Warm Deep Drawing of Aluminium Sheet

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Abstract

Aluminium sheet drawing processes can be improved by manipulating local flow behaviour by means of elevated temperatures and temperature gradients in the tooling. Forming tests showed that a substantial improvement is possible not only for 5xxx but also for 6xxx series alloys. Finite element method simulations can be a powerful tool for the design of warm forming processes and tooling. Their accuracy will depend on the availability of materials models that are capable of describing the influence of temperature and strain rate on the flow stresses. Two models, an adapted Nadai power law and a dislocation based Bergström type model, are compared by means of simulations of a cup drawing process. Experimental drawing test data are used to validate the modelling approaches, whereas the model parameters follow from tensile tests.

Keywords: aluminium, warm forming, simulation

1 Introduction

The need for lighter car bodies on the one hand side and the complicated shapes of car parts on the other hand side result in a quest for improving the formability of aluminium sheet. Aluminium has a large potential for weight reduction, but press operations are more critical than with steel. The alloys used for automotive sheet components are mostly 5xxx and 6xxx alloys. The 5xxx alloys have the best formability, but cannot be used for outer panels because of stretcher strains. These are mostly made from 6xxx alloys, which are however less suitable for complicated inner parts because of a lesser formability.
The formability can be improved by using elevated temperatures and temperature gradients in the tooling and blank, which make it possible to manipulate local flow [1-3]. An extra benefit of warm forming is that stretcher strains do not occur in 5xxx series alloys at elevated temperatures.
In this paper the effect of warm drawing (in the temperature range up to 250°C) on the process limits of a 1.2 mm gauge 5754-O and 6016-T4 alloy sheet and on the mechanical properties of the formed material are demonstrated. The introduction of warm drawing technology will be greatly helped if finite element method simulations are available for process and tooling design. Hence FEM simulations, including material models of warm flow behaviour, are developed and validated.

2 Effect of temperature on formability of aluminium

2.1 Flow behaviour

The temperature affects the plastic deformation of aluminium in two ways: by changing the work hardening and the ductility. How depends strongly on the alloy system.
Fig. 1 depicts flow curves of 5754-O sheet for a series of temperatures and strain rates. The flow curves do not change significantly between RT and 100°C. At a higher temperature the serrated flow (due to dynamic strain ageing, which may result in stretcher strains in drawn products) disappears. For a strain rate of 0.02 s^{-1} this occurred at 137°C. 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 results from an increased positive strain rate sensitivity. The dynamic recovery result afterwards in a higher room temperature ductility but lower yield strength relative to cold formed aluminium [4].
The 6016-T4 alloy behaves differently, see Fig. 2. The flow stress is already significantly lower at 100°C and the fracture strain decreases with temperature (especially for the low strain rate). The latter results from the increased precipitation rate of Mg_2Si particles (ageing) at higher temperatures. The higher the temperature and longer the process time are, the larger the precipitates will be, with more loss of ductility. The room temperature strength afterwards will be less than after cold forming, but to a lesser degree than for 5754-O. But contrary to 5754-O, the remaining fracture strain after warm forming will be smaller than after cold forming [4].

2.2 Process limits

The lower flow stress and hardening at elevated temperature can be used to control and improve deep drawing processes. A heated die and blankholder results in a softer flange and a lower draw-in force. If the punch is kept at a lower temperature, an increase in drawability can be expected. In order to test this, products were drawn with partially heated tooling. Heat rods warmed die and blankholder, whereas water cooling kept the punch at room temperature. Products were round cups and rectangular conical shapes. The latter are made by a combination of deep drawing and stretching, which is often encountered in stamping of automotive panels. Lubricant was a water based paste. 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 were air cooled afterwards.
Figs. 3 and 4 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 and 15 mm respectively.
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. 5 shows the effect of the punch speed on the limit draw ratio. The flange heating results as expected also in a lower hardness of the cup wall, although it is still harder than the undeformed material, see Fig. 6.

