Comparison of different forming methods on deep drawing and springback behavior of high-strength aluminum alloys

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Abstract. High-strength aluminum alloys of the 7XXX series have a high potential for safety and crash-relevant components due to their advantageous density-to-strength ratio. Currently, the use of these alloys is limited because of the low formability at room temperature. By using thermal supported forming strategies, failure-free deep drawing is possible for these materials. At present, several thermal-assisted forming processes exist, but so far there is no comparison between these forming operations. For this purpose, this study compares the deep drawing behavior of the alloy AA7075 by using different thermally-assisted forming operations. Aim of this work is to enhance the understanding and comparability between different thermally-assisted forming processes for high-strength aluminum alloys. First, a thermal simulator is used to investigate the mechanical material behavior according to different temperature-time curves by using uniaxial tensile tests. Subsequently, the formability and springback behavior is determined numerically and experimentally in a model test. Finally, for one thermally assisted forming method, the experiments are scaled up to a real size process with drawbeads to validate the transferability. This study can help to improve the scientific knowledge for the use of these materials in future.

1. Introduction, state of the art and goal

In the past decades, the weight of vehicles has risen continuously due to increased comfort, performance and safety requirements. At the same time, the demand for fuel-efficient, environmentally friendly and electrified vehicles is becoming stronger due to growing environmental awareness. As a result, vehicle manufacturers are facing new challenges. One approach according to the demands is the consequent lightweight construction of vehicles. High-strength aluminum alloys are highly attractive as lightweight materials for automotive construction due to their advantageous density-to-strength ratio, bending stiffness, corrosion resistance and recyclability [1]. As a result, there is the potential to replace steel materials by lighter aluminum components. At present, aluminum alloys of the 5XXX and 6XXX series are already in use for serial vehicle production in the area of shell or structural parts [2]. In comparison, the 7XXX aluminum alloy series offers higher lightweight potential for structural and crash-related applications in the future due to its superior mechanical properties. Up to now, the use of this group of alloys has been very limited because of the low formability of these materials at room temperature. In the past, it has been shown several times that thermally assisted forming operations can positively influence the forming behavior of high-strength aluminum alloys [3]. Nevertheless, companies in the industry often avoid the use of these technologies. Reasons are the increased costs, which are directly related to the higher cycle times, additional costs for heating furnaces as well as increased wear and
friction problems of the tools as well as the difficult temperature control [4]. Because of these reasons, only forming processes which do not require additional tool heating will be compared in this paper. Aim of the present investigation is to analyze and compare different thermal-assisted forming processes with respect to deep drawing capability and springback behavior. In addition, one process strategy will be transferred to a large-volume, practice-oriented component with integrated drawbeads. This offers the opportunity to compare both the transferability and the influence of production-related tool elements on the deep-drawing and springback behavior of the heat-assisted forming operations.

2. Process routes for thermal-assisted forming operations
Aluminum alloys of the 7XXX alloy series are usually delivered in the stable condition T6. In this condition, these alloys have high strength combined with limited formability because of their precipitation hardened condition. For high-strength aluminum alloys, several different heat-assisted forming processes exist that expand the forming capabilities significantly. The heat treatment of the components can be done before or during the forming process. Both, for components formed in the so-called W-Temper [4] condition and for the use of Tailor Heat Treated Blanks (THTB) [5], the aluminum sheets are thermally heat treated before the deep drawing operation in order to improve formability. In the case of warm forming [6] and hot forming and quenching (HFQ®) [7], heat treatment takes place inside the tool during the forming process. Because both the W-Temper and the HFQ®-process are part of the investigations in this publication, they are explained in more detail below.

