Effect of elevated temperatures on the drawability of aluminium sheet components

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ABSTRACT: The process limits of aluminium sheet drawing processes can be improved by manipulating local flow behaviour by means of elevated temperatures and temperature gradients in the tooling. An experimental study showed that a substantial improvement is possible not only for 5000 but also for 6000 series alloys. Hardness measurements and tensile tests on high temperature prestrained samples indicated that warm drawn parts properties can significantly differ from cold drawn parts

A FEM process simulation was used to investigate the temperature distribution and evolution before and during deep drawing of a cup. The materials model and friction coefficients used were based on tensile test data and friction tests. The calculated and measured effect of warm drawing on the wall thickness profile agreed reasonably well.

Key words: deep drawing, elevated temperatures, aluminium, finite element method

1 INTRODUCTION

Because of the need for weight reduction in transport industry, in order to save energy as well as to reduce CO_2-emission, the use of light weight aluminium sheet is taken increasingly into consideration [1]. But although aluminium is lighter than steel, the formability is less, hence press operations are often more critical.

Alloys used are typically 5xxx alloys for inner panels because of the better formability and 6xxx alloys for outer panels because of the absence of stretcher lines. It is of course preferable to use one alloy type, especially from the point of view of re-use of the materials.

Press operations could be improved by optimising the mechanical properties (distribution) of the sheet by using (local) heating or cooling [2-4]. An extra benefit of warm forming is that stretcher strains do not occur in 5xxx series alloys at elevated temperatures.

A study is carried out on warm drawing (in the temperature range up to 250°C) of 1.2 mm gauge 5754-O and 6016-T4 alloy sheet with respect to process limits and product properties and on modelling of the drawing process and sheet material.

In the next sections results are presented of drawing and tensile tests at elevated temperatures, of room temperature (RT) tensile tests on samples that are prestrained at an elevated temperature and of FEM process simulations. The latter yielded information on the temperature distribution and evolution in tooling and blank. The required sheet material modelling is subject of an accompanying paper [5].

2 PROCESS LIMITS

2.1 *Experimental set up*

Drawing tests with circular and rectangular products were performed on a 1000 kN hydraulic press with a die cushion. The die and blankholder plates were heated by means of electrical heat rods. These were located at the corners in case of a rectangular product. The punch could be kept at room temperature by water cooling.

Lubricant was a water based paste and the tests were performed with a constant blankholder force. The punch speed was 120 mm/min unless otherwise stated. The corresponding strain rate in the drawn-in flange is in the order of magnitude of 0.02 s^{-1}.

The die and blankholder heated the blanks; no heating outside the tooling was used. The products stayed a total of three and halve minute inside the tool (including positioning the blank, which was most time consuming, closing the tool, forming, opening the tool and removing the product) and were air cooled afterwards.

2.2 *Cup deep drawing*

Fig. 1 and 2 show the effect of the die and blankholder temperature on the limit draw ratio for cylindrical products without tears or wrinkles. The punch diameter was 110 mm and the punch and draw-in radii were 10 mm.

Presented are data from tests with a blankholder force at which the largest limit draw ratio is obtained. This force decreases actually with temperature. Fig. 3 shows the effect of the punch speed on the limit draw ratio.

Because of the die heating, the flange material is softened and the drawing force reduced, see Fig. 4. Because the punch cools the bottom part of the cup, the critical drawing force at which the process fails is less reduced and the total effect is a higher limit draw ratio. The flange heating results also in a reduced cup wall hardness, although it is still higher than the undeformed material, see Fig. 5.

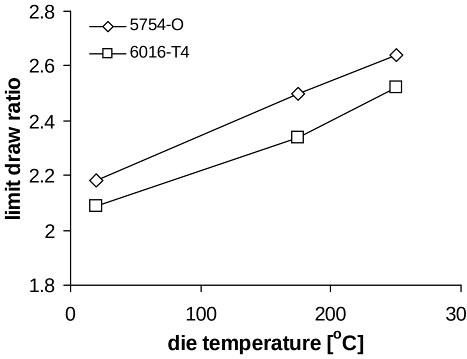
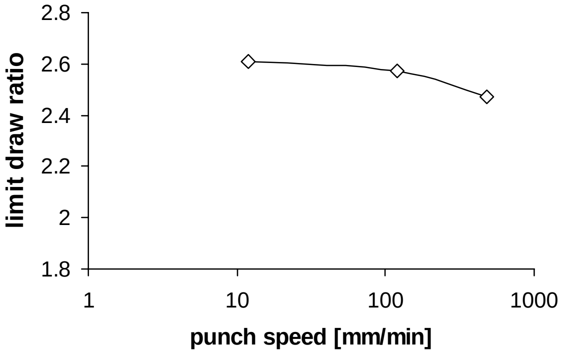


