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Towards High Strength 7xxx Aluminium Sheet Components Through Warm Forming

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Aluminium has become the material of choice for lightweight design. Today medium strength 5xxx and 6xxx-series alloys are widely used in automotive sheet components, substituting conventional steel because of superior strength to density ratios. 7xxx-series (AlZnMgCu) alloys, with a peak tensile strength of up to 650MPa, offer the potential for further light weighting; but formability at ambient temperature is severely limited without the employment of pre- or post- forming heat treatment processes.
A promising approach to improve the formability of the 7xxx aluminium alloys is to utilize warm forming at process temperatures below the material's recrystallisation temperature.
Using experimental methods and numerical sheet forming simulations, this study describes the material behavior (flow, anisotropy, forming limit etc.) of EN AW-7075 sheet in heat treatment condition T6 during warm forming and demonstrates its applicability for mass production of complex, deep-drawn components.

Keywords: *7xxx, 7075 alloy, warm forming, numerical simulation, lightweight potential*

1. Motivation

In lightweight steel car production, there is a tendency to shift to ultra high-strength steels. Press-hardened manganese boron steel components are increasingly used in car bodies [1]. Through the use of hot stamping technology the sheet thickness, and therefore component weight, can be reduced.

There are several approaches to replacing steel, which is the conventional material for body-in-white structure and chassis, with other material classes which offer a high potential for lightweight design. Among the alternative materials, the popularity of aluminium has increased in recent years. The density of aluminium is about one third of steel; combined with its relatively high strength, this leads to a significantly lower component weight compared to equivalent parts made from steel.

The aluminium alloys commonly used for sheet metal parts in automotive are work hardening alloys of the 5xxx series and precipitation-hardening alloys of the 6xxx series. They combine the potential for light-weighting with good formability and weldability, but do not exceed the strength to density ratio of high-strength steels.

Higher strength and therefore a greater light weighting potential can be achieved with 7xxx series precipitation hardening AlZnMgCu aluminium alloys, which are already well established in aircraft manufacture. The ultra high-strength AlZnMgCu alloys of the 7xxx series have limited formability at room temperature in heat treatment condition T6 (solution heat treated, quenched and subsequently artificially aged). As today's standard, good formability can be achieved only if forming takes place immediately after solution heat treatment and quenching. This option requires time- and energy-consuming heat treatment steps (solution heat treatment, quenching, artificial ageing) in order to produce components with high strength (T6). The availability of suitable heat treatment equipment has to be taken into account as well.

2. Approach

The approach to improve the formability of 7xxx ultra high-strength aluminium alloys by increasing the temperature to the warm forming range but below the material recrystallisation temperature is promising. At these temperatures, the metal formability increases due to recovery, characterised by a reduction in dislocation density and polygonisation. At temperatures above 150°C the ductility of aluminium alloys and the forming limit increases and flow resistance decreases. Typical features of aluminium warm forming are an increase in the strain rate sensitivity and the coefficient of friction [2].

Warm forming of sheet metal EN AW-7075 in T6 at temperatures of 150°C to 250°C followed by a heat treatment (cataphoretic painting, typically at 170–180°C for 20–30 minutes) will cause overageing of the material, thus, causing the material's strength to decrease. However, overageing (T7x condition) leads to an increase of the ductility and has a positive effect on the stress-corrosion cracking resistance.

This work investigates the material behaviour of high-strength aluminium EN AW-7075 T6 (2 mm sheet thickness) at warm forming temperatures. The descriptions of the temperature dependent material characteristics (flow curves, anisotropic values, forming limit) take into account the dependence on strain rate. Using isothermal FEM simulation, the potential for the production of automotive sheet metal components from high-strength aluminium alloy EN AW-7075 T6 by warm forming is demonstrated.

3. Experimental methods and discussion of results

3.1 Cupping tests at elevated temperatures

To determine temperature dependent forming behaviour of ultra high-strength EN AW-7075 T6 during deep drawing, Swift cupping tests were carried out at various elevated temperatures. An axially symmetrical deep-drawing tool with a heated die ring and blank holder was used. The test parameters for the cupping tests are listed in Table 1.