The W-Temper process consists of six process steps: solution annealing, quenching, lubricant application, forming, cleaning and aging (see figure 1, a)). In the first step, the Al-Zn-Mg alloy is heated up to solution heat treatment temperature (SHT), in order to dissolve all precipitates in the aluminum matrix. In the next step, the component is quenched at a high cooling rate to generate a supersaturated solid solution (SSSS) [8]. In the quenched condition W, the material has an increased ductility and a low strength compared to the initial condition T6. Choi et al. [9] showed, that the material AA7075 exhibited a yield stress reduction from about 530 MPa to 165 MPa by a solution heat treatment and subsequent quenching operation. Because the generated condition is not stable, the components are then oiled and formed as quick as possible. Argandona et al. [4] have demonstrated for the material AA7075 that it has to be formed within ten minutes after the quenching operation, after that time an increase in hardness can already be observed. After the forming operation at room temperature, the components are cleaned and subsequently, age hardened. Lee et al. [10] showed that the alloy AA7075 achieves final component strength of about 400 MPa after a W-Temper forming operation in combination with a subsequent age hardening operation at 180 °C for 30 minutes.

The Hot Forming Quench (HFQ®) process (see figure 1, b)) is a hybrid forming process that combines thermal and mechanical treatment of parts during deep drawing and consists of four process steps:
solution heat treatment, forming and quenching, component cleaning and aging. First, the component is heated to solution heat treatment temperature, similar to the W-Temper process, which dissolves the alloying elements in the aluminum structure [8]. Subsequently, the components are transferred in the hot condition into the forming tool and are then formed and quenched simultaneously. The HFQ® of high-strength aluminum alloys enable the generation of a supersaturated solid solution during the forming operation, which has the potential for an artificial aging operation [11]. For the alloy AA7075, the crucial temperature range in which a high cooling rate must be achieved in the forming tool is between 400 °C and 290 °C [8]. Investigations by Behrens et al. [12] show that the alloy AA7075 exhibits different mechanical properties depending on various quenching rates. In this way, it was shown that the highest mechanical properties are achieved at a quenching rate of more than 100 K/s. Studies by Degner et al. [13] revealed, that the applied contact pressure during the forming operation has a direct influence on the heat transfer coefficient, and thus has an active influence on the quench rate during the forming operation. After forming, the components are cleaned and the final strength properties are reached by using an artificial aging operation. For the alloy AA7075, investigations have shown that using a quenching and artificial aging operation, higher mechanical strengths can be achieved compared to the W-Tempering process [4].

For the HFQ®-process, the lubrication step is transferred to the forming tool, because up to now there are no temperature-resistant lubricants on the market with sufficient lubricating effect after a solution heat treatment operation at more than 450 °C. In own studies, it was shown, that the use of dry lubricants prevents the generation of toxic emissions and has advantageous forming and cleaning characteristics for the HFQ®-process [14].

3. Experimental tests
In this study, the age-hardenable aluminum alloy AA7075 in the delivered condition T6 was used in the sheet thicknesses t₀ = 1.5 mm as well as t₀ = 1.0 mm.

3.1 Characterization of the thermomechanical material properties
To identify the mechanical properties as a function of different thermal heat treatments, tensile test specimens based on the A50 test geometry were laser cut and subsequently milled according to DIN EN ISO 6892-2 to reduce the influence of the thermal cutting operation. By using the thermomechanical simulator of type Gleeble 3500 (DSI, USA) in combination with an optical strain measurement system Aramis (GOM GmbH), tensile tests were carried out. The applied temperature was controlled by means of centrally applied thermocouples type K. In Table 1, the testing configuration is given. The material is tested in the as-received condition (T6) as well as in the conditions during thermal assisted forming (W-Temper, HFQ®) at a nominal strain rate of 0.667 s⁻¹. The specimens are first heated to the solution heat treatment temperature TSHT and subsequently quenched with air to the required test temperature using integrated quenching nozzles. To model the mechanical behavior of the AA7075 alloy under non-isothermal conditions more precisely, two temperature variants were determined for quench forming (HFQ®). Each test was performed at least three times for statistical assurance.

