Investigation of the Influence of Slightly Increased Process Temperatures on the Extrusion of Functional Aluminum Components in Sheet-Bulk Metal Forming

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Abstract. By using high-strength aluminum, weight savings can be achieved. However, limited formability of these alloys at room temperature is a challenging aspect regarding the manufacturing of components with filigree functional elements within sheet-bulk metal forming. So as to derive detailed process knowledge and to improve the achievable process results, forward extrusion of geared components made of EN AW 6082 sheets at room temperature is investigated within this work. Furthermore, robust large-scale industrial cold forming is a demanding task, as tool temperatures increase over time due to forming and frictional heat, leading to varying material and process properties. In order to determine measures for the compensation of these fluctuations, additional experiments are carried out with slightly increased tool temperatures. By analyzing workpiece and process related parameters for both sets of experiments, potential approaches to control the outcome of forming operations under variable conditions are discussed.

Keywords: Sheet-Bulk Metal Forming · Extrusion · Aluminum

1 Introduction

Ecological and economic challenges define the requirements for modern manufacturing of components in the industrial environment [1]. In various domains, this leads to the fact, that high volume manufacturing processes become more complex and more demanding in terms of a robust implementation [2]. On the one hand, it is increasingly important to produce near net-shape and functionally integrated components, which then leads to difficulties in forming these workpieces [3]. On the other hand, this challenging setting is further intensified by the fact, that high-strength lightweight materials like precipitation hardenable aluminum are increasingly used [4]. These are characterized by low formability at room temperature. However, cold forming of these alloys is beneficial as process chains can be shortened, as preliminary and subsequent energy-intensive heat treatment can be avoided. Furthermore, good mechanical properties of the components can be achieved due to strain hardening in cold forming [4]. Another main aspect of

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modern manufacturing is the development of a robust production chains with the lowest possible scrap rates across different production batches [2]. However, transient process conditions can occur during the run-in phase in cold forming. As a consequence of forming and frictional heat, the temperature of the used tool set increases [5]. During the manufacturing of the first 100 components tool temperature rises [6] and may reach values up to 80 °C [7] and thus altering tribological conditions in this timeline [5]. In the course of this study, it is the objective to investigate the effects of these fluctuations on an extrusion process of geared components within sheet-bulk metal forming (SBMF). Characteristic for this process class is the application of bulk forming operations on sheet metal in order to manufacture filigree functional elements. This results in complex process conditions, leading to restrictions with regard to the geometric accuracy of components and the overall achievable die filling of functional elements [8]. In previous studies, the local adaption of the tribological system presented an effective approach to control the material flow, therefore improving the process results [9]. For this reason, the influence of fluctuating mechanical and tribological conditions as a consequence of tool heating in high volume manufacturing and possible compensation measures for this behavior will be investigated in the following.

2 Experimental Setup and Methodology

In order to analyze the impact of tool heating as a consequence of frictional and forming heat in high volume manufacturing on an extrusion process within sheet-bulk metal forming, both the implication on the mechanical forming and on the tribological conditions are investigated within this study. For this purpose, experiments are conducted at room temperature (RT), 50 °C and 80 °C, which represents the temperature range cold forging tools can reach [7].

2.1 Materials

As workpiece material for the investigation the precipitation hardenable aluminum alloy EN AW 6082 in the artificially aged T6 condition and an initial sheet thickness of $t_0 = 2$ mm is chosen. Due to its lightweight potential, which is a consequence of its high mechanical properties, application areas for this alloy are for example forgings and structural components in the automotive sector [10]. For the mechanical characterization of the material layer compression tests in accordance to DIN 50106 [11] were conducted on a thermomechanical simulator Gleeble 3500 by Dynamic Systems Inc. With a constant upsetting speed of 5 mm/min. This machine enables the controlled heating of the specimen during the experiment through resistance heating. At room temperature (RT) the material is characterized by an initial yield stress of $k_{f0,RT} = 252.4$ MPa. When increasing the temperature, the initial yield stress is reduced to values of $k_{f0,50\,°C} = 240.5$ MPa at 50 °C and $k_{f0,80\,°C} = 233.4$ MPa at 80 °C, which correlates to a total reduction of 7.5%.