Figure 1: Limit draw ratio versus die temperature

Figure 2: Deepest 5754-O cups drawn at RT and 250 °C



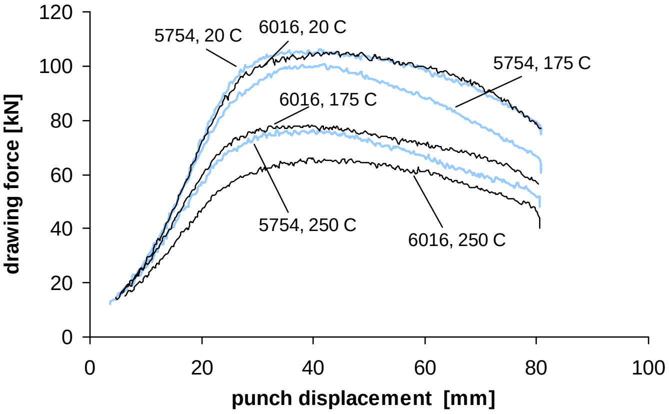


Figure 3: 5754-O aluminium limit draw ratio versus punch speed; die temperature is 250 °C

Figure 4 : Deep drawing force versus punch displacement when drawing cups with a 2.09 draw ratio and an initial blankholder pressure of 1.0 MPa

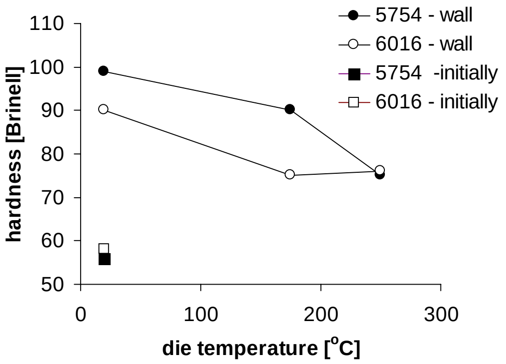


Figure 5: Effect of die temperature on the hardness of the wall (measured 20 mm below the flange) of a 80 mm high cup with a 2.09 draw ratio.

2.3 *Stretch-drawing of a conical rectangular shape*

Fig. 6 and 7 depicts the effect of the die heating on drawing a conical box shape (210 mm by 130 mm, 30 mm corner radii). The blank is stretched over the punch and drawn into the die clearance, as often encountered in stamping of automotive panels. The maximum depth is either limited by tearing due to a draw-in restriction (blankholder force or blank too large) or by wrinkling due to a too easy draw-in (blankholder force too low, blank too small). The heating increases the drawing depth, but at 250°C the 6016-T4 blank with 50 mm flange (that gives the deepest product at RT) becomes so weak near the draw-in radius that it tears and the beneficial effect is lost. But a smaller blank gave a sound part, that could not be drawn at room temperature due to excessive flange draw-in.

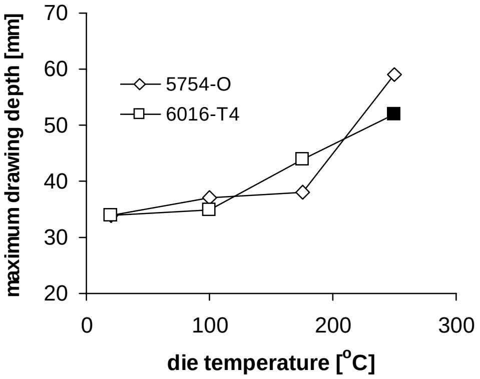


Figure 6: Stretch-drawing: critical punch displacement for tearing of blanks with an initial blankholder pressure of 4 MPa and (open symbols) 50 mm (this combination gave the deepest part at RT) or 40 mm flange width (closed symbol ■)

Figure 7: Deepest conical product of 6016-T4 aluminium drawn at RT (left) and at 250°C (right)

3 TENSILE TESTS

The first step in modelling warm drawing processes is to look at high temperature flow curves, see Fig. 8. The flow curves of the 5754-O alloy don't change significantly between RT and 100°C (in agreement with Fig. 6). At a higher temperature the serrated flow (due to dynamic strain ageing, which may result in stretcher strains in drawn products) disappears. The flow stress and work hardening decrease, due to dynamic recovery, and the fracture strain increases proportionally to the temperature - especially at the lower strain rate. The latter indicates an increased strain rate sensitivity. The dynamic recovery will result afterwards in a higher RT ductility but lower strength relative to cold formed parts (see Fig. 5 and 9).