Table 1: Test parameters for cupping tests

Parameter	Unit	Value
Alloy, heat treatment condition		EN AW-7075 T6
Sheet thickness	[mm]	2
Lubricant		high-temperature resistant lubricant
Punch diameter	[mm]	50
Punch rounding radius	[mm]	7
Drawing ring radius	[mm]	10
Punch speed	[mmmin^{-1}]	800
Blank holder pressure	[MPa]	1.1 constant
Duration of test run (heating+deep drawing)	[s]	< 60
Punch temperature		room temperature
Temperature in the forming zone	[°C]	200, 230

The influence of the draw ratio on the punch force at 200 and 230°C is shown in Fig. 1 a) and b). When the draw ratio is increased from 2.2 to 2.3 the drawing force at a forming temperature of 200°C increases by 4 %. An increase in forming temperature from 200 to 230°C allowed the limiting draw ratio (LDR) to increase from 2.3 to 2.4.

At room temperature, EN AW-7075 T6 is difficult to form. At this temperature it was not possible to achieve a draw ratio of even 1.8 in the cupping test.

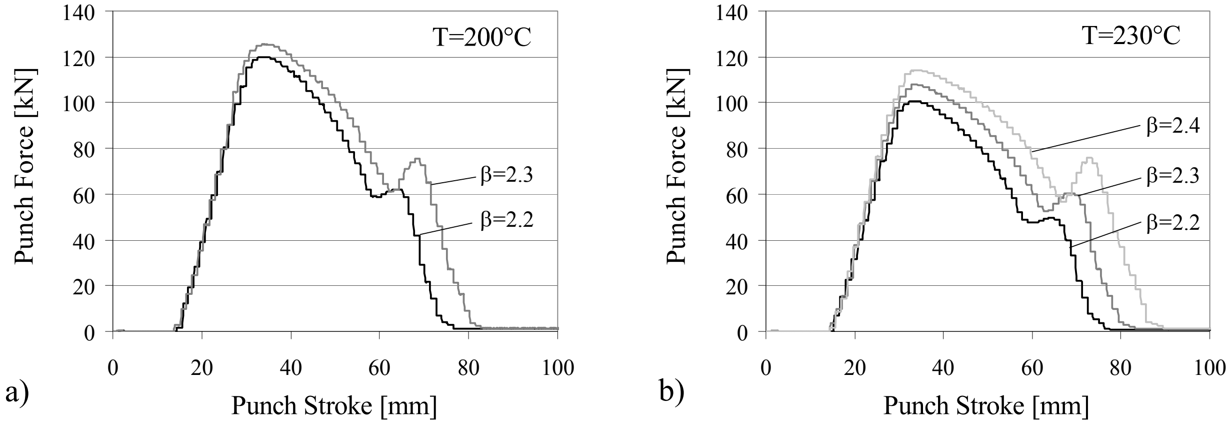

Fig. 1: Influence of draw ratio and temperature on punch force: a) at 200°C; b) at 230°C

3.2 Flow behavior at elevated temperatures

To assess the formability of EN AW-7075 T6 during warm forming, flow curves at 170 to 230°C were determined at strain rates of 0.001 and 1 s^{-1}. The specimens were heated within a few seconds to the forming temperature by conductive heating, and the tensile tests were performed as soon as the forming temperature was reached.

Fig. 2 shows the determined flow curves for EN AW-7075 T6 for strain rates 0.001 and 1 s^{-1} as a function of forming temperature. With increasing temperature initial flow stress and hardening decreased at both strain rates. This points to an increase in dislocation mobility due to dynamic recovery processes counteracting the material hardening during deformation [3]. A higher strain rate results in increased hardening. The influence of forming speed on flow stress is noticeable at all temperatures evaluated, as dynamic recovery is time and temperature dependent.

