Experimental study on the warm forming and quenching behavior for hot stamping of high-strength aluminum alloys

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Abstract. Within the last decades, stringent regulations on fuel consumption, CO₂ emissions and product recyclability forced the automotive sector to implement new strategies within the field of car body manufacturing. Due to their low density and good corrosion resistance, aluminum became one of the most relevant lightweight materials. Recently, especially high-strength aluminum alloys for structural components gained importance. Since the low formability of these alloys limits their application, there is a need for novel process strategies in order to enhance the forming behavior. One promising approach is the hot stamping of aluminum alloys. The combination of quenching and forming in one step after solution heat treatment leads to a significant improvement of the formability. Furthermore, higher manufacturing accuracy can be achieved due to reduced spring back. Within this contribution, the influence of forming temperature on the subsequent material behavior and the heat transfer during quenching will be analyzed. Therefore, the mechanical and thermal material characteristics such as flow behavior and heat transfer coefficient during hot stamping are investigated.

1. Introduction

Due to the fact that cars are responsible for around 12% of total EU emissions of carbon dioxide, the EU legislation has set mandatory emission reduction targets for new cars. By 2021, the fleet average to be achieved is set to 95 grams of CO₂ per kilometer [1]. Since the emission limits are set according to the mass of a vehicle, automotive industry focuses on lightweight strategies. Due to their low density and the good corrosion resistance, aluminum alloys became one of the most relevant lightweight materials. State of the art is the usage of aluminum alloys of the 5000 and 6000 series for inner and outer shell car body parts [2]. One new approach is the implementation of high-strength aluminum alloys of the 6000 and 7000 series for structural parts such as B-pillars, in order to pursue a holistic lightweight approach. Since these grades offer high strength but low formability and the occurrence of spring back, there is a need for novel methods in order to enable the manufacturing of complex car body parts. In 2005, Garrett et al. proposed a novel process consisting of a combination of solution heat treatment (SHT) and subsequent hot stamping followed by cold die quenching [3]. In conventional hot forming processes the material is formed in temper T6, a condition after thermal heat treatment to maximum strength where the mechanical properties of the material can be severely destroyed during its exposure to the high temperature [3]. This new approach has the advantage that forming is completed prior to any strengthening of the material due to ageing effects. Furthermore, forming process is realized with cold dies, resulting in reduced tool costs. Since the mechanical
properties of aluminum alloys are temperature dependent [4], for process design and the prediction of the mechanical properties of the part in post forming condition, an accurate modeling of the thermal phenomena during forming and quenching is essential. Besides convection and radiation, heat transfer via means of conduction is the predominating mechanism for cooling of the blank throughout the forming operation (see Figure 1). Conduction can be influenced by the blank thickness, surface roughness, coating thickness and the contact pressure [5]. Within this contribution, the temperature-dependence of the mechanical properties such as yield strength and strain hardening of the high-strength aluminum alloys AA6111 and AA7075 will be investigated. Furthermore, the influence of contact pressure on the resulting heat transfer coefficient of both alloys will be analyzed using a quenching tool.

Figure 1. Heat transfer mechanisms during hot stamping: conduction, convection and radiation [5].

2. Experimental

2.1. Material
Within this investigation, the age-hardenable high-strength aluminum alloys AA6111 in temper T4 (solutionized and quenched) and AA7075 in temper F (cold rolled) with an initial sheet thickness of $t_0 = 2.0$ mm are provided by Novelis, Switzerland.

2.2. Determination of the thermomechanical properties
For performing tensile tests at elevated temperatures, specimen with geometry according to DIN EN ISO 6892-2 are firstly laser cut and subsequently milled within the measuring zone in order to remove laser induced change of mechanical properties due to heat input. The thermomechanical simulator Gleeble 3500 (DSI, USA) is used and the recording of strain evolution is realized via optical strain measurement system Aramis (GOM mbH). Heat input results from resistance heating and the control loop is realized via thermocouples type K, which are placed in the middle of the specimen via welding operation. The experimental setup is illustrated in Figure 2.

Table 1. Configurations for tensile testing at elevated temperatures.

| Configuration                  | AA6111     | AA7075     |
|-------------------------------|------------|------------|
| Testing temperature $T_{Test}$ (°C) | 350, 400, 450, 500 | 250, 300, 350, 400 |
| Strain rate $\dot{\phi}$ (1/s) | 0.1, 1.0   | 0.1, 1.0   |
| Solution heat treatment temperature $T_{SHT}$ (°C) | 545 ± 5    | 465 ± 5    |
| Solution heat treatment time $t_{SHT}$ (s) | 180        | 180        |
Specimens are heated to solution heat treatment temperature $T_{SHT}$ and solutionized for $t_{SHT} = 3$ minutes. Subsequently, specimens are quenched to testing temperature with a quenching rate according to transfer from furnace to press, where convection is the predominating cooling mechanism. Strains and forces are subsequently measured at isothermal conditions. Tests are performed at various testing temperatures and strain rates and the configurations are listed in Table 1. Each test is performed for at least 3 times for statistical assurance.

