

# Influence of Macro-Structured Tools on the Formability of Aluminum Alloys in the Cryogenic Temperature Range

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**Abstract.** Aluminum materials are popular materials for research in terms of lightweight construction. How cryogenic forming can be used to increase material utilization in terms of resource efficiency is one of the areas being investigated. Subject of this study are numerical and experimental investigations regarding the formability of the aluminum alloy AA6014-T4 with macro-structured deep drawing tools at cryogenic temperatures. The macro-structure of the deep drawing dies significantly reduces the heat flux between the dies and the blank due to the reduced contact area. For this reason, active cooling or heating of the dies is not required. The process of heat conduction between the tool and the blank, as well as the deep drawing process, is calculated using the FE-method and compared with the experimental investigations. In addition, the induced residual stresses are determined using the hole-drilling method and compared with the computational solution. The presented examination shows an improved deep drawing ratio of the aluminum alloy AA6014-T4 at cryogenic blank temperature without active tool cooling. Additionally, the influence of the blank temperature on the forming regarding the residual stresses in the cups is analyzed and discussed.

## Introduction

Due to the currently prevailing shortage of resources and the general intention to switch from internal combustion engines to alternative, environmentally friendly drives, lightweight construction and the materials that can be used are receiving increased attention. Aluminum, as one of the well known materials, is appreciated as a lightweight material mainly due to its high strength compared to its weight. Deep drawn magnesium is particularly popular for use in the bodywork. In order to explore the limits of the deep drawing process and to achieve a higher drawing ratio, deep drawing at cryogenic temperatures is a well-known process and is being investigated by the GRABNER et al. [1], among others like [2]. Drawing ratios  $\beta > 2$  have been achieved for certain alloys [3]. Inspired by the results and the proven extension of the usable process window by macro-structured tools, a combination of the approaches is investigated in order to achieve a further improvement of the deep drawing process of aluminum materials under cryogenic temperatures via the extension of the process window and an improved distribution of the stresses in the component.

In this context, macro-structured tools, as investigated by MOUSAVI [4], are used to enable deep drawing at cryogenic temperature without active tool cooling due to reduced heat transfer between blank and tools.

## State of the Art

**Macro-structured deep drawing.** In sheet metal forming lubricants play an important role for the reduction of friction between tools and blank that results in advantages like the reduction of forming energy and increasing process limits. However, the usage of lubricants has ecological and economical disadvantages like additional process steps for cleaning work pieces. From this motivation MOUSAVI ET AL. developed a new deep drawing process with macro-structured tools to reduce the friction forces [5]. The approach of macro-structuring is to reduce the full surface contact between the sheet metal and the tools to a line contact. The risk of wrinkling increases because of the non-active blank

holder force at the non-contact areas of the sheet metal in the macro-structured tools. For that reason, the blank holder immerses slightly into the die. Depending on the immersion depth, an alternating bending is induced in the sheet metal so that the geometrical moment of inertia increases which results in an increasing resistance against wrinkling [4] and enables a reduction of the required blankholder force up to 90 % [6]. The process parameters are the variable immersion depth  $\delta$  and the wavelength  $\lambda$ , which affects the contact area and induced bending. The macro-structured deep drawing shows a better control of the material flow and a higher resistance against wrinkling that results in an increasing process window compared to deep drawing with standard tools. The concept of the macro-structured deep drawing is depicted in Fig. 1.

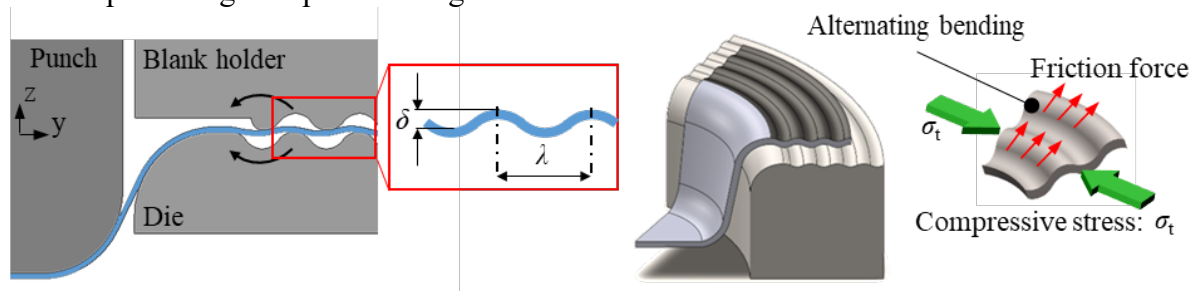


Fig. 1: Schematic principle of macro-structured deep drawing according to [6]

