A study on economic tooling concepts for dry deep-drawing using environmentally benign volatile lubricants

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Abstract. Dry processes represent promising approaches in forming technology to improve environmental aspects and human health by avoiding harmful substances and additives of conventional lubricants. Among many different approaches for dry forming investigated within the priority program SPP 1676, this paper addresses the use of volatile media as lubricants such as CO_2 or N_2. These volatile media are introduced directly into the interstice between sheet metal and tool surface via microinjectors. Indeed, this does not contradict the principle dry forming approach, as dry forming is defined as a process in which no residues are left on the surfaces [1]. This is ensured by the complete evaporation of the volatile media. The general feasibility of this novel tribological system has already been demonstrated in previous research work. However, despite good tribological results, the manufacturing costs of the required tool inserts and the media consumption per component are not yet economically competitive with conventional tribological systems. Therefore, this paper focuses on new designs of dry deep-drawing tools utilising volatile lubricants, considering the economics of different manufacturing processes.

Introduction

The use of lubricants has always been mandatory in sheet metal forming. The purpose of lubricants includes the reduction of wear phenomena such as abrasion and adhesion, both on the tool and on the components, as well as the reduction or modification of friction forces. Mineral oils, water/oil emulsions and wax-type dry lubricants are usually used for this purpose. These lubricants often contain ingredients that are harmful to health and environment such as chlorinated paraffins, which are intended to improve the properties of the lubricants. On the one hand, these lubricants have to be applied onto the surface of the sheet metal, on the other hand, they have to be removed from the component´s surface after forming in order to enable subsequent processes such as painting, welding or bonding. These efforts can be avoided by using volatile, additive-free lubricants. Fig. 1 shows the approach for applying such volatile lubricants in deep drawing processes. Here, CO_2 or N_2 are introduced directly into the friction zone under high pressure via microinjectors integrated into the tool surface. After opening the tools, the lubricants evaporate without leaving any residues.

In a basic research project lasting several years, various parameters of dry forming with volatile media were investigated experimentally, starting with simple strip drawing tests. In this way, the influences of different microinjector designs and arrangements, structured tool surfaces, surface coatings, sheet metal materials, varying contact normal stresses and media pressures were investigated [1].

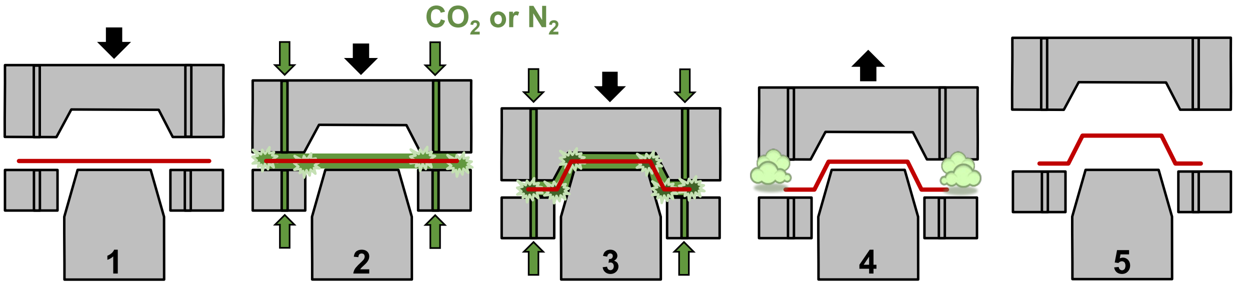

Fig. 1: Process scheme of dry deep drawing lubricated by volatile media. According to [2]

Subsequently, the tribological conditions at tool radii were also investigated experimentally using specific stretch bending tests. Thus, the influence of different radii, injection angles of the volatile lubricants, locally deviating contact stresses and media pressures were analysed. As a result, the critical tribological area of tool radii could be optimised.

The findings gained were used to realise a deep-drawing tool of a rectangular cup for single-stroke investigations. Here, a two-part shell design (cf. Fig. 2b) was used to simplify the integration of feeding and distribution channels into the die and blank holder. Afterwards, these tool inserts were utilized to experimentally determine the process window for CO_2 (liquid) and N_2 (gaseous, 60 bar), N_2 (gaseous, 100 bar) as well as for a conventional mineral oil-based drawing oil (ZO3368) as lubricants. The result of this investigations demonstrate the clear increase of the process range and therefore the process reliability for all volatile lubricants [3].