2.3. Determination of the heat transfer coefficient

For the investigation of the quenching behavior after solution heat treatment in dependency of the contact pressure, a tool in laboratory scale with contact plates out of 1.2379 in combination with a hydraulic press type Lasco TSP100S0 is used, see Figure 3. Solution heat treatment is carried out with a chamber furnace type Rohde ME 17/13 SG and the temperatures for AA6111 and AA7075 are listed in Table 1. The solutionized aluminum sheets with the dimensions of 58 x 160 mm are transferred from the furnace to the press within 5 s and placed on spring-seated pins in order to avoid cooling during closure of the tool. Afterwards, a constant contact pressure ranging from 10 MPa to 40 MPa is applied via modulation of the press force on the surface of the specimen. The temperature-time evolution during quenching is recorded by thermocouples type K which are positioned inside the specimen via drilled holes with a diameter of $d = 1.1$ mm. The resulting temperature curves are subsequently used for the determination of the heat transfer coefficient according to the thermodynamic approach including the heat flux $\dot{q}$ generated by temperature gradients of two bodies with unequal temperature [6]:

$$\alpha = \frac{\dot{q}}{\Delta T}$$

(1)

The heat flux $\dot{q}$ is the total heat energy transferred from the hot workpiece to the cold dies across the contact area $A$ and can be calculated as written in (2):

$$\dot{q} = \frac{c_p \cdot \Delta T_{workpiece}}{\Delta t \cdot A}$$

(2)

$\Delta T_{workpiece}$ represents the discrete temperature change of the specimen and $\Delta T$ the temperature difference between the specimen and the contact plates at each time step $\Delta t$. According to [7] an average value of 920 J/(kgK) concerning the specific heat capacity $c_p$ can be assumed in the relevant
temperature range. For the calculation of the heat transfer coefficients $\alpha$ per increment, the time-temperature-data between 500 °C and 350 °C for AA6111 and 400°C and 250°C for AA7075 is used in which the forming operation takes place. Subsequently, the calculated values $\alpha_i$ are averaged to a representative heat transfer coefficient $\alpha$ [8].

![Figure 3. Tool for investigation of quenching behavior of the aluminum alloys AA6111 and AA7075.](image)

### 3. Results and discussion

#### 3.1. Determination of the thermo-mechanical properties

Based on the recorded true stress - true strain curves from tensile testing at elevated temperatures, the thermomechanical properties such as flow stress and strain hardening can be identified for the evaluation of the temperature-dependent material behavior. Fig. 4 shows the evolution of yield stress in dependence of the process relevant temperature range after solution heat treatment for both investigated aluminum alloys.

![Figure 4. Evolution of yield strength of the aluminum alloys AA6111 and AA7075 during tensile testing in dependence of temperature and strain rate.](image)
In case of AA6111, a temperature rise from 350°C to 500°C at a strain rate of 1.0 s⁻¹ leads to a reduction in flow stress of about 60%. By decreasing the strain rate to 0.1 s⁻¹, the reduction is about 75%. For the aluminum alloy of the 7000 series, the temperature-related decrement at strain rates of 1.0 s⁻¹ and 0.1 s⁻¹ in the temperature range between 250°C and 400°C amounts to about 30% and 45%, respectively. Comparing both alloys leads to the assumption that the temperature associated reduction of the flow stress is more pronounced for AA6111 which can be related to the higher testing temperatures, resulting from higher solution heat treatment temperatures due to the alloyed elements. In general, the phenomenon of temperature-related reduction of yield strength can be explained by thermal softening effects due to dynamic recovery. Higher deformation temperatures can enhance the thermal activation process of the alloys, leading to an acceleration of the dislocation motion and annihilation. Thereby, the dynamic softening is enhanced and stresses are reduced [9]. Additionally, change in strain rate has a higher impact on flow stress for AA7075 than for AA6111, represented by greater deviation of flow stress for both strain rates. This could also be associated with the more pronounced softening behavior of AA6111. Variations in yield strength at same temperatures but different strain rates can be explained by lower strain rate providing more time for energy accumulation for effects as for instance dynamic recrystallization, whereas the effect of dynamic recrystallization occurs more frequently at higher temperatures [10].

Figure 5. Evolution of strain hardening of the aluminum alloys AA6111 and AA7075 during tensile testing in dependence of temperature and strain rate.