**Deep drawing at cryogenic temperatures.** Aluminum alloys are often used sheet metal because of material properties like corrosion resistance, high strength and low density but their usage at room temperature is often limited due to a limited formability and defects in the surface, resulting in flow lines [7]. However, in [1] it is shown that yield strength, tensile strength as well as the tensile elongation of aluminum alloys increases at cryogenic temperature. YUAN ET AL. examined the deep drawing ability of aluminum alloy (AA2219) in [3] and reached an increased drawing ratio  $\beta = 2.08$  at cryogenic conditions ( $-160\text{ }^{\circ}\text{C}$ ) compared to  $\beta = 1.80$  at room temperature. SOTIROV ET AL. showed a suppressed Portevin-LeChatelier effect while forming at cryogenic temperature [8] and Kumar et al. pointed out similar effects on the strength and elongation at fracture of the aluminum alloy AA 6016 in [9].

According to the current state of the art, deep drawing at cryogenic temperatures and deep drawing with macro-structured tools have several positive effects on the forming behavior of aluminum alloys and the material flow. This leads to the question, if the combination of approaches results in an increasing process window. In [10] it was already shown that deep drawing of aluminum sheets with a sheet temperature in the cryogenic range with macro-structured tools leads to a reduction of the required punch force and spring back.

### Macro-Structured Deep Drawing under Cryogenic Conditions

Subject of the study are numerical and experimental investigations regarding the formability of the aluminum alloy AA6014 in a deep drawing process with macro-structured tools at cryogenic blank temperatures. The object of this investigation is the increasing drawing ration of AA6014 and represents the continuation of the preliminary tests in [10]. 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. An additional lubrication like Teflon in [3] or foils and oil in [8] was not applied and the tools were cleaned after each test. Comparative investigations are carried out using standard tools with a sheet temperature of  $20\text{ }^{\circ}\text{C}$ . The principle concept of the approach is depicted in Fig. 2.

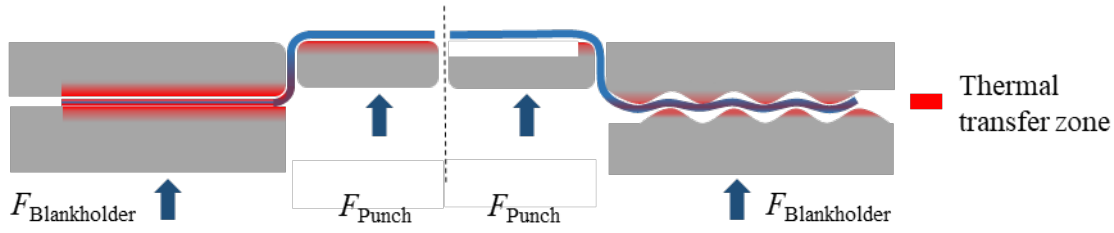


Fig. 2: Thermal transfer zone of standard (left) and macro-structured deep drawing tools (right)

