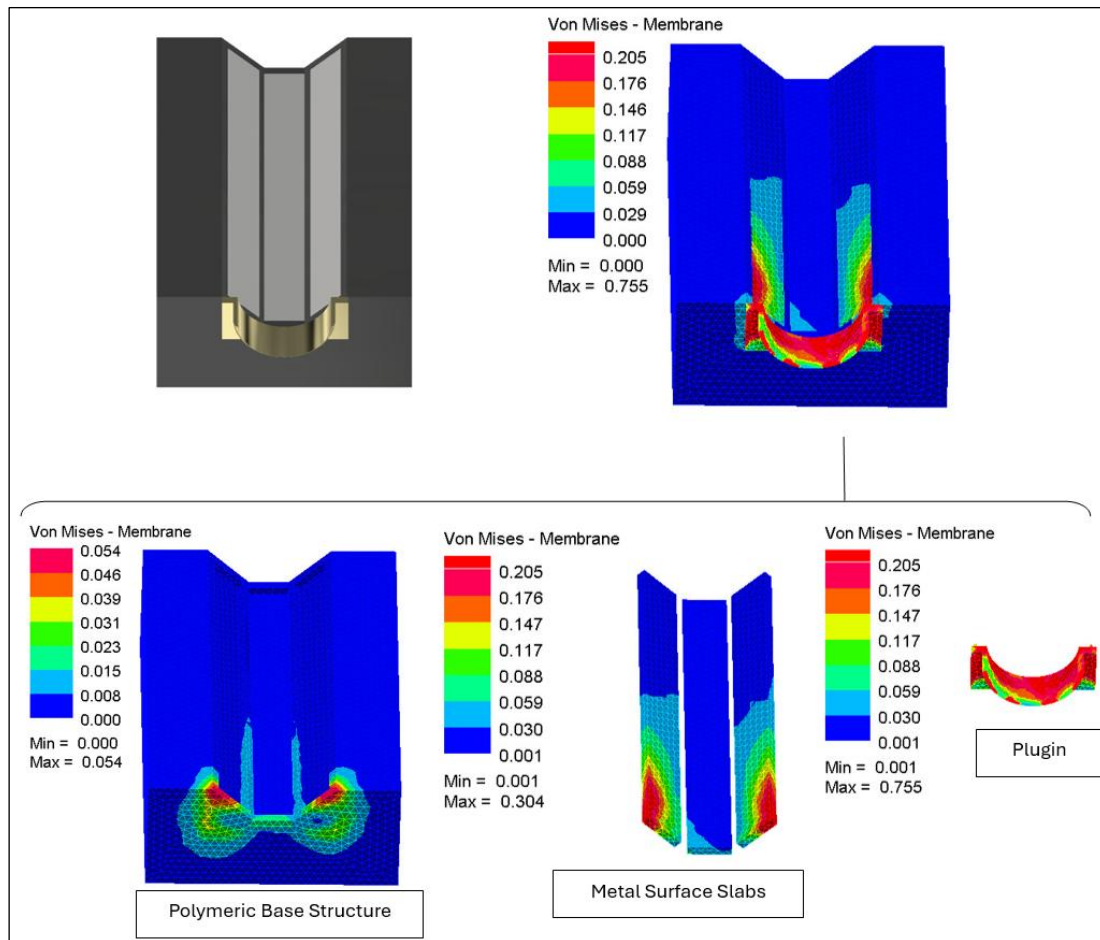


Figure 11.15. von-Mises Stress in hybrid wiper die at $\alpha = 89^\circ$. A maximum von-Mises stress of 755 MPa is developed in the Plugin. The complete geometry of the Plugin experienced high stress. The polymeric base structure experienced a maximum stress of only 54 MPa.

This section summarized the overall mechanical behaviour of hybrid tools in RDB process. In addition to hybrid tools, the tool performance of conventional circular (steel) tools is also shown. Due to change of material and a change in tool geometry between hybrid tools and conventional circular (steel) tools, a direct comparison cannot be made between hybrid tools and conventional circular (steel) tools yet results presented in this section showed that both the types of tools are capable of executing RDB process. In hybrid tools, the surface displacements contribute to decreased contact forces. The lesser contact forces should ideally develop lesser contact pressure P_{CN} . However, due to the V-shaped geometry of the hybrid tools, only a line contact is established between the hybrid tools and the tube. The line contact enhances the P_{CN} on the tool surface. The von-Mises stress generated as a result of enhanced P_{CN} do not surpass the yield strength of the hybrid materials and as a result the bending operation is executed safely.

The decrease in contact forces on tool surfaces also shows that lesser forces are applied by the bending machine and correspondingly lesser energy is consumed which leads to lesser CO₂ emissions and enhanced environmental sustainability. The machine energy conservation is not the focus of this research thesis therefore the quantification of saved machine power has not been carried out. However, the reduction of contact forces due to the use of hybrid tools illustrate the potential of energy conservation through reduced application of machine force on bending tools. In addition to conservation of machine energy, the use of hybrid tools result in significant process improvements which are quantified using digital twin of the RDB process. These process improvements are highlighted in the proceeding sections.

11.4 Process improvements

The process improvements due to the use of hybrid tool set in RDB process are highlighted in following sections:

11.4.1 Forming limits of the RDB process

The forming limits for sheet metal materials are generally described in the form of forming limit diagrams [179]. The forming limit diagram (FLD) was initially presented by Keeler in 1965 and later Goodwin made some substantial refinements in 1968 [180]. Till today, many researchers working in the field of sheet metal forming have conducted research on FLDs. It has been identified that FLDs are influenced by strain hardening coefficient 'n' of materials, thickness of sheet metal and ultimate tensile strength of the sheet metal material [181]. The FLD provides information about sheet metal material failure or fracture due to an increase in major and minor strains. In case of metal tubes, the FLD is used to detect the tube failure by identifying potential cracking at tube extrados and foreseeable development of wrinkles at tube intrados [182]. In this section, the tubes bent by using hybrid tool set and conventional tool set are compared with each other in terms of tube-FLD. The FLDs of the bent tubes obtained from hybrid tool set and conventional tool set are shown in Figure 11.16 (a & b).

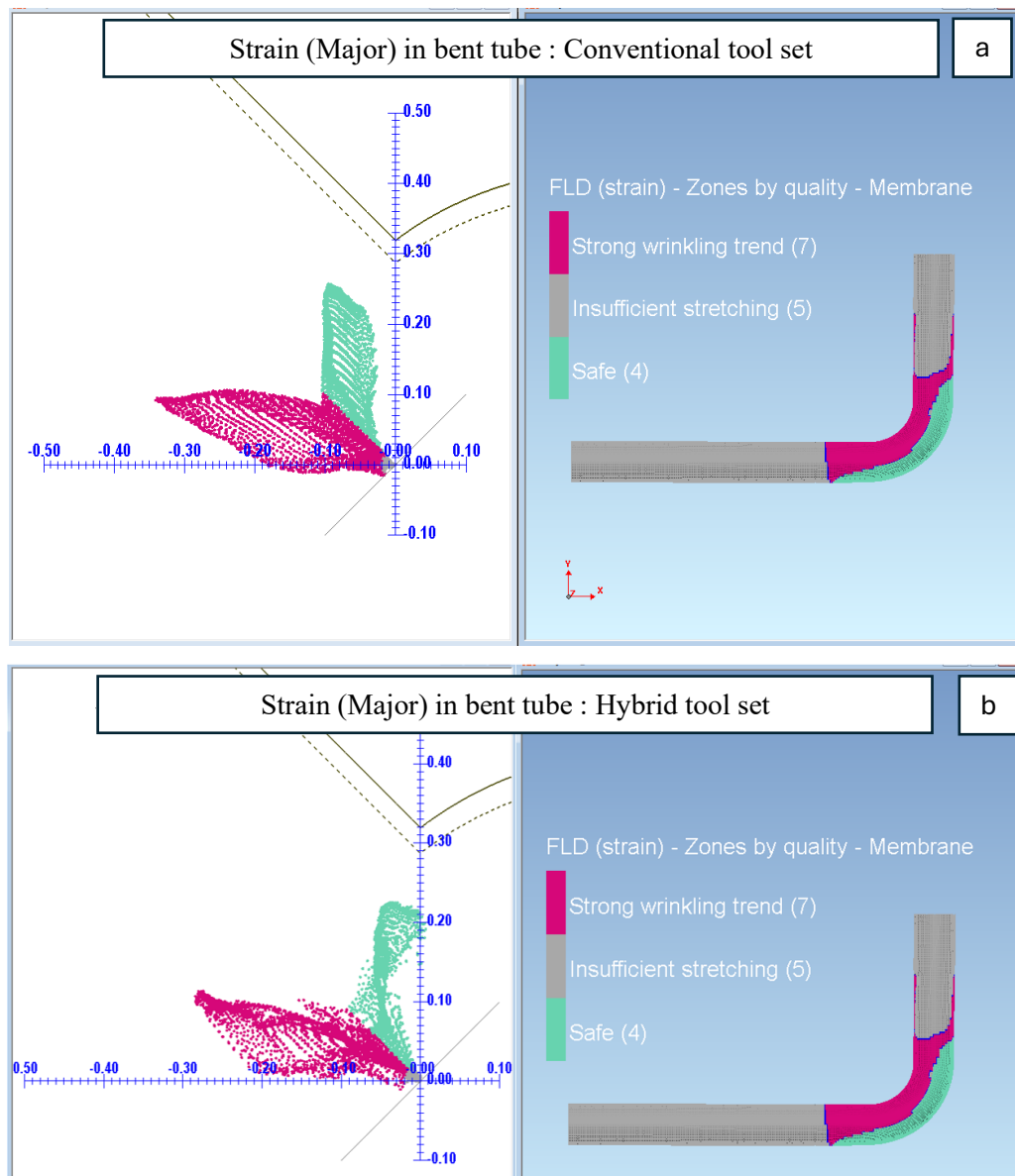


Figure 11.16 FLD (Forming Limit Diagram) of the tubes bent from (a) conventional tool set and (b) hybrid tool set. Both tubes executed the process safely with no cracks at the extrados.

It can be seen from Figure 11.16 that there is no significant difference in the FLD of both tubes. The FLD shows that there is no rupture at the extrados since the maximum major strain developed at the tube extrados is significantly lesser than the failure limit of the tube material. The tendency of wrinkle development at the intrados exists in both the cases however no wrinkles are manifested on the surface. In nutshell, it is concluded that both the tool sets (hybrid tool set and conventional tool set) executed the RDB process within safe forming limits of the steel tube. Hence, in terms of process safety, the hybrid tool set is considered as safe as the conventional tool set.

11.4.2 Tube ovality

A lesser tube ovality is a desirable outcome of the RDB process [183]. FE-simulation has shown that the use of a hybrid tool set in a RDB process delivers lesser ovality to bent tubes as compared to a

conventional tool set. The ovality of bent tubes produced from a hybrid tool set and a conventional tool set are shown in Figure 11.17. Although the difference of tube ovality is not considerably significant at the initial and end portions of the bent, yet there is a considerable difference in tube ovality between radial angles of 40° to 60° . The decrease in the tube ovality provided by the hybrid tool sets is attributed to the development of comparatively less contact forces in hybrid pressure die which in turn provides lesser frictional at the surface of pressure die. The comparison of contact forces developed in hybrid pressure die and conventional pressure die is previously shown in Figure 11.9. In case of hybrid pressure die, the lesser contact forces allow enhanced material flow towards the tube extrados and hence tube ovality is reduced. On the other hand, in case of conventional pressure die, high contact forces restrict material flow towards tube extrados and ovality is increased. A lesser tube ovality is a desirable feature in the RDB process as it contributes to safe process execution with lesser possibility of cracking at tube extrados [184]. The larger tube ovality results in larger possibility of crack development at tube extrados.

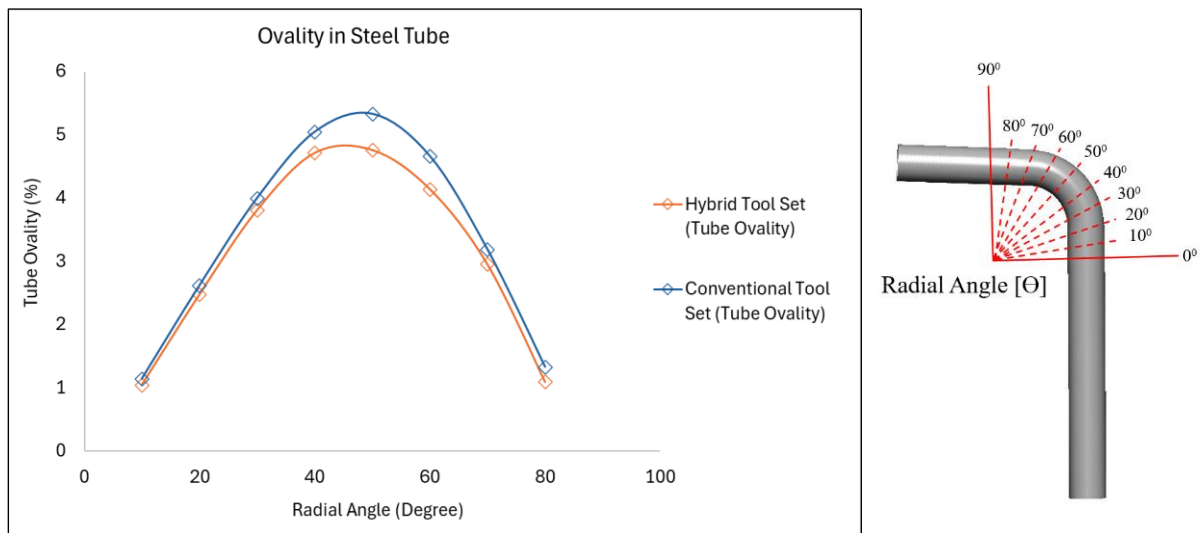


Figure 11.17. Tube ovality (%) of steel tubes obtained from hybrid tool set and conventional tool set.

Considerable reduction in tube ovality is observed for Radial Angles between 40° to 60° . The tube ovality is determined in the Digital Twin of the RDB process. Tube ovality is measured according to VDI 3430

11.4.3 Suitability of hybrid tools for Plasto-Mechanical Model of RDB process

Hassan et al. [185] presented a Plasto-Mechanical Model to determine the neutral axis shifting in a RDB process. The Plasto-Mechanical Model numerically determines the distance of neutral axis shifting of bent tubes in a RDB process. Based on the neutral axis shifting in bent tubes, the bending radius is also shortened during the bending operation [42]. The numerical computation involved in the Plasto-Mechanical Model consists of two steps. In the first step, the neutral axis is computed by using measurements based on the geometric model. In the second step, a correction factor (C_T) mentioned in equation (11.1) is introduced. The correction factor (C_T) is empirically driven from practical experiments and empirical knowledge attained by process experts over substantial years of practical bending experience.

$$\text{Correction factor } (C_T) = \left| \ln \frac{n \cdot R_b}{t_{o,100}} \right| \dots\dots\dots(11.1)$$

Here, 'n' represents strain hardening coefficient, R_b represents the original centre line radius and t_o is the original wall thickness of the tube (*The values represented in equation (i) should be read in conjunction with ref[185]: Plasto-Mechanical Model in RDB Process, Figure 3*).