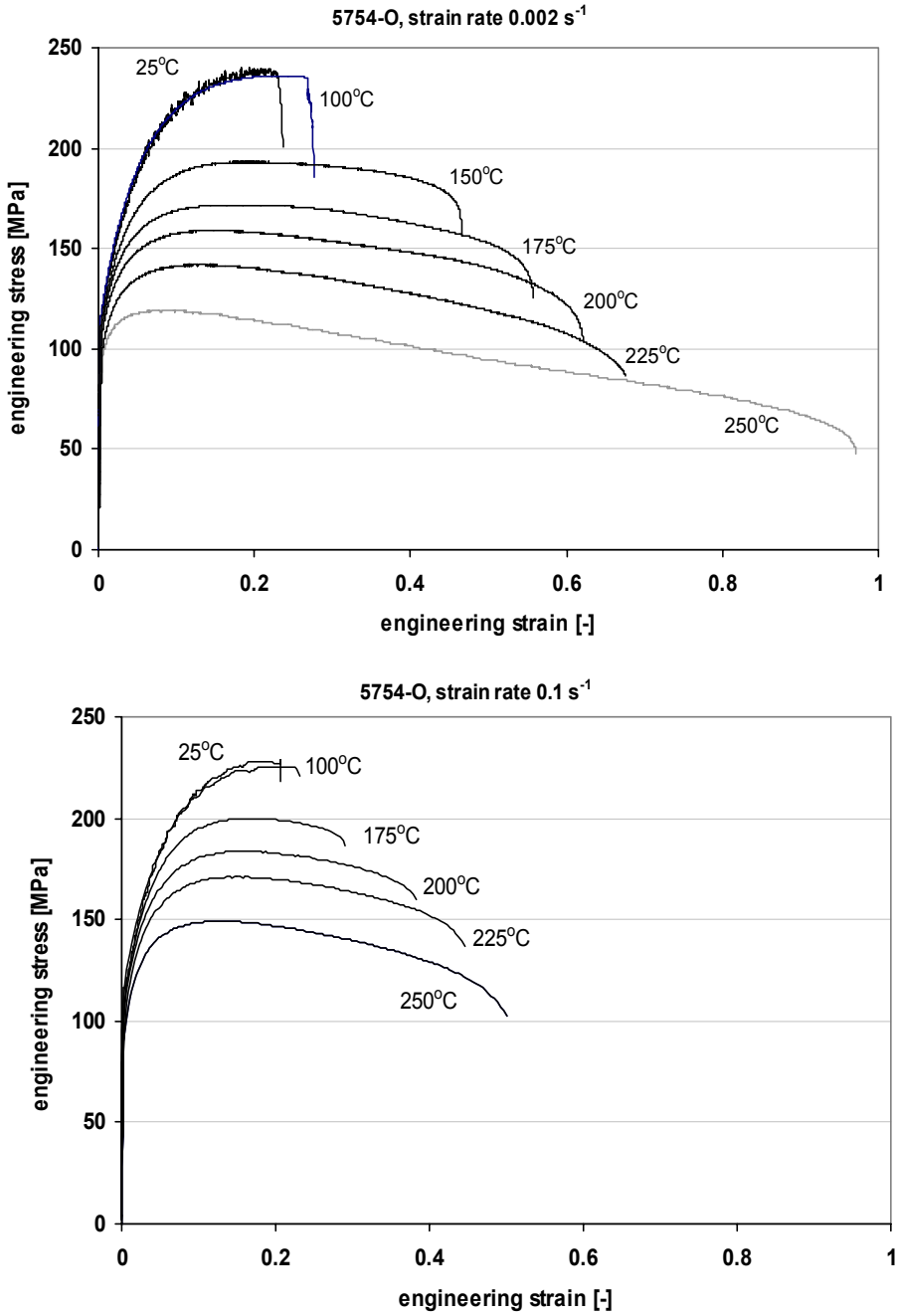

Figure 1: *Engineering flow curves for 5754-O at a strain rate of 0.002 s^{-1} (top) or 0.1 s^{-1} (bottom)*