**Experimental setup.** Comparative investigations are carried out with a macro-structured rotationally symmetrical die and sheet metal temperatures  $\vartheta$  at room temperature (RT) and  $\vartheta = -196^\circ\text{C}$ . Spacer rings are used to set a defined immersion depth. The die radius  $r_{\text{die}} = 10\text{ mm}$  and the punch diameter is  $d_{\text{punch}} = 100\text{ mm}$ . In contrast to standard tools, the punch is designed hollow in the end face to reduce the heat flux from the blank to the punch. The profile of the macro-structured tools and the punch as well as the test setup is shown in Fig. 3. For the investigations, blanks from AA6014-T4 with an initial sheet thickness  $t = 1.0\text{ mm}$  are laser-cut with different blank diameters of  $D = 160\text{ mm}$ ,  $D = 180\text{ mm}$  and  $D = 200\text{ mm}$ . The symmetrical cups were completely deep drawn with no remaining flange area. Thus, drawing ratios of  $\beta = 1.6$ ,  $\beta = 1.8$  and  $\beta = 2.0$  are investigated. Three different approaches to workpiece cooling are used in the investigations: without cooling, cooling in a nitrogen bath to  $-196^\circ\text{C}$  and cooling in a nitrogen bath with additional cooling in the blank holder with dry ice ( $\text{CO}_2$ ). For testing at cryogenic work piece temperature, the sheet metal is placed in liquid nitrogen and cooled to  $-196^\circ\text{C}$ . The investigated parameters for the immersion depth vary between  $\delta = 0\text{ mm}$  and  $\delta = 0.6\text{ mm}$ . After a transfer of the sheets from the nitrogen bath to the drawing tools, the deep drawing process starts immediately. The tools themselves are not cooled. However, for individual tests, the macro-structure of the blank holder is filled with powdered dry ice ( $\text{CO}_2$ ) to maintain the cryogenic temperature of the sheet for a longer time period.

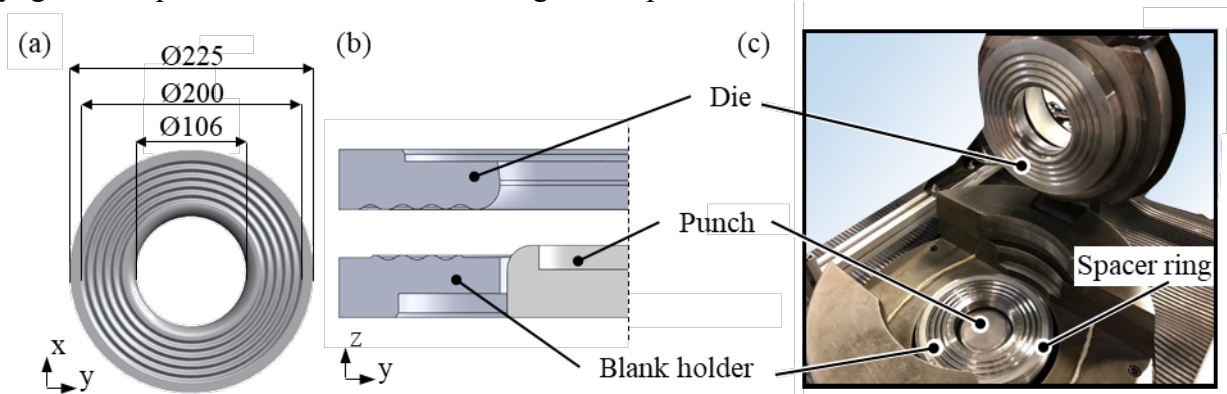


Fig. 3: Macro-structured tools (a) with sectional view (b) and test setup for deep drawing (c)

For investigating the springback, the ring splitting method, developed by SIEBEL AND MÜHLHÄUSER [11], is used, shown in Fig. 4 left. By cutting a ring from the wall of the deep drawn cup and subsequently splitting it open, the resulting gap correlates with the residual stresses [4]. The split rings have a width of  $10\text{ mm}$  and were cut of the cups with electrical discharge machining at a distance of  $15\text{ mm}$  from the bottom. Additionally, the residual stresses are measured with the hole-drilling system PRISM from STRESSTECH that works with an electronic speckle pattern interferometry [12], depicted in Fig. 4. The Prism system measures surface distortion optically using laser light that is diffusely reflected from the sample surface. The residual stresses are evaluated in direction of the sheet thickness in  $0.04\text{ mm}$  increments up to drilling depth of  $0.4\text{ mm}$ . The measurements are performed in a distance of  $20\text{ mm}$  from the bottom of the deep drawn cups that corresponds to the middle of the split rings width.