At the end of the fundamental investigations carried out, wear tests were performed with a new, series-oriented laboratory endurance run of a rectangular cup tool and the most promising volatile lubricating medium $CO_{2,\ \text{liquid}}$. The results were compared to experimental series with the conventional mineral oil ZO3368. During the endurance test series with CO_2 and the mineral oil ZO3368, 1000 rectangular cups each were drawn from the sheet metal material DC05+ZE. Neither adhesions on the tool surface nor abrasions on the surface of the parts could be detected for all 1000 deep-drawn rectangular cups using liquid CO_2 as volatile lubrication [4].

Despite the promising findings regarding the tribological performance, the tool insert design used in the basic investigations (two-part shell) reveal some economic disadvantages. For example, the valves controlling the media flow could not be mounted directly onto the tool inserts, which resulted in an increase in media consumption per part due to longer supply tubes to the tool. The dismountable sealing concept between the two shell parts of blank holder and die was also associated with high efforts in cost and time regarding manufacturing and assembly. Overall, the manufacturing costs of the tooling inserts used for the investigations on volatile lubrication described above were more than four times higher than those of the conventional tool inserts for the reference test series with ZO3368.

Tooling concepts

Hence, the aim of the study described as follows was, on the one hand, to reduce high tool costs and, on the other hand, to improve economic aspects of the new lubrication system by developing new tool concepts for blank holders and dies in dry deep drawing processes using volatile lubricants. For this purpose, based on design catalogues and literature research a morphological list of alternative features for tools with media supply was elaborated. Based on this, the most valuable concepts were selected and specified in detail.

When elaborating the morphological list, five essential tool features were identified by abstracting the deep-drawing tools for dry forming using volatile lubricants. These tool features are in detail the basic tool material, the design, the joining method of tool components, the sealing method and the manufacturing process of the microinjectors. A brief excerpt of alternatives of identified features are listed in Table 1. Based on this list, six solution concepts were extracted, which are colour-coded in Table 1. Each concept was named on the basis of the individually selected design, as this ensures a clear identification.

Table 1: Morphological listing of feature alternatives and solution concepts

Feature	**Alternatives/ characteristics**					
	1	**2**	**3**	**4**	**5**	**6**
Material	Steel	Powder	Cast iron			
Design	Laser deposite welding	Shell design	Layer laminate (LOM)	3D - SLM	Casting	Monobloc
Joining method	No joining required	Screwing	Bonding	Soldering		
Sealing method	No sealing required	Static sealing	Joining pressure-tight			
Manu.microinj.	EDM	Laser drilling	Convent. drilling	Integr. with 3D-SLM		

Solution concepts:	**3D-SLM**	**Shell design**	**Laser deposite welding**	**Layer laminate**	**Monobloc**	**Casting**

Rating of the solution methods

The evaluation of the six solution concepts was carried out on the basis of selected criteria corresponding to the general requirements for forming tools with integrated media channels and microinjectors defined and developed during the former basic research investigations. For each criterion, a score of zero points (not suitable) to ten points (fully suitable) were assigned. For scoring, numerous literature sources, product examples, expert opinions and the experience gained from the basic investigations were used in order to ensure the most objective and balanced rating of an appropriate tool design. The relevant results of the evaluations, including all criteria, are provided in Table 2.

Table 2: Evaluation of all proposed solution concepts

Solution concepts / **Evaluation criteria**	**Stiffness**	**Tightness**	**Producibility**	**Fatigue strength**	**Strength**	**Production time**	**Geometric accuracy**	**Flexibility of design**	**Repair capability**		**Total score**	**Rating**
3D-SLM	10	9	10	8	9	8	9	10	3		**76**	**1**
Shell Design	8	10	10	10	9	5	10	7	5		**74**	**2**
Laser Deposite Welding	10	10	10	8	8	7	8	7	3		**71**	**3**
Laminated Object	6	8	10	8	7	8	6	8	4		**65**	**4**
Casting	6	8	8	9	7	3	7	9	3		**60**	**5**
Monobloc	10	10	0	10	10	0	8	2	3		**53**	**6**

In general, the four best-ranked solution concepts show a beneficial manufacturability from a technical point of view. In the case of casting (5th rank), there are limitations in terms of manufacturability with regard to channels with small cross-sections and cross-sectional changes in the form of distortion and cracking as well as shrinkage. Due to the small channel structures, only a complex and expensive fine casting process can therefore be considered for this solution method. The solution as a monobloc with complex deep-hole drilling and the small wall thicknesses is extremely questionable and can only be implemented to a very limited extent. Therefore, the manufacturability of this method is rated with a score of zero points. In the following, only the four best-ranked solution concepts are considered and specified in more detail.

