Temperature-controlled tools for multi-stage sheet metal forming of high-strength aluminium alloys

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Abstract. The high-strength aluminium alloys EN AW-6082 and -7075 possess great lightweight construction potential due to their high specific strength. However, their range of applications is limited by the low cold formability and high springback at room temperature, especially for EN AW-7075. An expansion of formability and a significant reduction in springback can be achieved with increasing temperatures. The possible process routes for forming high-strength aluminium alloys are shown in Figure 1. In warm forming, the sheet is heated to 200 °C and formed in an isothermal tool. Due to the low temperatures, the mechanical properties are retained and no subsequent heat treatment is required. For

1. Introduction

Increasing energy prices and growing environmental awareness among the population [1] as well as legal requirements such as the European Union’s target of reducing energy consumption by at least 32.5 % by 2030, [2] are making energy efficiency an increasingly important issue. Lightweight construction offers a possible way for implementation. In addition to the automotive sector, which is usually mentioned, the growing automation sector [3] also offers great potential. A lighter design of components can reduce the moving masses and thus also the energy requirements. [4]

Due to their high strength-to-weight ratio the high-strength aluminium alloys EN AW-6082 and -7075 represent a suitable choice for lightweight applications. But their range of applications is limited by two essential factors: Poor formability and high springback at room temperature, especially for EN AW-7075. An expansion of formability and a significant reduction in springback can be achieved with increasing temperatures. [5]

The possible process routes for forming high-strength aluminium alloys are shown in Figure 1. In warm forming, the sheet is heated to 200 °C and formed in an isothermal tool. Due to the low temperatures, the mechanical properties are retained and no subsequent heat treatment is required. For
hot forming, the sheet is solution heat treated at an alloy-dependent temperature of 470 - 530 °C before being formed and quenched in the tool simultaneously. [6]

![Diagram](image)

**Figure 1.** Possible process routes for forming high-strength aluminium alloys [based on 7]

If the components to be produced have a high degree of complexity, several drawing stages or even different process combinations are required in one multi-stage tool. This results in heat transfer from the preheated components to the tool parts, which, due to the temperature sensitivity of the material, affects the mechanical properties and thus also the formability [8]. In order to counteract this temperature drop or to maintain the temperature throughout the forming stages, it is therefore necessary to control the tool temperature in all relevant components. Tempered tools with resistance heating by cartridge heaters are already being operated at about 230 °C for single-stage warm forming [9]. If the temperatures exceed this temperature, the material properties are significantly affected [10]. This can be used to create graded components [11].

In addition to temperature-supported process routes, cold forming of preconditioned semi-finished products in the W-Temper (solution heat treated and water quenched) or O (soft annealing) state can also be performed. A problem in this context is the strain hardening that occurs, which minimizes the formability that can be achieved [12].

### 2. Temperature-controlled multi-stage forming tool

In order to meet the above-mentioned requirements and to ensure the necessary forming temperature in the individual stages, a temperature-controlled forming tool was developed. The tool design is shown in Figure 2. a). It includes four stages and covers the deep drawing, blanking, collar drawing and upsetting processes to achieve the demonstrator geometry with adapted wall thickness, shown in Figure 2. b).

All stages are of similar design and allow a precise temperature-control for all active parts interacting with the workpiece. The punches can be heated to the desired temperature by means of heating cartridges and the ring-shaped dies and blank holders can be heated with specially bent tubular heaters for a homogeneous temperature distribution, which can be seen in Figure 2. c) with the heated area marked in red. All heating components were previously designed using the mass of the tool component to be heated, the associated thermal material parameters and the target temperature, and were provided with a geometry-dependent loss factor (based on [13]). The heating components were positioned as close as possible below the tool surface, but this was partly limited by the geometric dimensions.

Furthermore, thermocouples type K are inserted a few millimeters below the tool surfaces and allow the measurement and control of the effective temperature. Due to the limited installation space and the large number of active parts that can be regulated, only one thermocouple was installed per control circuit. For this purpose, holes with a diameter of 1,6 mm were made by wire erosion so that the
thermocouples with a diameter of 1.5 mm could be inserted and fastened with screws. The thermocouples tested by the manufacturer were calibrated using a Pt100 before they are installed.

Figure 2. Tool construction: a) multi-stage forming tool with targeted temperature control, b) demonstrator geometry with adapted wall thickness and c) geometry of the tubular heater

In order to minimize the heat flow from the heated components made of Uddeholm’s hot-work tool steel Unimax® into the remaining tool or the press, isolation layers made of AGK’s K-Therm® AS 600M and water cooling are used in the upper and lower tool. This results in a total of 12 heatable and 8 coolable tool components.