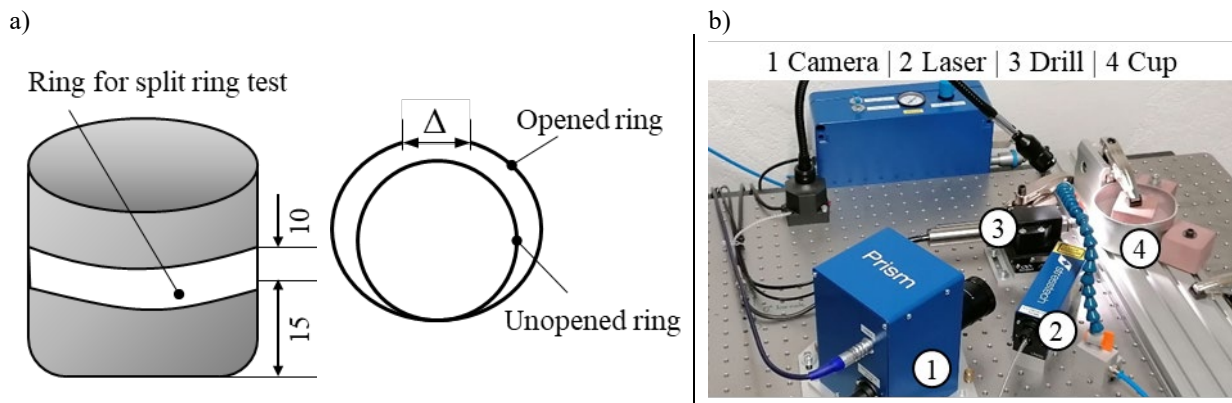


Fig. 4: Measuring residual stresses: Split ring method a) and hole drilling system PRISM b)

**Numerical Setup.** The finite element model is built in LS-Dyna R12.0.0. The blank is meshed with an initial element length of 2 mm with adapted refinement with a minimal allowed element length of 0.5 mm. The element type is a fully integrated 3D-shell element with nine integration points through the shell thickness. The material behavior is modelled by material type MAT36 (3-Parameter-BARLAT) to consider the anisotropy. The rotational symmetrical cup is reduced to a quarter in an isothermal model to save resources in calculation. The tool parts are defined as rigid bodies while the friction is modelled by a Coulomb friction model with a friction coefficient  $\mu = 0.15$ . The immersion depth of the blank holder and the movement of the punch are describes by a predetermined displacement. The values for the material behavior at room temperature based on the tensile tests performed material testing machine Inspect250 of HEGEWALD&PESCHKE combined with the DIC system GOM® Aramis 2019 according to EN ISO 6892-1 [13]. The parameters for the flow curve at cryogenic temperatures are determined inversely with the aid of simulation. A yield curve from SCHNEIDER ET AL. [14] is used as initial input and then the parameters are adjusted until the material flow in simulation is similar to the experimental material flow. The reason for this approach is, that the non-isolated test setup does not allow tensile tests under cryogenic conditions and the changing the material behavior during deep drawing due to the changing blank temperature.

In order to estimate the sheet temperature at the start of the deep drawing process, numerical investigations are carried out with Simufact.forming 16.0 in a 2D-model in order to reduce calculation time. Both the transfer time from the nitrogen bath to the die and the time for closing the die are taken into account. The result is a radial temperature profile in the blank with the lowest temperatures in the center of the sheet and the highest temperatures at the edge. This results from the heat conduction from the sheet to the blank holder and die while the punch encounters contact with the sheet later and has only minimal contact with it due to its hollow front surface. The numerical results show that after transfer time of 3.5 sec which includes the closing of the tools, there is still a temperature  $\vartheta = -172\text{ °C}$  in the center of the sheet, while at the edge there is only a temperature of  $\vartheta = -119\text{ °C}$ , presented in Fig. 5. From these findings, an isothermal flow curve for  $\vartheta = -100\text{ °C}$  is selected due to the fast increasing blank temperature during the deep drawing process.

