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The way forward in rotary draw bending: a review

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Abstract. Presently, Rotary Draw Bending (RDB) process is one of the most common tube bending techniques used in industrial production around the world. The process is executed on a specially designed machine being fitted with specific forming tools. The quality of final products in RDB largely depends on process parameters being selected by the machine operator. These process parameters are selective balance of movements and effect of forming tools on the tubes. Substantial development has been done in identification of optimum process parameters for improving the quality of bent tubes. Each process parameter has a unique and versatile effect on quality aspects like ovality, wrinkling and fracture of the tubes. This review-based research is focused on gathering published information on so-far identified process parameters in RDB and their eventual effect on the tube's quality. In the end, authors present their own perspective about the future of a RDB process. The authors perspective suggests merging of AM (Additive Manufacturing) with conventional RDB process to impart enhanced efficiency and improved quality to forming tools and bent products respectively. Apropos, a concept of hybrid pressure die is presented which encompasses manufacturing of a fundamental forming tool (pressure die) using AM techniques. The suggested model of hybrid forming tools opens a new avenue for industrialists to manufacture more flexible, cost effective and substantially beneficial tools for the RDB process in future.

Introduction

The process of Rotary Draw Bending (RDB) is presently used by many industries around the world [1]. RDB is a reliable and accurate method for bending tubes and pipes at ambient temperatures [2]. The process is mostly used for metallic or alloyed tubes. One of the fundamental benefits of RDB is that the tubes with considerably small bending radii can be bent with this process [3]. The forming tools used in the process are constructed and designed according to the geometric dimensions of the tubes. The contact force, frictional restraint and movement speed of the tools play decisive role in the outcome of the process [4a]. Springback is an essential undesirable outcome of all RDB processes and the effect of springback is more pronounced in case of small batch sizes [4b]. In a RDB process, some in-process characteristics can be observed which influence the accurate outcome after bending operation. These in-process characteristics may be called as the process parameters of a RDB process. The process parameters are the critical balance of movements and position of forming tools with respect to straight tubes [5]. The quality of bent portions of the tube being bent by RDB process depend mainly on the operator skills which in turn substantiates in the form of process parameters being used by the operators [6]. Over the last few decades, researchers have identified the process parameters which contribute towards quality enhancement of bent tubes. The quality of the bent portion is ascertained mainly according to VDI 3431 which comprises of twenty seven quality characteristics to establish the quality level of the tubes [7]. All these characteristics can be tested both qualitatively and quantitatively as per the requirements of the industry. BORCHMANN et al. have demonstrated that wrinkling at the intrados and the tube ovality of the bent portion of the tube are the major criterion for establishing tubes quality [8]. In addition to aforementioned criterion, the fracture strength of tubes also play a significant role specially at the extrados as the tube thinning largely occurs at the higher strained portions of the tube [9]. In nutshell, the effect of process parameters is measured with respect to improvement in tubes ovality, wrinkling and tendency towards cracking.

This research is aimed to compile the data of so-far identified process parameters in RDB and highlight their specific effects on tubes quality related characteristics. Moreover, owing to incorporation of AM (Additive Manufacturing) in industrial setups, a futuristic prognosis of RDB is also presented. The futuristic perspective highlights the combination of conventional RDB process with AM techniques like LMD (Laser Metal Deposition) and SLM (Selective Laser melting). The focus will be kept on manufacturing forming tools while preserving the advantages of both AM and conventional RDB process. The innovative prognosis of manufacturing hybrid forming tools facilitate new thinking avenues for manufacturers to seek variety of intricate designs of forming tools which otherwise were not deemed feasible for manufacturing by conventional manufacturing processes. The hypothesis is that hybrid forming tools will be more cost effective, highly flexible and last but not the least, a better choice for product customization.

Process parameters in RDB

In order to understand the process parameters involved in a typical RDB process, it is essential to possess the knowledge of the position and geometry of the forming tools. The forming tools which fundamentally influence a standard RDB process are pressure die, wiper die, clamping dies (inner and outer), bend die, mandrel and collet [10]. A standard arrangement of forming tools used in a standard RDB process is shown in Fig. 1.