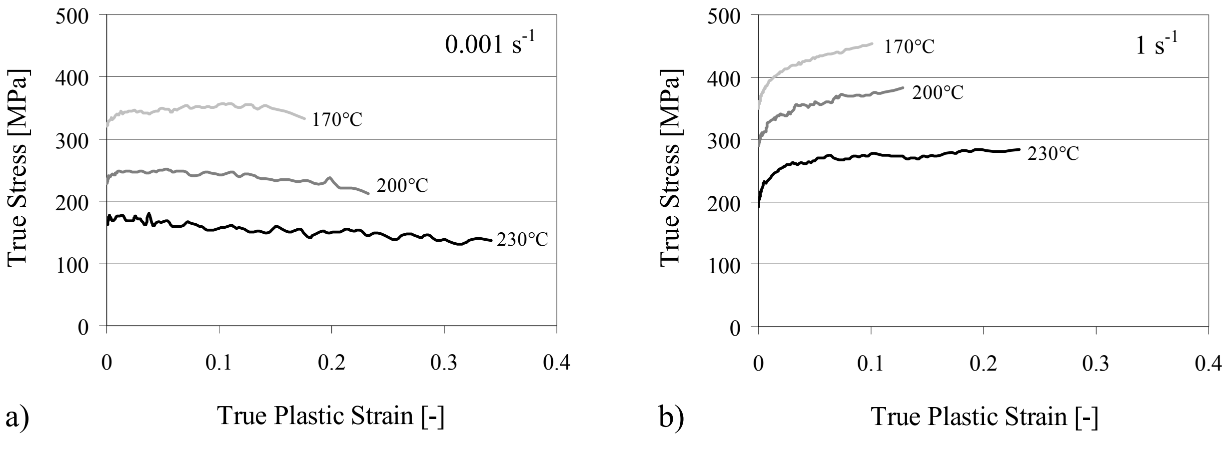

Fig. 2: Warm flow curves of 7075 T6: a) at strain rate 0.001 s^{-1}; b) at strain rate 1 s^{-1}

The results for the elongation to fracture in the tensile tests vary significantly within the warm forming temperature range, as the flow curves (Fig. 2) and the overview in Fig. 3a show. With increasing temperature within the 170 and 230°C band, the elongation increases by a factor of 1.6 to 4.5 depending on the strain rate. The lowest elongation value was recorded at 170°C for 1 s^{-1}, which lies within the typical range for EN AW-7075 T6 at room temperature of about 10%.

For mathematical modelling of the sheet forming process the anisotropy must be taken into account. The magnitude and distribution of the r-value affects the form of the yield locus and is used for its determination. The determined average anisotropy of EN AW-7075 T6 (2 mm) in the temperature range of 170 to 230°C at a slow strain rate of 0.001 s^{-1} ranged from 0.5 and 0.6 (Fig. 3b). As the strain rate increases, the average anisotropy also rises slightly, reaching values of up to 0.67.

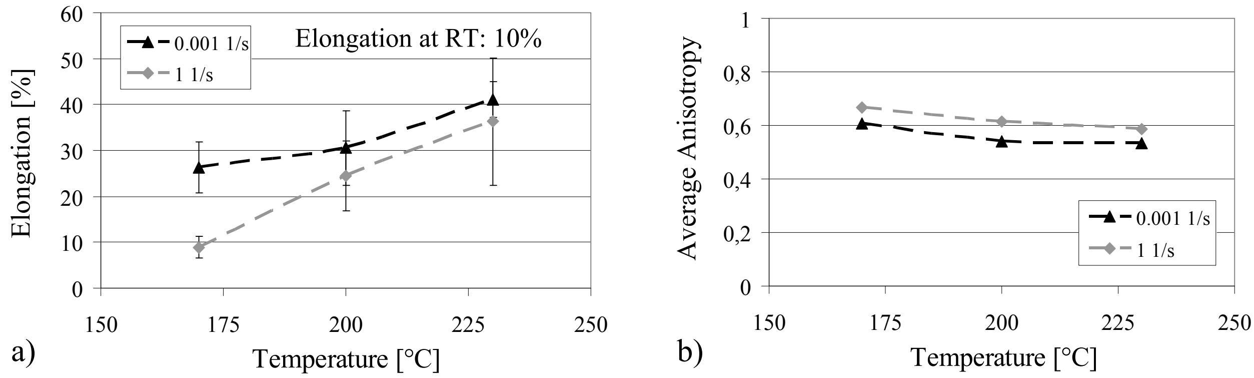

Fig. 3: a) Influence of forming temperature and strain rate on elongation to fracture; b) Average anisotropy for 7075 T6

3.3 Forming limits at elevated temperatures

To investigate the influence of the temperature on forming limits, forming limit curves were recorded at elevated temperatures using the Nakazima test method. In order to ensure an even heating of the specimen, the punch, blank holder and die were all electrically heated. The specimens were heated and tested within a short time to prevent any significant overageing during forming. The test speed was 90 $mmmin^{-1}$.

Fig. 4 shows a temperature-dependent forming limit plot for EN AW-7075 T6. At room temperature the alloy exhibits a low major strain of $\varphi_1 \approx 0.15$ at the lowest point of the curve. As temperature increases, the forming limit curve is offset to higher values due to increased ductility. Increasing the temperature to 230°C raises the forming limit curve up to a major strain of $\varphi_1 \approx 0.3$ at the lowest point of the curve.