The neutral axis shifting using Plasto-Mechanical Model is calculated by equation (11.2)

$$\text{Distance of neutral axis shifting } e_A = e_\alpha \cdot C_T \dots\dots\dots(11.2)$$

Here, e_A is the formula to calculate the distance of neutral axis shifting using Plasto-Mechanical Model and e_α is the distance of neutral axis shifting using geometric model (*The value of e_α using geometric model can be calculated according to ref[185]: Plasto-Mechanical Model in RDB Process, equation-3*).

From equation (11.2), the reduced bending radi $R_{b,th}$ is calculated by equation (11.3)

$$\text{Reduced bending radius } R_{b,th} = R_b - e_A \dots\dots\dots(11.3)$$

For the under investigated RDB process ($B=1.5$, $W=22$, tube diameter=22, tube material=EN 1.4301), the shift in neutral axis of the tube and corresponding reduced bending radius is numerically calculated by using Plasto-Mechanical model with equations (11.2) and (11.3). The results of the Plasto-Mechanical Model are compared with the results obtained from digital twin (FE-simulation) of the RDB process. The comparison is presented in the form of bar graphs shown in Figure 11.18 (a & b).

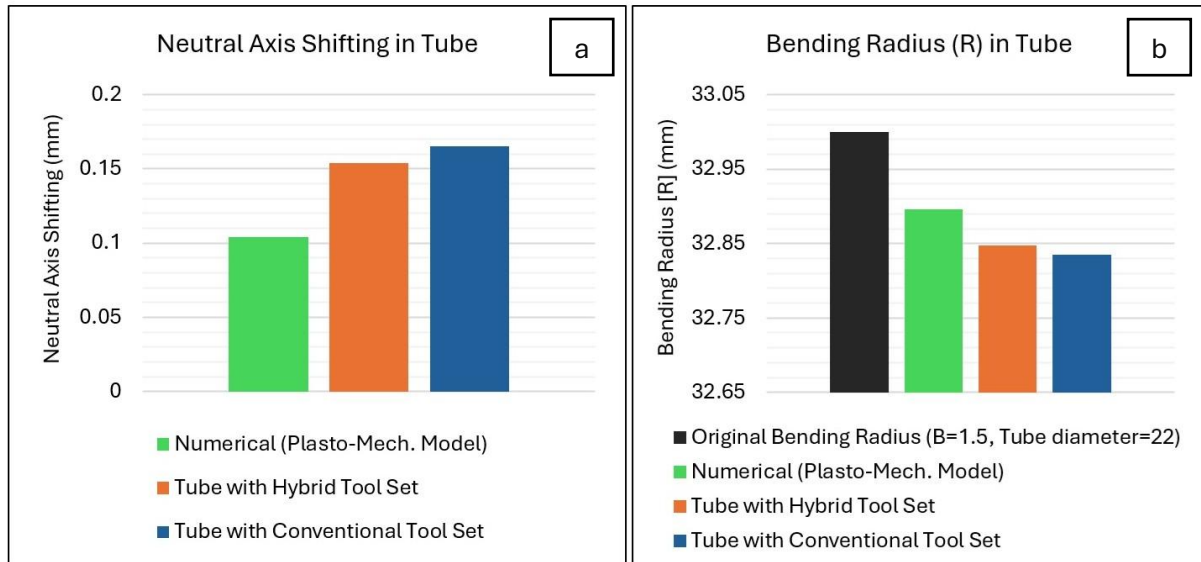


Figure 11.18. Comparison of results (a) Neutral Axis Shifting (b) Bending Radius. The numerical computation of Neutral Axis Shifting is conducted according to Plasto-Mechanical Model [185] shown in green colour. The results obtained from digital twin (FE-simulation) are shown in orange and blue colour. The tube with hybrid tool set is shown in orange colour and the tube with conventional tool set is shown in blue colour

It can be seen from Figure 11.18 that the result of neutral axis shifting in tube with hybrid tool set and conventional tool set is significantly close to each other. Amongst these, the distance of neutral axis shifting of tube with hybrid tool set is comparatively closer to the numerically computed results of Plasto-Mechanical Model. Likewise, the result of reduced bending radius of tube with hybrid tool set is also relatively closer to the computed reduced bending radius provided by Plasto-Mechanical Model.

From Figure 11.9 (preceding section), it is noticed that the hybrid tool set produces less contact forces on the tube as compared to a conventional circular (steel) tool set. Therefore, keeping in view Figure 11.9 and Figure 11.18, following points are identified:

- (a) The numerical formulas presented in the Plasto-Mechanical Model of the RDB process are more suited to hybrid tools as compared to conventional tools. Hence, in case of manufacturing hybrid tool set, the process feasibility can be accurately obtained beforehand by conducting numerical computations through Plasto-Mechanical Modelling of the RDB process with hybrid tools.
- (b) It is identified that contact forces between tools and tube have a direct relationship with Plasto-Mechanical Model. In case of hybrid tool set, lesser contact forces are developed as compared to conventional tool set therefore the numerical calculations provided by Plasto-Mechanical Model are more accurate for hybrid tools. In other words, it is identified that the Plasto-Mechanical Modelling is more accurate for RDB process with lesser contact forces.

11.5 Efficiency of hybrid tools

The efficiency of the hybrid tools can be determined by using the formula of tool efficiency index (TEi) previously presented in section 10.1. The TEi of each hybrid tool is calculated separately depending on the process performance provided by the respective tool. The TEi of conventional tools is also computed and compared with the TEi of the corresponding hybrid tool. The comparison of tool efficiency of the hybrid tools and conventional tools is presented in Table 11.2. It can be seen that hybrid tools provide substantially high tool efficiency as compared to the conventional bending tools made entirely from alloy steel. It may be noted that the TEi classifies the tool efficiency on the basis of process flexibility, tool cost, light weight and rate of production. The process flexibility plays the fundamental role in determining the tool efficiency. In this research work, the RDB process is conducted for a 22mm wide tube which lie within the range of $S_f=2$ (Figure 10.2). For different diameter ranges (e.g., tube diameters more than 30 mm or less than 22mm) the S_f will change and the efficiency of the hybrid tool will also change correspondingly. Therefore, in case of practical applications, the manufacturers should select the S_f (of hybrid tools) according to the tube diameter. It is pertinent to mention that TEi takes into consideration four discrete aspects i.e., cost effectiveness, process flexibility, light weight of tools and manufacturing time of each tool. These four aspects are given equal consideration in the calculation of TEi. In this doctoral thesis, the TEi provides tool efficiency on the basis of equal weightage of aforementioned four aspects. The TEi provides a general yard stick for tool manufacturers to compare the efficiency of tools in RDB process. The methodology used to calculate TEi in this doctoral thesis

can be used to formulate process specific TE_i by tool manufacturers. Hence, more aspects can be added according to each process requirements and a weight of each aspect can be included in the calculation of respective TE_i.

Table 11.2: Comparison of tool efficiency of bending tools in RDB process

Ser	Bending Tools in RDB process	c_M	f_R	w_L	t_N	V_C	Tool Efficiency*
1.	Pressure die						
a.	Conventional Pressure die	0.21	1	3.32	3	1	1.26
b.	Hybrid Pressure die	8.47	9	0.41	4	0.91	49.98
2.	Bend die						
a.	Conventional Bend die	0.18	1	5.85	2	1	0.54
b.	Hybrid Bend die	3.77	9	0.92	2	0.91	14.60
3.	Clamp dies						
a.	Conventional Clamp die	0.11	1	1.80	5	1	3.39
b.	Hybrid Clamp die	13.41	9	0.26	5	0.91	95.93
4.	Wiper die						
a.	Conventional Wiper die	0.14	1	2.42	4	1	2.12
b.	Hybrid Wiper die	10.32	9	0.34	4	0.91	62.41

c_M = Cost Effectiveness (Calculated according to Ashby cost performance index : Table 9.3)

f_R = Process Flexibility (Range of tube diameters which can be used with respective tool : section 10.1.1)

w_L = Weight of the tool measured in kg (Light weight tools: section 10.1.3)

t_N = Manufacturing Time (Number of tool that can be fabricated in one hour using multiple machines)

V_C = Material composition factor (Calculated according to section 10.1.6)

* Tool Efficiency is calculated using the formula of tool efficiency index (TEi) presented in section 10.1.7

Chapter 12 : Discussions

12.1 Suitability of hybrid tools for customized production

The production regime generally follows a unique pattern in which cost of manufactured products decreases with an increase in the scale of production and likewise the cost increases with a decrease in the batch size [186]. For very small batch sizes (or individualized productions), the manufacturing cost per product increases exponentially [187].

In modern manufacturing setups, the product customization has increased due to the versatile customer requirements [188]. Many private enterprises for example PwC Alliance [189], Grey construction [190], and Tencom [191] have declared mass customization as the top trend in the foreseeable near future. The customized products require an enhancement of process flexibility which can be obtained by using a flexible tool set in production processes [192]. In case of a RDB process, the hybrid tool set is particularly suited for customized production as hybrid tools transforms the inflexible RDB process into a partially flexible process. A single tool set of hybrid tools can be used to bend a range of tube diameters hence meeting the requirements of customized production. It has been discussed in the previous sections that the cost of a hybrid tool is considerably less than the cost of a conventional metallic tool. The cost comparison between hybrid tools and conventional tools is further exaggerated when the process flexibility offered by the hybrid tools is considered. Therefore for customized productions, the overall cost of production of a hybrid tool set is significantly less as compared to a conventional tool set.

The product customization can be considered as the product changeability. Schiller et al. [112] has shown that the product changeability is currently in the development phase (year 2025). The outlook presented in his research has shown that the product customization will enter in the application phase in the coming decade. This means that the requirement of product changeability will increase in the future and standardized tools will be required which can conduct the manufacturing processes for a wide range of customized products. In general, the production processes follow a unique trend in which an increase in the tool cost is associated with a decrease in the batch size [193]. However, if the manufacturing tools are standardized, then the tool costs decrease significantly for smaller batch sizes [194]. Hence, it is critically important to reduce the cost of production tools. In this research thesis, the hybrid tools are manufactured by using the inexpensive and lightweight polymeric materials. The use of polymeric material reduces the cost of tools. Moreover, the standardization of tools allow product changeability by using standard tools for a wide range of products. In addition to product changeability, Schiller et al. [112] identified mass reduction as an increasing requirement of the future. The hybrid tools are light weight and significantly reduced in size as compared to the conventional tools. Hence, the futuristic requirement of mass reduction is also addressed by the hybrid tools. The enhanced cost effectiveness and lightweight of the hybrid tools is obtained due to the presence of substantial polymeric material in the tool geometry.

The degree of cost effectiveness and lightweight performance depends on the volume percentage of the polymeric material in the tool geometry. A high percentage of the polymeric material will bring high cost effectiveness and enhanced light weight and vice versa.

One of the disadvantage of the polymeric materials is the high rate of wear and low wear resistance as compared to steels (Chapter 6 - Table 6.4: calculations conducted according to Archards equation). It is also highlighted in the literature review that, in comparison to metals and alloys, the polymers have significantly high rate of wear and low wear resistance [195]. The increased wear of a polymeric materials do not affect the tool performance in case of fewer operation cycles (or lower batch sizes) [196]. However, if the operation cycles are increased (as in the case of large batch sizes), the increased wear of tool material is likely to adversely affect the tool operation and production process. Therefore, the manufacturing tools consisting of polymeric materials are not considered suitable for high (or medium) batch size productions. On the other hand, material wear is not considered as a limiting factor for small batch productions [197].

In nutshell, the hybrid tools consisting of substantial volume of polymeric materials are suitable for low batch productions because of cost effectiveness in terms of product changeability and customization. On the other hand, the hybrid tools are not recommended to be used for large batch sized productions due to increased rate of wear in polymeric materials. A high material wear is likely to affect the tool performance for large number of operation cycles.

12.2 Light weight tools for futuristic production setups

The light weight tools are foreseen as a critical requirement of the modern manufacturing factories [198]. In the modern manufacturing setups, collaborative robots (commonly known as cobots) are envisioned to execute the manufacturing processes without human intervention on workshop floor [199]. The cobots are foreseen to place and fix the tools on the manufacturing machines. In this regard, the weight of a tool is envisaged to be critically important in these futuristic manufacturing setups. In case of hybrid tools, the use of a polymeric material decreases the weight of the tool to a considerable extent. In this research thesis, the total weight of a hybrid tool set and conventional tool set is shown in Table 10.2. The tool set consists of five fundamental tools (i.e., bend die, clamp die-outer, clamp die-inner, pressure die and wiper die). The total weight of the tool set is:

- (a) Total weight of the hybrid tool set = 2.15 kg.
- (b) Total weight of the conventional metallic tool set = 15.19 kg.

Hence, due to the light weight, the hybrid tools are envisioned to be suitable for use in futuristic production setups as the light weight tools can be easily handled by cobots. Comparatively smaller cobots with lesser energy consumption will be able to handle and place the lightweight tools on the manufacturing machines.

12.3 Hybrid tools for cold form processes

In comparison to steels, the polymers have significantly low melting temperatures [200]. In general, the melting temperature of tool steels ranges around $1400 \pm 50^\circ\text{C}$ whereas the polymeric material PLA melts around at $150 \pm 20^\circ\text{C}$ [201] & [202]. The significantly low melting temperatures of polymeric materials do not allow polymers to be used in high temperature forming operations. Hence, the polymers can only be used in cold form operations conducted at room temperatures. The RDB process is a cold form bending process in which metal tubes are not recrystallized by temperature variations. Rather, the metal microstructure deforms plastically below the recrystallization temperature. The contact forces between the tube and the tool surfaces are used to conduct the tube bending without any significant temperature variations. This research thesis proposes the design and development of the hybrid tools according to the requirements of a RDB process. In a RDB process, the process temperature remains close to the ambient temperature therefore the slight variations in temperature do not affect the tool performance. On the other hand, a tube bending operation in a RDB process is primarily conducted by the application of contact forces on the tool surfaces. Keeping this in view, the quantification of contact forces and pressure development on the tool surface is critically important for accurate process execution.