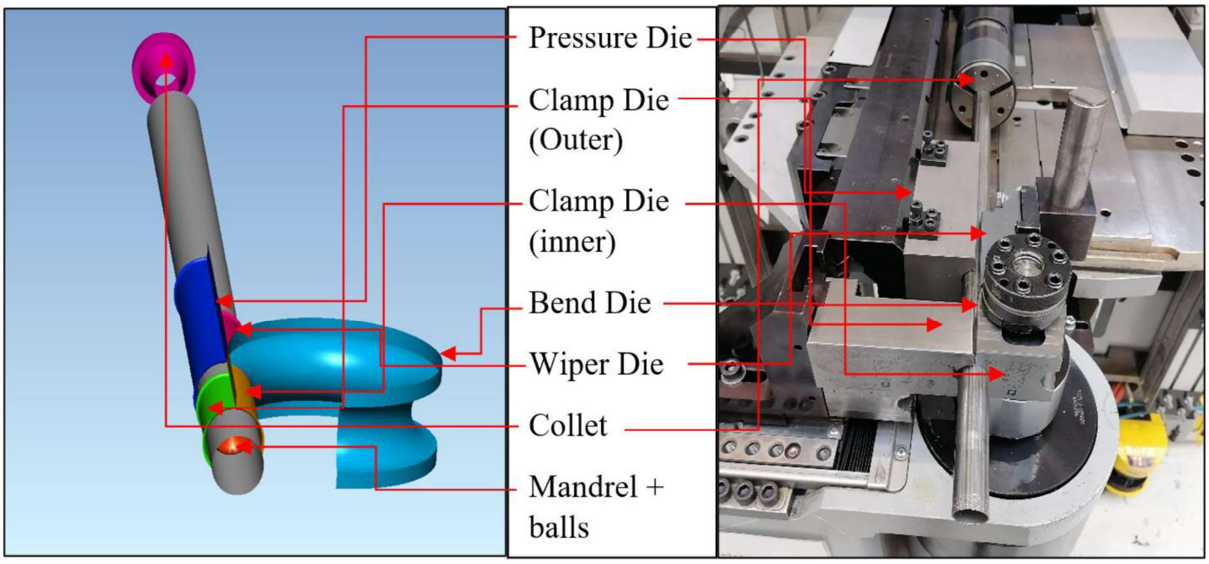

Fig. 1: Simulated and practical tool positions in a RDB process

In modern RDB machines, the collet is usually fixed within the machine housing and the collet grip is operated by means of pneumatic or hydraulic mechanisms [11]. The process parameters are thus the critical balance of relative speeds and effect of aforementioned forming tools on the tubes. These process parameters are further related to the material of forming tools and desired bending profiles depending on product geometries [12]. Since materials affect the

RDB process, it can be inferred that coefficients of friction of in-contact surfaces will contribute significantly in identifying the effect of forming tools on the tubes. A certain threshold limit of the bending factor also exists above which the process of RDB can be easily performed [13]. The bending factor is the ratio of bent die radius to the diameter of the tube. Generally, bending factors of more than 1.5 are considered safe for RDB processes [14]. However, RDB can be performed for bending factors as low as 0.8 yet the exact limits are determined by the geometric dimensions of bend die, tube's diameter, material's tensile strength and holding radii of clamp dies [15]. Selection of process parameters falls in dynamic equipping process of RDB [16]. BORCHMANN et al. mentioned in her research that usually it takes around six months to set up the complete dynamic equipping part of a RDB process during which the operator carries out various hit and trials and selects the most optimum process parameters thereby effecting substantial material and time loss [17]. In order to avoid this hit and trial approach by the operator, following process parameters with their corresponding benchmark values have been identified by the researchers in recent years:

Pressure Die Speed For Crack Reduction

BORCHMANN et al. demonstrated that various speed of pressure die in the direction of the tube have different effects on crack probability and wrinkling at intrados [18]. It can be seen from Fig. 2 that by increasing relative speed of pressure die to the speed of the tube, the major strain decreased. Thus, the relative movement of pressure die with reference to tube decreases the strain and crack probability at the extrados. HEFTRICH simulated the relative speed of pressure die with reference to tube at three different levels i-e 0.0, 1.0 and 1.7. Minimum crack probability was obtained at relative speed of 1.7.