3. Material and experimental setup

3.1. Material

In this study the two heat treatable aluminium alloys EN AW-6082 and -7075 were investigated. Both alloys are in the high-strength initial T6 state (solution heat treated, quenched and artificially aged). The chemical compositions of the investigated materials are listed in Table 1.

| Chemical elements [wt%] | Si   | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | Others |
|--------------------------|------|-----|-----|-----|-----|-----|-----|-----|--------|
| EN AW-6082 – T6          | 0.98 | 0.46| 0.06| 0.55| 0.94| 0.03| 0.06| 0.02| 0.01   |
| EN AW-7075 – T6          | 0.08 | 0.12| 1.60| 0.04| 2.70| 0.19| 5.90| 0.05| 0.14   |

The materials were characterized by yield strength (YS) and ultimate tensile strength (UTS) of 289 and 316 MPa for EN AW-6082 and of 531 and 588 MPa for EN AW-7075, respectively. Both materials were supplied in the form of coils with a thickness of 1.5 mm and then stamped into blanks with a diameter of 102 mm.

3.2. Experimental setup

For the tests on the temperature-controlled tool the experimental setup in Figure 3. a) is employed. For this purpose, the servo motor press Synchropress SWP 2500 with a maximum press force of 2.500 kN is used. In addition, the electrically heated, forced convection chamber furnace N 15/65 from Nabertherm is suitable for heating or heat treating the blanks. A multi-zone heating controller with a maximum power of 20 kW and 16 individually regulated heating zones as well as eight regulated cooling zones is utilized to control of the heated tool parts.

To determine the heating, cooling and quenching behaviour of the sheets, the circular blanks are prepared with four longitudinal notches of 1 mm depth. Two type K thermocouples with a diameter of
1 mm and two wires for better handling during the tests were inserted into the grooves as shown in Figure 3 b). The thermocouples used were calibrated before use as described in chapter 2. As a reference, single measurements were also carried out with a spring-loaded surface probe, since the use of thermal image cameras for aluminium is non-trivial and associated with large uncertainties due to the reflective surface as well as limited accessibility.

![Figure 3](image)

**Figure 3.** Experimental setup: a) forming tests with the temperature-controlled tool on the servo motor press and b) determination of the temperature behaviour of the sheet

### 4. Results of the experimental investigations

#### 4.1. Temperature influence during the forming tests

The sensitivity of the high-strength aluminium alloys to temperature changes can be seen in Figure 4. The blank made of EN AW-6082 in the T6 state is first deep-drawn and blanked at room temperature. This is followed by a heating of the part to 250, 300 or 350 °C in the forced convection chamber furnace. After heating, the part is transferred to stage 3. There, the hole diameter of 32 mm is expanded to 50 mm by means of collar drawing in unheated tools. While severe cracks still occur at 250 °C, these can be significantly reduced by increasing the temperature to 300 °C and completely avoided at 350 °C, so that the forming can be considered successful. For EN AW-7075, the first two stages can only be formed with a previous W-Temper heat treatment. Subsequently, a similar result emerges.

![Figure 4](image)

**Figure 4.** Stadium sequence and temperature influence in the third stage by forming EN AW-6082
4.2. **Heating, cooling and quenching behaviour of the sheet**

To determine the temperature behaviour of the sheet (without any lubrication), the prepared blanks were subjected to various heating and quenching methods. Since the two alloys exhibit almost identical behaviour, only the values of EN AW-7075 are presented below. Furthermore, the temperature curve of the second thermocouple (compare Figure 3. b)) was not shown, since no difference at all was apparent with the convective methods and only negligible differences occurred with the conductive ones. The corresponding trajectories are shown in Figure 5. With regard to the nomenclature in the diagrams, it should be noted that the gray lines represent the target variables. The type of line also assigns a concrete temperature to the curves.

![Figure 5. Temperature behaviour of EN AW-7075 sheet: a) convective heating, b) conductive heating, c) convective cooling and d) conductive cooling and quenching](image)

Figure 5. a) compares convective heating for a chamber furnace with and without forced convection at target temperatures of 250, 400 and 480 °C. This shows that a forced convection chamber furnace is required for precise and rapid heating of the sheets. The target temperature is thus reached after approx. five minutes for all temperatures, while the normal chamber furnace shows a clear offset after ten minutes. The achievable heating rate from 100 - 470 °C with this system amounts to 1.7 °C/s.

In comparison, Figure 5. b) shows the equivalent procedure for conductive heating by means of a heated forming tool and a contact heating unit, specifically designed for heating flat sheets. Both methods represent heating between two heated tool parts under pressure and show almost identical behaviour. The target temperature is reached within a few seconds with a heating rate of 43.7 °C/s in the range of 100 - 470 °C. In case of one-sided tool contact with a heated tool on the bottom side and air on the upper side (Tool (tempered) / Air) only low heating rates are achieved. The main reason for this is the reduced contact surface between the tool parts and the component, which results from the pressure-free state and springback from previous forming operations. This is particularly relevant for the heat transfer during the transfer of parts between the stages. The same applies to the contact between...
a heated and a cooled tool (Tool (tempered / RT)). The high heat transfer from the heated to the cooled tool also becomes problematic because the tool temperatures converge and this leads to a large difference between target and actual temperature in the sheet. Sheet heating in the tool within a few seconds is thus feasible, but contact on both sides should be ensured.