12.4 Pressure mapping through sensors

The digital twin of RDB process showed that, in case of circular profile of conventional tools, the contact pressure on tool surfaces do not show a homogenous pattern. Due to the process kinematics, the contact pressure pattern changes with the change in bending angle (α) [113]. A phenomenological outcome is identified from the investigations conducted in this doctoral thesis i.e., the development of contact pressure is comparatively high at the centre and fringes of a semi-circular tool profile. Hence, in case of circular geometry of tools, the contact pressure is not uniformly distributed rather it is focused towards the centre and edges of the circular geometry. In order to validate this phenomenological identification, a 'Pressure Mapping' experimental test is performed using physical contact pressure measurement sensors. The pressure mapping examination consists of following steps:

Step 1: CAD modelling and FE-simulation of the examination setup

A simple examination setup is modelled using FEM. The model consist of a metallic circular tube placed between two opposite conventional metallic tools. The lower tool is static where as a uniform force of 20 kN is applied on the top surface of the upper tool. The model is developed by feeding relevant material properties of the material of conventional tools (EN 1.2363 or X100CrMoV5) and material the tube (Stainless Steel EN 1.4301). The model of the examination setup is shown in Figure 12.1(b). In the setup, the force is transmitted from the upper tool to the tube and the tube transmits the force on the lower tool. The simulation of the force transmission is conducted in FE-solver software PAMSTAMP using dynamic simulation mode. In the dynamic simulation, the inertia of the tools and the tube is considered during the process. This allows incorporation of minor vibrations and fluctuations in lateral and horizontal direction. The force is applied in vertical direction therefore the kinematics occurring in vertical direction are already covered. The dynamic simulation model considers small vibrations during

the process therefore simulation results are considerably accurate and they correspond substantially with the practical process. However, following aspects cannot be covered by the FE simulation setup:

- a. In FE-simulations, the tube and tool geometries are perfect circular geometries. That is why they are homogeneously aligned and completely mated with each other during the process. However in practical setups, the physically manufactured tube and circular tools are not perfect circular geometries. Therefore, the tube and the tool surfaces are not perfectly aligned and mated with each other.
- b. In FE-simulations, the microstructure of the tool and tube material is uniformly built with homogenous lattice structure. In actual (practically manufactured) tools and tubes, the microstructure is not 100% homogenous and slight deviations exist in the lattice structure of the actual material.

Step 2: Practical setup of pressure mapping using sensors

A practical setup of pressure mapping is established by using a pressure measurement sensor sheet. The Tekscan pressure measurement sensor sheet is a specialized measurement thin foil consisting of piezoresistive sensors which can detect force and pressure acting on the surface of the sheet foil [158]. The practical setup is established by placing metallic tube made from stainless steel (EN 1.4301) between two opposite semi-circular tools made from tool steel (EN 1.2363). The tools and the tube are placed on the lower jaw of universal testing machine and a force is applied on the top surface of the upper tool through upper jaw of the universal testing machine. The setup is identical to the FE-simulation setup. In the practical setup, the Tekscan scan sensor sheet (I-scan 5051) is placed in-between metallic tube and the mating surface of the lower tool. The sensor sheet detects the pressure exerted by the metallic tube on the surface of the sensor sheet placed on the top of semi-circular geometry of lower tool as shown in Figure 12.1(a).

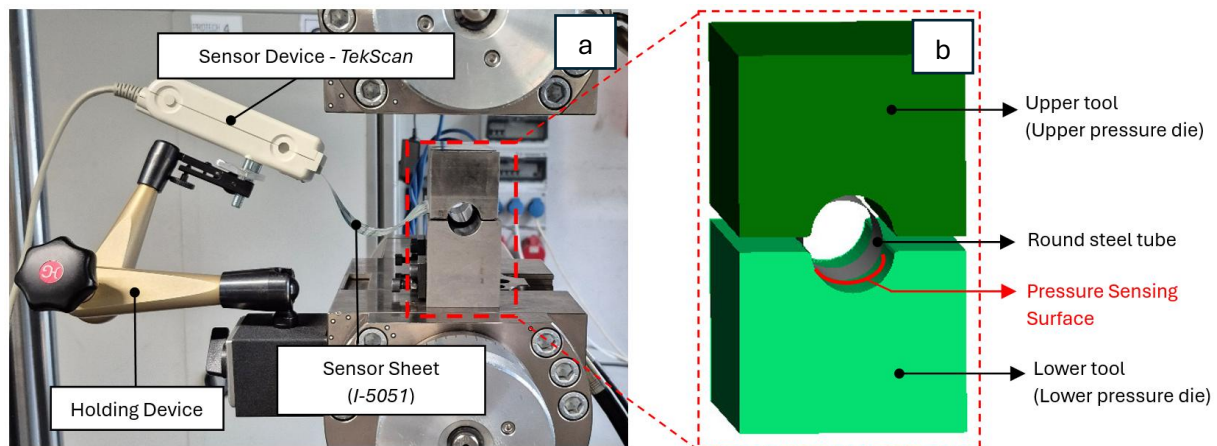


Figure 12.1(a & b): Experimental setup consisting of steel tube placed in between upper and lower metal tools (a) Practical setup (b) FE-simulation model

Step 3: Comparison between results from physical sensor and FE simulation

The magnitude of contact pressure at the surface of lower tool is shown in Figure 12.2(a). It can be seen that substantial agreement exist between FE-simulation and practically measured pressure. In order to identify that which tool surface areas received higher pressure, a comparison of the contact pressure pattern on tool surface is investigated. FE-simulation model provides the pattern and magnitude of contact pressure which tube exerts on the lower tube as shown in Figure 12.2 (b-1). This pattern and magnitude of contact surface pressure is compared with the pressure pattern obtained from practical measurements through sensor sheet. The contact pressure pattern detected on the surface of the sensor sheet is shown in Figure 12.2 (b-2).

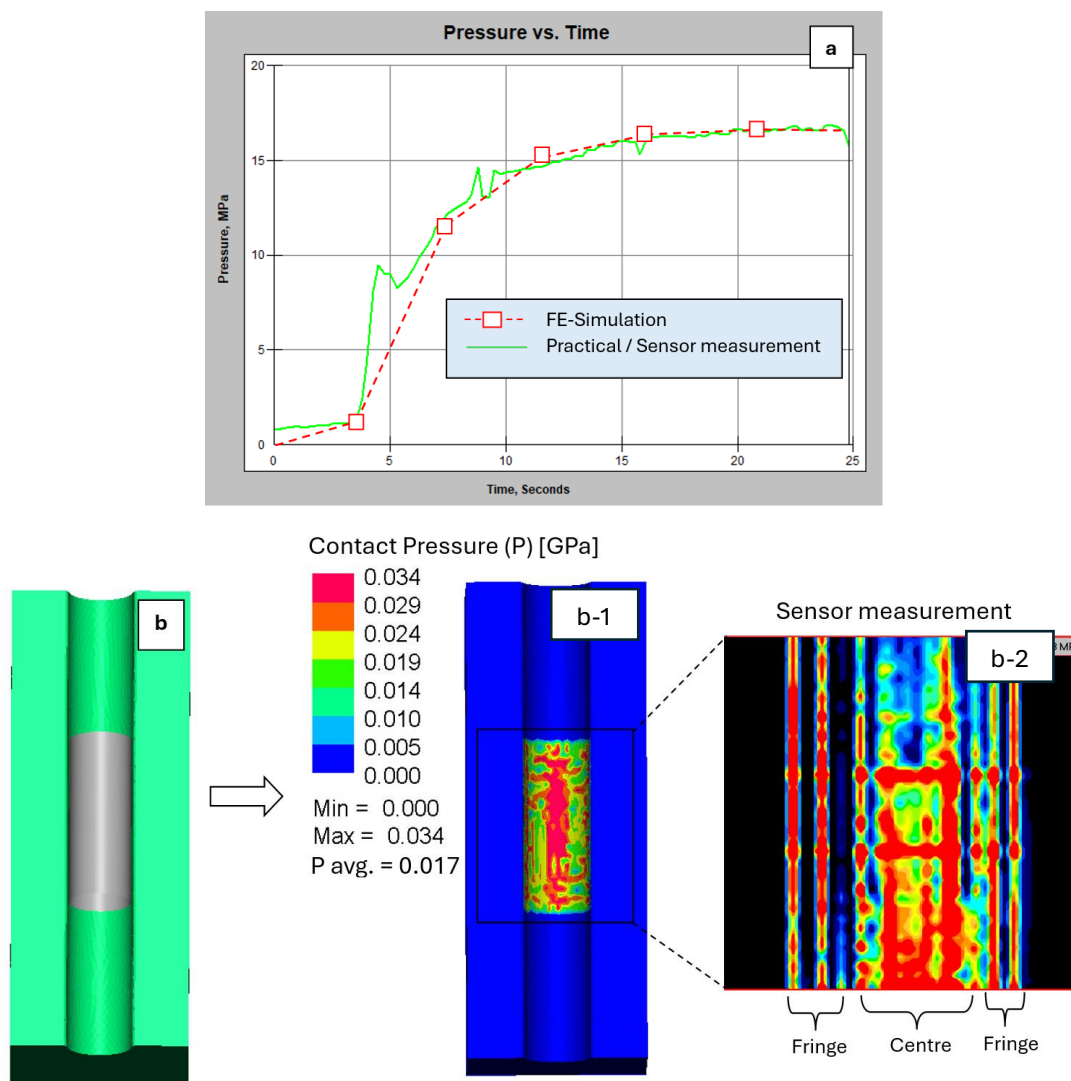


Figure 12.2(a). The magnitude of pressure development on the tool surface (b). The pattern of contact pressure on tool surface (b-1) pressure pattern obtained from FE-simulation and (b-2) pressure pattern obtained from practical measurement through sensor sheet (Tekscan I-scan 5051)

It can be seen that substantial agreement exist between the pressure pattern obtained from FE-simulation and practical measurements. Both (FE-simulation and practical measurements) show that the

pressure exerted by the tube onto tool surface is non-uniform. At certain areas, the pressure is greater whereas at other patches the pressure is considerably lower. From Figure 12.2 (b-1 & b-2), it can be seen that the high pressure areas are developed in the centre and edges of the sensed area. These areas represent the centre and side areas of the semi-circular geometry of the lower tool surface. The contact pressure pattern at the tool surface provided by the practical sensors and the FE-simulation is significantly similar. However, the pressure pattern is not completely identical. The small in-similarity is attributed to aforementioned points mentioned in this section (Step1: a & b). The Tekscan sensor sheet provides contact pressure measurement in terms of pressure peaks. These peaks are shown in Figure 12.3. It can be seen from the practical measurement shown in Figure 12.3 that high pressure peaks are developed in the centre of the sensor sheet (centre of the semi-circular tool geometry) and fringes (sides of the semi-circular tool geometry).

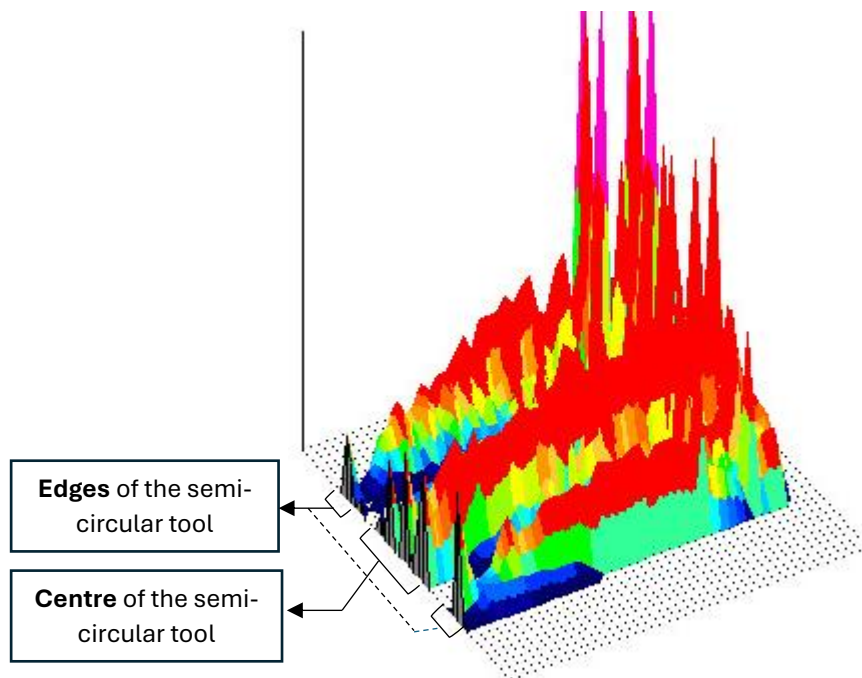


Figure 12.3. Practical measurements of contact pressure peaks on piezoresistive sensor sheet Tekscan I-scan 5051. The investigation shows that high pressure peaks are located at the centre and edges of the sensor sheet

A general deduction obtained from this investigation is that the central areas of the semi-circular geometry are under high influence of contact pressure. In addition, the side areas at the edges of semi-circle tool also experience high contact pressure. However, the surface areas in between centre areas and side edges experience comparatively lesser surface pressure. The reason of higher pressure development at the centre and edges is that circular tube tends to deform its shape and tries to become oval in vertical and lateral directions. Due to this tendency to acquire ovality, a comparatively larger pressure is exerted at the centre and edges of the semi-circular tool geometry. The overall transmission of pressure from tube onto semi-circular tool surface is shown in Figure 12.4. It is highlighted that this investigation is conducted at one particular position in which tube is static at the tool surface. In case of RDB processes,

the tube slides laterally on the tube surface and therefore the pressure pattern on the tool surfaces change correspondingly.

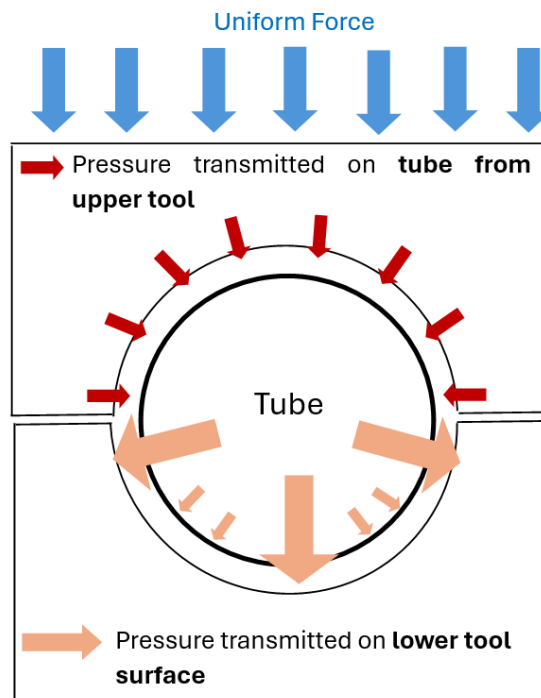


Figure 12.4. Transmission of pressure from tube onto tool surface. The pressure is not transmitted uniformly rather comparatively higher pressure is directed towards centre and fringes of the tool surface

12.5 Data driven modelling for faster computations

This research thesis presented a novel design concept in which hybrid tools are designed by using digital twin of the RDB process. The development of a comprehensive digital twin model of the RDB process require extensive computation of the FE-simulation model. These computations take substantially long time to complete the simulation. Moreover, cluster based simulation setups are generally required to compete the process simulation of digital twin [203]. The under investigated FE-simulation of the digital twin of a RDB process took almost 88 hours (3.6 days) to complete the simulation at the OMNI-Cluster installed at the Institute of Forming Technology (UTS) at the university of Siegen. In industrial setups, such large computation resources are not available. Therefore, following restrictions are encountered in the industrial setups:

- (a) The long simulation times (for example 2 to 3 days) are not acceptable because manufacturers want to design the tools as soon as possible and production machines cannot be kept waiting for the design process. Moreover, the requirement of customized tools require faster production of tools in small batches for which manufacturers are required to fabricate the tools as quickly as possible. Essentially, time is required to be saved in the design process and FE-simulation is required to be completed in 1-2 hours.

- (b) The elaborate simulation equipment like computation clusters (for example OMNI-Cluster) are only available in the academic setups. These setups cannot be maintained at industrial level specially small and medium size enterprises (SMEs). Therefore, a simpler computation strategy is required in which a single computer can complete the FE-simulation of the digital twin.