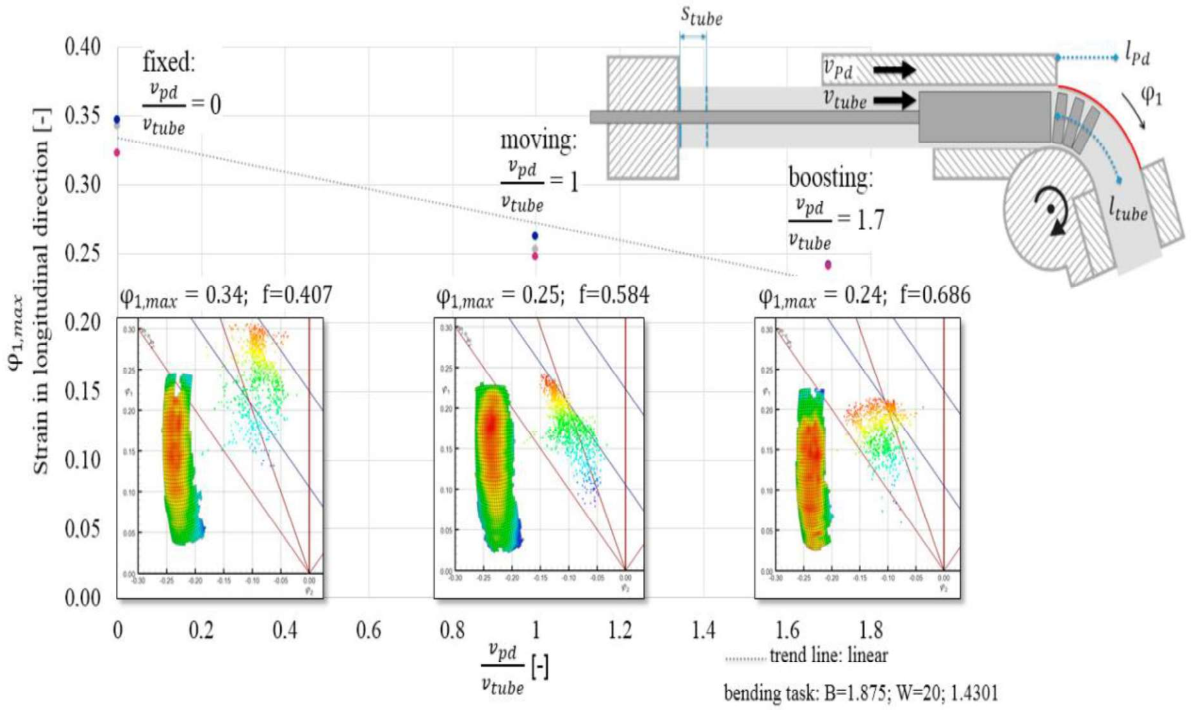

Fig. 2: Effect of relative pressure die speed on crack reduction

Collet Speed For Crack Reduction

In the same research discussed above, it was highlighted through simulations that as the relative speed of collet increases, the strain at extrados decreases. Thus, crack probability reduces with increasing relative collet speed of 0.89, 1.0 and 1.05 respectively as shown in Fig. 3.