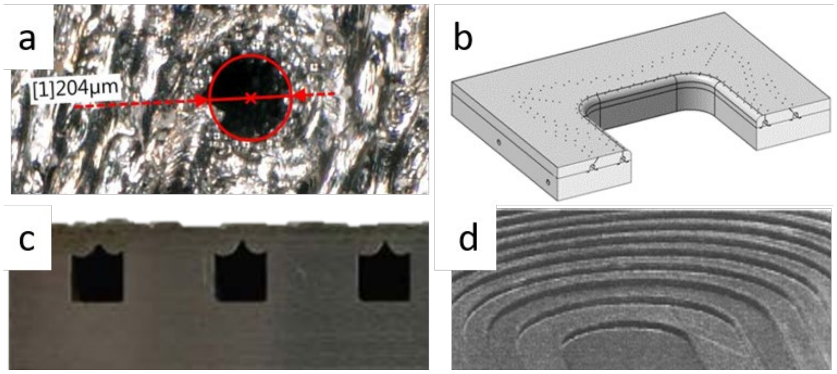

Fig. 2: a: 3D-LMF [5], b: Shell design [6], c: LDW cover layer [7], d: LOM [8]

1st rank solution concept “3D-SLM”. The metal 3D printing process received the highest score in the evaluation of the different solution concepts. Due to the high geometric accuracy, laser metal fusion (LMF) is intended for this application [9]. With this process, the microinjectors presumably can be introduced directly into the tool components during printing, thus avoiding subsequent laser drilling or EDM in the three-dimensional tool body. According to current preliminary tests, bore-shaped structures with a minimum diameter of 0.1 to 0.2 mm can be produced with the LMF process using appropriate metal powders and equipment (see Fig. 2a). Due to the surface roughness of printed surfaces (approx. 30-55 µm with LMF), however, a machining of the tool surfaces will be required. A limitation of this concept could be the availability of high-strength materials in powder form. Available tool steels (e.g. 1.2709) today only achieve a hardness of approx. 43-52 HRC [10]–[12]. Hence, the characterisation of the variety of shapes of the tool inserts in relation to the economic efficiency by printing with regard to the achievable strength and surface topologies is in the focus of this solution concept. Furthermore, the relatively high nickel content of 1.2709 leads to a higher adhesion tendency. Here, the use of relatively new, qualified tool steels in powder form taken from the group of 8% chromium steels (e.g. W360) promises a remarkable improvement. The achievable working hardness for this group of steels is approx. 55-57 HRC [10], [13], so that almost the same results could be achieved with printed tool inserts as with conventional tool steels.

2nd rank solution concept “Shell Design”. The shell design is frequently used for deep-drawing tools in press hardening technology and is therefore established and well known as a design principle in industrial application. Press hardening tools have a segmented design into separate shells to enable the manufacturability of complex internal cooling devices. The cooling channels, necessary for quenching the blanks, are usually located in the basic tool structure of the punch and die. This is closed with a cover layer (upper shell) often made of hot work steel having a high wear resistance. The inlet and outlet holes to the cooling channels often require deep-hole drilling [14]–[16]. The design principle of segmentation in shells already was successfully used for the basic investigations in the above-mentioned dry forming project (c.f. Fig. 2b). Here, however, cost-intensive deep-hole drilling was necessary for the media supply channels in the two-part shell design. A further optimisation of the shell design is therefore a three-part segmentation to simplify the insertion of supply channels.

The advantages of the shell design are a relatively high rigidity and a relatively simple and cost-efficient production of the individual segments. The sealing of the shells to each other has so far been carried out in a complex way by dismountable sealing systems. In order to improve an economic manufacturing process, non-demountable joining processes such as soldering or gluing will be considered in future.

