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High wear resistant deep drawing tools made of coated polymers

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A R T I C L E I N F O

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A B S T R A C T

A methodology for the rapid production of drawing tools with high wear resistance to form free-form shaped sheet metal parts is developed. Hard material shells are thermally sprayed on an original mould and supported by a polymer. The bonded shell is removed from the original mould and acts as the surface of the forming tool. Deep drawing experiments show that the wear resistance of these hybrid tools is adequate to form high-strength steels. The tools are a suitable alternative to existing tool systems for the intended use in small up to medium size productions.

1. Introduction

Deep drawing tools made of polymer materials are used basically for prototyping, tryouts, and zero batch size production [1]. Investigations in [2] demonstrate the possibility to draw mild steels with such tools also for small and medium batch size production. Tools made of polymer material have the advantages to be cost-effective as a result of low material costs and rapidly producible due to a good machinability [3]. However, tools made of polymer material have the disadvantage of low wear resistance compared to conventional tool materials, especially if high strength steels are drawn [4]. The use of coating is an approach to increase the durability of polymer deep drawing tools. Investigations in [5] and [6], in which diamond-like carbon and chrome as well copper coatings applied by physical vapor deposition were used, revealed an unsatisfactory durability of the coatings. A successful process is galvanic coating of nickel [7]. However, the galvanic process is time consuming to manufacturing the necessary coating thicknesses. Low durability, in case of thin galvanic coatings, was observed in [8]. Due to high deposition rates, thermal spraying of hard materials is a time-efficient coating process. Besides a high wear resistance, hard material coatings show an excellent performance in drawing processes [9]. Investigations on using atmospheric plasma spraying show that a direct spraying process to produce hard material coatings results in too low adhesion strengths due to the low hardness and thermal resistance of the polymer material used [10]. An approach to avoid this disadvantage is the use of indirect spraying techniques [11]. Here, the hard material coating is not directly sprayed on the tool body but applied on an original mould. This paper covers the development and performance of rapidly producible deep drawing tools to form free-form shaped parts made of high strength steels. These tools are cost-effective and geometrically complex. They are indirectly coated and reinforced.

2. Method of manufacturing coated deep drawing tools

The principle of the hybrid deep drawing tool is shown in Fig. 1(a). The surfaces of the die and the punch are protected by a shell of a thermally sprayed coating of fused tungsten carbides. The coating acts as the effective surface and is in contact with the sheet during the forming process. The coating itself is supported by an appropriate cast material such as polymer. Fig. 1(b) shows the approach to produce the coating. First, the coating is sprayed on an original mould and then backfilled with the cast material. The mechanical properties of the cast material can be modified by reinforcement [12]. Finally, the reinforced bonded coatings are removed from the original mould. The non-destructive removal of the coatings from the original mould requires the consideration of the adhesion between the coating and original mould during the spraying process. If adhesion is too low, the coating will separate from the mould during the spraying process. If adhesion is too high the coating will be destroyed during the removal process. Investigations to achieve a suitable adhesion are carried out in [13] and are not within the scope of this paper. In summary, to achieve optimum adhesion between the coating and the mould, the mould surface has to be non-blasted, the spraying distance as large as possible, and the primary atomizing air at a low limit. A clean surface of the original mould is recommended.

3. Performance of hybrid forming tools

The performance of the hybrid tools are investigated with the help of a specially designed evaluation tool geometry including also free-form shaped sections. The dimensions of the tools are given in Fig. 2.

For the investigations, a high strength steel DP600 is used as the workpiece material. The polymer for the tool bodies is a thermosetting polymer and belongs to the group of polyurethanes. Reinforcement materials are carbon and aramid fabrics. Epoxy resin is used to form the matrices of the laminates. By electric arc wire spraying, the original moulds are thermally coated with hard material. For this process, a WC-FeCSiMn cored wire flux (EN ISO 14919-5-1.6-4) with 50% FTC (fused tungsten carbide) is used.