| Material condition | Heat treatment (°C; sec) | Quench (K/s) | Testing temperature (°C) | Orientation (°) |
|--------------------|--------------------------|--------------|--------------------------|----------------|
| T6                 | -                        | -            | RT                       | 0, 45, 90      |
| W-Temper           | 480 ±5; 180              | 100 ±15      | RT                       | 0, 45, 90      |
| HFQ® @ 300°C       | 480 ±5; 180              | 100 ±15      | 300°C ±5                 | 0, 45, 90      |
| HFQ® @ 400°C       | 480 ±5; 180              | 100 ±15      | 400°C ±5                 | 0, 45, 90      |

3.2 Characterization of the springback and deep-drawing behavior
To characterize the springback and deep-drawing behavior, experimental and also numerical investigations were carried out. For the experimental determination of the springback and limit drawing
ratio (LDR), deep-drawing tests were carried out using a hydraulic press type Lasco TSP100 S0. A rotation symmetrical unheated cup tool (see figure 2, a)) was used for the experiments. To determine the influence of drawbeads on thermally assisted forming operations, an unheated large-volume die was used in combination with the hydraulic press type Hydrap HPDZb 603 (see figure 2, b)). All specimens were placed in the tools by using positioning devices to ensure repeatability.

| a) | Rotational symmetrical die | b) | Die with drawing beads |
|----|----------------------------|----|------------------------|
| ![Drawing tool](image) | ![Picture tool](image) | ![Drawing tool](image) | ![Picture tool](image) |

**Figure 2.** Experimental tool geometries

To investigate the influence of different thermal supported process routes on the springback behavior, rectangular blanks (see figure 3, a)) were formed in the rotation-symmetrical tool (see figure 2, a)) at a constant drawing depth of 44 mm and a constant drawing gap of 2 mm between blankholder and die. To take the influence of the rolling direction (RD) of the sheet into account, specimens were cut out 0°, 45° and 90° to the rolling direction respectively. For the identification of the LDR, rotation-symmetrical blanks (see figure 3, b)) with different blank diameters were used. Depending on the blank size, the drawing depth and the blankholder force were set individually. The necessary blankholder pressure was set according to Siebel [15] as a function of the determined material properties. To investigate the influence of drawbeads on the deep drawing and springback behavior of high-strength aluminum alloys, rectangular blanks 0° to the RD (see figure 3, c)) were formed in the forming tool with drawbeads (see figure 2, b)). For this purpose, a constant drawing gap of 1.5 mm and a drawing depth of 150 mm were set.

For the forming operations carried out with unheated blanks during forming, the components were lubricated on both sides with a deep-drawing oil (KTL N16, Zeller+Gmelin GmbH & Co. KG) before the forming operation. For the HFQ® tests, a lubricant specially developed for this purpose (HTP 30, Holifa Fröhling GmbH & Co. KG) was applied onto the forming tool before the forming tests.

| Springback behavior with drawbeads | Limit drawing ratio |
|-----------------------------------|---------------------|
| ![Springback behavior](image) | ![Limit drawing ratio](image) |

**Figure 3.** Specimen geometries for the identification of the deep drawing and springback behavior

### 3.3 Optical component characterization

After the forming operations, the components were cleaned and coated with a reflection-reducing paint for optical component measurement. Then, the components are optically scanned by using an optical 3D measurement system type ATOS (see figure 4, a)). The digitized components are then optically analyzed using the software GOM-Inspect to determine the component springback (see figure 4, b)). For this purpose, a section plane is placed in the middle of each digitized component. In this cross-
section, three regression lines are applied by using a Gauss best-fit method in the flange and the bottom area of the components. Thereby, the determination of the component springback by using angle measurement is possible. The dimensions of the simulated components are analyzed with the same measurement strategy and evaluation software (see figure 4, c)). This allows a direct comparison between the experimental and simulated springback angles.

![Figure 4. Digitalization and measurement of the formed a) and the simulated components c) for the identification of the springback angle b)](image)

4. Results and discussion
To determine the forming and springback behavior of high-strength aluminum alloys, first, the material characteristics were determined, then the springback characteristics were determined numerically and experimentally, followed by the production of large-volume components.