12.5.1 Strategy of faster computations of FE-simulation

A comprehensive digital twin of the RDB process executes the complete tube bending process with actual environmental conditions and process parameters. In the forming simulations, the inertia of the solid objects is taken into account which is computed by complex mathematical computations involving partial differential equations (PDEs) and fast Fourier Transformations [204]. These computations take substantially long time to execute the simulation process as they compute precise process kinematics of tools, tube and bending apparatus [205]. The time of simulation is also dependent on the meshing strategy of the digital twin model. A large number of finite elements with smaller mesh sizes require high computation time and vice versa [206]. Therefore, it is essentially important to investigate that at which mesh size the results of the simulation converge. In tube bending simulation involving curves surfaces, generally the simulation results converge at smaller mesh sizes. Literature review suggests that for RDB process, meshing converge at a mesh size < 2.0 mm [13]. Heftrich et al. [14] conducted FE-simulation of the RDB process. He highlighted that the results of the simulation converge at a mesh size of 1.0 mm. For these smaller mesh sizes, FE-simulation model consisting of solid elements require substantially higher simulation times.

In contrast to the comprehensive forming simulations involving solid object's inertia, a static analysis of the FE-simulation model can provide substantially accurate results at much faster speed of computations. The static analysis do not incorporate inertia of solid objects and vibrations of the tool or tube are not considered. Therefore, fast Fourier Transformations are not computed during the static simulation process [207]. However, static analysis require exact quantification of loads (Force and Pressure) during the forming process alongwith process constraints and material properties [208]. Here, a computation strategy based on the available (and gathered) data from FE-simulations is devised which allows faster computations to investigate tool performance in RDB process using static FEA. In the faster computation strategy, a database of contact forces (F_{CN}) is maintained. This database will be made through simulation of comprehensive digital twin of the RDB process at each process parameters (bending factor and wall factor). The contact forces obtained from comprehensive simulations will be stored in the databank and these forces will be used to investigate tool performances through static FEA. The strategy of faster computation of tool performance is termed here as data driven modelling of tools in RDB process. The data driven modelling of tools in RDB process is demonstrated by a test case scenario in proceeding sections.

12.5.2 Test case of data driven modelling of hybrid pressure die

In this section, a test case of tool performance of a hybrid tool (hybrid pressure die) is presented. A CAD model of the hybrid pressure die is first tested in the comprehensive digital twin model of the RDB process. The contact forces acting on the hybrid pressure die are obtained from the digital twin. These contact forces are applied on the CAD of the hybrid pressure die in static simulation analysis. The results of tool performance (von-Mises stress and tool surface displacement) are obtained from static analysis. These results are compared with the results obtained from comprehensive digital twin. It will be demonstrated that the tool performance results obtained from static analysis are similar as the results of the comprehensive digital twin. It will be shown that the simulation time of static analysis is substantially less than the simulation time of comprehensive digital twin. The comparison of computation time of simulations of static analysis and comprehensive digital twin are highlighted in succeeding sections.

12.5.2.1 Tool Performance of hybrid pressure die in comprehensive digital twin of the RDB process

The digital twin model of the RDB process is shown in Chapter 11- Figure 11.7(a). The meshing of the hybrid pressure die in the digital twin is done with global meshing method at a mesh size of 1.00 mm. The process parameters and the material properties of the digital twin model are presented in Table 12.1. The process conditions consisting of machine constraints and bending kinematics are applied according to the actual RDB process conducted on a WAFIO's machine (For details of actual process conditions please see chapter 9, Figure 9.2 & Figure 9.3).

Table 12.1: Process parameters and material properties of hybrid pressure die used in digital twin of the RDB process

Process Parameters / Process Conditions		Material properties		
		Property	Polymer (PLA)	Steel (EN 1.4301)
Bending Factor (B)	1.5			
Wall Factor (W)	22	Young's Modulus	2.75 GPa	210 GPa
Tube thickness (mm)	1.00	Yield strength	72 MPa	550 MPa
Bending Angle (α)	0 - 90 ⁰	Density	1.24 g/cm ³	7.8 g/cm ³
Pd Mode	Static	Poisson's ratio	0.35	0.3
Tube velocity	$V_{\text{tube}}/V_{\text{collet}}=1$	Coefficient of friction (μ)	0.3	0.1
Pd clearance	< 0.4 mm			

The design of hybrid tools is made on the basis of two significant outcomes of the tool performance : i) von-Mises stress developed within the tool geometry and ii) surface displacement of the metal slabs fixed at the surfaces of the hybrid pressure die. The results of these two outcomes obtained from the comprehensive FE-simulation of the digital twin model of the RDB process are shown in Figure 12.5.

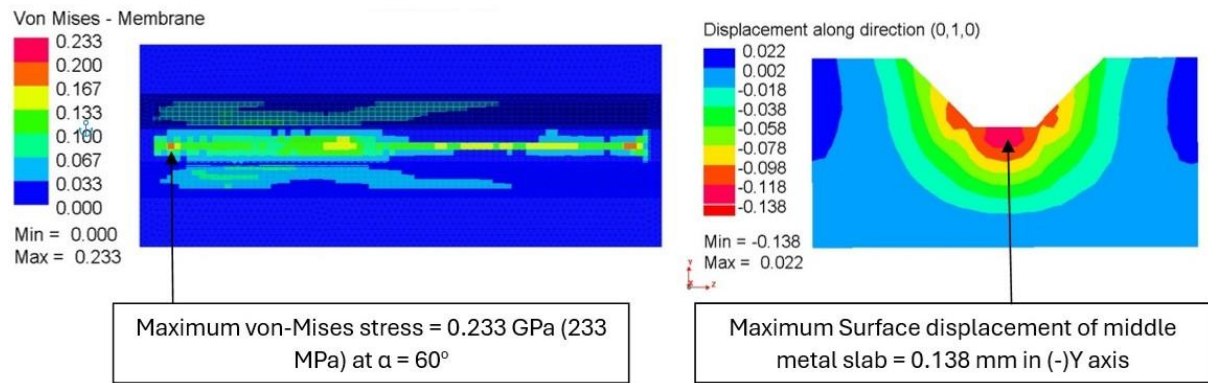


Figure 12.5. Tool performance results (von-Mises stress and vertical surface displacement) obtained from comprehensive digital twin of the RDB process

The simulation time of the comprehensive digital twin was almost 88 hours (3.6 days) with total number of 172050 finite volume elements and 271129 edge elements computed at a mesh size of 1.00 mm with global meshing method. The contact force acting on the hybrid pressure die during the RDB process is shown in Figure 12.6. It can be seen that a maximum contact force of 18 kN is developed at the surface of the hybrid pressure die at $\alpha = 80^\circ$. This contact force is used to conduct the static FEA of the tool performance of hybrid pressure die in RDB process.

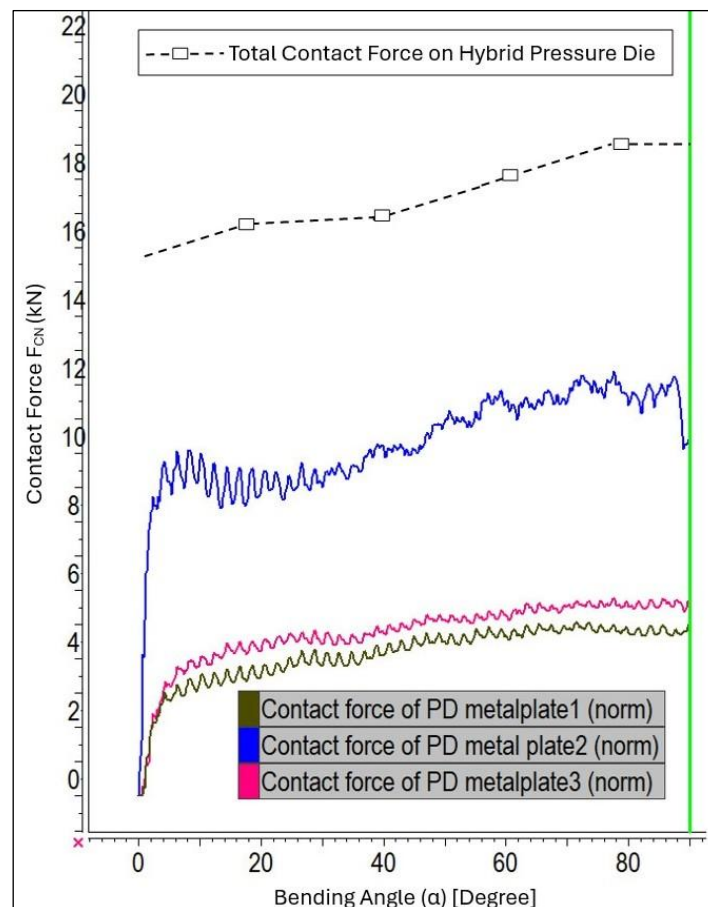


Figure 12.6. Contact Force (F_{CN}) acting on the surface of hybrid pressure die ($\alpha = 0^\circ$ to 90°). A maximum of $F_{CN} = 18\text{kN}$ is developed at bending angle $\alpha = 80^\circ$

12.5.2.2 Tool Performance of hybrid pressure die with static FEA

In the static stress FEA, a force $F_{CN} = 18$ kN is applied on the surfaces of the hybrid pressure die. The tool material and mechanical properties are kept exactly the same as fed to the comprehensive digital twin of RDB process. The constraints are imposed according to the practical machine. The results obtained from the static FEA are shown in Figure 12.7.

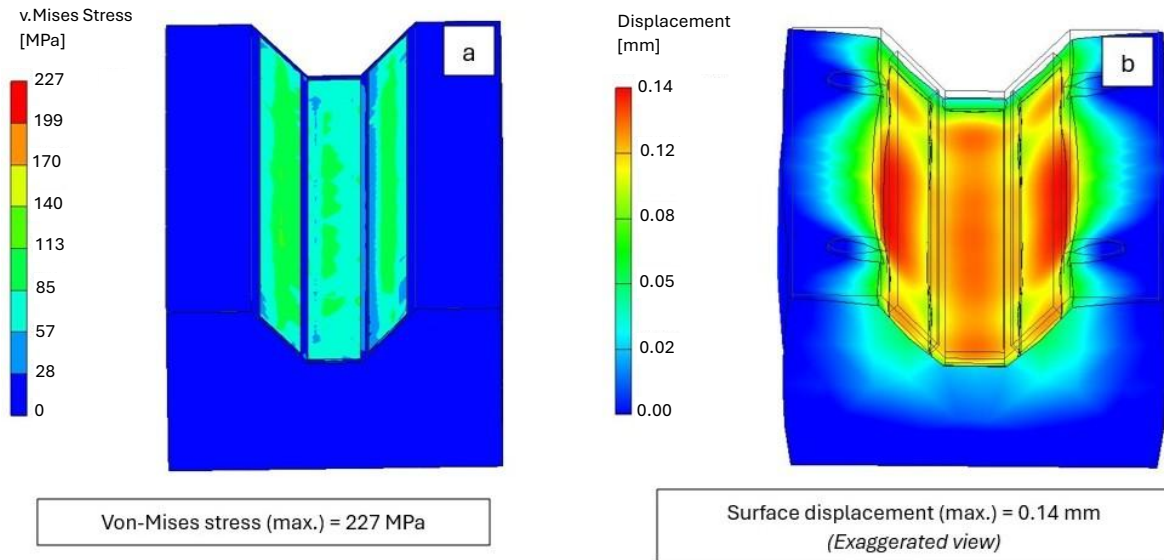


Figure 12.7. (a) The von-mises stress (max.) of 227 MPa is obtained by applying a force $F_{CN} = 18$ kN in the static analysis. (b) A maximum surface displacement of 0.14 mm is obtained at force $F_{CN} = 18$ kN in the static FEA.

11.5.2.3 Comparison of results and simulation time

The FE-simulation results (von-Mises stress and tool surface displacement) obtained from the comprehensive digital twin are accurate as they are already verified by the accuracy meter (details mentioned in chapter # 9). In this section, the results obtained from comprehensive digital twin and static FEA are compared. The FE-simulation of the comprehensive digital twin is conducted in the specialized forming software PAMSTAMP and the static FEA is conducted in the CAD Modelling software Autodesk INVENTOR. It can be seen that the results (von-Mises stress and tool surface displacement) of both the simulation regimes are substantially close to each other as shown in Figure 12.8. The results are significantly close, yet a substantial difference in the simulation time is manifested. The simulation time of the comprehensive digital twin = 88 hours whereas the simulation time of the static FEA is only 30 minutes. It has been demonstrated that, with the availability of the database of contact forces (F_{CN} developed at the tool surface at particular process parameters), the results of tool performance in RDB process can be obtained very quickly through static FEA.

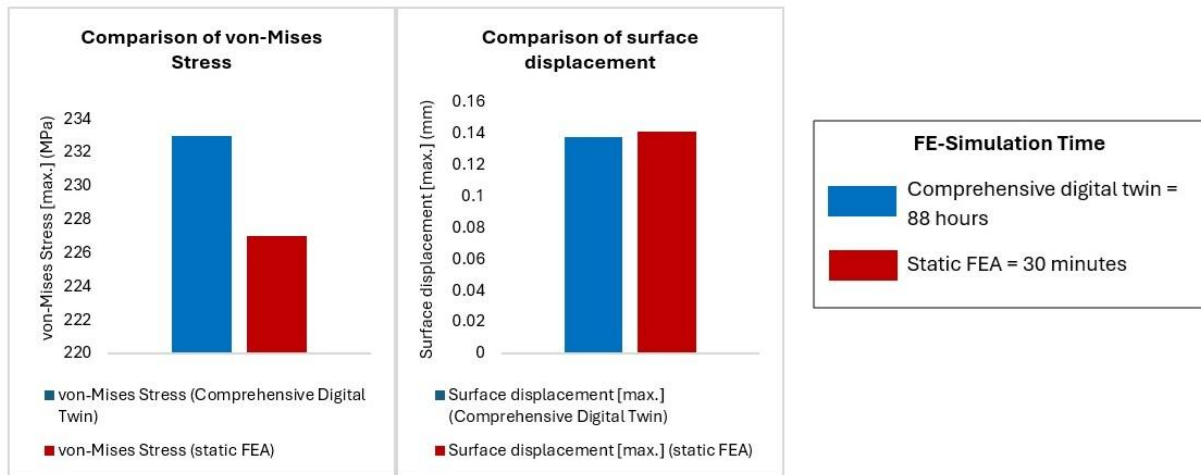


Figure 12.8: Comparison of FE-simulation results (von-Mises stress and tool surface displacement) between simulations conducted with comprehensive digital twin and static FEA. In case of static FEA, the contact forces obtained from comprehensive digital twin are used as the input. The investigation shows that: if database of contact forces is established for a large set of different process parameters, then the tool performances can be obtained in significantly shorter time using static FEA.

The investigations conducted in this section presents a computation strategy in which tool performances can be obtained in significantly shorter time as compared to the comprehensive simulations conducted by the digital twin of RDB process. The block diagram of computation strategy (data driven modelling for faster computations) is summarized in the form of a block diagram and mentioned in Annex-1 to this doctoral thesis. This strategy can be considered as an outlook for conducting future investigations. The strategy requires development of a database of contact forces at different process parameters. After development of the requisite database, this strategy can be used to obtain tool performances in a significantly shorter time.