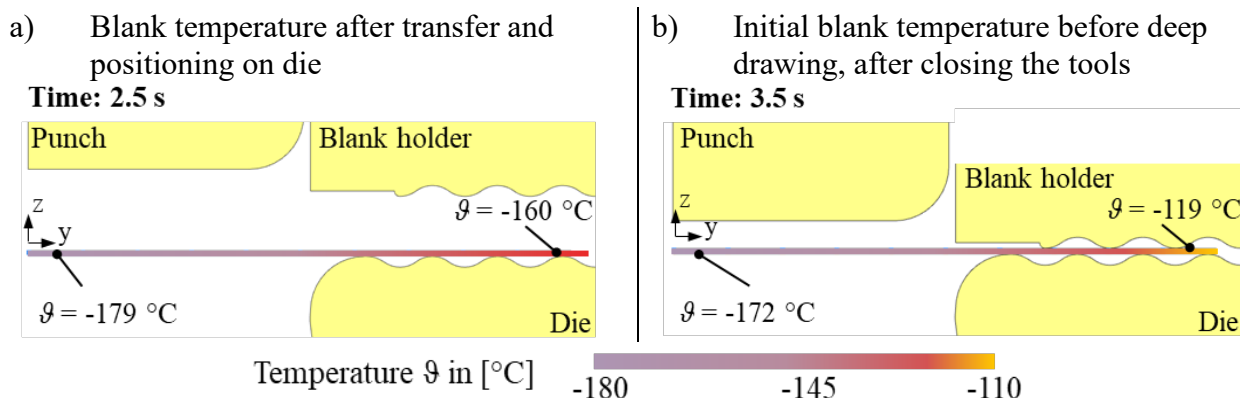


Fig. 5: Results of the numerical examinations regarding the initial blank temperature of the deep drawing process

## Results and Discussion

**Experimental results.** The deep drawn cups for the different drawing ratios  $\beta = 1.6$ ,  $\beta = 1.8$  and  $\beta = 2.0$  are shown in Fig. 6. In general, good results are obtained for the three drawing ratios. While the cups do not show any wrinkles at a draw ratio  $\beta = 1.6$  (Fig. 6 a) up to  $\beta = 1.8$  (Fig. 6 b), an incipient wrinkling at the cup end presents itself at the draw ratio 2.0, see Fig. 6 c. Furthermore, the anisotropy of the aluminum alloy AA6014 can be clearly seen in the formation of tails, which is most pronounced at the drawing ratio 2.0 according to the drawing depth.