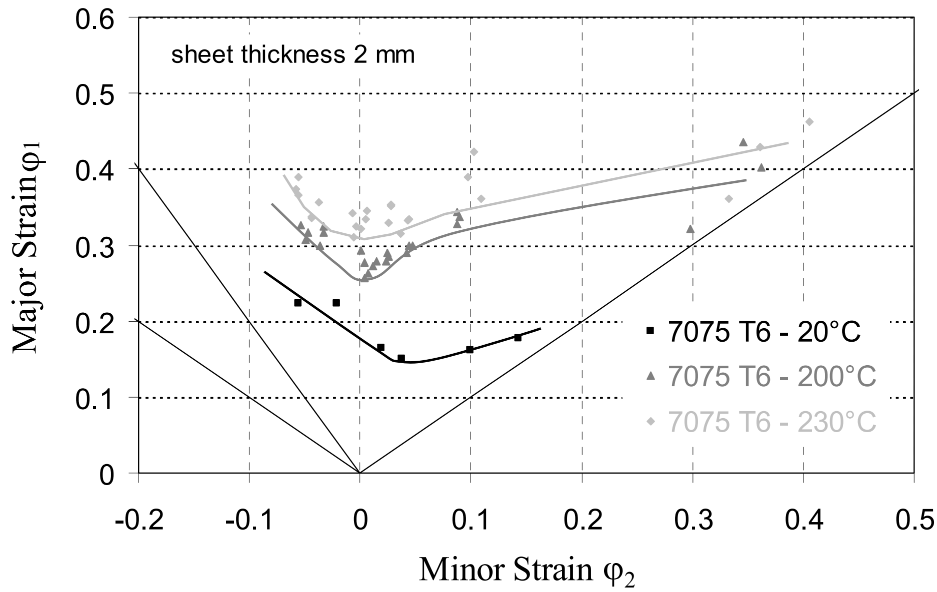

Fig. 4: Temperature-dependent forming limit curves for ultra high-strength aluminium alloy 7075 in heat treatment condition T6

4. Simulation Results

To estimate the feasibility of manufacturing deep-drawn components from ultra high-strength EN AW-7075 T6 by warm forming, FEM process simulations were performed with the explicit simulation program LS-DYNA [4]. Initially CAD data for a cross-die, which is used to characterise forming behaviour in the automotive industry, and a B-pillar designed for steel were used.

The tools (die, drawing punch and blankholder) were formulated as rigid bodies. To describe the blank using shell elements, the Barlat-Lian material model [5] was used, by which the anisotropic behaviour of the blank was mapped. The friction between the blank and the tools was taken into account by use of Coulomb's Law of Friction. A coefficient of friction of 0.2 was entered based on literature [2]. The punch speed in the simulation was 2 ms^{-1}.

A comparison of the calculated true strain in warm forming of the cross-die at 200°C with the corresponding forming limit curve yielded a drawing depth to cracking of 47.5 mm (Fig 5a). Cracking occurred in the bottom corner radius because tensile forces could no longer be transmitted.

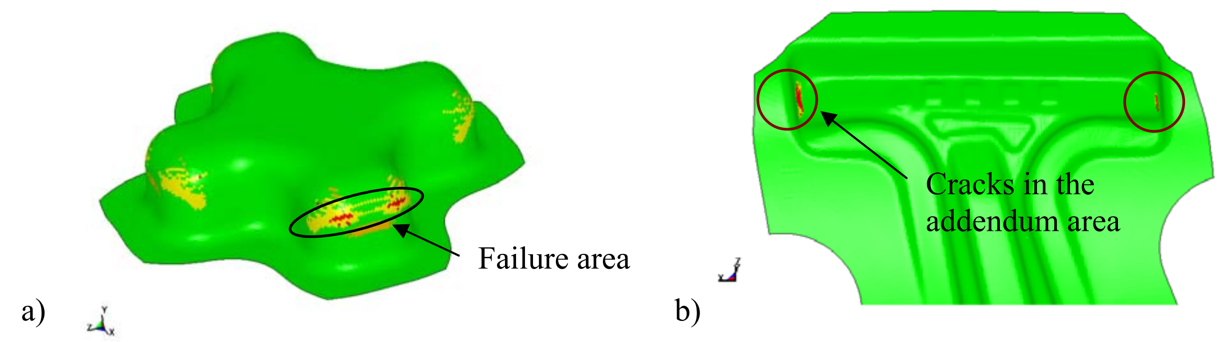

Fig. 5: Simulated strain at 200°C: a) cross-die; b) B-pillar

Fig. 5b shows the B-pillar after simulating warm forming at 200°C. The allowed strain is only exceeded in the area of the corner radius in the addendum of the B-pillar, which has to be removed by final trimming operation anyway. A local thinning is apparent only in the area of the corner radius (remaining thickness approximately 1.5 mm), which corresponds with the predicted cracking location. Further research should aim to optimise the component or die geometry and the process parameters through simulation with the aim of optimizing sheet thickness distribution.