Chapter 13: Conclusion

Rotary draw bending (RDB) is a cold form bending process which is widely used for profile bending of metal tubes. Presently, the bending tools used in RDB process have fixed geometries which means that they can be used to bend tubes of one specific diameter. These conventional tools are bulky and possess semi-circular cross section at the mating surfaces. Due to the fixed geometrical design of bending tools, RDB process is considered to be inflexible because multiple tube diameters cannot be used with one tool set. In addition to the limitation of in-flexibility, the challenge of incorporating cost effectiveness in production processes has grown more than ever before. Moreover, the futuristic manufacturing setups are foreseen to be dominated by cobots and light weight tools are considered compatible for handling by the cobots. Keeping in view these challenges (process inflexibility, tool cost effectiveness and light weight design of tools), additive manufacturing (AM of 3D printing) processes offer significant advantages which can be adroitly used and exploited. A fundamental advantage of AM processes is their ability to fabricate complex geometrical shapes. This advantage is specifically important for low batch and customized productions where individual products are required to be manufactured. In this doctoral thesis, AM is effectively used to fabricate complex geometrical designs of bending tools that are capable of conducting tube bending operations at a wide range of tube diameters. To make tools cost effective, topology optimization of the conventional tool design is conducted beforehand which provides information about the minimum material essentially required within the tool geometry. Hence, cost effectiveness is targeted by material saving within the tool geometry. In order to develop lightweight tools, polymeric material is used in addition to metal (steel). The tools made from a combination of polymers and steel are called here as hybrid tools. Due to the lightweight and low cost of polymeric materials, the developed hybrid tools are significantly lightweight and cost effective as compared to conventional steel tools.

In order to design hybrid tools, digital twin of the RDB process is developed by taking into consideration process parameters, material properties, tool kinematics and actual process conditions. The accuracy of the digital twin is validated by conducting a practical RDB process and comparing the tube bending results obtained from digital twin with the results obtained from practical process. After validation of digital twin, the design factors which significantly affect the tool performances are identified. The design factors are identified by using polymeric prototypes of a fundamental bending tool 'pressure die'. The polymeric pressure dies were constructed in semi-circular and V-shaped geometries and tested in the digital twin model of the RDB process. The tool performance of each geometrical shape was examined in relation to the corresponding process results. This investigation identified the design factors which are critically significant in tool performance. The identified design factors are tool material stiffness, effective area on tool surface, friction coefficients of tool material, inter-dependence of contact forces of tools, fatigue strength of tool material, process flexibility range, contact pressure enhancement (pressure localization) due to line contact and wear resistance of mated

tool surfaces. After identification of tool design factors, topology optimization of a conventional pressure die is conducted. A topology optimized pressure die (TO-Pd_p) is obtained. The TO-Pd_p is tested in the digital twin and the tool performance is evaluated. The process outcome shows that TO-Pd_p can conduct the RDB process safely without any tool defect and failure. In order to validate the results, a practical process is conducted in which tube bending is conducted by using TO-Pd_p. The practical process validated the results of FE-simulation/digital twin. After validation of the tool performance of topology optimized tool, a material reduction criterion is derived for polymeric material - PLA. This criterion identified that the tool material of conventional tool geometry can be reduced to 30% of its original volume. In parallel, numerical modelling of the tools is conducted using Ashby material model. The numerical modelling identified that the safe limit of material stiffness of bending tools is 16.2 GPa. The Ashby material model shows that the polymers which have a material stiffness < 4 GPa cannot be used as bending tools in RDB process. Therefore, a hybrid material is considered by selecting the materials from Ashby material selection charts. The hybrid material consists of stainless steel (EN 1.4301) and polymer (PLA). The stainless steel slabs are fixed at the tool surface whereas rest of tool geometry consists of polymer – PLA. The tube only come in contact with the steel slabs fixed at the tool surfaces of hybrid tools. Based on the identified tool design factors, material reduction criterion and material selection of the hybrid material, a V-shaped model of the hybrid tool (hybrid pressure die) is constructed.

The model of hybrid pressure die is imported in the digital twin of the RDB process and tube bending is simulated. The process simulation is conducted smoothly without any process failure or tool defect. In order to validate that the digital twin provides accurate tool performance results, the hybrid pressure die is practically 3D printed and tested in actual RDB process. The practical 3D printing of the hybrid pressure die encompassed two different 3D printing techniques. The polymeric base structure is 3D printed by using FFF (Fused Filament Fabrication) and the metal slabs are obtained by LMD (Laser Metal Deposition). The practically developed 3D printed hybrid tool is used in practical RDB process. The process results obtained from practical conduct of the process validates the accuracy of the digital twin. After validation of the accuracy digital twin with hybrid tool, the tool performance of the hybrid pressure die is evaluated in terms of von-Mises stress, contact forces and displacement of tool surfaces. The tool performance of hybrid pressure die is highlighted in the form of curves with respective feature vs bending angle (α). In addition to hybrid tool, the tool performance of conventional (steel) pressure die is also shown for comparison. In comparison to conventional (steel) pressure die, comparatively lesser contact forces are developed at the surfaces of hybrid pressure die. This lesser force development is attributed to the slight displacement of metallic slabs fixed at the surfaces of the hybrid pressure die. Tool performance and practical conduct showed that the hybrid tool conducted the RDB process successfully. The geometric comparison between the two tools (hybrid tool and conventional tool) showed that the weight of the hybrid pressure die is 0.41kg (volume = 265 cm³) whereas the weight of the conventional (steel) pressure die is 3.32kg (volume = 430 cm³). The cost comparison evaluated on

the basis of Ashby cost comparison index (CPI) showed that the hybrid pressure die is significantly cost effective as compared to conventional pressure die (CPI of hybrid pressure die = 8.47 and CPI of conventional metallic pressure die = 0.206). These investigations are conducted on a tube diameter of 22 mm. Next, the tube diameter is increased from 22 to 30 mm and RDB process is simulated in the digital twin by using same geometry of the hybrid pressure die. In order to keep unanimity, process parameters e.g., bending factor ($B=1.5$) and wall factor ($W=22$) are kept the same. The digital twin showed that the hybrid pressure die conducted the RDB process safely with a tube diameter of 30 mm. Hence, the range of tube diameters which can be used with hybrid pressure die is between 22mm to 30mm. In nutshell, the hybrid pressure die transformed the inflexible RDB process into partially flexible process.

The comparison of the hybrid pressure die and conventional metallic pressure die is evaluated on basis of four discrete evaluating criteria; process flexibility, cost comparison, lightweight and manufacturing time of the tool. Based on these evaluated criteria, a formula of tool design is developed. This formula is called here as 'Tool Efficiency index' (TEi). The TEi determines the tool efficiency of bending tools in RDB process on the basis of aforementioned four criteria. The developed formula shows that the TEi of conventional (steel) pressure die = 1.28 whereas the TEi of hybrid pressure die = 49.92. The TEi can be used to compare the efficiency of tools in RDB process. In addition, hybrid tool are standardized on the basis of aspect ratio. A basic aspect ratio is basic defined geometry of the tool and a size factor ' S_f ' is multiplied by the basic aspect ratio. Four size factors are defined with each size factor representing a specific range of tube diameters. The size factor ' S_f ' helps the manufacturers to select the size of the hybrid tool which is required for their bending process (for example, if the manufacturer wants to bend a tube with tube outer diameter = 26 mm, then he/she should select $S_f = 20$ which supports bending of tube diameters ranging between 22mm to 30mm).

Based on the methodology used to develop hybrid pressure die and the respective role of each bending tool in RDB process, a tool set of hybrid tools is modelled. Pressure die, clamp dies, wiper die and bend die are designed according to the novel standardized geometry of the hybrid tools consisting of hybrid material (polymer 'PLA' and stainless steel 'EN 1.4301'). Due to the requirement of circular geometry, mandrel and collet remained in conventional geometry. The hybrid tool set (consisting of hybrid bend die, hybrid clamp dies, hybrid pressure die and hybrid wiper die) is imported in the digital twin of the RDB process and bending operation of 22 mm tube is simulated. The tool performance of each hybrid tool is compared with the tool performance of respective conventional (steel) tool having erstwhile circular geometry. The tool performance is compared on the basis of surface displacement of tool surfaces, contact forces generated at tool surfaces, contact normal surface pressure and von-Mises stress developed within tool geometry. The final results showed that the hybrid tool set successfully bent the metallic tube with same precision as it was bent by conventional (steel) tool set.

The digital twin of the RDB process showed some process improvements with the use of hybrid tool set. Although the process improvements are not significantly large yet keeping in view that the

hybrid tools are designed essentially for enhanced process flexibility and cost effectiveness, these process improvements should only be considered as overhead advantages. The process improvements are:

- The tube ovality of bent tube obtained from hybrid tool set is slightly lesser than the tube ovality of conventional tool set. The maximum tube ovality provided by hybrid tool set is 4.6% whereas the tube ovality provided by the conventional tool set is 4.9% (*the tube ovality is measured according to VDI 3430*).
- The Plasto-Mechanical Model of the RDB process is a numerical model to determine neutral axis shifting of tubes in bending process [185]. The computation of neutral axis shift in the tube provided by Plasto-Mechanical Model is comparatively accurate for the case of the tube bend by using hybrid tool set. Hence, the Plasto-Mechanical Model accurately predicts the neutral axis shifting in tubes which are bent by hybrid tool sets.

Based on TEi, the tool efficiency of the hybrid tool set is computed and compared with the respective conventional (steel) tool set. It is seen that the hybrid tools have significantly high efficiency as compared to conventional tools. During the investigations conducted during design, development and testing of hybrid tools in RDB process, few requirements, pre-conditions, limitations and possible improvements are identified. These aspects are mentioned in the chapter of discussions. A pointwise summary of the discussed points is mentioned below:

- The hybrid tools substantially consist of polymeric materials therefore they are primarily foreseen for customized production. Polymers possess less wear resistance and low fatigue strength as compared to steels. For the investigated RDB process, a polymer made tool is expected to fail after 60 tube bending operations whereas conventional steel tool is foreseen to conduct unlimited bending operations. Therefore, hybrid tools consisting of polymeric material are considered suitable only for small scale, individualized or customized productions.
- The hybrid tools are significantly lightweight as compared to conventional metallic tools. The lightweight is attributed to the reduced tool geometry and lesser weight of polymer - PLA. In futuristic manufacturing setup, cobots are foreseen to handle the production processes. In such modern and futuristic setups, lightweight tools will be considered critically important as the cobots can easily handle and place lightweight tools on manufacturing machines.
- The melting temperature of polymers is significantly less as compared to steel. Therefore, hybrid tools consisting of polymers and steels can only be used in cold forming processes like rotary draw bending process. For other forming processes involving high temperatures, the hybrid tools are not recommended for usage.
- During the course of investigations, it was identified that the contact pressure exerted by a tube in RDB process is mainly directed towards the centre and fringes of the tool surfaces. This phenomenon was investigated by conducting pressure sensing using physical measurement

sensors and keeping the tube in static condition. Contact normal force is applied on the static tube and pressure transmission from tube onto tool surface is investigated. The physical measurement of contact pressure through sensors demonstrate that the circular tube geometry do not exert uniform pressure throughout circular tool surface, rather a relatively high pressure is directed towards the centre and fringes of the circular tool surface.

- The digital twin of the RDB process takes significantly large processing time which may not be viable for the industrial tool manufacturers. Keeping this in view, a strategy of data driven modelling is presented in which tool performances can be obtained with significantly shorter computation times using static FEA. The strategy encompasses development of contact force database at different process parameters and using the established database of contact forces to determine the tool performance through static FEA.

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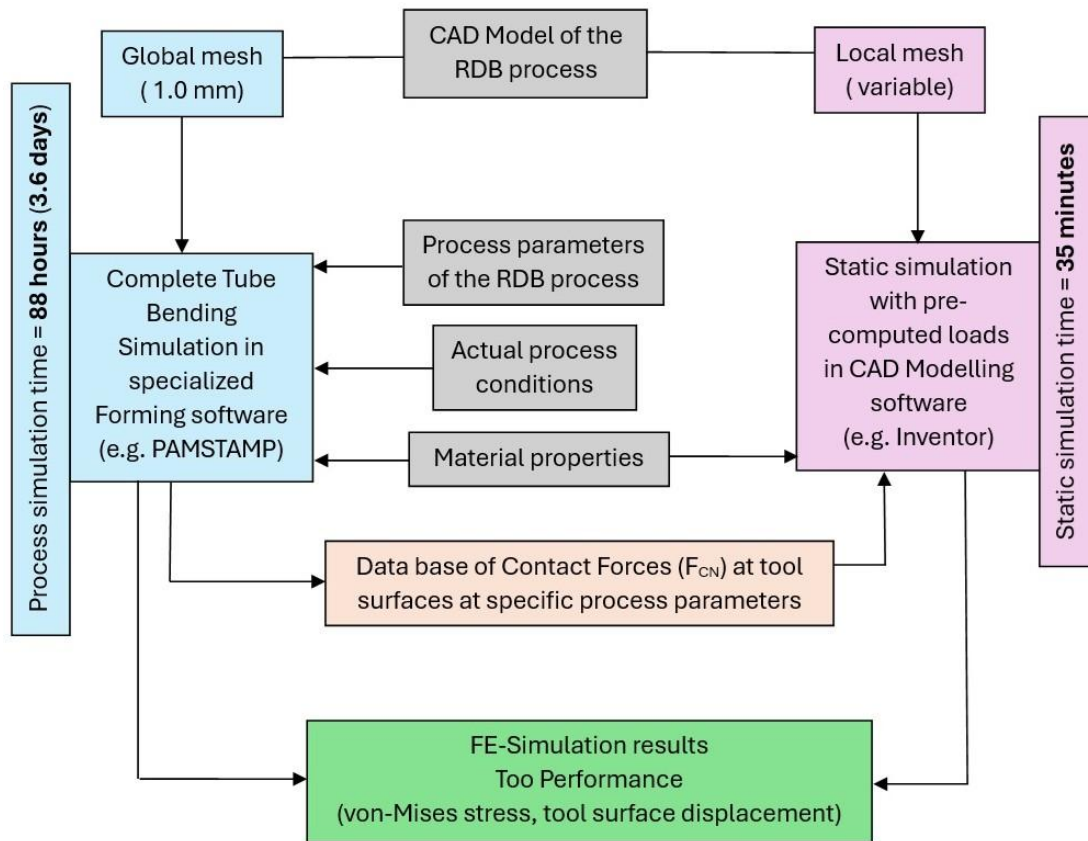
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Standards and Guidelines:

Following standards and guidelines are followed in this research thesis:

- | | |
|------------|--|
| VDI 3432 | Rotoationszugbiegemaschine, version 2019-03 Beuth Verlag GmbH, Berlin. |
| VDI 3430 | Rotary draw bending of profiles, version 2014-06, Beuth Verlag GmbH, Berlin. |
| DIN 8580 | Fertigungsverfahren Begriffe, Einteilung, version 2003-09, Beuth Verlag GmbH, Berlin. |
| DIN 8586 | FertigungsverfahrenBiegeunformun Einordnung, Unterteilung, Begriffe, version 2003-09 Beuth VerlagGmbH, Berlin. |
| DIN 604 | Mechanical properties for 3D printed polymers, version 2017-05. |
| ASTM 52900 | American society for testing materials, used for conducting laser metal deposition of sheets, version 2022-3. |
| ISO 23247 | Digital twin framework of manufacturing, version 1, 2021. |
| ASTM | Additive manufacturing, qualification principles, version 1, 2023. |