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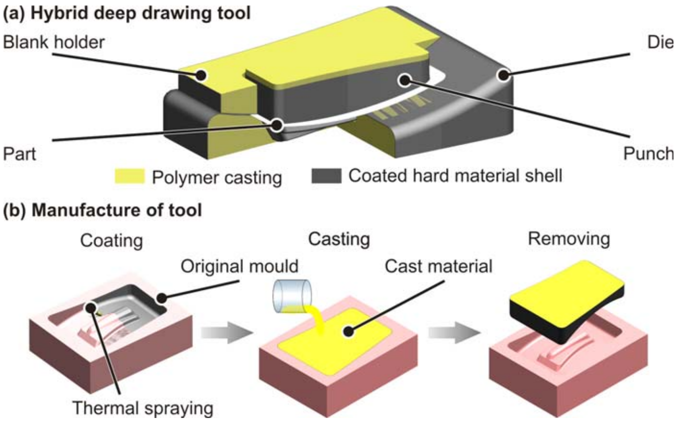

Fig. 1. (a) Design and (b) manufacture of the hybrid deep drawing tool.

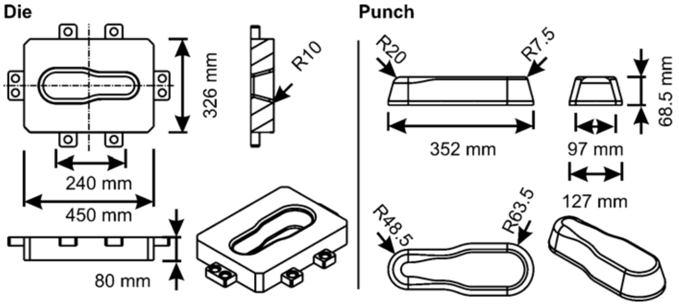

Fig. 2. Dimensions of the hybrid deep drawing tools.

Properties of the materials used are given in Table 1. The mechanical properties of all materials are determined by universal testing machines in tensile or compression tests. Other properties are given by manufacturers' data.

In order to evaluate the stresses in the tool a numerical analysis of the deep drawing process is conducted using the general purpose FE code LS-DYNA® (V.9.71). For symmetry reasons, only the halves of the tools and the workpiece are modeled (Fig. 3). The sheet (thickness 1 mm) is modeled by Belytschko–Tsay shell elements with seven integration points over the thickness using the anisotropic material model by Hill [15]. The initial element length is 2 mm. The flow curve of DP600 is measured by tensile tests and extrapolated according to the Swift equation. All tools are modeled elastically and are built up of hexahedral elements. The element lengths depend on the local geometry and are between 1 and 20 mm. The punch and the blank holder are modeled by a linear-elastic material model. According to the experimental set-up, steel material (E = 210 GPa, Poisson ratio: 0.3) is used for the blank holder. The blank holder force of 220 kN is applied by a support plate, which is modeled as a rigid body discretized by shell elements. The punch is modeled as a polyurethane elastic material. The die consists of two parts: die body and die reinforcement, which wraps the die body on the inner surface. The die body is modeled by a linear-elastic material model using parameters for the polyurethane as in the case of the punch. The die reinforcement is modeled by a transversal orthotropic material in order to simulate the directional behavior of the carbon fabrics [16]. In fiber direction, the parameters of the carbon reinforcement fabrics and, in orthogonal direction, the material parameters of the epoxy resin are used. Three layers of fabrics are modeled as one unit of a 1 mm thick hexahedral element to avoid too small element lengths. The number of units varies from one to four to evaluate the influence of reinforcement fabrics especially with respect to stresses in the die body. This results in a reinforcement thickness of 1 mm up to 4 mm. The connection between the die reinforcement and the die body is realized by using the same nodes at the interface. The coating is not modeled due to its low thickness. A Coulomb friction coefficient of 0.14 is used between the blank and the tools, which is based on results of [17]. In an additional analysis the die is modeled without reinforcement for comparison purpose. Here, the die is homogeneous and is made of pure polyurethane. Furthermore, for a reference analysis, all tools are taken as steel to model a conventional tool set-up. Drawing depth is set to 62 mm.