For the realization of the forming experiments, the wax-based and water-soluble Lubricant Beruforge 152DL (BF 152DL) is used. The application of the lubricant is possible without the necessity of a conversion layer on the workpiece [12], thus providing shorter process chains and ecological benefits. Furthermore, BF152DL was characterized as suitable for the demanding process requirements of SBMF as it provides advantageous tribological conditions with low friction factors during forming [13]. All used active tool components are made of the powder metallurgical cold working steel K890 microclean by voestalpine Böhler, which is hardened to 63 + 2 HRC. The resulting surfaces of the active tool set is obtained by hard-machining operations.

2.2 Forming Experiments

Tribological Charactization. For the tribological characterization ring compression tests (RCT) according to Male and Cockroft [14] are carried out at the chosen temperatures in order to inversely derive the corresponding friction factors m. The inner diameter of the ring-shaped specimen is evaluated after upsetting, since the predominant friction conditions have a significant influence on this characteristic value. The adaption of this test procedure to the process conditions of SBMF was conducted by Vierzigmann [13]. For the characterization of sheet metal, the specimen geometry is machined by wire electrical discharge machining to an inner diameter of 9 mm and an outer diameter of 15 mm. The upsetting of the specimens to 50% of the initial sheet thickness is performed on a hydraulic press Lasco TSP100SO with a forming speed of 5 mm/s using cylindrical and parallel anvils, which are also equipped with ceramic insulated heating bands. Subsequently, the resulting inner diameters are measured on a coordinate measuring machine. For the experiments, the lubricant amount is set to 10 g/mm2. The numerical modeling of the RCT is carried out in the simulation software Simufact. forming 2021.1, in order to inversely determine the resulting friction factors. For this purpose, calibration curves in dependence of the inner specimen diameter are interpolated with a rational model in Matlab for each forming temperature.

Experimental Analysis of the SBMF Process. The experimental analysis of an SBMF forward extrusion process is carried out on a tool setup, which can be seen in Fig. 1. This setup is used in a triple acting hydraulic Press Lasco TZP400/3 at a forming speed of 5 mm/s. The active tool set consists of the forming punch and die, which can be heated up by ceramic insulated heating bands, and a counterholder. To control the forming stroke of the process, mechanical stops are integrated in this tool setup, which can be adjusted with steel foils in a minimum of 0.05 mm increments. In order to achieve a uniform temperature distribution in the components for the forming experiments at elevated temperatures, the experiments are started minimum 50 s after the workpiece have been placed into the tool system.

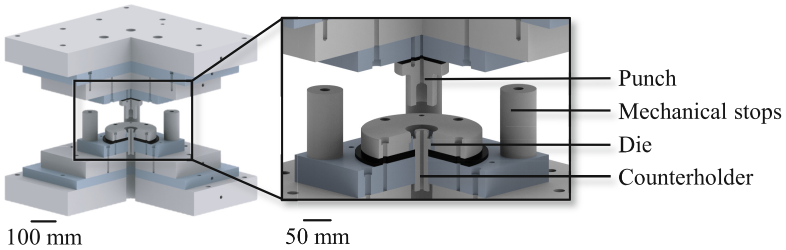
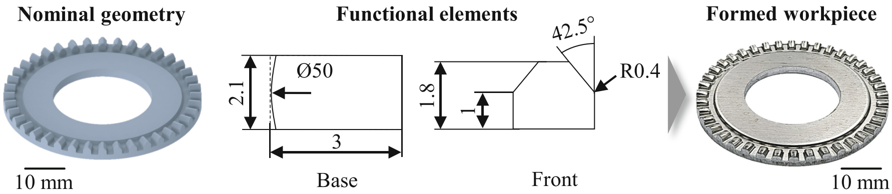


Fig. 1. Tool setup for the forward extrusion of geared functional elements

The investigation geometry for the forming experiments within this study is a planar and geared workpiece (see Fig. 2) with 40 abstracted locking teeth on its outer diameter. These functional elements are formed on ring-shaped blanks with an inner diameter of 25 mm and an outer diameter of 50 mm. The performed forming stroke is set to a reference value of s = 0.6 mm, which in theory results in a complete die filling of the functional elements. This is controlled by the measurement of the residual material thickness in the displacement zone around the functional elements with a micrometer.