‘Framework for Data Driven Modelling To Determine Tool Performance With Shorter Computation Time’

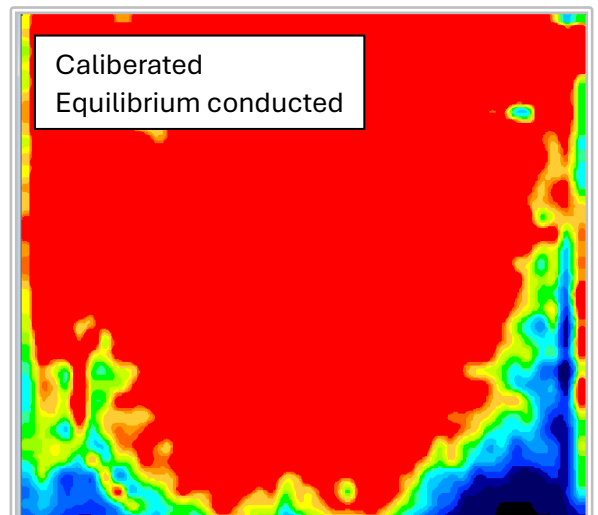
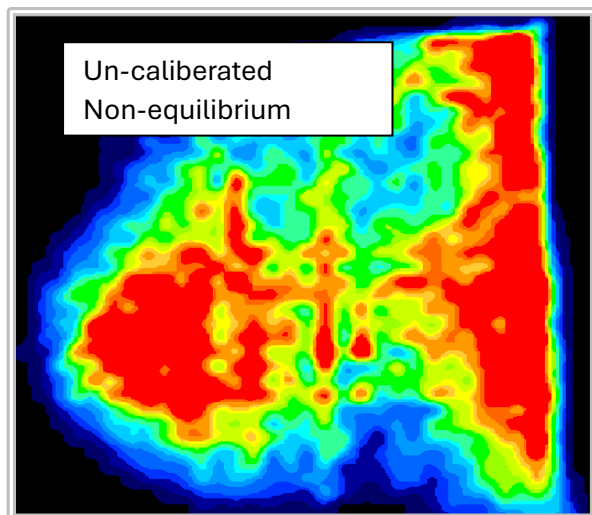
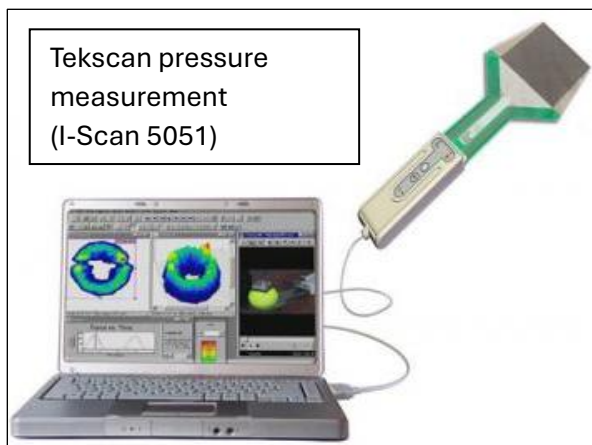


Block diagram of the proposed computation strategy which may assist manufacturers to obtain tool performance results in significantly less time. A database of Contact Forces (F_{CN}) is required to be developed. This database will be established through simulations of comprehensive digital twin of the RDB process at each process parameters (bending factor and wall factor).

Calibration and Equilibration of Tekscan (I-Scan piezoresistive sensor sheet 5051)

[Calibration pressure range 20 – 30 MPa]

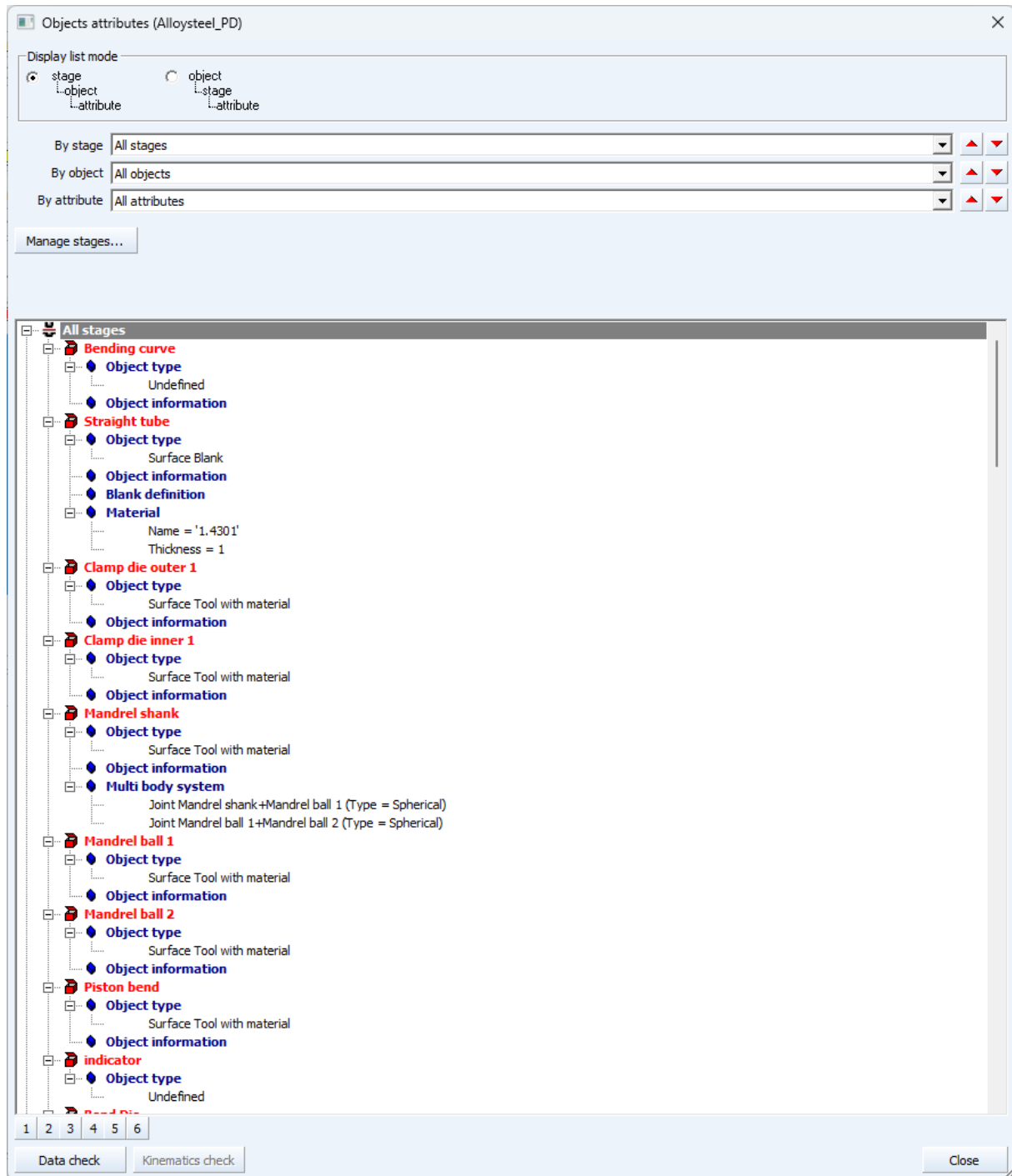
- Calibration pressure range = 20 – 30 MPa
- Equilibrium pressure = 25 MPa
- Calibration points = 3
- Measurement time = 5 secs
- Pressure fillet: Polymer square (length x width x height) = 112 x 112 x 60 mm



Programming code for development of Digital Twin of Rotary Draw Bending Process

PAMSTAMP (PAM-Tube Environment)

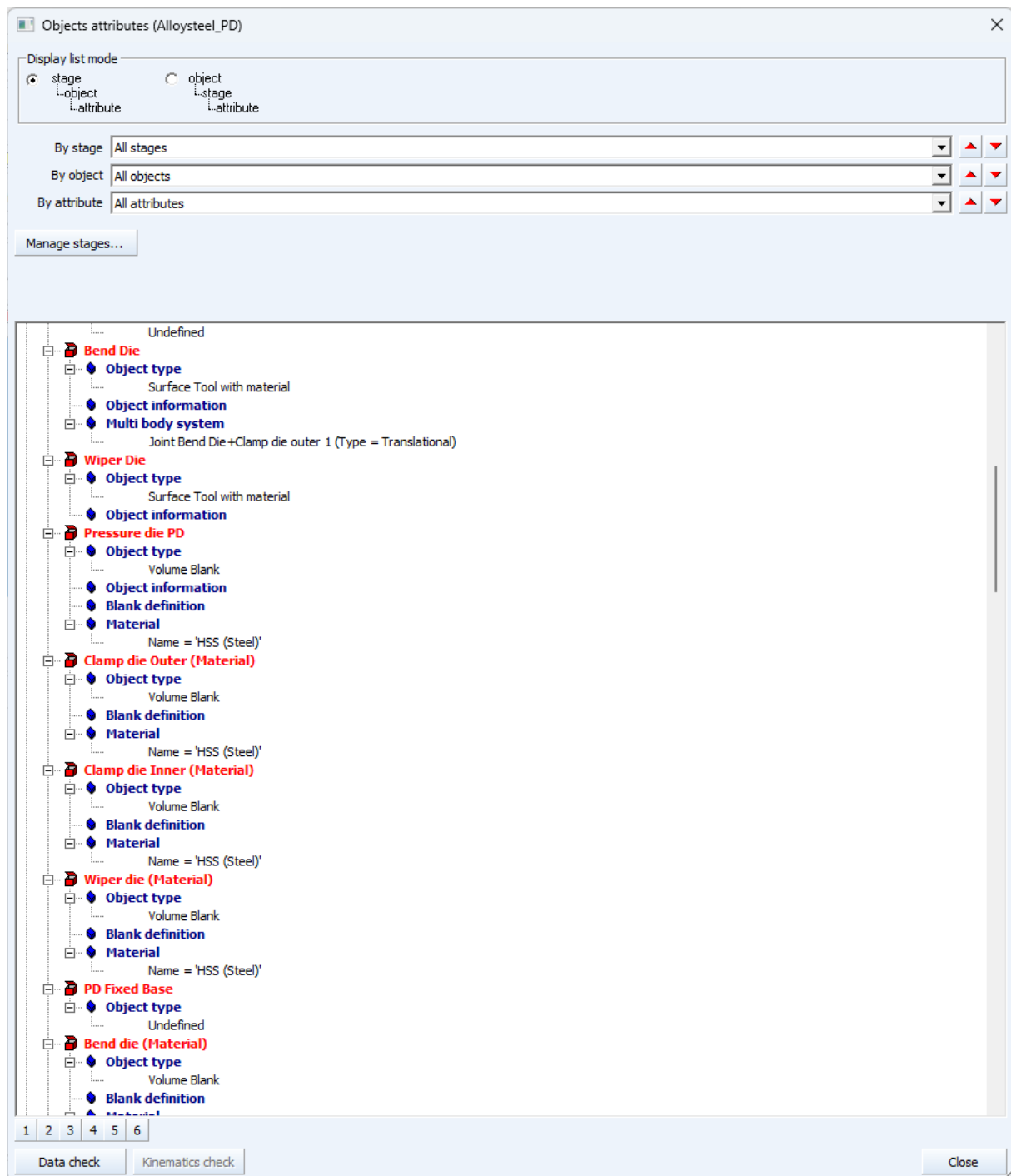
PAGE # 1



Programming code for development of Digital Twin of Rotary Draw Bending Process

PAMSTAMP (PAM-Tube Environment)

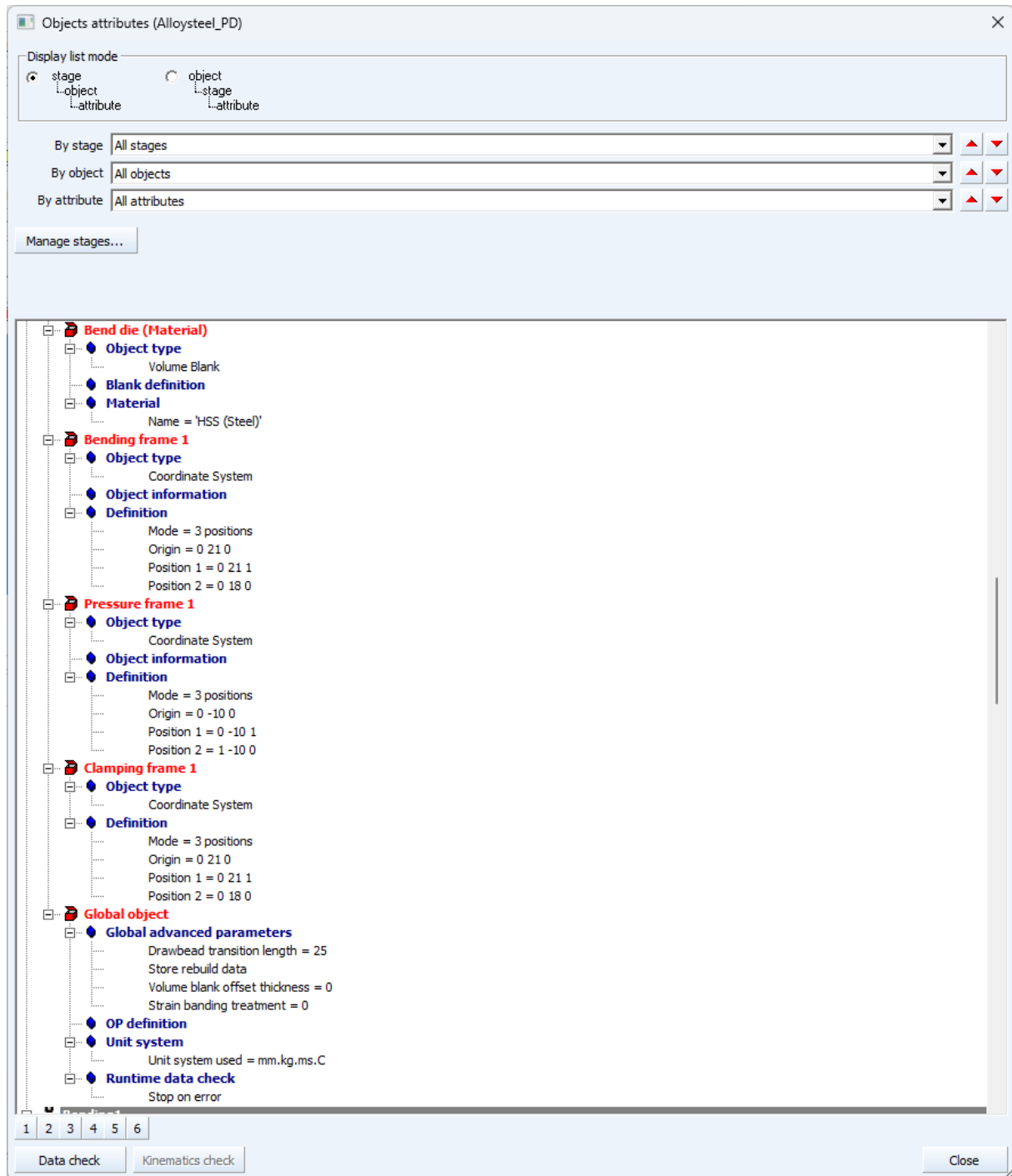
PAGE # 2



Programming code for development of Digital Twin of Rotary Draw Bending Process

PAMSTAMP (PAM-Tube Environment)

