Cryogenic deep drawing of aluminum alloy AA6014 using macro-structured tools

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Abstract. For functional lightweight construction, 6xxx aluminum alloys are essential materials for exterior components due to their low weight to stiffness ratio and acceptable formability. The formability of the 6xxx alloys is lower compared to other aluminum alloys but they are free of flow lines. MOUSAVI ET AL. [1] demonstrate an alternative method of improving the forming limit with a deep drawing process using macro-structured tools. Another approach increasing the formability of aluminum alloys is forming at cryogenic temperatures [2]. This paper presents an advancement of deep drawing on macro-structured tools at cryogenic temperatures. This assumes a lower heat flux due to the reduction of the contact area between the blank and deep drawing tools, enabling forming at cryogenic blank temperature. After characterization of the material, experimental investigations are carried out on a cup test geometry. In addition to the required punch force at different temperatures, this paper presents the influence of macro-structured tools at cryogenic temperatures on springback and hardness distribution. Finally, the extension of the process limits and options by cryogenic macro-structured deep drawing are discussed.

1. Introduction
Functional lightweight design is an essential factor in production processes in terms of resource efficiency and environmental considerations. Optimized material utilization with the usage of FEM and adapted tools for improving the material flow in forming processes repeatedly push process limits and production advances into new unknown fields. The main fields are the automotive industry with their structural and body components whereas parts for household applications, e.g. white goods and the aerospace sector are other versatile fields of application [3]. Various research projects are carried out in order to increase the forming capacity without forming defects such as thinning and wrinkling in the deep-drawn part [4]. In addition to new developments in materials with anisotropic behavior which involves new challenges for testing and modeling material behavior [5], tribology in the forming process is one of the crucial factors for component quality [6].
2. State of the art

2.1. Lubricant-free deep drawing processes with macro-structured tools

In order to manage the lubricant free deep drawing on the one hand, and at the same time to reduce the number of process steps in an environmentally conscious manner by making cleaning processes unnecessary on the other hand, a special research area on dry forming has been established [7]. Starting with the oil crisis of the 1980s, there has been ongoing research for realizing lubricant-free forming that can be divided into three main categories: the use of ceramic tools [8], self-lubricating coatings [9], and hard coatings [10]. All these methods follow the same underlying principle, namely to use a coating or a special material surface in order to reduce the friction between tool and sheet metal without overall changes in the tool geometry. As an alternative approach, the macro-structuring of the tool in the flange area as presented in [11] has proven to be extremely advantageous for the forming process. The macro-structured tool works with a defined wavelength \( \lambda \) and immersion depth \( \delta \), see Figure 1 (a). By turning away from the conventional design of deep-drawing tools with a standard flat blank holder/drawing ring combination, several positive effects can be observed with regard to the process and the component. The contact area changes from full-surface contact to point or line contact and is reduced by up to 80%. Due to that, friction force is reduced dramatically. During deep drawing, the part shows a resistance against wrinkling, a better control of the material flow and a larger process window can be achieved, see Figure 1 (b). The alternating bending induced in the flange area increases the buckling stiffness of the sheet metal, which prevents the formation of wrinkles and thus enables a significant reduction in the required blank holder force [12]. Regarding the springback MOUSAVI ET AL. have shown in [1] that springback in deep drawing cups can be reduced by macro-structured tools due to the load reversal and restraining force caused by the macro-structure. In the broadest sense comparable to this approach are tailor-made adaptation of the tool surface [13] or the micro-structuring of the tool faces especially in the field of micro-forming processes [14]. The macro-structuring of the tools represents an innovative novelty in the field of sheet metal forming.

2.2. Deep drawing at cryogenic temperatures

Cryogenic manufacturing processes are mostly common in the area of machining and cutting applications [15]. Forming processes are usually performed at or above room temperature (RT), in case of hot forming up to several hundred degrees Celsius, for the best results [16]. However, aluminium alloys can be processed in cryogenic as well as at RT and warm temperatures. In the late 70s a patent was presented for a hydrostatic bulge test at -196 \(^\circ\)C [17]. In these tests, an increasing work hardening and a reduced thickness variation
was observed. Further investigations were performed in the early 80s by Binning and Partridge [18] for greater sheet thicknesses on AW2xxx aluminium and titanium alloys in tensile tests, whereas similar effects occur.

The usage at room temperature is sometimes limited due to defects in the surface, resulting in flow lines and a limited tensile elongation [19]. It is known, that yield strength, ultimate tensile strength, and tensile elongation of such aluminium alloys increases at cryogenic temperature while the fracture mechanism is similar to the one at room temperature. [20]. Sotirov et al. [21] examined the increasing strength, ductility and forming limits at decreasing temperature for AW5182 and showed a suppressed Portevin-LeChatelier effect [22] at cryogenic conditions. Beside the strength and ductility, deep drawing of aluminium alloys at cryogenic temperatures enhances the deep draw ability. Yuan et al. reached an increasing deep draw ration of 15.6 % compared to deep drawing at room temperature [23]. Similar effects on AW6014 were investigated by Kumar et al. who pointed out a significant increasing elongation at fracture and strength of AW6016 with decreasing temperature [24].