3rd rank solution concept “Laser Deposit Welding”. In this solution, the intended tool inserts are not to be produced completely by laser deposition welding (LDW). Rather, LDW aims to completely cover the media channels introduced by machining in a conventional steel plate as depicted in Fig. 2c. In this way, a relatively high degree of design freedom can be achieved for the feed and distribution channels introduced into the tool inserts. Properties such as hardness and strength can be positively influenced by suitable additive materials applied to the surface of the tool insert by means of LDW.

Due to the application of individual welding paths, however, a geometric notch effect (c.f. Fig. 2c) occurs in the freely spanned areas of the channels, which is supplemented by a metallurgical notch effect due to the successive microstructure solidification during welding. This reduction in component-strength can be countered by a high tensile strength and residual ductility of the additional material of the cover layer. Even with the LDW concept, the microinjectors still have to be introduced subsequently by electrical discharching, laser drilling or conventional micro-machining. Sealing of the individual layers is not necessary due to the metallurgically-bonded microstructure [7].

4th rank solution concept "Laminated Object Manufacturing". The laminated object manufacturing (LOM) process is a well-known concept for prototype and small-series forming tools. Here, the tool inserts are constructed from individual, stacked sheet metal laminates (see Fig. 2d). The idea is to divide the complex tool geometry into individual, easy-to-make laminates. These laminates can be produced inexpensively using common processes such as laser cutting, water jet cutting or punch nibbling [8], [17]–[19]. The advantage is that with the horizontal arrangement of the laminates the feed and distribution channels can be freely designed avoiding expensive drilling of deep boreholes. The disadvantages of this technology are given by the additional machining of the stair-step effect occurring between the individual sheet metal layer and the reduced structural rigidity of the tool body compared to solid tools. The compressive strength due to the media pressure in the tool inserts can be ensured by a sufficiently dimensioned cover plate (possibly made of tool steel).

Furthermore, all laminates must be joined together in a pressure-tight manner by surface bonding, welding or soldering, as otherwise the volatile media would escape. Especially bonding with epoxy resin and furnace brazing will be investigated because of their simple and cost-effective application. The two-dimensional joining of the individual layers also increases the structural rigidity of the tool inserts, as shear stresses can be transferred between the individual layers. The internal pressures in the channels of the media are a maximum of 10 MPa (= 100 bar), and the areas exposed to the internal pressure are very small. According to Volkersen's calculation method [20] and the geometric boundary conditions, the shear stresses occurring in the joint layer amount to $\tau\text{max} \approx 5$ MPa. The equivalent stress (Tresca) including the normal stress reaches a calculated maximum of approx. 17 MPa. This strength can be easily achieved with commercially available epoxy adhesives and solders [21].

Economic considerations

From an economic point of view, the equipment investments for oil application, component cleaning and the disposal costs for the cleaning residues may be found as the main cost drivers of conventional tribo-systems in sheet metal forming. These costs are completely eliminated by using dry forming with volatile media. Especially when using CO_2 as volatile lubricant, a cleaning effect of anti-corrosion oils attached to sheet metal materials could be observed. This cleaning effect has to be quantified in future investigations by recording the basic oiling and the residual oil quantity after forming. This could also enable application in the fields of electrical systems, food technology as well as medical and pharmaceutical engineering.

However, according to current purchasing costs, the use of conventional lubricants is significantly cheaper than the volatile media to be used. In the previous experimental investigations on volatile lubricants, approx. $9 \cdot 10^{-2}$ kg CO_2 was used per component. This is not only due to the outflow under high pressure during forming, but also to the blind volume of the supply line from the valves and the distribution channels in the tool. Above all, the blind volume due to the distance of the valves from the tool surface need to be significantly reduced in a new tool design in order to reduce the amount of volatile lubricant used.

Regarding the different tool designs, no final evaluation can be made yet without actual production and endurance testing. However, some expected trends and correlations already can be outlined. In the 3D-LMF process, utilise material volume will correlate directly with costs. For an economical application, it is essential to keep the mass of the tool inserts as low as possible while maintaining high strength and stiffness by optimising the structure of the tool inserts. If the microinjectors can be integrated into the tool inserts during the printing process, the economic efficiency of the 3D printing process will increase significantly. The costs for the shell design and the laser deposition welding design will be close to each other. For the shell design the joining and sealing technology is more complex and for the laser deposition welding the process is more cost-intensive. The sheet metal laminates will be moderately cheaper in terms of the sheet metal material used. Here, the expenditure for joining will be decisive for the total costs.