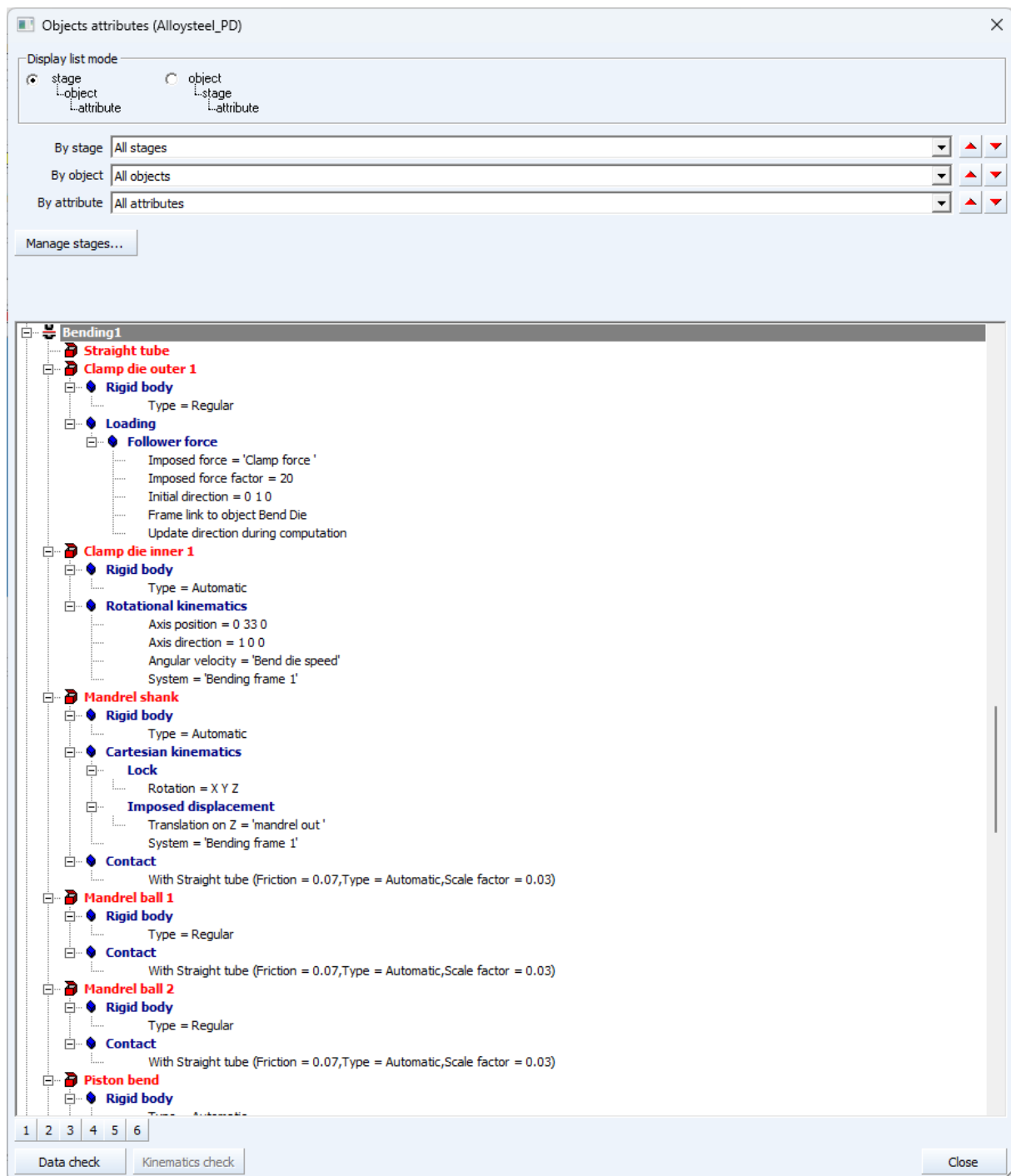
PAGE # 3



Programming code for development of Digital Twin of Rotary Draw Bending Process

PAMSTAMP (PAM-Tube Environment)

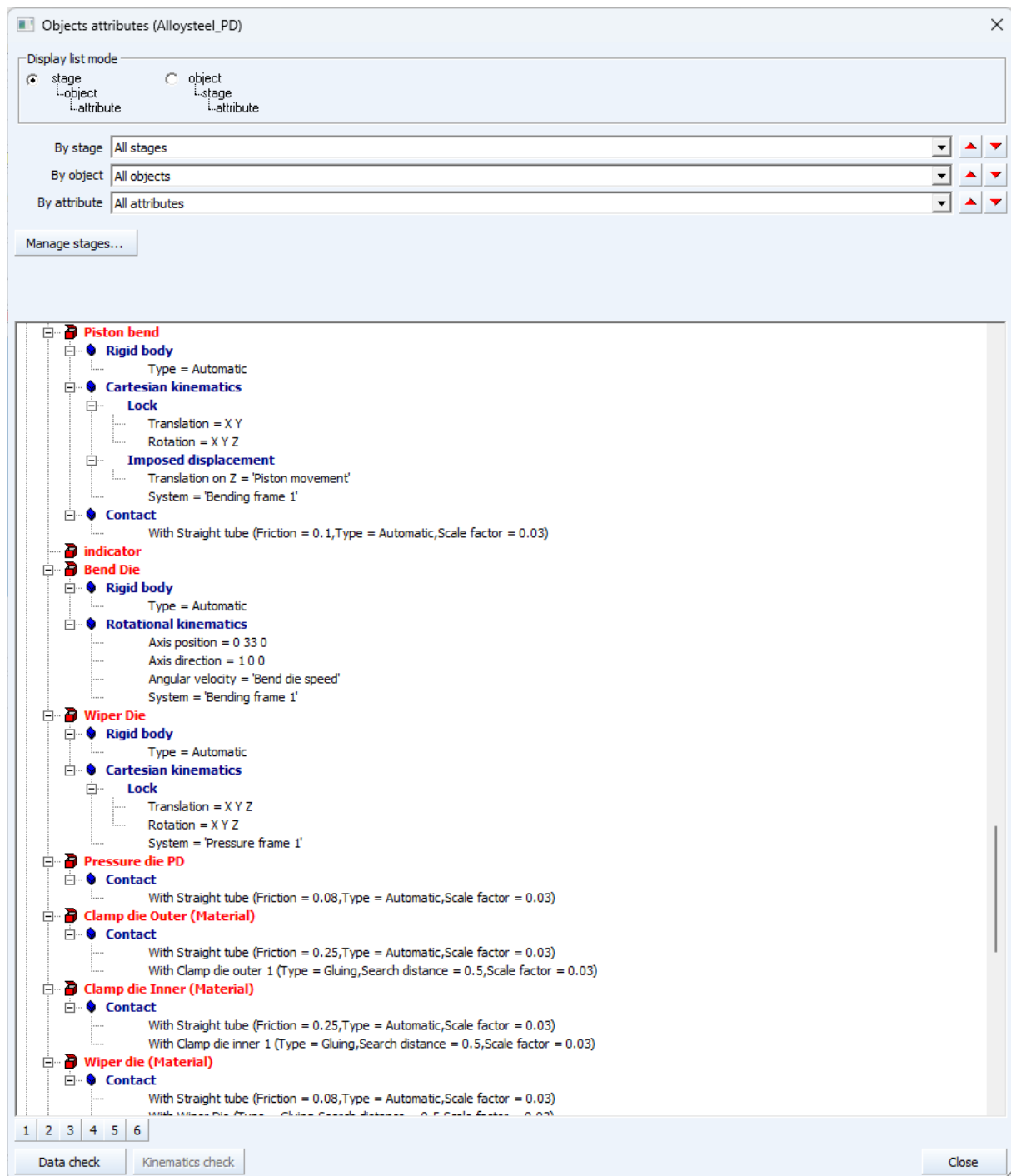
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Programming code for development of Digital Twin of Rotary Draw Bending Process

PAMSTAMP (PAM-Tube Environment)

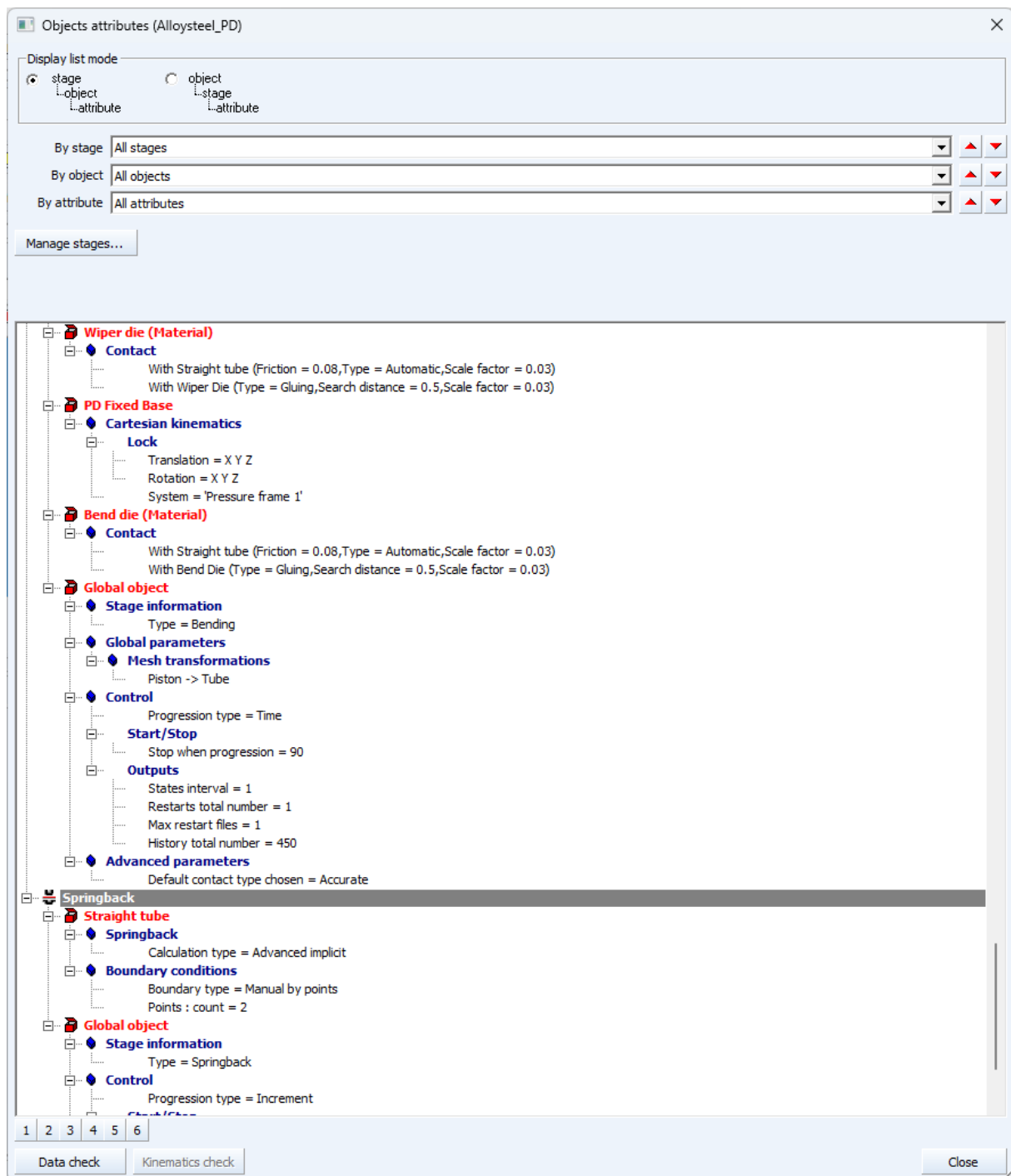
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Programming code for development of Digital Twin of Rotary Draw Bending Process

PAMSTAMP (PAM-Tube Environment)

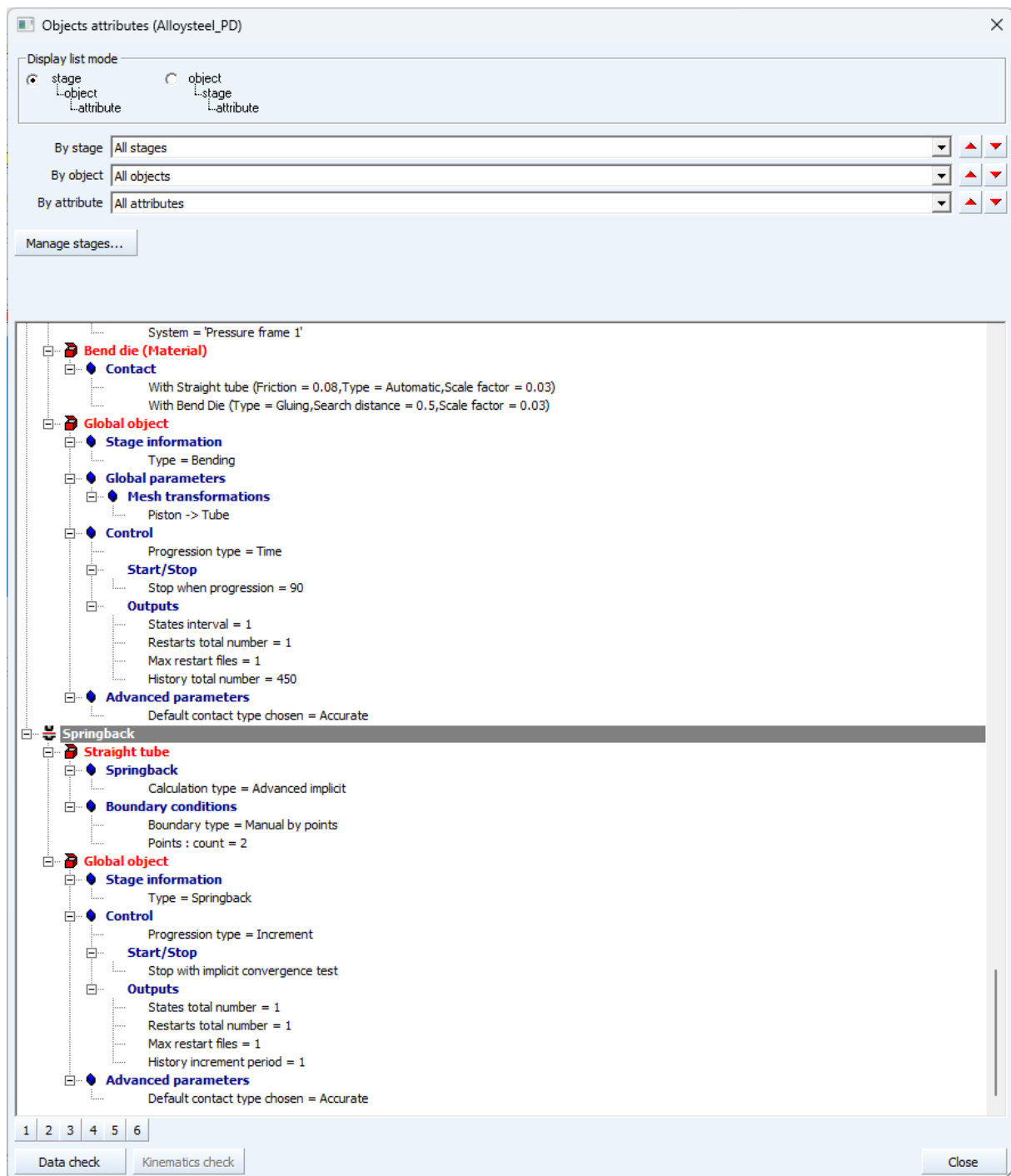
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Programming code for development of Digital Twin of Rotary Draw Bending Process