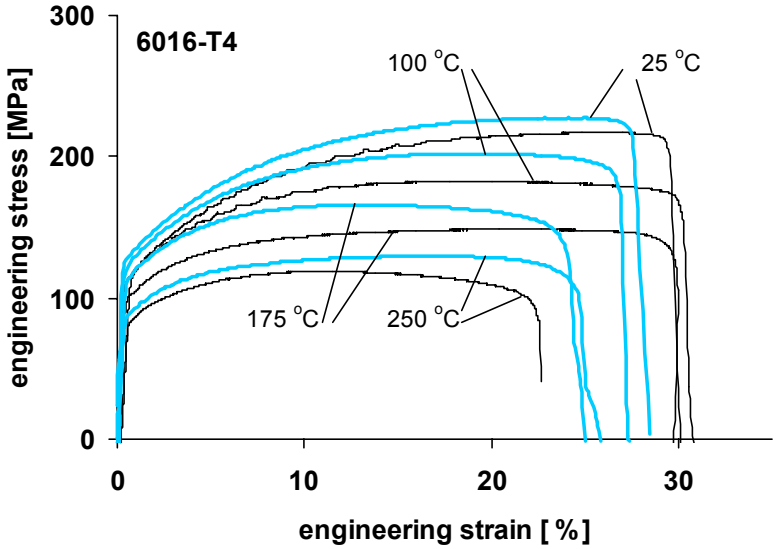

Figure 2: *Engineering flow curves for 6016-T4 at strain rate of 0.002 s^{-1} (black lines) or 0.02 s^{-1} (grey lines)*

Figs. 7 and 8 depict the effect of partial heating on stretch-drawing of the conical box shape (210 mm by 130 mm): an increase in maximum drawing depth of 65%. In this case the maximum depth is either limited by tearing due to a draw-in restriction (blankholder force or blank too large) or by wrinkling in the die clearance due to a too easy draw-in (blankholder force too low, blank too small). At 250°C, 6016-T4 becomes so weak that near the draw-in radius the product tears. But a smaller blank gave a sound part, which could not be drawn at room temperature, due to excessive flange draw-in.

3 Modelling of temperature dependent flow behaviour

The accuracy of finite element method simulations will greatly depend on the models that describe the influence of temperature and strain rate on the flow stresses, which are governed by time dependent recovery and/or ageing processes. In this study two strain hardening models are tested for the 5754-O alloy, which are introduced only briefly in this paper. More details and parameter values, which follow from tensile tests, are presented in [5,6]. The first is based on the Nadai flow curve fit:

$$\sigma = C(\varepsilon + \varepsilon_0)^n (\dot{\varepsilon}/\dot{\varepsilon}_0)^m \qquad (1)$$

Temperature dependence is introduced by defining C, n and m as exponential functions of the temperature.

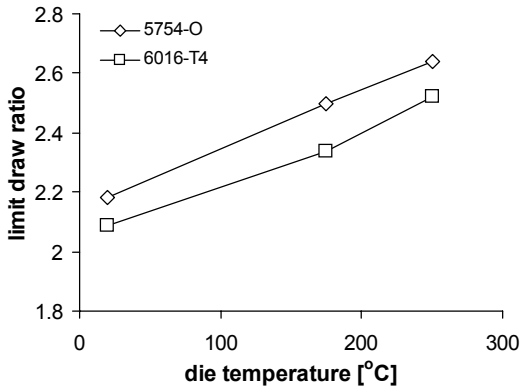

Figure 3*: Limit draw ratio versus die temperature*

Figure 4: *Deepest 5754-O cups drawn at RT and 250 °C*

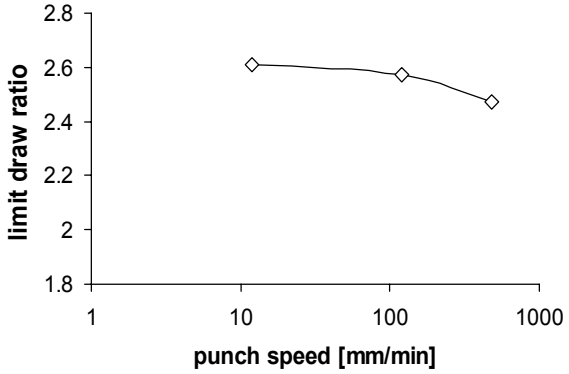

Figure 5*: 5754-O limit draw ratio versus punch speed; die temperature is 250 °C*