The 6016-T4 alloy behaves differently. The flow stresses are already significantly lower at 100°C and the fracture strain decreases with temperature (especially if the strain rate would be reduced). The latter is due to precipitation of Mg_2Si particles (ageing). This process, which has strongly temperature dependent kinetics, could be used to counter the loss in RT strength of warm formed parts relative to cold formed parts, but results in a lower fracture strain (see Fig. 5 and 9).

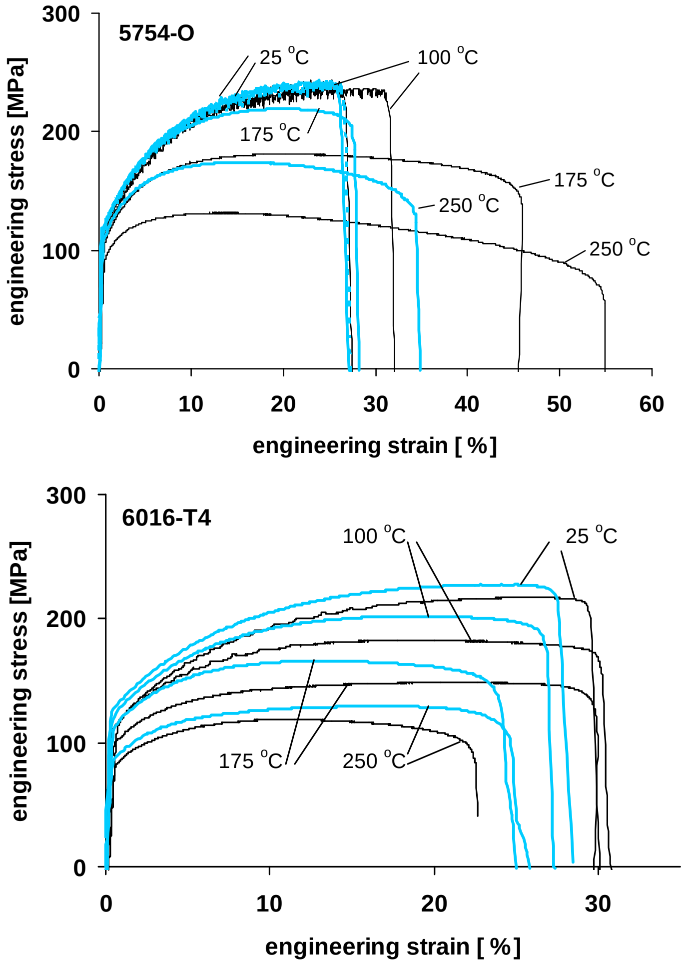


Figure 8: Engineering flow curves for a strain rate of 0.002 s^{-1} (black lines) or 0.02 s^{-1} (grey lines)

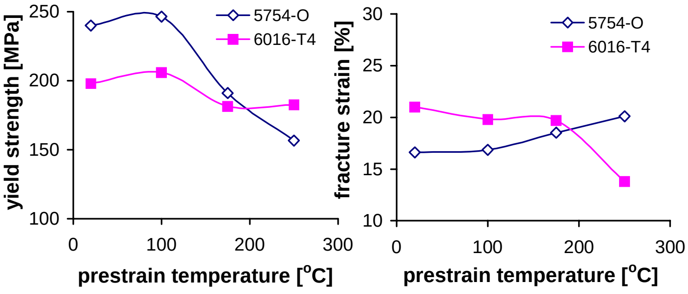


Figure 9: Room temperature yield strength and fracture strain versus prestain temperature; prestrain is 10 %, the strain rates are 0.002 s^{-1}

4 TEMPERATURE IN TOOLING AND BLANK

An FEM model is made for investigating the temperature evolution in the tooling and blank before and during drawing a 5754-O cup. The FEM code used was MSC.MARC and the model included the punch, die and blankholder with cooling and heating elements. The sheet material model was an empirical fit to the tensile test data and is not discussed here [5]. Based on slider on sheet tests, the friction was taken to be 0.05 below and 0.12 above 100°C.