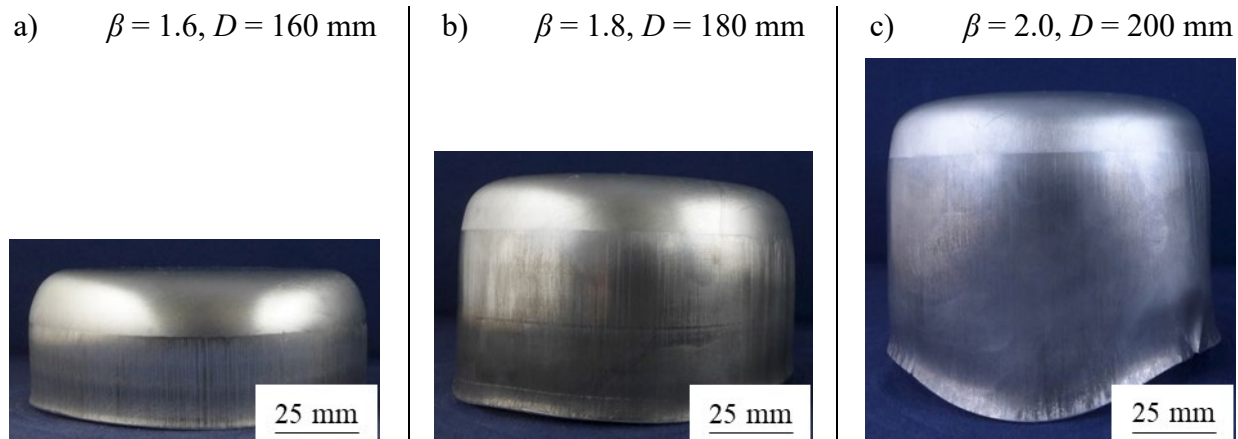


Fig. 6: Deep drawn cups with different drawing limits

The results of the experimental investigations show a significant increase in the deep drawing capability of AA6014-T4 as a result of the cryogenic work piece temperature with no active cooling of the tools. Thus, the combination of macro-structured tools and cryogenic work piece cooling increased the draw ratio up to  $\beta = 2.0$  compared to the maximum achieved drawing ratio  $\beta = 1.8$  with standard tools. However, this result requires filling the macro-structure of the blank holder with dry ice powder, thus keeping the sheet in the cryogenic temperature range for a slightly longer time. In the course of the investigations, the required immersion depth  $\delta = 0.6 \text{ mm}$  was found for the blank diameters of  $D = 160 \text{ mm}$  and  $D = 180 \text{ mm}$ . For higher immersion depths bottom fracture occurs and for smaller immersion depths of  $\delta < 0.6 \text{ mm}$  wrinkling occurs. For sheet diameters  $D = 200 \text{ mm}$ , a significantly lower immersion depth  $\delta = 0.1 \text{ mm}$  must be set to prevent bottom cracks.

Fig. 7 shows the required experimental punch force for the standard tool at room temperature compared to the macro-structured tool with no cooling and with the two different cooling strategies. Since it has already been shown in [11] that the punch force at room temperature and cryogenic temperatures is the same with standard tools, this parameter combination is neglected here and only the force curve of the standard deep drawing process is included for comparison. For a diameter of  $D = 160 \text{ mm}$  (Fig. 7 a), the punch force curves for macro-structured tools are similar at room temperature and cryogenic work piece temperature. However, the slightly lower punch force compared to the standard process is advantageous. This effect is caused by the reduced contact area and therefore reduced friction forces between blank and tool. For the use of cryogenic blank temperature at a drawing ratio  $\beta = 1.8$ , there is no improvement with regard to the punch force, see Fig. 7 b. The maximum punch force even increases slightly compared to the standard process. However, Fig. 7 clearly shows the extension of the process limits. The drawing ratio  $\beta = 2.0$  is only achieved under cryogenic conditions, where additional support by small amounts of dry ice powder is also required, recognizable by the course of the punch force in Fig. 7 c. An interesting aspect here is the small increase of the punch force for  $D = 200 \text{ mm}$  compared to the sheet metal diameter  $D = 180 \text{ mm}$ .