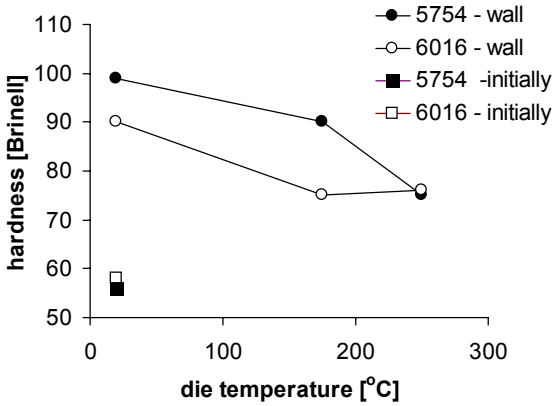

Figure 6*: Effect of die temperature on the wall of a cup with a 2.09 draw ratio*

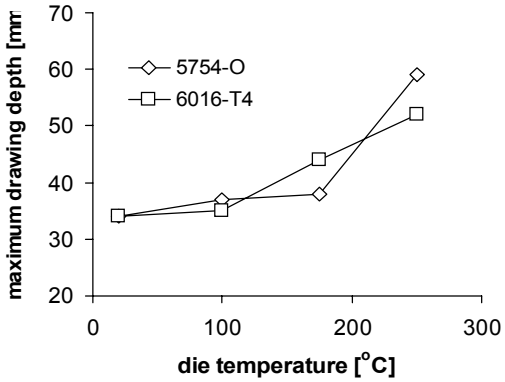

Figure 7*: Stretch-drawing: limit depth for*

Figure 8:*Deepest 6016-T4 product at RT (left) and at 250°C (right)*

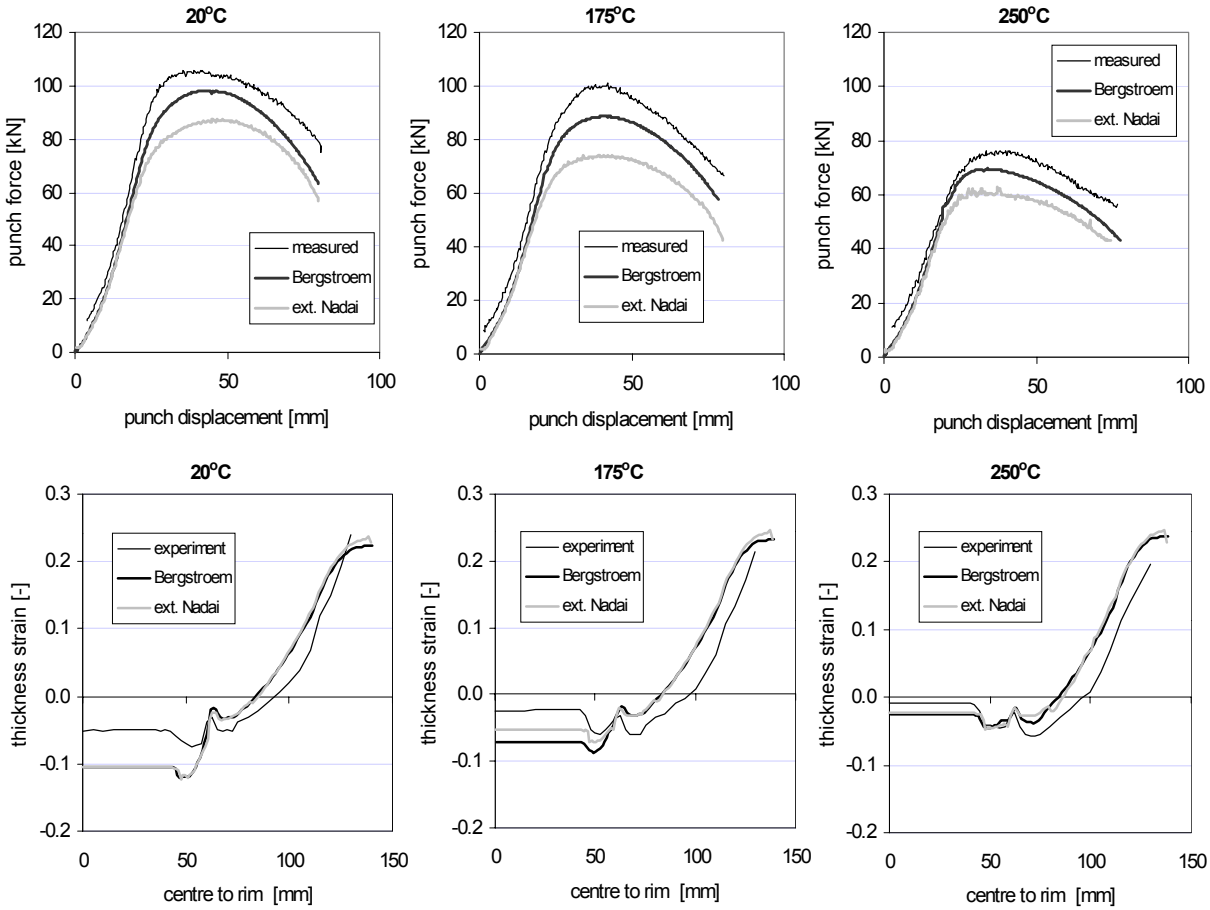

Figure 9: *Measured and calculated (with Bergström en extended Nadai model) force – displacement curves and true thickness strain distribution when deep drawing a 80 mm deep cup with draw ratio 2.09. Initial blankholder pressure is 1.0 MPa*

The second model is dislocation based and is originally proposed by Bergström [7,8]. It describes the flow stress as a function of dislocation density ρ and drag:

$$\sigma = g(T)(\sigma_0 + \alpha G_{ref} b\sqrt{\rho} + \sigma^*(\dot{\varepsilon}, T)) \qquad (2)$$

The function g(T) is the ratio of elastic shear modulus G(T) at temperature T and G_{ref} at a reference temperature. The first term is a strain and strain rate independent stress contribution, the second describes work hardening due to micro-structural evolution and the third models the effect of strain rate and temperature on the required driving force for dislocation movement. The last term, the dynamic stress, is neglected in this paper on basis of the small effect of strain rate on the yield stress in the considered temperature interval (see Fig. 1). The second term is the Taylor equation (b is the Burgers vector, α a scaling factor close to unity) and links flow stress to dislocation density [9]. The evolution of the dislocation density ρ is described by:

$$\frac{\mathrm{d}\rho}{\mathrm{d}\varepsilon} = U_0\sqrt{\rho} - (\Omega_0 + C\exp\left(-\frac{Q_v}{3RT}\right)\dot{\varepsilon}^{-1/3}) \qquad (3)$$

The first term in this equation represents storage (immobilisation) of dislocations (which increases work hardening), the second dynamic recovery by remobilisation and annihilation of dislocations (which decreases work hardening). The appeal of this approach is that it is potentially applicable for a wider range of forming process conditions and histories because it models the underlying physical phenomena of the macroscopic behaviour.