4.1 Determination of the process dependent material properties
The temperature- and process-dependent material behavior of the alloy AA7075 was characterized for the initial state T6 as well as for the conditions W-Temper and HFQ®. Because the material behavior changes according to the material temperature during quenching, for the HFQ®-process tensile tests were carried out for 400 °C and 300 °C. In figure 5, the material behavior is illustrated by means of flow curves 0° to the rolling direction. It can be seen that the material in the initial state T6 has a yield stress of (556.3 ± 3.3) MPa and a minimum elongation of 0.15. After the thermal process route of the W-Temper process, yield stress of (174.1 ± 8.8) MPa and a minimum elongation of 0.24 are achieved. Using the thermal process route HFQ® and quenching to 300°C, yield stresses of (138.71 ± 2.2) MPa and a minimum elongation of 0.5 are realized. When cooling to a test temperature of 400°C, the yield stress decreases to (60.5 ± 1.3) MPa and the elongation increases to 0.65. A similar trend of the mechanical properties can also be seen at 45° and 90° to the rolling direction, however, a significant directional dependence of the materials was observed.

![Figure 5. True stress- true strain curves of AA7075 for different material conditions in 0° RD](image)

Subsequently, the determined flow curves were interpolated and extrapolated using the law of Hockett-Sherby [16]. The biaxial material behavior was calculated using the mathematical assumption of Abspoel et al. [17]. With the help of the yield criterion of Balart Yld2000 [18], the different material states were described.
4.2 Numerical and experimental analysis of the springback behavior

To compare the springback behavior of different process routes, the material behavior determined in section 4.1 was modeled in the simulation software LS-DYNA. For this purpose, the anisotropic material behavior was defined using *MAT133. The coefficient of friction between tool and blank was assumed to be a constant value of 0.1 for all processes. In order to validate the defined material properties, a one-element test was carried out for each material card and compared with the determined flow curves. Subsequently, a two-stage simulation consisting of an explicit forming simulation and an implicit springback simulation was built up. The boundary conditions of the forming tool (see section 3.2) were defined and the occurring component springback was subsequently measured using the measurement strategy described (see section 3.3). The simulations of the shell elements were performed by using the solver version mpp_d_R11_1. To ensure a high accuracy the element length was set to 1 mm.

In figure 6 a), the necessary maximum punch forces for the cold forming of the material AA7075 in the initial condition T6, the W-Temper process and the HFQ® process are shown. It can be seen that an average force of 4.53 kN is required for the cold forming in the initial state T6. It can also be seen that the blanks 45° to the rolling direction tend to generate the lowest punch force during forming. Cold forming of the specimens in the W condition show a reduction of the maximum punch forces of 55 % to an average force of 2.05 kN. With the HFQ®-operation, the maximum punch forces decrease to an average of 1.57 kN and thus the punch force can be reduced by 65 % in comparison to the initial condition. In both, the W-Temper and the HFQ®-process, an anisotropic material behavior is evident. However, it can be seen that for the HFQ®-process the differences are so small that they are in the range of the standard deviation.

Subsequently, the formed components were measured optically. In figure 6 b), the results of the experimental and numerical springback are shown as a function of the process routes and rolling direction. It can be seen that for cold forming average springback angles of 30.2° result in the experiment and around 27.0° in the simulation. The reason for the average deviation of 3.2 % between experiment and simulation can be explained by the missing modeling of the kinematic hardening behavior in the simulation. For the W-Temper process, average springback angles of 11.3° can be seen experimentally and 10.8° numerically. In addition to the reduction in springback, a small deviation of approximately 0.4° between experiment and simulation is evident. For the HFQ®-process, minimum springback angles of 3.0° experimentally and 1.7° numerically are recognizable and thereby a springback reduction of up to 90 % compared to the initial material condition T6 is possible. The deviation of 1.3° can be explained by the changed tribological conditions during quench forming in combination with a dry lubricant which is not taken into account yet. The observed results show that the forming forces, as well as the occurring springback angles, depend on the material properties and therefore on the process used. Differences in kinematic hardening behavior are also expected.