Summing up the current state, macro-structured deep drawing as well as deep drawing at cryogenic temperatures have several positive effects on the material flow, the microstructure and especially the drawing limit ratio of aluminium alloys. The logical question now is, whether a link of both approaches leads to a further expansion of the process window.

3. Macro-structured cryogenic deep drawing
Motivated by the possibility to expand the process window for deep drawing the aim of the investigation is to evaluate the effects of deep drawing of Al–Mg–Si alloys with macro-structured tools at cryogenic and room temperatures that represents the limits of temperature range for these feasibility study. It is assumed that the line contact between the macro-structured tools and the blank results in a reduction of the heat flux between tools and blank that enables deep drawing with improved material properties at cryogenic temperatures of the sheet metal. In addition, a forming process without the usage of lubricants is implemented.

As a first step, experimental investigations with a rotationally symmetric cup were performed on a universal testing machine BUP600. The evaluated parameters are the needed punch force for receiving a part without wrinkles or other failures. Thereby the influence of the temperature on the punch force can be demonstrated. Following the tests, destructive examinations of the drawn cups are carried out in order to determine results for the springback inside split rings. Additionally, the hardness distribution on the cup cross section is proved for cryogenic and room temperature and the surface. A numerical analysis finally compares the deep drawing process of the cup at room temperature and cryogenic temperatures.

3.1. Experimental setup
Basic comparative tests are carried out with a macro structured, rotational symmetric tool, see Figure 2b, and sheet metal temperatures $\theta = 20 \, ^\circ C$ and $\theta = -196 \, ^\circ C$. The tool consists out of a die and a blank holder, both with a wavelength $\lambda = 12$ mm. The immersion depth $\delta$ is realized by spacers with defined thickness, placed on the outer part of the tools. The die radius $r_{\text{die}} = 10$ mm and the suitable punch diameter is $d_{\text{punch}} = 100$ mm. For a better understanding, the profile of the macro structure is depicted in Figure 2.

Before testing, the tools and the specimens from AW6014-T4 with an initial sheet thickness $t = 1.00$ mm were cleaned with an abrasive sponge and acetone in order to guarantee a clean and lubricant free surface. The round blanks were laser-cut with a diameter of $D = 160$ mm. For the tests, the specimens were placed in an isolated box filled with liquid nitrogen to reach a temperature of $\theta = -196 \, ^\circ C$. The investigated immersion depth parameters are $\delta = 0.2$ mm and $\delta = 0.4$ mm according to Mousavi [12] who pointed out a good process stability for these amounts of immersion depth. The testing was performed at cryogenic and room temperature, consistently without lubrication. After a short transfer process into the prepared tool, the
deep drawing process started immediately. The tool itself was not cooled in this experimental setup. The cups were fully drawn with no remaining flange area with a height of about 40 mm.

For investigating the springback, the ring splitting method, developed by SIEBEL AND MÜHLHÄUSER [25], is used to evaluate the residual stresses in the specimen, by cutting a ring from the wall of the deep drawn cup and subsequently split open. Additionally, the hardness distribution in the cross section of the deep drawn cups are determined.

3.2. Numerical setup
In order to investigate the forming process a finite-element-model was built using LS-Dyna R12.0.0. Due to the rotational symmetry, the cup is reduced to a quarter to save time and resources in the calculation process but allows the consideration of the anisotropy, see Figure 3 (a).

The setup was prepared and evaluated in LS-PrePost V4.8.9. The blank was meshed with an initial element length of 2 mm with adapted refinement with maximum of four refinement steps. A fully integrated 3D-shell element was used (ELFORM16) with nine integration points through the shell thickness in order to ensure accuracy in simulation. All tool parts were defined as rigid bodies. The movement of the punch was described by a predetermined displacement-curve. The contact conditions are set by a one-way surface to surface definition. The calculation was performed explicit with a mass scaled solution. Friction was realized by a Coulomb friction model with a friction coefficient $\mu = 0.15$. The material behaviour is modelled by material type MAT36 (3-Parameter BARLAT) [26]. The values for RT based on the tensile tests performed on a HEGEWALD&PESCHKE inspect250 material testing machine according to and
EN ISO 6892-1 [27], evaluating using the DIC system GOM® Aramis 2019. For calculation of the cryogenic forming process, the material data from SCHNEIDER ET AL. [28] for an aluminium alloy AW6016 was used. Taking into account the examination of YUKI ET AL. [29], AA6016 and AA6014 show similar characteristics regarding the elongation and flowcurve, the same characteristic values were used for the first investigations. With the current, non-isolated test setup for material characterization, it was not possible to guarantee a uniform temperature distribution in the samples, which is why literature values were used in the investigations for now. Figure 3 shows the geometry of the model (a) and exemplary a comparison of the resultant numerical and experimental punch force for standard and macro-structured tools ($\delta = 0.2$ mm) at cryogenic temperature in Figure 3 (b).

