Additive Manufacturing of Tailored Blank for Sheet-Bulk Metal Forming Processes

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Abstract. Functional integration and lightweight construction pose increasing demands on manufacturing processes and require innovative approaches. In this context, sheet-bulk metal forming combines the advantages of conventional sheet and bulk forming processes expanding the limitations of these particular processes. However, the intended three-dimensional material flow contains major challenges regarding the material flow control. To enhance material flow control and part quality the application of process-adapted semi-finished products is an expedient approach for sheet-bulk metal forming processes. So-called Tailored Blanks have a process-adapted sheet thickness profile or combine different mechanical properties within a single blank and were applied in the 1980s for the first time. Since then tailored approaches gained in importance and find broad application in research and industry. At present, various technologies are used to manufacture Tailored Blanks. The Tailored Blanks applied in sheet-bulk metal forming are often manufactured by sheet-bulk metal forming processes themselves. The achievable gradient in thickness depends on various factors but is eventually constraint by the material volume of the initial blank. In this regard, Additive Manufacturing offers new possibilities to overcome those limitations and to expand the limits of sheet-bulk metal forming processes further. Additional material can be allocated with high geometric flexibility. Besides the allocation of additional material, this technology allows the manufacturing of discrete functional elements within the production of Tailored Blanks. In this investigation, Tailored Blanks made out of stainless steel are produced using sheet material and additively manufactured elements. These Tailored Blanks are processed in a deep drawing and a subsequent upsetting operation to manufacture a functional component with an external gearing. Conventional sheet material is also processed to compare the resulting part properties and to evaluate the different semi-finished product strategies. For this purpose, an analysis of geometrical as well as mechanical Tailored Blank properties is conducted. Furthermore, the part properties after deep drawing and upsetting are analysed. The investigation evaluates the potential for Tailored Blanks consisting of sheet metal with additively manufactured elements in sheet-bulk metal forming and conclusively points out the need for further research in this field.

1. Introduction

Nowadays, production technology is driven by increasing demands regarding lightweight construction and functional integration [1]. Conventional forming processes are often limited in terms of their flexibility as they are based on costly and time-consuming tool manufacturing. Hence, formed components can only be produced economically at high quantities. Innovative processes, such as Additive Manufacturing (AM), offer a high geometrical flexibility. However, these processes are often not profitable at high quantities. Therefore, a combination of AM and forming technology seems to be a promising approach to utilize the advantages of both processes while reducing the major disadvantages [2]. As forming technology, a combined deep drawing and upsetting process is used. This sheet-bulk
metal forming (SBMF) process enables the manufacturing of externally geared functional components out of sheet metal by inducing two- and three-dimensional stress and strain states [3]. These components are manufactured with different gear geometries. To realize failure-free parts at minimum weight, Tailored Blanks are manufactured and applied [3]. These blanks are manufactured in an orbital forming or a flexible rolling process and require a deep process understanding as well as costly tools and machinery to produce various Tailored Blank geometries. In this context AM enables the flexible manufacturing of different geometries with process-adapted sheet thickness profile without costly tooling.

2. State of the Art

SBMF forming processes combine the advantages of conventional sheet and bulk forming operations. The occurring two- and three-dimensional stress and strain state enable the manufacturing of parts with functional elements having a significantly higher thickness than the initial sheet thickness. As semi-finished product, sheet material with a thickness between one and five millimetres is used, according to [3]. To extend the forming limits even further, the bulk forming process is often combined with a sheet forming process, as in the process investigated. The basic shape of the component is deep drawn operation before the final contour is formed by an upsetting process within the same press stroke. As process failures for the application of conventional steel blanks with an initial diameter of \( d_0 = 100 \text{ mm} \) and an initial sheet thickness of \( t_0 = 2 \text{ mm} \) buckling and folding were identified in [4]. The reduction of these failures by the application of orbital formed Tailored Blanks was presented in [4] before they were avoided by adapting the Tailored Blank layout in [5].

By AM processes like powder bed fusion using a laser beam (PBF-LB) parts with high degree of geometric freedom can be produced. However, compared to conventional manufacturing processes as forming, the process time is relatively long. Therefore, it is beneficial to reduce the amount of additively manufactured part volume to a minimum. Hence, an innovative approach is the combination of additive manufacturing and forming, which is already investigated for hybrid parts consisting of a sheet metal body with an additively manufactured element [6]. Besides the application of AM material, the sheet metal is formed by bending or deep drawing, where two process chains; AM followed by forming or forming with subsequent AM are investigated [7]. In order to increase the flexibility of this process combination, incremental forming of the sheet metal body is beneficial, since geometric limitations with regard to the forming tool are avoided [8]. The approach of hybrid blanks can also be used to increase the sheet thickness locally by applying material to the sheet metal [9], which also can be used to reinforce a deep drawn cup leading to higher stiffness and load-bearing capacity of the formed part [2].