Equivalent to the heating behaviour, Figure 5. c) shows the convective cooling at resting air and Figure 5. d) the cooling and quenching behaviour in water or in the tempered tool. Especially in hot forming as well as W-temper heat treatment, it is necessary to keep the critical quenching rate of 100 °C/s [14], because only then do the alloying elements remain dissolved in the crystal lattice of the aluminium [8]. The critical quenching rates in the range of 400 - 200 °C are only achieved in water with 752,1 °C/s or in a cooled tool with 140,6 °C/s. At resting air, the cooling rate is only 1,4 °C/s and does not yield the desired effects in the material. Even between heated tools with temperatures of 100, 200 and 300 °C, the sheet almost reaches the tool temperature within a few seconds. Also, with a one-sided contact to the cooled tool, the component cools down significantly within seconds. This illustrates the high temperature losses over the individual forming stages and thus the necessity of tool temperature control, due to the high thermal conductivity of aluminium and the large surface to volume ratio.

4.3. Temperature application through preheated blanks

In the next step, the heat input by heated blanks is investigated. For this purpose, the first tool stage with a deep drawing process is considered. As shown in Figure 6. a), the blanks are heated to 480 °C and inserted into the uncooled tool while varying the cycle time (30, 60, 120, 240 s). The thermocouple in the punch can thus be used to determine the temperature curves presented in Figure 6. b).

The curves show the temperature input per stroke. As the cycle time decreases, the time for convective heat transfer to ambient air is reduced, resulting in a stronger temperature rise. Due to the experimental conditions, the minimum cycle time of 30 s could only be determined for 15 minutes. It is clear that the curve continues to rise sharply and no steady state is reached. However, this is absolutely necessary for a robust production. For industrial mass production, a significantly shorter cycle time is to be aimed for, which therefore requires very precise temperature regulation in all tool parts. In this context, it is also important to consider energy efficiency through the counterplay of heated and cooled tool parts.

![Figure 6. Temperature behaviour in the forming tool due to the insertion of heated blanks: a) experimental setup and b) results under variation of the cycle time](image)

4.4. Temperature distribution in a heated tool

In addition to the heat input by the blanks, the heat conduction within the tool also influences the temperature distribution in the tool stage. To characterize this, die and blank holder are heated up to 200 and 400 °C, respectively. A temperature sensor was then used to measure the surface temperatures of all accessible components in the force flow in a stationary condition without forming operations. The measuring points (marked with an x) and the corresponding measured values are shown in Figure 7.
The target temperatures in the heated tool components have a maximum deviation of 7 %, but this is due to the temperature measurement. While the controlled temperature is recorded in the tool itself, the one measured here is determined at the surface. The exact temperature control also detects heat transfers into adjacent components despite the implementation of isolation plates between heated and cooled/non-tempered tool parts. In the upper tool, the intermediate piece (shown in orange) reaches a temperature of 119.5 °C at a die temperature of 400 °C. This temperature can be reduced to 27.4 °C within 30 minutes by switching on the cooling. The high gradient can be achieved because the heated die and the cooled intermediate piece are only separated by the isolation layer. However, this also leads to a slight drop in die temperature.

In the lower part of the tool, the blank holder plate (shown in blue) is close to the heated blank holder, so that the plate reaches a temperature of 158 °C. Since it has no direct connection to the cooling part, the temperature is not reduced when cooling is activated. This illustrates how strongly individual components heat up during the operation of heated tools and thus influence the process, e.g. also through thermal expansion.

Consequently, precise temperature control of the dies as close as possible to the forming process and cooling of the surrounding components is required. The heat transfer via the necessary screw connections must also be emphasized as critical.

![Figure 7. Temperature distribution in a single heated tool stage in the steady state condition](Image)

5. Summary and Outlook
This paper has shown how temperature-sensitive the high-strength aluminium alloys EN AW-6082 and -7075 are and how much their formability can be improved at higher temperatures. However, as the temperature increases, so do the demands on the tools and the process control, especially in multi-stage forming processes. The reason for these are the disturbances within the control loop, first and foremost the heat transfer between the individual components, but also the thermal expansion and resulting dimensional deviations.

In addition, there is the field of tribology, which has been left out of the considerations here, and also the influence of temperature on the mechanical properties. In order to ensure reproducible, robust and
economic forming processes, a very precise process design and control is required. This can also be optimized in terms of resource efficiency, for example by targeted oversteer in the heating phase for shorter cycle times.

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