Fig. 10 depicts the calculated and measured (with a thermo-couple) temperature inside the punch near the radius. After the punch is brought into contact with the blank, the temperature rises due to a heat flow from the die via the blank to the punch.

Calculated temperature profiles of the blank at various punch displacements are presented in Fig. 11. When the punch starts to move, five seconds after being brought into contact with the blank, the blank is bent over the punch radius and looses contact with the punch centre. Hence the punch centre does not cool the blank and it heats up to the temperature of the punch radius. During the drawing process, the contact and cooling improves and the temperature decreases. In general, the blank assumes the temperature of tooling contact surfaces quickly (seconds). The temperature gradient in the cup wall between die and punch is nearly constant.

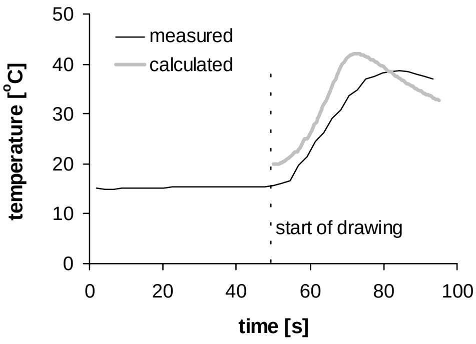


Figure 10: Calculated and measured temperature rise inside the punch near the radius during the drawing process

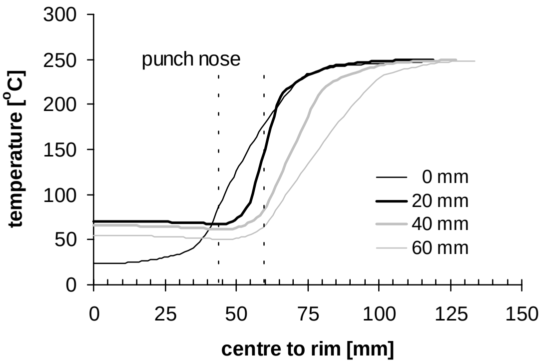


Figure 11: Calculated temperature on the centre line of the blank from the centre to the rim for four punch displacements (the 0 mm data are taken after 5 seconds holding time)

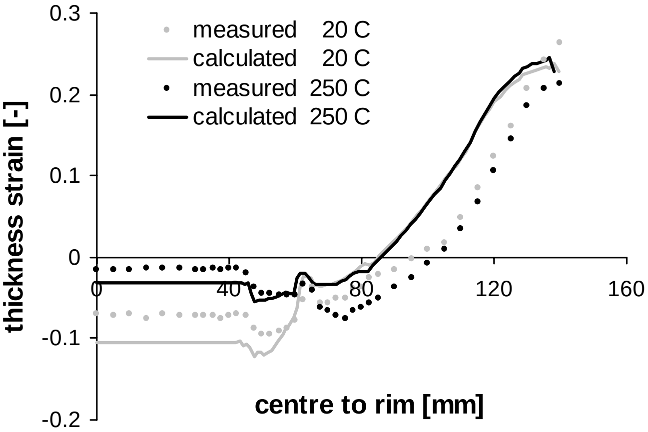


Figure 12: Calculated and measured thickness strain distribution over a radial from the centre to the rim of a 80 mm high 5754-O cup; draw ratio is 2.09 and die temperature is 20°C or 250°C

Finally, Fig. 12 shows measured and calculated thickness strains. The effect of the heated die and cooled punch is less thinning of the material under the punch and near the punch nose. The simulation was able to reproduce this effect reasonably well.

5 CONCLUSIONS

Use of temperature gradients in the tooling can yield a large increase (> 65 %) in product height when drawing both 5754-O and 6016-T4 sheet.

The strength of warm formed 5754-O parts is less than of cold formed parts, but ductility is better. Due to ageing, there is less loss of strength in 6016-T4 parts, but the ductility is lower than when cold formed.

Warm drawing tooling and process design will be greatly helped by FEM modelling even when using simple empirical flow curve based material models. Complicated processes however may require more advanced modelling.

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