Figure 5 shows the strain hardening exponent of the aluminum alloys AA6111 and AA7075 in dependence of temperature and strain rate. The progress of strain hardening evolution corresponds to the evolution of yield stress, \( n \) decreases with increasing temperature. AA6111 exhibits a strain hardening of about 0.1 at a temperature of 350°C and a strain rate of 1.0 s⁻¹. By increasing the temperature to 500°C, strain hardening is zero, representing a balance between work hardening due to dislocation accumulation and softening effects caused by thermal effects, as discussed above. Decreasing the strain rate to 0.1s⁻¹ leads to negative strain hardening exponents for temperatures of 450°C and 500°C, which means that softening effects are predominating and lower forces are required for proceeding of the deformation [11]. In case of AA7075, higher strain hardening exponents than for AA6111 can be seen which might be associated with the different temperature ranges again. Due to less pronounced softening effects, work hardening is still prevailing. For AA7075 the highest value of 0.2 can be reached at a temperature of 250°C and a strain rate of 1.0 s⁻¹. For a temperature of 400°C, the strain hardening exponent also becomes negative at a strain rate of 0.1s⁻¹.
3.2. Determination of the heat transfer coefficient

For the investigation of the heat transfer within the hot stamping process, the temperature evolution after closure of the tool has been recorded. Fig. 6 illustrates the temperature-time curves for AA6111 and AA7075 with varying contact pressures of 10, 20, 30 and 40 MPa. It can be seen that for both materials a higher contact pressure results in faster cooling, represented by higher gradients. Furthermore, both alloys exhibit different quenching behaviors. For AA6111, quenching rates are higher and differences between the varying contact pressures are not as pronounced as for AA7075. This can be explained by the higher temperature during solution heat treatment resulting in increased softening of the material. Therefore, roughness peaks might be smoothened faster resulting in earlier full contact of the tool with the specimen leading to faster cooling.

![Temperature-time curves during quenching of AA6111 and AA7075 after closure of the tool.](image)

The heat transfer coefficient $\alpha$ is subsequently calculated within the relevant temperature range between 500°C-350°C and 400°C-250°C for the aluminum alloys AA6111 and AA7075, respectively (Figure 7). For both alloys, increasing the contact pressure leads to higher heat transfer coefficients. This results from the increase of the real contact area with increasing contact pressure. The real contact area is the area where the atoms of one surface get in contact to the atoms of the other surface. Since the heat transfer between the specimen and the tool is realized through the real contact area rather than the apparent contact area, at low contact pressure condition, the real contact area is low, leading to a low value of heat transfer coefficient by means of conduction. As the contact pressure increases, the real contact area increases correspondingly leading to a gentle increase in the heat transfer coefficient [12]. In case of AA7075, the heat transfer coefficient is constantly raising with higher contact pressure. An increment of pressure from 10 MPa to 40 MPa results in a scale-up of heat transfer of about 80%. In contrast to that, AA6111 reveals no significant increase in heat transfer coefficient with increasing contact pressure from 10 MPa to 20 MPa. An explanation might be the higher surface roughness leading to a delayed full contact of the tool with the specimen due to a low real contact area at low pressures. For higher contact pressures an increase of the heat transfer coefficient can be noted and the maximum of about 9 kW/m²K can be calculated. Comparing both alloys, it can be stated that AA6111 shows higher heat transfer coefficients which might be associated to a higher thermal conductivity due to the chemical composition of the alloy.
4. Summary
In the presented research, experiments have been performed to study the thermomechanical behavior during isothermal tensile testing and the effect of varying contact pressures on the quenching behavior of the high-strength aluminum alloys AA6111 and AA7075. Firstly, yield stress and strain hardening exponent have been used for the investigation of the influence of temperature and strain rate on subsequent material behavior. It has been elaborated that both yield stress and strain hardening exponent show temperature dependent behavior, expressed by descending values with increasing temperatures. Main mechanisms are thermally activated softening mechanisms due to for instance dynamic recovery and dynamic recrystallization. Additionally, it has been shown that the softening effects are more pronounced for AA6111 which might be explained by the higher testing temperatures due to higher solution heat treatment temperature. Furthermore, the heat transfer by means of conduction was investigated by a laboratory-scale quenching tool. Based on temperature-time data, the heat transfer coefficient was calculated for both aluminum alloys within the relevant temperature region. It has been depicted that heat transfer increases with increasing pressure, due to the increment of the real contact area where the atoms of one surface contact the atoms of the other surface. Within this context it was shown that heat transfer behavior is different for both alloys, exhibiting higher heat transfer coefficients for AA6111. Finally, on the basis of the obtained data, a numerical simulation of the thermo-mechanical material behavior can be implemented and used for process design for the manufacturing of high-strength aluminum parts.

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