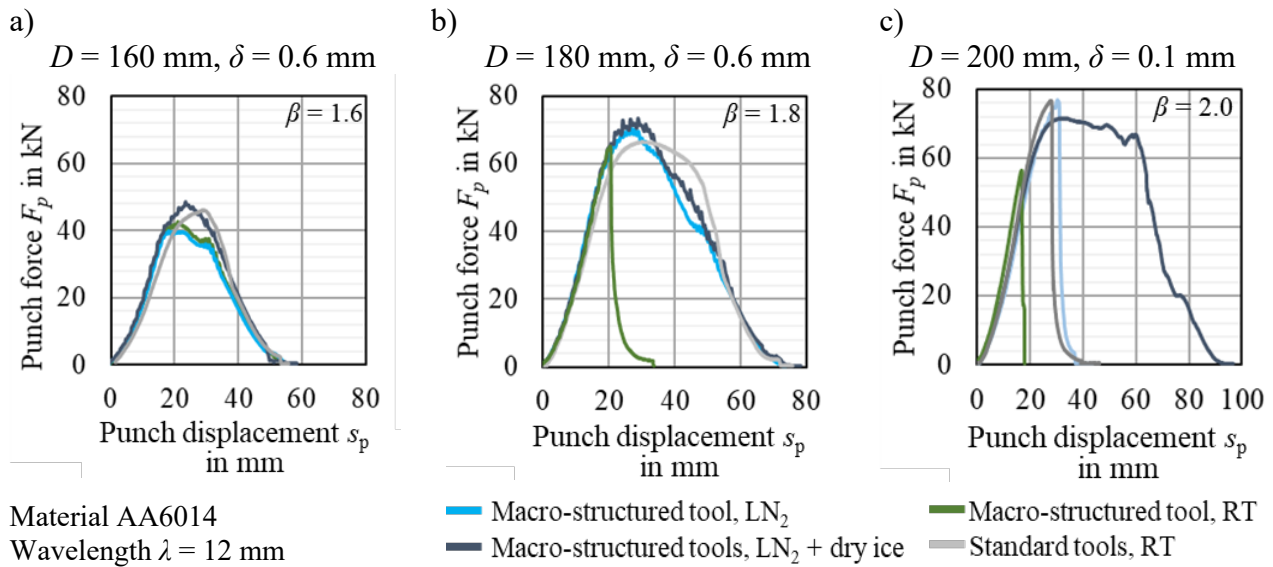


Fig. 7: Experimental punch force at different blank temperature with macro-structured tools and standard tools

**Residual stress.** Another advantage of the macro-structured deep drawing compared to the standard process can be seen in the evaluation of the residual stress measurement. The split rings from the macro-structured tools have a smaller gap than the split rings from the standard process for the blank diameter  $D = 160$  mm and  $D = 180$  mm. This shows that the residual stresses in the cup can be reduced by the alternating bending as a result of the immersion depth in macro-structured process. The results of the split ring method are shown in Table 1. For  $D = 200$  mm with standard tools is no opening gap listed because all tests resulted in bottom cracks.

Table 1: Resultant opening gap  $\Delta$  of the split ring test: Standard deep-drawing and macro-structured at cryogenic temperature (LN<sub>2</sub>)

Tool type	$\Delta$ [mm]			Principle of split ring method
	$\beta = 1.6$	$\beta = 1.8$	$\beta = 2.0$	
Macro-structured, LN <sub>2</sub>	47.1	50.8	58.1	
Standard	51.8	55.3	/	
Difference	4.7	4.5	/	

**Numerical results.** The results of the numerical investigations show good agreement with the experimental results. As an example, the punch force for macro-structured tools under cryogenic sheet temperatures and a blank diameter  $D = 180$  mm is shown in Fig. 8 on the left. The course of the numerically and experimentally determined punch force curve is very similar and the force maximum is almost identical. At the beginning of the process, the experimental force curve shows a slightly stronger increase than the numerical course. However, there are differences with regard to the onset of wrinkling and residual stresses. While no wrinkles occur in the experiment, the simulation shows slight wrinkling at the end of the process. The reason for this is probably the constant flow curve in the simulation, while in the real process the flow stress decreases due to the changing sheet metal temperature.