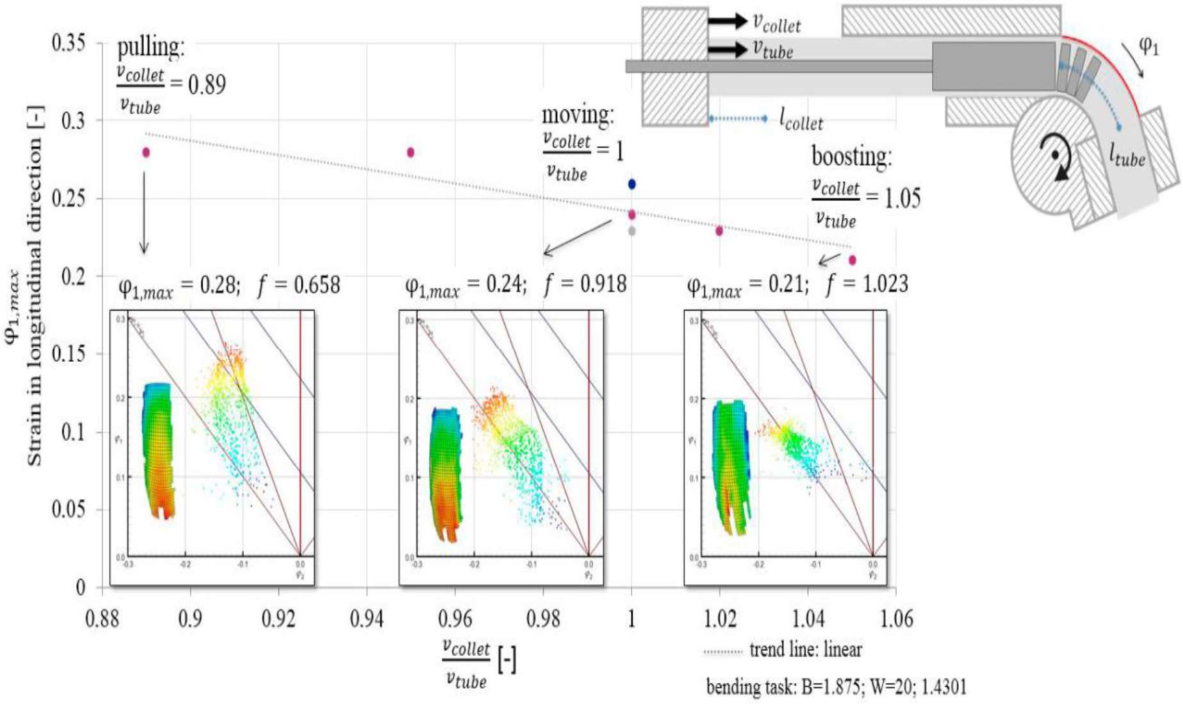

Fig. 3: Effect of Relative Collet Speed on Crack Reduction

Relationship Of Pressure Die Clearance And Relative Collet Speed On Wrinkle Formation

There is an influencing relationship between pressure die clearance and relative speed of the collet and tube [19]. This relationship contributes to formation of wrinkles at the intrados. The brief analysis of the effect of pressure die clearance and relative speed of collet is shown in Fig. 4. Here, it can be seen that for pressure die clearance of 0.8 mm, the wrinkling increase if the relative speed of collet is increased at three intervals; 0.89, 0.95 and 1.0 [19]. A complete wrinkle free tube is obtained at a relative collet speed of 0.89 with pressure die clearance of 0.8 mm. Similarly, when the relative speed of the collet is fixed at 1.0 and the pressure die clearance is changed from 0.0 to 0.8 at intervals of 0.2 mm, the wrinkle formation starts to emerge after pressure die clearance of 0.4 mm. The wrinkle free tubes were obtained between pressure die clearance of 0.0 and 0.4 mm.