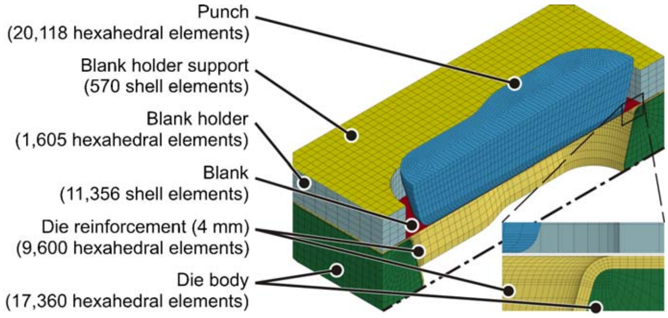

Fig. 3. Finite element discretization of the deep drawing process.

The indirectly coated tools are manufactured on the basis of results of the numerical analysis. For the coating process, original moulds made of an easy-to-machine, unalloyed steel 1.0037 are used. The punch is coated completely. For the die, only the flange and die radius areas are coated. The inner wall is uncoated. All moulds are machined by a milling process, which results in a mean roughness depth of $R_Z = 2\ \mu\text{m}$. The initial temperature of the non-blasted original moulds for the coating process is room temperature. The spraying distance is 250 mm and the primary atomizing air has a level of 0.2 MPa. The number of overruns is three. Here, the meander-shaped path of the spray gun has a length of 500 mm and a path distance of 5 mm. Afterwards, the punch is cast of polyurethane. The die is first laminated by reinforcement fabrics and then cast. The thickness of the reinforcement is based on the numerical analysis. Finally, the geometries of the tools are measured by a three-dimensional optical surface measuring system.

The performance of the hybrid deep drawing tools is investigated by deep drawing experiments based on the geometry of the test workpiece. A lubrication made of solvent refined mineral oil with a dynamic viscosity of 66 mm^2/s is used. The tools are installed in a 1000 kN hydraulic double-acting press. The blank holder is made of tool steel 1.2312. The formed parts are compared

Table 1
Properties of materials used.

Sheet metal	Thickness (mm)	E (GPa)	YTS (MPa)	UTS (MPa)	R_0	R_{45}	R_{90}
DP600	1.0	203	349	640	0.9	1.1	1.2
Polymermaterial	Density (g cm^{-3})	E (GPa)	UCS (MPa)	Poisson ratio			
PUR	1.67	8.3	92	0.4			
Epoxy	1.16	3.1	110	0.42			
Reinforcement fabric	E (GPa)	UTS (MPa)	Fabric weight (g m^{-2})	Weave			
Aramid	20	320	110	Twill			
Carbon	40	450	160	Twill			
Coating[a]	E (GPa)	UTS (MPa)	Wire diameter (mm)				
WC-FeCSiMn	~65	170	1.6				

E: modulus of elasticity, YTS: tensile yield strength, UTS: tensile ultimate strength and UCS: compressive ultimate strength.

[a] Measured at Chair of Materials Engineering at TU Dortmund [14].

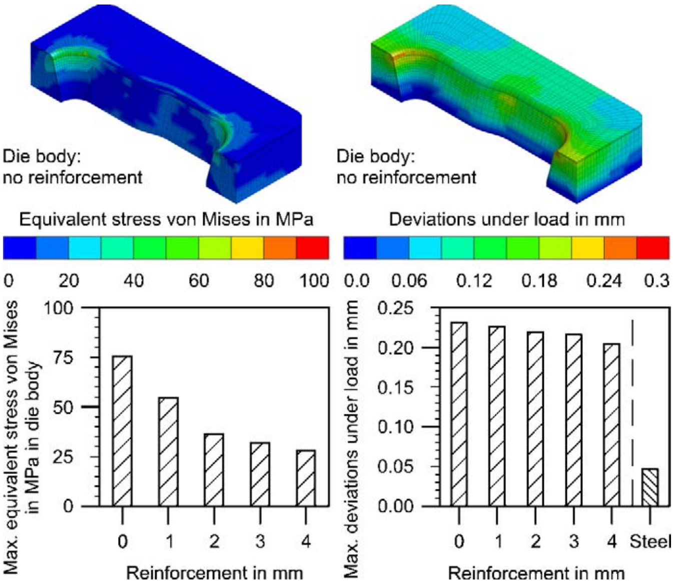

Fig. 4. Calculated stress distribution and form deviations of the die body.

with parts drawn by a reference tool made of conventional steel material 1.2436. For a wear resistance analysis the geometry of a hat geometry is measured repetitively after a defined number of forming operations.