Workpiece Geometry			
All dimensions in mm			
Initial sheet thickness	2 mm	Functional elements	40
Inner diameter	25 mm	Outer diameter	50 mm
Radii functional elements	0.3		

Fig. 2. Workpiece geometry of the investigated functional component

In Fig. 3a schematic depiction of the forward extrusion process is given. At the beginning, the blank is placed on the hydraulically actuated counterholder, which applies a constant pressure of $\sigma_{CH} = 120$ MPa in the workpiece center, preventing a crowning of the blank during forming. The punch movement then displaces the counterholder until the forming die is reached and the functional elements are formed onto the workpiece. Due to the locally varying forming loads, which are characteristic for SBMF, unintended material flow towards the workpiece center occurs, resulting in incomplete die filling of the functional elements [9]. In order to analyze this behavior for the conducted experiments, the complete geometry of the formed parts is optically measured with the system ATOS by Carl Zeiss GOM Metrology GmbH. Subsequently, the volume of only the functional elements is derived in the OpenSource software CloudCompare by boolean operations.

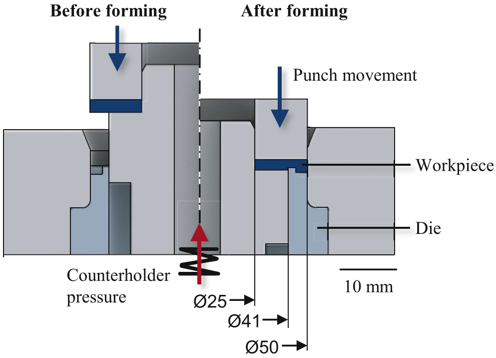


Fig. 3. Forming procedure for the forward extrusion of geared components

3 Results and Discussion

A significant influencing factor for the forming results in SBMF is the resulting tribological condition during forming [13]. For this reason, temperature dependent friction factors are inversely determined in RCTs. In order to verify the validity of the simulation model and the derived calibration curves, the experimental and numerical findings are at first compared in Fig. 4 according the procedure in [15]. Regarding the maximum forming force F_{max} (Fig. 4a) a deviation of 1.2% at room temperature and 2.0% at 80 °C is evident, when comparing the numerical and experimental data for the determined friction factor. Another indicator for good accordance of the numerical model is the correlation of the deformation behavior in experiment and simulation. Therefore, the simulation based true plastic strain φ and the microhardness HV 0.05, which correlates with the degree of plastic material deformation in experiments [16] and which is measured on a Fischerscope HM2000 by Helmut Fischer GmbH according to DIN EN ISO 14577–1, are contrasted. For both temperatures, the deformation distribution is in good agreement, proving the validity of the model.

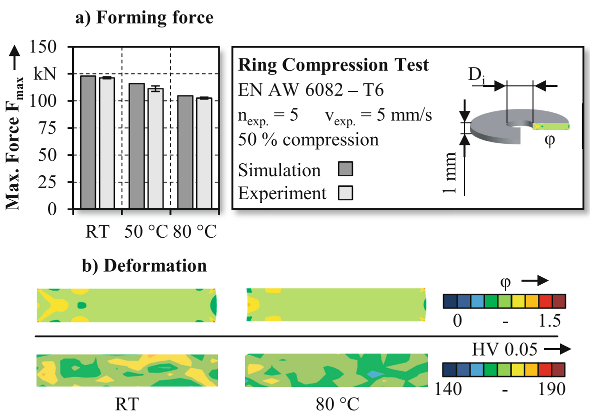


Fig. 4. Comparison of the resulting a) forming forces and b) deformation distribution in the numerical analysis and experimental data of ring compression test

The influence of the forming temperature on the resulting friction factors of EN AW 6082 when using the lubricant BF152DL in RCTs is shown in Fig. 5. At RT, the friction factor of $m = 0.08 \pm 0.02$ is determined as a reference. As a consequence of this relatively low value, it can be concluded that the lubricant provides a sufficient tribological systems for the requirements of SBMF, as stated in former studies [13]. When the forming temperatures are increased, a reduction of the friction factors up to $m = 0.06 \pm 0.01$ at 80 °C is measured. This is can be explained by two overlapping influencing parameters, since increasing the forming temperature changes the mechanical flow behavior of the material on the one hand and the lubricant properties on the other. Similar results were also reported by Bay [6] in the bulk forming of steels, where the coefficients of friction decreases up to minimum at a forming temperature of 130 °C.