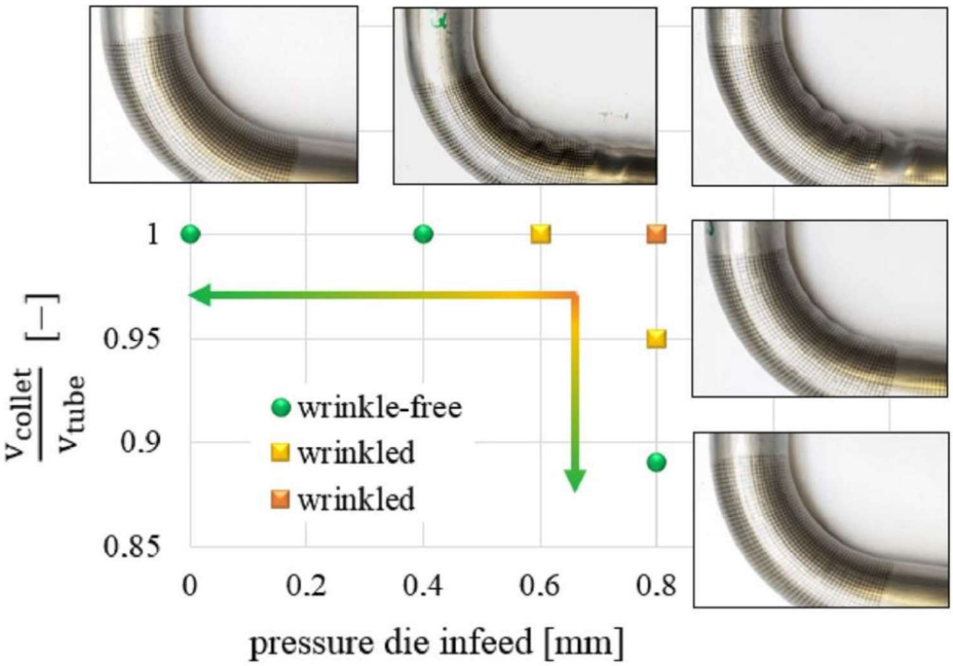

Fig. 4: Effect of pressure die clearance and relative collet speed on wrinkle formation

Effect Of Friction Coefficients

HINKEL et al. highlighted the significance of friction coefficients of clamping tools and their influence on tube bending processes. [20] SAFDARIAN et al. also highlighted that friction coefficients between tube and all in-contact tools are significantly important yet the friction coefficient between tube and the pressure die has the most profound effect in a RDB [21]. He investigated the effect of friction coefficient between tube and pressure die on the wall thickness of the bent tube. Three values of friction coefficients (i-e 0.05, 0.3 and 0.8) were used. The tube's thickness at extrados decreases by increasing the value of friction coefficients.

Mandrel Position In The Tube For Avoiding Wrinkles

KAJIKAWA demonstrated that mandrel position is a significant characteristic in avoiding wrinkles at intrados [22]. He showed that wrinkles are bound to occur when mandrel is kept at substantially large backward position relative to the bending direction of the tube. However, there is a limit up to which the mandrel can be pushed forward towards the bending direction. This limit is case specific as by increasing the tube diameter or bending radius, the ideal position of the mandrel also changed. Hence the general rule of keeping the mandrel as far forward as technically feasible is largely possible depending on the bending radius.

SAFDARIAN demonstrated that the distance between mandrel and centre of bending radius affects tube fracture and ovality [23]. He conducted the experiment with mild steel tube BS-3059 having an outer diameter of 47.5 mm and a thickness of 4 mm. He noticed that the fracture occurs when the distance between last ball of mandrel and the centre of the bending radius is 5 mm. On the other hand, minimal ovality difference was obtained when this distance was kept at 15 mm. Similarly, highest ovality was noticed at a distance of 35 mm. Thus, most optimal distance between mandrel and bending radius was noticed to be 15 mm.

Effect Of Number Of Mandrel Balls On Tubes Ovality

The number of mandrel balls has a profound effect on tubes ovality and fracture [24]. SAFDARIAN found out that for a bending angle of 90 degrees, two mandrel balls are preferred for use as compared to one or three mandrel balls. There has been no indication of fracture in FE-simulations when two mandrel balls were used during the process. Although the tubes ovality decreases by increasing the number of balls yet the increased probability of fracture and the requirement of accurate positioning of mandrel suggests the use of mandrel with two balls.