With regard to current research, the approach of hybrid parts focuses on the sheet metal or apply additively manufactured material on a formed part or a flat blank to increase die filling and improve part properties. A new approach is the use of additive manufacturing to accumulate material on a flat sheet metal to generate sufficient material for forming of functional elements from the AM material.

3. Process chain – Additive Manufacturing and Forming Concept

In this section the fundamentals of the processes to form and manufacture Tailored Blanks will be introduced. The conventional process chain consists of sheet bulk metal forming operations. In order to increase the material amount for forming of functional elements a material accumulation is applied to the sheet metal before the forming operation. The resulting subsequent process steps are PBF-LB for material accumulation on the sheet metal, followed by laser cutting to extract the specimens form the sheet metal body and finally forming by deep drawing and upsetting (Figure 2).

3.1. SBMF process combination

The process combination investigated combines a deep drawing and an upsetting operation within a single press stroke to enable the efficient manufacturing of externally geared functional components. The tool concept features four active components, as shown in Figure 1 a). Drawing die and upsetting punch are part of the upper tool, whereas drawing punch and upsetting punch are part of the lower tool.
In the initial position the semi-finished product is placed onto the deep drawing punch with a drawing punch radius of \( r = 1 \) mm and then clamped by the upsetting punch before the drawing die moves downwards to draw the cup. Subsequently, the upsetting punch displaces the drawing punch. As soon as the cup gets in contact with the upsetting plate, the cup wall is upset. The reduction of the cup height forces the material to flow radially into the gear cavity of the drawing die. The hydraulic press is a Lasco TZP 400/3 and the process proceeds force-controlled.

The functional component manufactured with the tool set-up described above is an externally geared cup with 80 teeth, as shown in Figure 1 b). The external diameter amounts to \( d_P = 82.72 \) mm and cup height depends on the maximum upsetting force \( F_U \). Due to the occurrence of identified process failures according to the State of the art, Tailored Blanks are manufactured by forming and applied in the process combination. For the target geometry two different Tailored Blank layouts were used within the research project. For layout 1 the area with increased material volume begins at a radial position of \( r = 40 \) mm on a blank with an outer diameter of \( d = 100 \) mm. This enables the preventions of buckling of the cup wall in a first step. With ongoing investigations, the radial position was adjusted to \( r = 35.2 \) mm to prevent folding of the material at the drawing punch radius as well. To investigate the fundamental applicability layout 1 was chosen in the first step, because layout 2 is much more challenging for the additively manufactured structure as in this case it is drawn over the drawing punch radius causing higher stress and strain states.

![Diagram of the combined deep drawing and upsetting process](image)

Figure 1: a) Set-up of the combined deep drawing and upsetting process and b) Functional component manufactured within the process

### 3.2. Additive Manufacturing

The manufacturing of Tailored Blanks is based on PBF-LB. The integration in the process chain is depicted in Figure 2. The process chain starts with laser cutting of a conventional sheet metal which is the initial plate of the PBF-LB process. The conventional sheet has the shape of the built plate of the AM machine. The second step is the manufacturing of AM structures on the sheet metal by PBF-LB. After additive manufacturing the specimens with a diameter of 100 mm are separated from the sheet metal by layer cutting. Due to the maximum size of the built plate four specimens can be manufactured on one conventional blank. These parts can be formed subsequently by deep drawing and upsetting. Regarding the final geometry of Tailored Blanks manufactured by SBMF the initial sheet thickness is \( t_0 = 1.5 \) mm with a material accumulation thickness of 0.9 mm. Since the process is a powder bed based layer by layer process starting from the surface of the conventional blank, the 316L sheet is clamped by counter sunk screws on the build plate.
As machine for PBF-LB is used a LT 30 SLM of the 2. Generation from DMG Mori, which is equipped with a 600 W fibre laser. The beam is shaped to a Gaussian profile with a minimum diameter of approximately 70 µm. To reduce residual stresses and avoid distortion of the sheet metal the heating of the build plate is set to 200 °C. In this type of machine the build plate has a maximum size of 300 x 300 mm², where the sheet metal is mounted. For manufacturing the material accumulation on the sheet metal by PBF-LB a volume energy of $E_v = 51 \text{ J/mm}^3$ is used. The powder size distribution ranges from 19 µm to 43 µm, which is typical for processing 316L by PBF-LB.