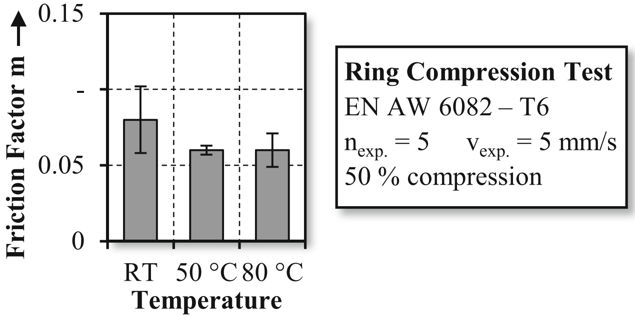


Fig. 5. Resulting friction factors at RT, 50 °C and 80 °C from RCT

In the next step, it will be investigated how these tribological conditions at slightly increased forming temperatures affect the extrusion of functional thin-walled workpieces. The results for the forming experiments with a constant forming stroke of $s = 0.6$ mm are given in Fig. 6. In order to compensate thermal expansion of the active tool set and differing forming conditions, adjustments to the mechanical stops are necessary to maintain the desired resulting forming stroke, which is the case for the experiments at 80 °C. Additional 0.05 mm have to be added to the mechanical stops at this forming temperature. Due to the reduced mechanical properties and frictional forces during forming, a linear decrease of the maximum forming force from $F_{max} = 634.1 \pm 8.0$ kN at RT to $F_{max} = 591.4 \pm 2.7$ kN at 80 °C is measured in the experiments (see Fig. 6a). Furthermore, the resulting die filling of the functional elements increases for the experiments at 50 °C and 80 °C, also as consequence of the reduced mechanical properties of the material (see Fig. 6b).. This influence apparently exceeds the effect of friction, since a reduced friction factor is accompanied by lower die filling in SBMF [9].

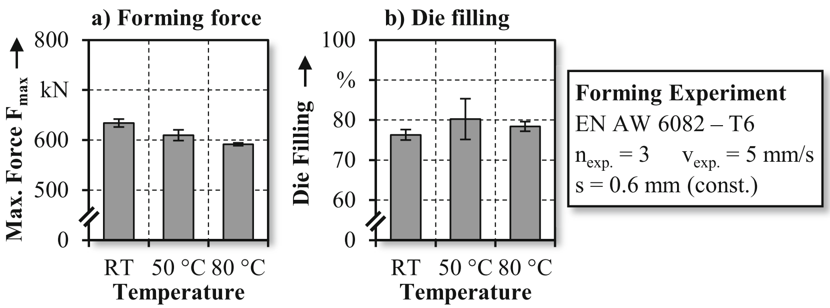


Fig. 6. Influence of the forming temperature on the a) maximum forming forces F_{max} and the b) resulting die filling at a constant forming stroke of s = 0.6 mm

To derive controlling measures for process control regarding the transient forming temperatures in high volume production, further experiments without adjustments to the mechanical stops at 80 °C were carried out. This results in an increased effective forming stroke as a consequence of thermal expansion of the active tool set. As can be seen in Fig. 7a, the maximum forming forces at 80 °C without the adjusted forming stroke reach the level of the experiments at RT with a forming stroke of s = 0.6 mm while the die filling approximately increases to the value of experiments with an set forming stroke of s = 0.7 mm at RT (see Fig. 7b). For this reason, only monitoring the forming forces of an ongoing production process with transient forming conditions may not be sufficient, to identify intervention points for in-situ process adjustment. Overlapping effects, in this case the increasing die filling, may mask the changes in the resulting forming force, so that the geometric result can deviate unnoticed over time.