Fig. 9 depicts measured and calculated drawing force-ram displacement curves and thickness strain distributions in deep drawn cups. The extended Nadai model was implemented in a MSC.MARC model, which included the punch, die and blankholder with cooling channels and heating elements. The Bergström model was implemented in a DIEKA code (from University Twente) model. The local sheet temperature was set equal to that of tooling contact surfaces, which were set constant. Although the MSC.MARC simulations as well as measurements show that the local tooling temperatures vary during the process, this assumption is a good approximation [3]. Von Mises isotropic hardening was used in both cases. The friction coefficient was set at 0.06 in all simulations. Measurements showed however an increase between 150°C and 175°C to an average value of 0.12, which is not taken into account here.
Both models underestimate the drawing force, extended Nadai more than Bergström, and overestimate the thinning of the cup bottom. The effect of temperature is calculated qualitatively well, though. More detailed information on the relationship between friction and temperature together with more advanced modelling of the yield surface are likely to improve the quantitative agreement.

4 Conclusions

Tests showed that temperature gradients in stamping tooling can yield a large increase (>65%) in drawing depth of 5754-O and 6016-T4 sheet. This effect is based on the local reduction of flow stresses. For 5754-O, but not for 6016-T4, the higher strain rate sensitivity at elevated temperature will improve stretchability, especially at low strain rates.
A heuristic and a dislocation based material model were compared for FEM process simulation purposes. Based on cup test simulations, both seem capable of qualitatively correct predictions, but drawing force and strains were predicted quantitatively only moderately. It is recommended to improve the friction and anisotropy models as well as explore more advanced (physically based) work hardening models.

5 References

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