Consolidated process parameters in RDB

The above-mentioned process parameters have been tested on different materials and geometric configurations. Moreover, their respective effect on the tube's quality has been validated in each case. Hence, these process parameters can be taken as a general yard stick to execute all RDB processes across all metal-based tube bending regimes. Since each bending operation specifically depend on multiple factors (e.g. wall thickness, tube diameter, bending radius etc) therefore a speculative tolerance may be possible in each case. As a standard reference for the machine operator, a consolidated list of process parameters in RDB is mentioned in Tab. 1.

Tab. 1: Reference process parameters for machine operator in RDB process

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

Legend: Desirable in green & undesirable in red

Future trends in RDB

Owing to inclusion of AM in almost all manufacturing regimes [25], the speculative future of RDB comprises incorporation of AM in RDB processes. The advantages of AM can be accrued to RDB by manufacturing more complicated tools in less time. Moreover, the versatile benefits provided by AM opens up possibility of manufacturing more flexible tools suitable for individualized production [26]. The authors present the concept of manufacturing hybrid bending tools by merging the processes of AM and RDB. A schematic representing the aforementioned concept as shown in Fig. 5.

Fig. 5: Concept of manufacturing hybrid bending tools

Additively manufactured (AM) pressure die or hybrid pressure die

Pressure die is one of the most fundamental forming tools used in a RDB process [27]. This study presents a conceptual model in which a pressure die can be manufactured by an AM process. This AM manufactured pressure die may be called as a hybrid pressure die since it represents a combination of conventional and AM processes. The hybrid pressure die will possess the advantages accrued by AM in terms of flexibility, repeatability and production time. A 3D model of hybrid pressure die is shown in Fig. 6.