Figure 6. Necessary punch forces a) and resulting springback angles b) for thermally assisted forming processes
4.3 Influence of the forming operation on the deep drawing behavior

The same tool from section 4.2 was then used to determine the limiting drawing ratio (LDR). In figure 7, the limiting drawing ratios and the maximum punch forces for the different process routes are shown. It can be seen that the material AA7075 in condition T6 does not reach the limiting drawing ratio of 1.8. In contrast, the material in the W-Temper condition can be formed without failure up to a limiting drawing ratio of 1.9. For the HFQ®-process, it can be seen that wrinkling occurs from a limiting drawing ratio of 2.0. The reason for this is the combination of minimum blankholder force required to form the part without failure. From a limiting drawing ratio of 2.1, the HFQ® components also fail due to excessive material folding and the resulting restraining force. It can be seen that the defined tool configuration causes uncontrolled component thinning and wrinkling for the HFQ®-process.

![Figure 7. Deep drawing behavior of AA7075 as a function of different thermally assisted forming processes](image)

| Diameter blank (mm) | 90 | 95 | 100 | 105 |
|---------------------|----|----|-----|-----|
| Limit drawing ratio (LDR) | 1.8 | 1.9 | 2.0 | 2.1 |

| Max. punch force (kN) | Crack | - | - | - |
|-----------------------|-------|---|---|---|
| T6                    | 115.4 ± 2.2 | - | - | - |
| W-Temper             | 47.8 ± 0.9  | 56.6 ± 0.7  | 65.0 ± 0.3  | - |
| HFQ®                 | 27.2 ± 0.4  | 31.3 ± 0.9  | 53.3 ± 2.5  | 27.2 ± 0.4 |

4.4 Transfer of methods to large component geometry with drawbeads

The investigations in section 4.2 and 4.3 show that thermally assisted forming processes have a positive influence on the forming and springback behavior. However, the HFQ®-process has previously demonstrated a tendency to uncontrolled thinning due to its low yield stress. As a result, the W-Temper process was chosen to investigate the influence of drawbeads on the springback behavior. The components were deep-drawn with a drawbead height of 2.2 mm and 5 mm. Figure 8 shows the digitized components. The results show that using 5 mm high drawbeads results in lower springback angles compared to 2.2 mm high drawbeads. Besides, it can be seen that the punch force increases with higher drawbeads. Thus it can be concluded, that drawbeads have a positive effect on the springback behavior of thermally treated components, but at the same time cause increased forming forces and stresses in the component.

![Figure 8. Influence of drawbeads on the springback behavior of components produced in the W-Temper condition](image)

\[
\begin{align*}
F_{mn,22} &= (17.4 \pm 0.3) \text{ kN} \\
F_{mn,5} &= (29.4 \pm 0.1) \text{ kN} \\
a_{22} &= (90.1 \pm 1.5) ^\circ \\
a_{5} &= (70.6 \pm 1.4) ^\circ \\
n &= 3
\end{align*}
\]

5. Summary and outlook

In this study, it was shown that the mechanical material behavior of high-strength aluminum can be reproduced well with thermal-assisted characterization tests. Experimental and numerical forming operations have shown that the springback and deep-drawing behavior of high-strength aluminum alloys can be influenced positively with the aid of thermally assisted forming operations. In addition, it was
shown that the anisotropic material behavior can be reduced with the aid of thermally assisted forming operations. Also, the use of drawbeads has shown that they have a positive influence on springback behavior as well but increase the necessary forming forces. To improve the design of the HFQ®-process in the future, it is necessary to carry out a detailed determination of the material properties and the tribological behavior during use. The transfer of other thermally assisted process routes, such as the HFQ®-process, to application-oriented tools with drawbeads would be useful to expand knowledge. In this way, the influence of drawbeads on the quenching and deep-drawing behavior of components could be investigated, for example. For the future design of thermally assisted process routes, additional compensation with other thermally assisted forming methods will be useful.

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