4. Results and discussion

Stresses and form deviations under maximal load of the different die configurations with up to 4 mm reinforcement fabrics calculated by the finite-element-analysis are given in Fig. 4. The highest stress and deviation values are at the smaller radius of the die. The stress values of the pure polyurethane tool with no reinforcement reach almost critical levels (around 75 MPa) of the strength (92 MPa) of the polyurethane. The use of carbon fabrics significantly decreases the stress level within the polyurethane. High but uncritical values of stresses are reached in the fabrics. In general, more layers of fabrics lead to lower stresses in the polyurethane. Additionally, the use of the fabrics decreases slightly the form deviation of the die during the forming process. The lowest values are reached by the reference tool, which is modeled of steel materials, due to the higher modulus of elasticity.

Based on the numerical analysis, the die is laminated with a 2 mm thick layer of carbon fabrics. This thickness reduces the induced stresses in the polyurethane to a safe level. A thicker layer is not necessary, but would increase the material costs. Because the die is coated partially, a single fabric of aramid is used as the top layer. Aramid has a higher wear resistance than carbon. Six carbon fabrics are alternately draped in 0°/90° and −45°/45° direction to produce a quasi-transversal orthotropic 2 mm thick material. Finally, polyurethane is used as the back-fill material. The manufactured die is shown in Fig. 5. Due to uncritical stress values found in the numerical analysis, the coated punch is directly cast of polyurethane without reinforcement.

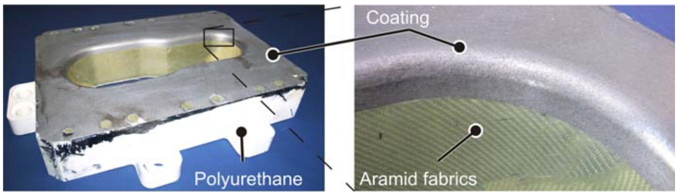

Fig. 5. Manufactured hybrid die with polyurethane cast material and aramid fabrics as reinforcement.

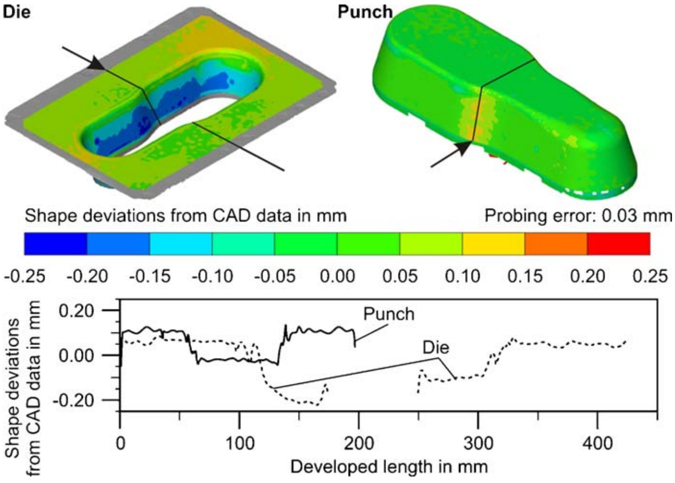

Fig. 6. Shape deviations from CAD data of manufactured hybrid tools.

The results of the shape deviations of the manufactured die and punch are shown in Fig. 6. The shape deviations of the die are higher than the deviations of the punch. The deviations of the punch range from −0.05 to 0.1 mm. Highest values are reached along the free-form shaped geometry (sectional view), which might be a result of the milling process which was applied to the original mould or a lack of a numerical description of the free-form shape. Form deviations of the die within the flange area are nearly constant, around 0.05–0.1 mm. The highest deviations are reached at the inner wall. Because this area is uncoated, the deviations are not a result of the coating process but of the milling process. In summary, the shape deviations are in an acceptable range. The tools are designed for immediate use in the deep drawing process. A finishing process is not necessary. The surface quality of the hybrid tools depends directly on the surface quality of the original mould. A selection of formed parts is shown in Fig. 7. All parts are formed without any process failure. Wrinkles are detectable at the round ends of the parts if the reference tool is used. Parts formed by the hybrid deep drawing tool show no wrinkles along the flange area. The reference tool made of steel has a higher stiffness due to the higher Young's modulus compared to the stiffness of the hybrid deep drawing tool. The lower stiffness of the hybrid tool leads to a more homogeneous contact pressure, because potential local inaccuracies of the tool manufacturing process are compensated. This homogeneous contact pressure prevents the development of wrinkles. However, compensation of inaccuracies of the manufacturing process is only possible as long as the local contact stresses are lower than the maximum strength of the polymer body. Both types of tools lead to smooth surfaces especially on the outer surface of the sheet metal parts. Here, parts formed by the hybrid tools have a smoother surface. Shape deviations between parts drawn by the hybrid tool and drawn by the reference tool are in a range of ±0.4 mm, which is a result of the accuracy of the