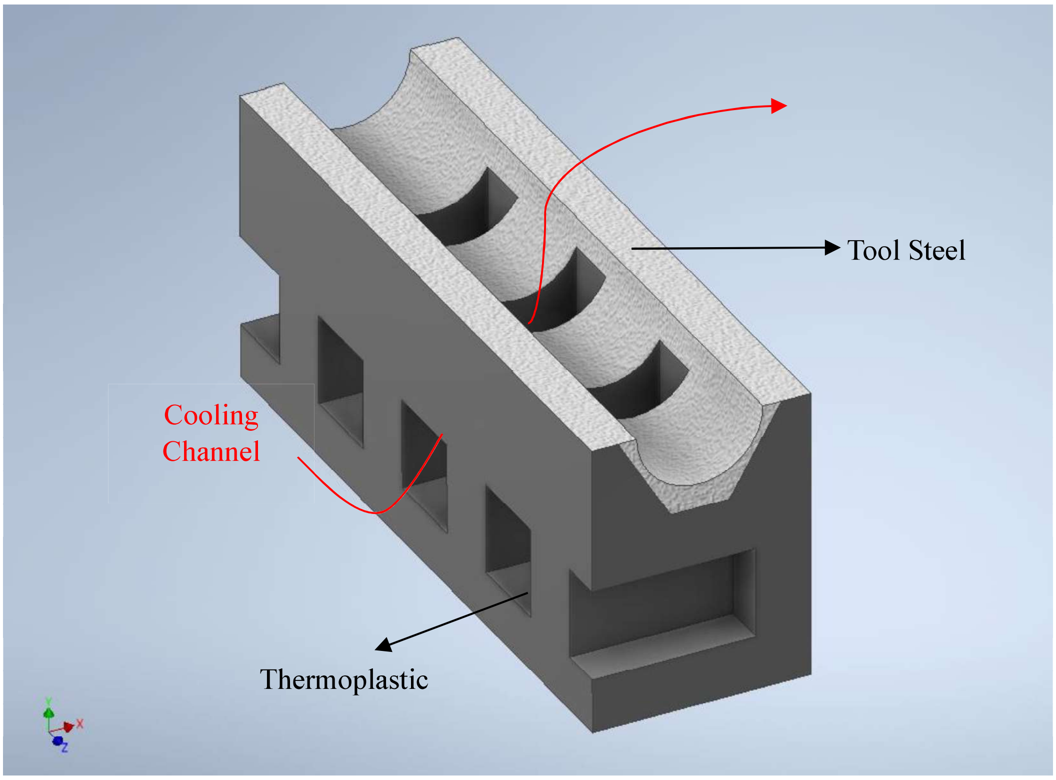

Fig. 6: Hybrid pressure die for RDB process

The hybrid pressure die essentially comprises of two distinct parts. The lower part is fabricated by FDM and the material used is thermoplastic polymer (ABS). The hollow portions within the lower part are kept for air circulation within the part so that in-process variations occurring in pressure die due to thermal fluctuations during the operation can be avoided. The thermoplastic polymer material (ABS) used as lower part is less in volume and substantially more cost effective as compared to tool steel. The whole lower part of the hybrid pressure die can be manufactured in less than 10 minutes by a standard FDM based 3D printer. The upper part essentially consists of strips of stainless steel 1.4307 fixed on the upper surface of the lower part and subsequent deposition of tool steel via LMD (Laser Metal Deposition). The circular geometry of the circumference is ensured by deposition of powder tool steel through LMD nozzle in a desired pattern. The powder deposition does not provide an even surface finish but on the other hand a considerably uneven and rough surface is obtained. In RDB process, this may also be advantageous as only certain portion of the surface of forming tools should be essentially remain in-contact with the tube while sliding with each other [28].

Advantages accrued by AM

The benefits accrued by manufacturing pressure die via AM can be summed up in terms of cost effectiveness, time of production and flexibility. A list of advantages of using hybrid pressure dies in RDB processes is summarized in Tab. 2. The advantages for each domain are shown in italics respectively.

Tab. 2: Advantages of using additively manufactured pressure die in RDB process

	Cost Effect	**Time of production**	**Flexibility**
Advantages of using hybrid pressure die	• *Less material is used as compared to conventionally manufactured pressure die.* • *The thermosetting plastic (ABS or PLA) material is much cheaper as compared to standard tool steel or alloy steel.* • *The unused material in the form of left out powder or removed support structures can be re-used for manufacturing the original tool.*	• *High level of complex designs with internally hollow geometries can be manufactured rapidly.* • *Individualized requirements can be met in less time as compared to manufacturing tools through conventional processes.*	• *Already built geometries can be built upon by deposition of additional material layers. Thus, one tool can be used on multiple tube geometries.* • *A variety of complex designs are possible to be manufactured.* • *AM manufactured tools can be milled and modified by subtractive techniques and used for larger tubes. Same tools can then be reused by adding more material layers on them.*

Conclusion

An accurate bending operation by RDB process largely depends on the expertise of the machine operator who in-turn use specific process parameters to impart accurate, precise and repeatable bending tasks. These process parameters have been identified over the years by many researchers working in the fields related to RDB process. This research compiles a list of process parameters which are considered fundamental in affecting accurate and error-free bending operation. Although most of these process parameters depend on the geometry of tube, bending factor, tube's material and many more characteristics, yet a standard value can be generally assigned to each process parameter so that the machine operator can use these values as a reference to begin the dynamic equipping process.

Owing to the ingression of AM in almost all manufacturing regimes around the world, the authors speculate that the refinement of RDB process in future will take the shape of a 'Hybrid-RDB' process in which AM will accrue its advantages to the conventional RDB process. Apropos, a concept of a hybrid forming tools is presented which encompasses manufacturing a pressure die by AM processes (FDM: Fused Deposition Modelling & LMD: Laser Metal Deposition). Substantial advantages in terms of cost effectiveness, time of production and flexibility in production are speculated to be offered by hybrid pressure die. Moreover, any intricate design possessing cooling mechanism within the pressure die can also be manufactured in quite less time thereby opening the avenues of individualized production.

In the future research, hybrid pressure die will be tested practically as an experimental test case and the advantages accrued will be compared with conventional forming tools.

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