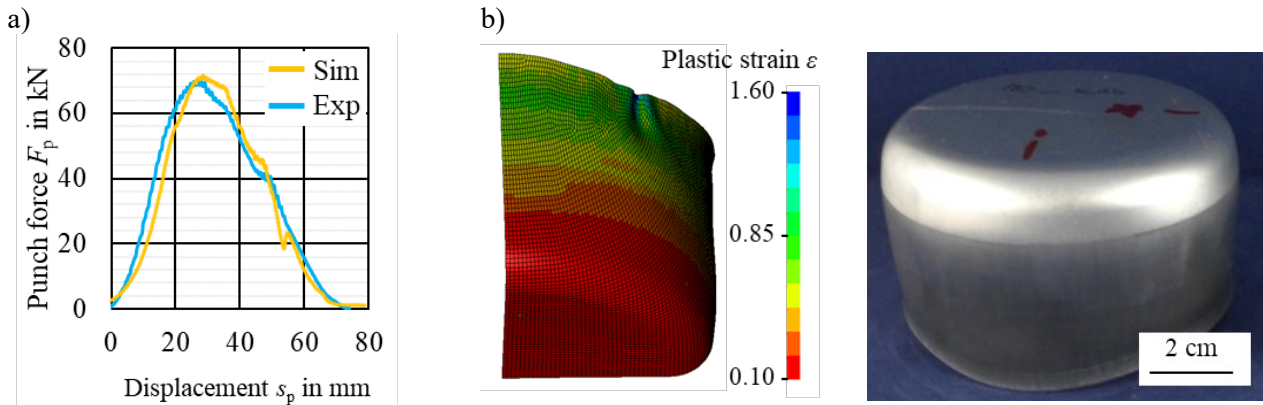


Fig. 8: Numerical and experimental results for blank diameter  $D = 180$  mm: a) Punch force and b) Geometry of the symmetrical cup

The results of the hole drilling method presented in Fig. 9 show the same tendency as the split ring method. Like in the results of the split ring method, the residual stresses in standard cups are higher than in the cups drawn with macro-structure while the development of the macro-structured induced residual stresses is more uniform from the surface to sheet thickness center. The numerically determined residual stresses, on the other hand, are significantly lower than the experimental ones. The differences can be attributed to the material modeling, because the used cryogenic flow curve is taken from literature for AA6016 that is similar to investigated AA6014 and the residual stresses are very sensitive to deviations in flow stress. Since, in contrast to the experiment, an onset of wrinkling is evident in the simulation and the kinematic hardening is neglected. Therefore, the numerical results are evaluated qualitatively and not quantitatively with respect to the experimental results.

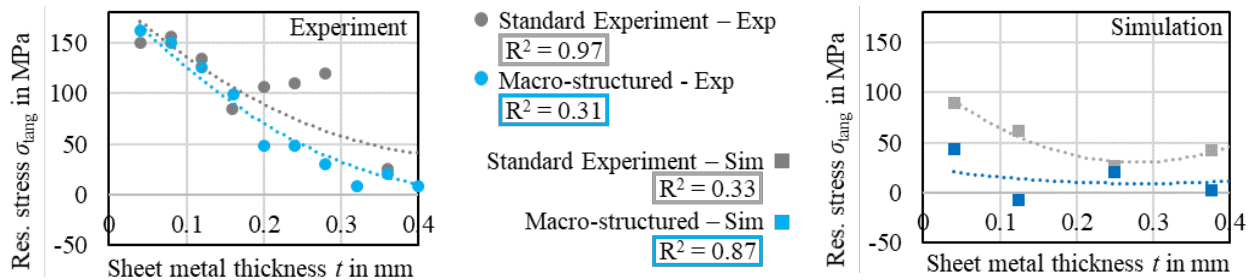


Fig. 9: Residual stresses in experiment and simulation with regression curve and coefficient of determination  $R^2$  for cup with  $\beta = 1.8$

## Summary and Outlook

The investigations show an approach for macro-structured tools to enable deep drawing at cryogenic blank temperature without tool cooling. Promising effects are the increasing drawing limit of AA6014 up to  $\beta = 2.0$  with nitrogen-cooled blanks and dry ice powder filled in the macro-structuring without additional lubricant. The reduction of the punch force while deep drawing with lower drawing limits compared to the standard deep drawing is an additional advantage of the presented cryogenic deep drawing process. Furthermore, it was shown that residual stress decreases with macro-structured tools compared to standard deep drawing, which results in reduced springback and therefore in a higher geometrical accuracy. Extending the results of MOUSAVI [4], it can be shown that cryogenic sheet temperatures are beneficial for AA6014 in order to use the macro-structuring at draw ratios greater than 1.8 otherwise bottom cracks occur. Thus, an improvement is achieved with respect to the process limits for AA6014.

Further investigations concern the experimental measurement of the blank temperature during the deep drawing process and the tribological conditions at cryogenic temperatures, especially regarding the influence of the dry ice powder on the friction and wear. Concerning the numerical modeling, a thermo-mechanical model with temperature-dependent material model will be implemented for investigating the effects on the punch force and wrinkling. Moreover, investigations are required regarding the kinematic hardening and its consideration in the material model.

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