4. Results

The results for the combination of AM within SBMF are presented along the process chain. To evaluate the resulting part properties, the component manufactured using an additively manufactured Tailored Blank is compared to a component manufactured from a conventional stainless steel blank with an initial sheet thickness of $t_0 = 2 \text{ mm}$, according to [4]. The geometrical properties of semi-finished products and components were analysed by using the optical measurement system ATOS by GoM. Furthermore, the micro hardness was measured with a Fischerscope HM2000 by Helmut Fischer to evaluate the mechanical properties.

4.1. Properties of additively manufactured Tailored Blanks

To analyse the properties of the Tailored Blank, the blanks have to be extracted from the built plate by a laser cutting process. After digitizing the Tailored Blank the geometrical properties are evaluated. The thickness profile of the Tailored Blank is shown in Figure 3. In the evaluation range the thickness corresponds to the target thickness of $t_T = 2.4 \text{ mm}$. However, due to occurring distortion of the built plate during AM the sheet thickness in the outer area varies tangentially. Figure 3 presents the additively manufactured Tailored Blank, the adapted sheet thickness profile and the results for the micro hardness in the inner and outer area of the blank.
The initial hardness of the sheet material is in accordance with the requirements of conventionally manufactured 316L material [13] and is similar to the hardness in the inner area after the AM process, which is 191.35 ± 13.9 HV. This indicates a minor impact of the PBF-LB process step on the mechanical properties of the sheet outside the interaction zone. Whereas in the outer area which includes sheet metal and additive manufactured material the hardness is increased to 217.88 ± 36.4 HV. The increase in hardness is reasoned by the grain structure of the additively manufactured material. The metallographic structure of the AM part is needle-like in columnar grains throughout the weld beads [14]. This structure results from the high cooling rates during powder bed fusion.

4.2. Deep drawing of additively manufactured Tailored Blanks

In the deep drawing operation, the basic shape of the component is formed. In contrast to the application of orbital formed Tailored Blanks the deep drawing process represents the first forming operation in the AM-supported process chain. The resulting cup height after deep drawing is $h_c = 14.74$ mm and the material volume in the cup wall amounts to $V_w = 6830.35$ mm$^3$. The increased sheet thickness in the outer area provides an increased material volume for a higher die filling within the subsequent upsetting process, as shown in Figure 4. Nevertheless, the contour of the drawn cup shows the minor sheet thickness in area of the drawing punch radius. This minor sheet thickness leads to folding of the material according to [5]. The geometrical properties correspond to the resulting properties for Tailored Blanks manufactured by forming.

The hardness in the area of the bottom of the cup amounts to 213.98 HV0.05. Compared to the initial hardness this is an increase of almost 12%. However, the hardness in the cup wall increases by 60% during the deep drawing operation in order to higher strains in this area.
Figure 4: Geometrical and mechanical properties for the additively manufactured Tailored Blank after deep drawing

4.3. Upsetting of additively manufactured Tailored Blanks

The upsetting operation proceeds after the deep drawing operation, though within the same press stroke. As intended, the comparison of the contours in Figure 5 shows, that the increased sheet thickness prevents buckling of the cup wall. A maximum upsetting force of $F_U = 1,000$ kN was chosen. This results in a cup height of $h_C = 9.32$ mm for the final component. To evaluate the properties of the functional component and to analyse the applicability of AM for Tailored Blanks in SBMF processes the manufactured component is compared to a component manufactured by applying a conventional semi-finished product with an initial sheet thickness of $t_0 = 2$ mm. The conventional semi-finished product was also upset with a maximum upsetting force of $F_U = 1,000$ kN. Compared to the Tailored Blank, the resulting cup height is 0.43 mm higher, due to uncontrolled buckling and strain hardening of the cup wall during the forming operation. For the material volume in the gear cavity, the Tailored Blank allows an increase of up to 15%. The weight of the component can be reduced by more than 10% with improved geometrical properties for the application of the additively manufactured Tailored Blank, assuming a density of 7.8 g/cm$^3$. Beside geometrical properties the upsetting process also has an influence on the micro hardness in the bottom and cup wall for conventional semi-finished blank and AM Tailored Blank. Regarding the initial hardness values for the austenitic stainless steels for both types of blanks the hardness increases moderately in the bottom area but severely in the cup wall. For the conventional semi-finished product with an initial hardness of 191.65 HV0.05 the micro hardness in the bottom amounts to 302.26 HV0.05 and to 426.60 HV0.05 in the cup wall. For the AM Tailored Blank the values amount to 219.78 HV0.05 and 363.87, respectively. The high increase in hardness in the cup wall is reasoned by strain hardening of the sheet metal and additively manufactured material due to the forming operation. Since the stress and strains during upsetting are significantly higher compared to the deep drawn condition the work hardening and hardness are higher in this area. For the conventional sheet metal with $t_0 = 2.0$ mm the forming operation results in higher hardness than for the Tailored Blank since the buckling and folding of the sheet lead to even higher strains and increased inhomogeneity of the hardness distribution. The inhomogeneity can be evaluated over the standard deviation, shown in Figure 5. The increase of material flow control and the improved part properties represent the main advantages of the application of Tailored Blanks in SBMF processes.
4.4. Adaption of the Tailored Blank layout