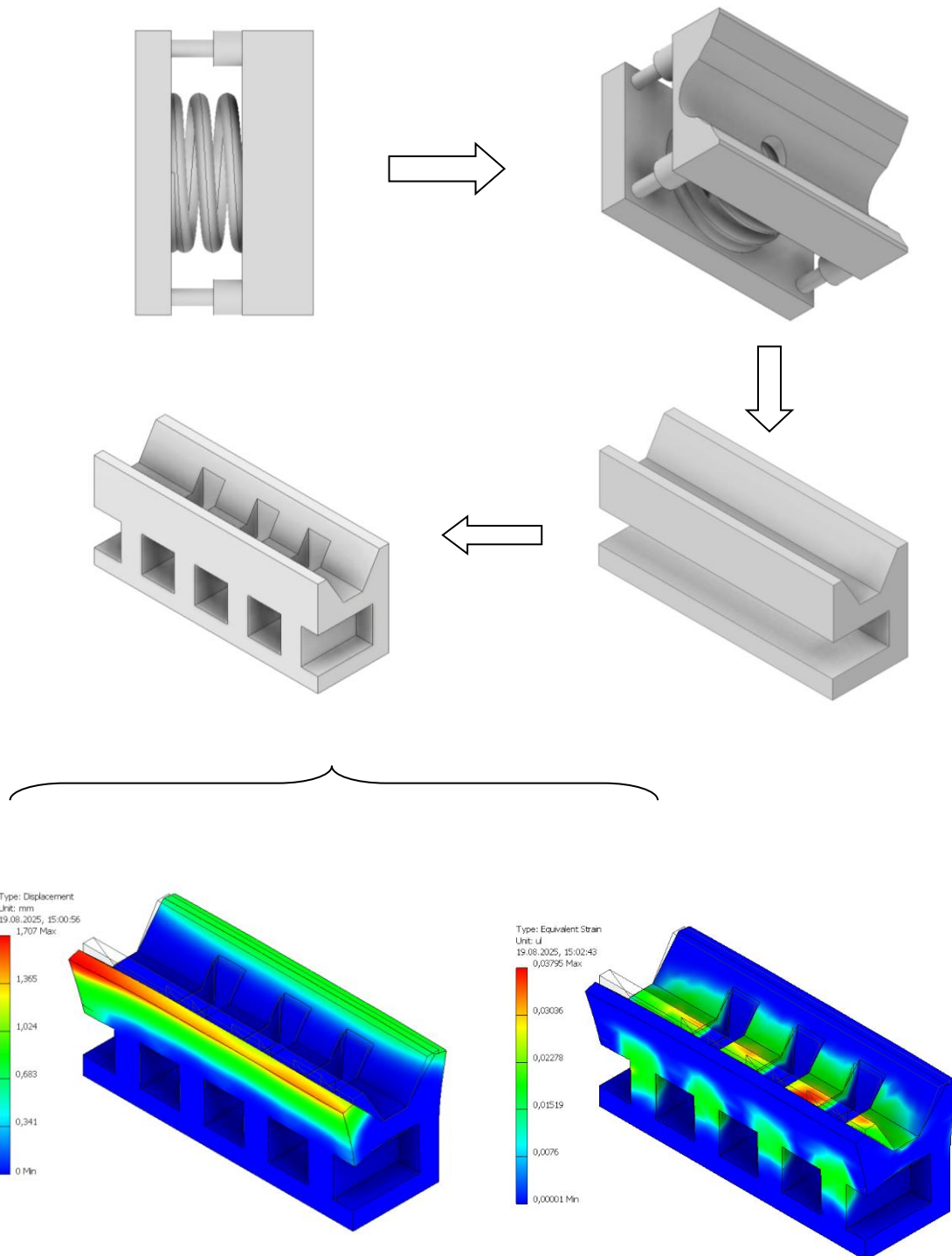
PAMSTAMP (PAM-Tube Environment)

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Designs to determine tool surface displacement and springiness in polymer made tools

Results are already published as a journal paper which constitutes research conducted as a part this doctoral thesis [81]

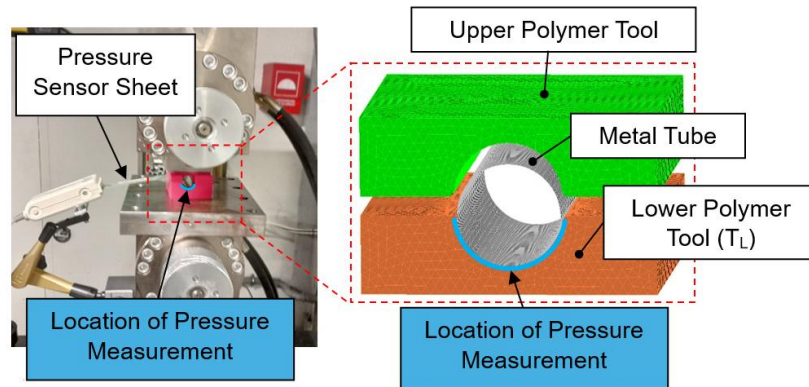


Polymers exhibit springiness upon loading. Various designs were developed to investigate the response of springiness in polymer made tools

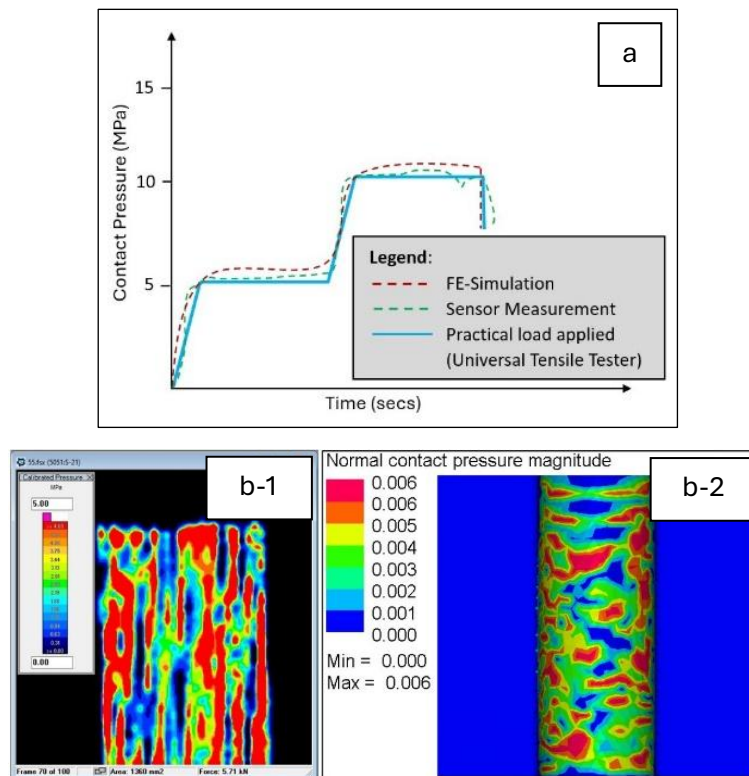
Accuracy of Tekscan Pressure Measurement Sensors (I-Scan 5051)

Results are already published as conference paper which constitutes research conducted as a part of this doctoral thesis [158]

Experimental Setup: Experimental setup to determine contact pressure on tool surface (T_L) through pressure measurement sensor sheet (Tekscan PMS-5051).

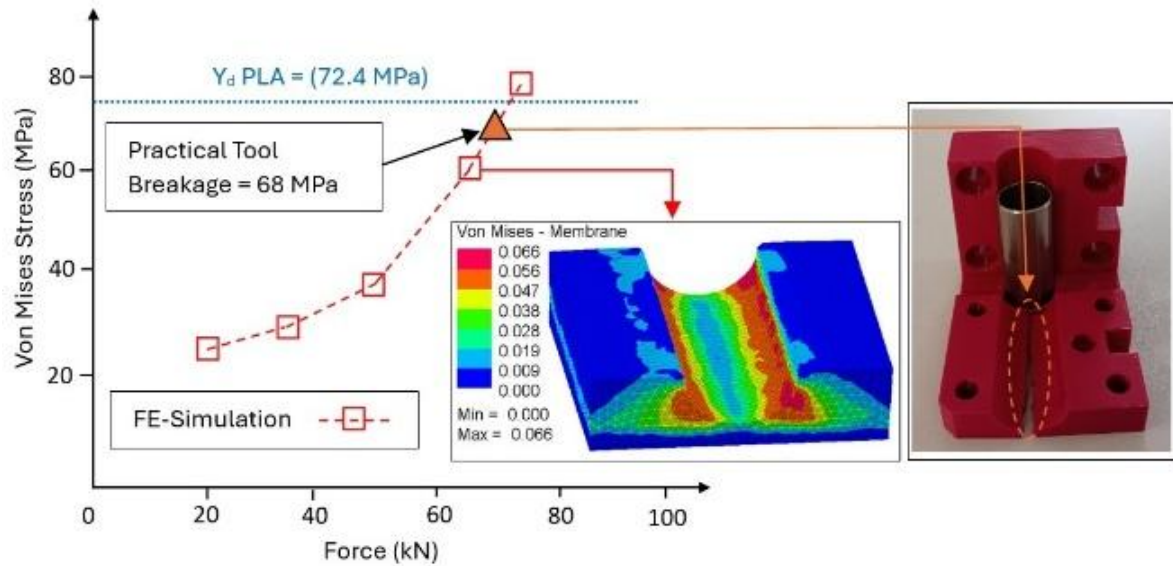


Results: (a) Comparison of Contact Pressure on tool surface and (b-1 & b-2) Pattern of Contact Pressure on Tool Surface (T_L) obtained from sensors (b-1) and FE-simulation (b-2)



von-Mises criterion for 3D printed polymers

Results are already published as a conference paper which constitutes research conducted as a part of this doctoral thesis [158]



$$\text{Tool failure in 3D printed polymer made tools} = \frac{\sigma_{VM}}{Y_d} \geq 0.94$$

$$\text{Safe performance of 3D printed polymeric tools in forming processes} = \frac{\sigma_{VM}}{Y_d} \leq 0.94$$

Tabular CV

Personal data:

Name: Muhammad Ali Kaleem

Academic Qualifications:

- | | |
|--------|--|
| B.Eng. | Bachelors of Mechanical Engineering (2001-2205) - National University of Sciences and Technology (NUST), Pakistan. |
| M.Eng. | Masters in Design and Manufacturing Engineering (2018-2020) - National University of Sciences and Technology (NUST), Pakistan. |
| PhD. | Doctor in Mechanical Engineering (2021-2025) – Institute of Production Technology (PROTECH), University of Siegen, Germany. |

Professional Experience:

- | | |
|-----------|--|
| 2006-2017 | Field & Regional Workshop for Automotive Maintenance, Rawalpindi, Pakistan. |
| 2021-2026 | Scientific staff at the Chair of Forming Technology (UTS-Siegen) at University of Siegen, Germany. |

List of Publications (Published as part of this doctoral thesis):

Journal Papers:

1. **Kaleem, M. A.**, Steinheimer, R., Frohn-Sörensen, P., Kotzian, T., & Engel, B. (2025). Topology optimization of forming tools: pressure die in rotary draw bending process. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 19(5), 3349-3362. DOI: <https://link.springer.com/article/10.1007/s12008-024-01932-w> (Published)
2. **Kaleem, M. A.**, Steinheimer, R., Frohn-Sörensen, P., Gabsa, S., & Engel, B. (2024). Additive manufacturing of polymeric pressure die for rotary draw bending process. *The International Journal of Advanced Manufacturing Technology*, 134(3), 1789-1804. DOI: <https://link.springer.com/article/10.1007/s00170-024-14221-3> (Published)
3. **Kaleem, M. A.**, Frohn-Sörensen, P., Reuter, J., & Engel, B. (2024). Surface roughness and coefficients of friction of 3D-printed clamp tools made from selective laser melting. *Progress in Additive Manufacturing*, 1-4. DOI: <https://link.springer.com/article/10.1007/s40964-024-00863-y> (Published)
4. **Kaleem, M. A.**, Frohn-Sörensen, P., & Engel, B. (2025). Topology optimization of die geometry through identification of high pressure areas on die surface. *The International Journal of Advanced Manufacturing Technology*, 1-8. DOI: <https://link.springer.com/article/10.1007/s00170-025-17265-1> (Published)
5. Kaleem, M. A., Frohn-Sörensen, P., Steinheimer, R., & Engel, B. Hybrid tools for tube bending processes using additive manufacturing and digital twin (*Under review at International Journal of Material Forming, Springer*). (Under Review)

Conference Publications & Presentations:

1. **Kaleem, M. A.**, Frohn-Sörensen, P., Steinheimer, R., & Engel, B. (2025). Design criteria to use 3D printed polymeric tools in metal forming processes. In *MATEC Web of Conferences* (Vol.

- 408, p. 01008). EDP Sciences. DOI: <https://doi.org/10.1051/mateconf/202540801008> (Published)
2. **Kaleem, M. A.**, Frohn-Sörensen, P., Geueke, M., & Engel, B. (2023). The way forward in rotary draw bending: a review. *Transformation in der Biegetechnik 6. Biegeforum Siegen*, 53. DOI: <https://doi.org/10.25819/ubsi/10394> (Published)
 3. **Kaleem, M. A.**, Frohn-Sörensen, P., Nebeling, D., & Engel, B. (2023, September). Refinement of process parameters in rotary draw bending processes. In *International conference on the technology of plasticity* (pp. 359-370). Cham: Springer Nature Switzerland. DOI: https://link.springer.com/chapter/10.1007/978-3-031-42093-1_35 (Published)

About the book:

This research work presents the concept of using hybrid tools in production processes. A hybrid tool consisting of steel surfaces and 3D printed polymeric base structure is developed and successfully tested in Rotary Draw Bending process. The research work is conducted through tool and process performances obtained from Digital Twin of Rotary Draw Bending process. Hybrid tools are cost effective, lightweight and an adroit design strategy of hybrid tools possess the potential to enhance process flexibility.

About the author:

Muhammad Ali Kaleem obtained his PhD degree in Mechanical Engineering from the University of Siegen-Germany under DAAD research scholarship financed by German international academic and research cooperation. The author possesses substantial experience to conduct industrial research projects in Germany and EU.