5. Light weighting potential of EN AW-7075 T6 compared to ultra high-strength steels

Besides form-based, composite and conceptual lightweight design, materials-based design is one of the promising strategies to reduce the weight of vehicle structures using materials with competitive strength to density ratios compared to steel. This group of materials includes aluminium alloys, which are increasingly used in vehicle body design. The assessment of a material's light weighting potential is based not on its absolute strength but on its specific strength (strength-to-weight ratio).

After press hardening, manganese boron steels have a high tensile strength of between 1300 and 1600 MPa, or a high specific tensile strength and a low elongation of about 4 to 6% (Fig. 6a). Through tailored tempering, components with variable specific material properties can be made [1]. More ductile, crash-optimised zones with elongation above 10% but with a reduced strength can be created.

Warm forming ultra high-strength 7xxx aluminium alloys in temper T6 could provide an opportunity for producing lower-weight, crash-optimised components in high volume. Subsequent heat treatment temperatures of up to 220°C and times of up to 30 minutes do not cause significant overageing of the investigated alloy. At 240°C, however, overageing occurs rapidly. The results of age-hardening tests on EN AW-7075 T6 are shown in Fig. 6b.

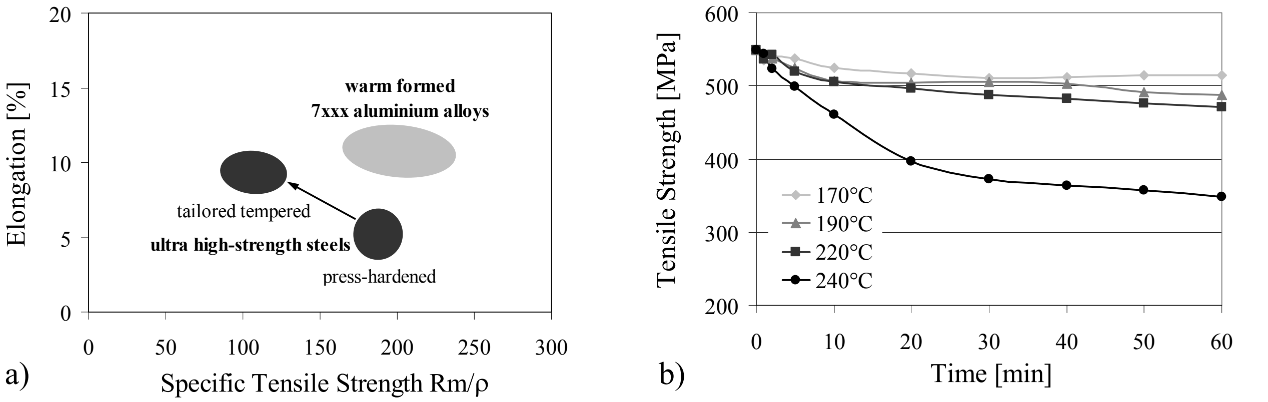

Fig. 6: a) Lightweight construction potential of high-strength 7xxx aluminium alloys compared with ultra high-strength steels; b) Age-hardening behaviour (overageing) of alloy 7075 T6

6. Summary

Because of their high specific strength, ultra high-strength 7xxx series aluminium alloys offer a significant potential for weight reduction of lightweight structures. They must be processed with forming methods that take the specific properties of this class of alloys into account.

The actual test results for flow stress reduction and increase in elongation at fracture, as well as the results of simulation modelling reveal the potential of ultra high-strength 7075 in temper T6 at higher temperatures for increased deformation. Initial FEM simulations demonstrate the possibilities for producing complex deep-drawing components.

These results, which were determined under laboratory conditions, need to be supplemented with further investigations to permit their reliable implementation in series production not only for automotive applications but also in consumer electronics and in aerospace.

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