Based on previous research, buckling was prevented by increased sheet thickness in the outer area of the blank and the fundamental applicability for additively manufactured Tailored Blanks in SBMF was verified. In a next step, the radial position of the area with increased thickness is adapted to prevent folding as well. The adapted layout was chosen according to [5] and is presented in Figure 6.

The broader radial material accumulation represented by layout 2 is beneficial for a longer tooth length and therefore results in a higher volume of functional elements along the cup wall. During deep drawing of the Tailored Blank with layout 2, fracture of the additively manufactured structure occurs on the upper side of the blank. In this area of the drawing punch bending stresses are predominant [15]. This indicates that the bending stress has an influence on the forming limits of the sheet metal with additively manufactured material. A possible explanation for the initialization of cracks is the increased stiffness in this area of the tailored blank due to the material accumulation. Regarding to the assumption of bending stresses a higher stiffness leads to higher bending resistance and with that to higher stresses on the surface. However, the fracture behaviour needs further investigation for example by analysing different forming states of the cup concerning crack initiation and fracture.

Furthermore, the high flexibility of AM enables the realization of a broader spectrum of Tailored Blank layouts. Analogous to the research on SBMF, the manufacturing of Tailored Blanks with discrete functional elements as well as a combination of additively manufactured and orbital formed Tailored Blanks is investigated. Exemplary layouts defined within the present investigations are shown in Figure 7.
Figure 7: a) Realizing discrete functional elements within the manufacturing of Tailored Blanks and b) combination of additively manufactured and orbital formed Tailored Blanks

The Tailored Blank with discrete functional elements can easily be adapted to various teeth geometries and the combination of AM and forming within the production of Tailored Blanks enables the flexible manufacturing of components with two-sided functional elements. However, the AM structures have to be manufactured first in the presented process chain and therefore, cavities for these elements have to be arranged in the tools for the subsequent forming process.

5. Conclusion and outlook

By combining additive manufacturing and sheet bulk metal forming operations as deep drawing and upsetting it is shown that the forming of tooth geometry can be improved by material accumulation compared to conventional blank without material accumulation. The presented approach offers the opportunity to manufacture different Tailored Blank geometries due to high geometric freedom of additive manufacturing, whereas the geometry is limited to the tool geometry in case of conventional forging operations. The radial material accumulation on the sheet metal surface is manufactured by PBF-LB, which results in higher hardness for AM material than for the sheet metal material. Compared to the initial state the hardness increases after deep drawing and especially after upsetting due to strain hardening. Regarding previous research two layouts of material accumulation with different radial position are investigated to evaluate the impact on the formability of the tailored blank. In case of a broader AM material accumulation the volume fraction of functional elements represented by the length of the tooth geometry is increased. This indicates that this layout is beneficial for manufacturing of functional parts made by additive manufacturing and forming. However, the bending stress in the area of the drawing punch results in fracture of the additively manufactured material characterized by cracks in the surface. Therefore, further investigations should focus on the identification of mechanisms of failure in the AM material and the sheet metal. Besides, the possibility of geometric flexibility of PBF-LB should be exploited to create a geometry which reduces the strains in the additively manufactured material. A promising approach is to process the Tailored Blanks with discrete functional elements manufactured by PBF-LB in the combined deep drawing and upsetting process. This could decrease strains in the forming zone and reduce form filling of the tooth geometry since the main part to be formed is the sheet metal. Furthermore, an upgrading of the tools for orbital forming should be taken into account for the manufacturing of two-sided functional components. In addition, the orbital forming process could also be used to calibrate and to adjust the geometrical and mechanical properties of the additively manufactured elements prior to the final processing.

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