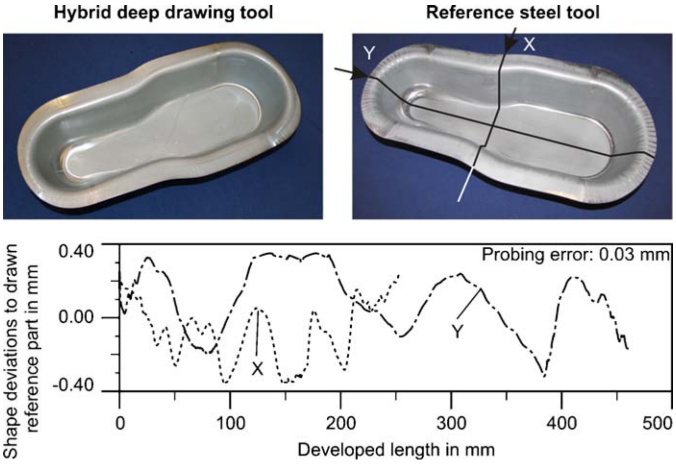

Fig. 7. Sheet metal parts drawn by hybrid and reference steel tool.

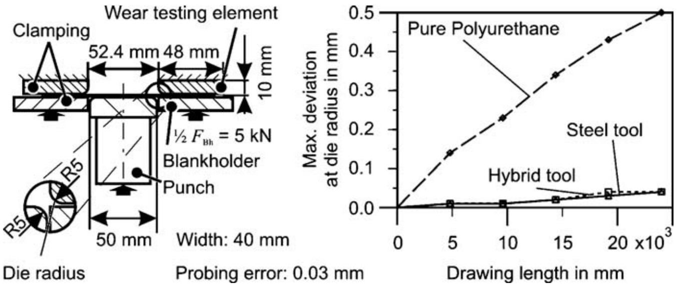

Fig. 8. Geometrical deviations of wear tool element.

manufactured tools and the different tool stiffnesses. In order to compensate springback effects, these differences have to be considered. At present, no compensating technique for the hybrid or reference tool is applied. Therefore, all parts have shape deviations to the CAD data.

After the forming process (50 strokes), defects on the hybrid tools are not observable. In some cases, small amount of zinc of the DP600 is deposited at the die radius. However, the deposited zinc deposition can be easily removed and shows no effects on the forming process. A second optical surface measurement of the geometries of the tools confirms that no plastic deformation occurred.

Similar results are confirmed in the wear analysis shown in Fig. 8. Due to the coated surfaces, the wear resistance is much higher compared to an uncoated polymer tool. The hybrid tool has a similar wear resistance like a reference tool made of conventional steel material in case of forming DP600.

5. Conclusions

In this study, a complex shaped deep drawing tool with a body of polymer, a layer of reinforcement and a hard coating is obtained by indirect spraying. A final finishing of the tool surface after the coating process is not necessary. The use of reinforcement fabrics of carbon in border areas of the hybrid tool reduces critical stresses, which occurs during forming of high strength steels, to safe levels in the polymer body. Additionally, the tool stiffness is modified by the reinforcement. Deep drawing tests show that the tool design is adequate to form high strength steels. Due to the lower stiffness of the tool compared to conventional tool setups, a more homogeneous contact pressure is realized, which avoid the appearance of wrinkles.

This new method of manufacturing deep drawing tools has proved to be applicable for small and medium batch productions of high strength materials. Advantages are the higher wear resistance compared to usual polymer tools and a more homogeneous contact pressure compared to conventional steel tools which reduces try-out time.

Acknowledgments

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