During future endurance tests planned, all four best ranked solution concepts will be investigated in the same progressive die in order to avoid an influence of the overall tool design. The aim of these tests is to quantify tool life, wear and friction force for the different tooling concepts.

Outlook

At present, a progressive die is being designed for the planned experimental investigation of the tooling concepts, in which the tool inserts considered for the dry deep-drawing operation will be installed (c.f. Fig. 3). A force measurement for the friction-sensitive punch force of the drawing stage will be integrated into this tool structure in order to measure the friction forces. The wear will be measured by means of the surface changes of the active tool surfaces using a confocal microscope. For this purpose, the tool inserts will be removed from the tool at defined intervals and measured.

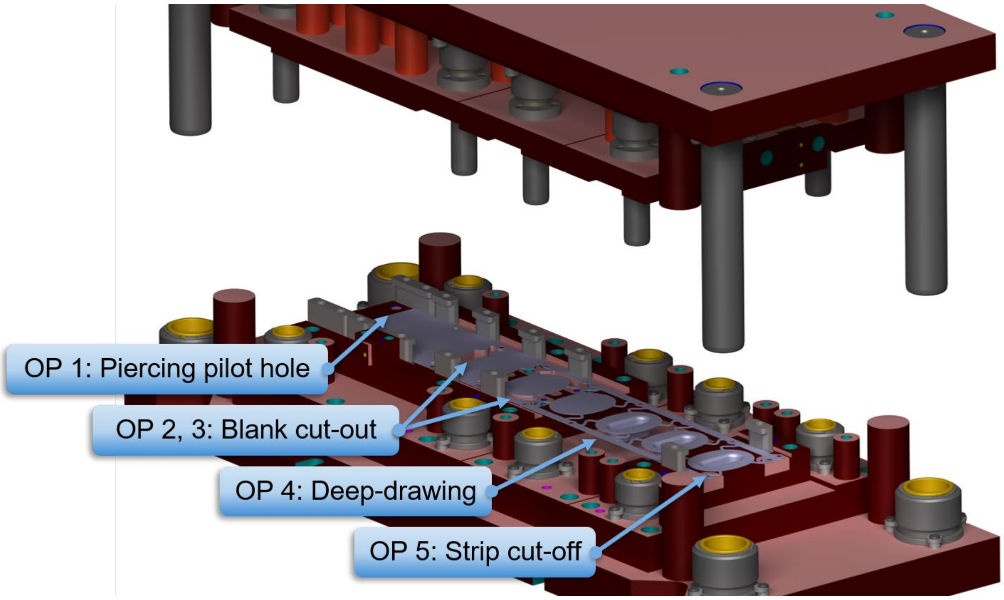

Fig. 3: Design draft of the planned progressive die with sheet metal strip

In order to cover a broader field of application of the novel lubrication system, three sheet metal materials (DC05+ZE, CR280BH and DP500) will be investigated. For each combination of lubricant, sheet metal material and tool design, 5000 components are scheduled. Thus, a total of 120.000 cups will be deep-drawn during the scheduled tests. To keep the material costs as low as possible, a relatively small oval cup geometry has been selected. The geometry of the cup and the design of the progressive die are shown in Fig. 3.

As shown in Fig. 3, the first operation in the progressive die is the piercing of the pilot holes. Subsequently, the blank geometry having four retaining sheet stripes is cut out on the progressive strip in operation two and three. In the fourth operation, the parts are deep-drawn and then cut off at the strip. The drawing and shearing stages are completely separated from each other by their own tool frames in order to adjust the part holder forces for shearing and the blank holder force for deep-drawing independently of each other and to remove the individual operation stages individually. This design ensures an easy access for surface measurements on the blank holder and die.

Summary

In this study, methods for the economic manufacturing of tool inserts for dry deep-drawing with volatile lubricants were presented based on a methodical approach. By means of a criteria-based evaluation, four suitable tooling concepts were selected, which will be examined and evaluated in detail in future investigations. The results of these investigations will show to which extent the preliminary evaluation of the concepts presented here needs to be adjusted. With the selected four solution methods for the deep-drawing tool inserts, the economic efficiency and thus also the acceptance in industrial application of volatile lubrication will improve significantly. These new approaches will be one step further to more economic, sustainable and ecologic manufacturing processes.

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