4. Results and discussion

In Figure 4, the required punch force at different temperatures is shown for macro-structured and standard deep drawing tools. The punch force curves for deep drawing aluminum with standard tools shows a similar course for blank temperature at cryogenic and room temperature. Due to the great contact area, the cooled blank heats up in short time according to the larger heat flux between the blank and the standard tools. Deep drawing of the rotationally symmetrical cup with macro-structured tools results in a reduction of the necessary stamping force compared to conventional tools by using a small immersion depth up to $\delta = 0.4$ mm. This effect is caused by the reduced contact area and therefore reduced friction forces between blank and tool. Larger immersion depths leads to punch forces corresponding to standard tools.

![Figure 3. Geometry of the model (a) and exemplary a comparison of the resultant numerical and experimental punch force for standard and macro-structured tools ($\delta = 0.2$ mm) at cryogenic temperature.](image)

| Immersion depth $\delta$ = 0.2 mm | Immersion depth $\delta$ = 0.4 mm |
|----------------------------------|----------------------------------|
| Punch force $F_p$ in kN          | Punch force $F_p$ in kN          |
| 0                                | 0                                |
| 10                               | 10                               |
| 20                               | 20                               |
| 30                               | 30                               |
| 40                               | 40                               |
| 50                               | 50                               |

![Figure 4. Punch force at different temperatures and immersion depths with macro-structured and standard tools](image)

In contrast, the required punch force with macro-structured tools at cryogenic temperature is lower than the punch force at room temperature. However, there is a clear difference in the course of the curves. This result indicates changed tribologic conditions when working under cryogenic temperatures that has to be investigated in more detail. While a smooth force curve can be seen for the conventional tool, there is an oscillation of the drawing force using the macro-structured tool. This can be explained with the changing contact conditions between the free ending of the blank and the macro-structured tools due to the alternating bending and the onset of wrinkling. In that case, the punch force increases due to the contact of the free ending and decreasing when the free ending is not in contact. This effect also shows a dependence on the immersion depth of the macro-structured tools. The required drawing force increases with increasing...
immersion depth for both investigated temperatures, due to the increasing alternating bending and associated hardening of the sheet due to the wave structure of the macro-structured tools. 

The results of the ring-splitting test are summarized in Table 1. The smallest amount of springback is reached at cryogenic temperature while there is nearly no difference between an immersion depth of 0.2 mm and 0.4 mm at this temperature. However, there is a significant decrease of springback with $\delta = 0.2$ mm compared to tests at room temperature while the split rings of the drawn cups with $\delta = 0.4$ mm shows a little change in springback behavior. These results show that the retention force induced through alternating bending reduces the amount of springback depending on the immersion depth. Due to different boundary conditions regarding the contact area and heat flux, the springback for deep drawn cups with standard tools are not considered in Table 1.

| $\delta$ | $\vartheta$ | $\Delta$ |
|---------|-------------|---------|
| $\delta = 0.2$ mm | -196 °C | 51.0 mm |
| | 20 °C | 60.4 mm |
| $\delta = 0.4$ mm | -196 °C | 52.0 mm |
| | 20 °C | 53.5 mm |

As the last part of the evaluation, hardness tests were performed on a Qness 60A with a VICKERS testing setup and a chosen test range of HV0.1 according to DIN EN ISO 6507 [30]. The hardness in the cross section was examined with 100 testing points. The gained data was smoothed and the results are presented in Figure 5. The hardness of the deep drawn cups with standard tools shows nearly the same course and is not depicted due to a better visualization.

The change in the hardness distribution in the different zones is in between a range of about 5 – 8 HV0.1 whereas the drawn specimen at cryogenic temperatures show a lower hardness than the cup drawn at RT. The change in the hardness for the RT specimen is with a $\Delta = 15$ HV0.1 slightly smaller than the change for -196 °C. The effect can be explained with the microstructure of the alloy. Already SELLINES ET AL. [17] mentioned a suppressed transformation due to the low temperatures inside the structure of the material. At this point, further material scientific evaluation for a more complex part is necessary

5. Conclusion and outlook

The investigations show some promising effects for the cryogenic deep drawing with macro-structured tools. The results of the presented investigations show the potential of macro-structured tools for deep drawing at low temperatures. In particular, the reduction of the punch force turns out to be very advantageous in order to be able to exploit the improved material properties of aluminum at cryogenic temperatures. Additionally, the deep drawn cups at cryogenic temperature shows a reduction of spring back and hardness compared to the process at room temperature, which results in a higher geometrical accuracy of the deep drawn parts at
cryogenic temperature. It was possible to validate the experiments with a simulated solution by a comparison of the punch force. Thus, the further evaluation can be relied on the FEM and supported by experimental test. Regarding the surface quality, no differences between deep drawing with macro-structured tools at cryogenic and room temperature are determined at this stage of investigation. Since the results shown here represent preliminary tests, the following investigations will deal with detailed material characterization at temperatures down to -196 °C for a more complex material model as well as the implementation of the experimental setup for deep drawing at this temperature. In addition to the presented deep drawn round cup, deep drawing of a T-cup as an industrial-scale demonstrator component will be part of the ongoing investigation.

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