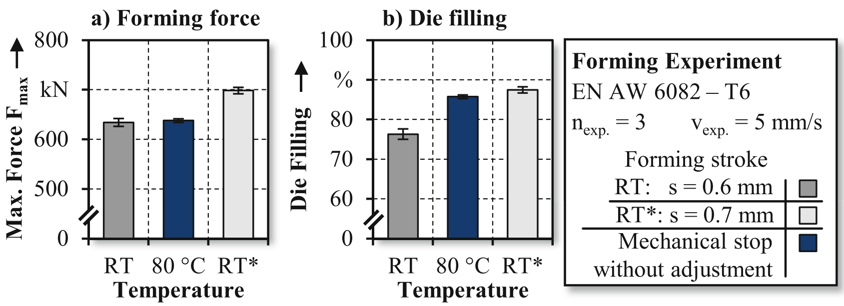


Fig. 7. Resulting a) maximum forming forces F_{max} and b) die filling without the adjustment of the mechanical stop due to thermal effects

Furthermore, the workpiece properties have to be analyzed, in order to evaluate the impact of differing forming temperatures on the manufactured components properties. For this reason, the microhardness distribution of the formed components is depicted in Fig. 8. In experiments with a constant forming stroke of s = 0.6 mm no significant differences are visible regarding the different forming temperatures RT, 50 °C and 80 °C. In general, an increase of the microhardness values can be seen within the displacement zone and the gearing elements. Maximum values occur in the radii of this area, as the main deflection of the material is located there. In the workpiece center, no significant material deformation takes place and therefore the measured microhardnesses remains at the level of the initial hardness of the base material. As discussed earlier, without the adjustment of the mechanical stops at the forming temperature of 80 °C, die filling of the functional elements is increased and therefore comparable to the results at a higher forming stroke s = 0.7 mm at RT. For this reason, the microhardness plots of these two variants are discussed in the following. To facilitate the increased die filling, a higher degree of material deformations is necessary, which then leads to overall higher microhardness values. Furthermore, more material is also displaced into the workpiece center unintentionally, which explains the higher microhardness values in these areas compared to the experiment with a forming stroke of s = 0.6 m. However, when comparing the last two variants, lower microhardness values are measured for the workpiece formed at 80 °C (without adjusted mechanical stops), indicating the influence of the raised forming temperature on reduced strain hardening of the material. This shows the challenging aspect of an in-situ adjustment of process parameters in high volume manufacturing, since interactions between a geometry-based process control and the resulting component properties are in part contrary.

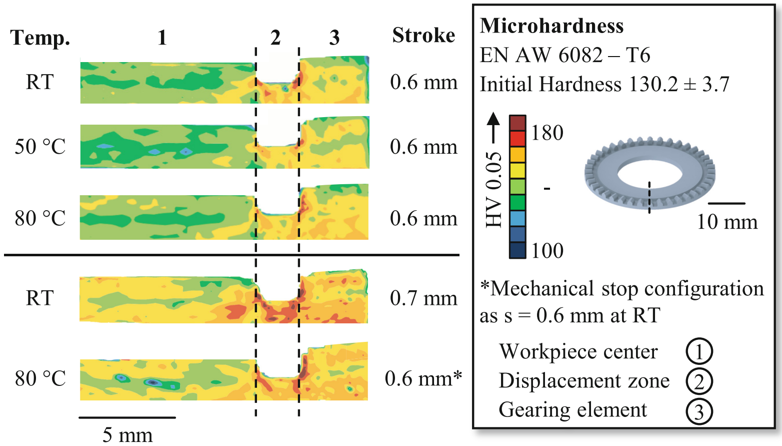


Fig. 8. Influence of the process temperature on the microhardness distributions of the formed parts

4 Summary and Outlook

Within this study, the influence of slightly increased forming temperatures as a consequence of frictional and forming heat in high volume manufacturing in a SBMF extrusion process was analyzed. These transient forming conditions were replicated by conducting experiments with a heated tool system. The results of these investigations show an increase in the die filling of functional elements, when the forming temperature is increased. If this requires an adjustment of the process parameters to guarantee a robust forming outcome, resulting forming forces are of limited suitability to define intervention points for the process control, as this parameter can partially mask changes in the resulting die filling. Further investigations should focus on the influence of transient forming conditions on the operational behavior of workpieces in order to derive holistic measures for robust in-situ process control incorporating the workpiece geometry and properties. Thereby, waste reduction in the run-in phase of high volume production can be achieved. Furthermore, interdependencies of transient forming conditions with local tool-sided surface modifications should be investigated, as these present a valid measure for improving the forming results in the field of SBMF. Additionally, transmission of these findings to coil-based forming operations is necessary in order to generate a fundamental and transferable understanding of the impact of transient forming conditions on the high volume forming of filigree functional components.

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