Development of a process chain 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 are characterized by low density and high strength but also limited cold formability and pronounced springback behaviour in the ultra-high-strength T6 state. In order to exploit their lightweight design potential, temperature-supported process routes such as warm or hot forming are applied. Alternatively, there is the possibility of cold forming preconditioned semi-finished products at the expense of the initial material properties. Common to all variants are complex interrelationships due to linked plant periphery resulting from up- and downstream heat treatments. In addition, occurring heat transfers in temperature-supported process routes or strain hardening effects during cold forming lead to reduced formability. Especially for multi-stage forming processes, as they are required for complex components, the above-mentioned process routes reach their limits. The different requirements of the four single-stages (deep drawing, blanking, collar drawing and upsetting) for the production of a demonstrator geometry with adapted wall thicknesses make a new type of temperature control necessary. This paper shows that the combination of temperature-supported and multi-stage forming contributes to a significant increase in formability. The temperature-controlled forming tool used for this purpose enables an inline heating of the components during the process, so that an industrially feasible and economical overall process chain for the fabrication of the demonstrator geometry out of those alloys is convertible.

1. Introduction

The low density and tensile strengths of at least 540 MPa [1] qualify high-strength aluminium alloys for various lightweight applications in the mobility sector [2]. A broad industrial application is limited by the low cold formability [3] and the high springback during cold forming [4]. To extend the process limits, complex and expensive temperature-supported process routes are required [5]. The most common method is hot forming, in which the sheets are first solution annealed and then quenched parallel to forming in the tool [6]. Alternatively, warm forming at 200 - 250 °C in an isothermal tool [7] or cold forming of preconditioned semi-finished products in the W-Temper-state (solution heat treated and water quenched) [8] or soft-annealed O-state are used [9]. Apart from warm forming, all routes require subsequent heat treatment to return to the high-strength T6-state [10].

If even these processes reach their limits, multi-stage forming is unavoidable. In this way, complicated components can be produced by a combination of various processes or drawing ratios [11].

Studies by Lai [12], Takalkar [13] and Pourkamali Anaraki [14] show the possibilities and challenges of multi-stage forming processes. Depending on the operation and process route, different stress conditions and thus forming requirements arise for the individual tool stages. In addition, there are complex interrelationships due to linked plant peripherals, heat transfers in the case of warm and hot forming [9] or pronounced strain hardening when using preconditioned semi-finished products [15, 16].

The combination of temperature-supported and multi-stage forming is a major challenge and will be illustrated based on the sequence of operations shown in Figure 1 (a). It contains the processes deep drawing, blanking, collar drawing and upsetting and enables the production of a demonstrator geometry with adapted wall thicknesses, which can be seen in Figure 1 (b). The need for targeted, novel temperature control is evident from the cold-formed specimen of EN AW-7075 in the high-strength T6 condition shown in Figure 1 (c). It already breaks down into several parts in stage 1 and illustrates the limited cold formability. For this reason, the development of a process chain for multi-stage sheet metal forming of high-strength aluminium alloys is of particular importance.

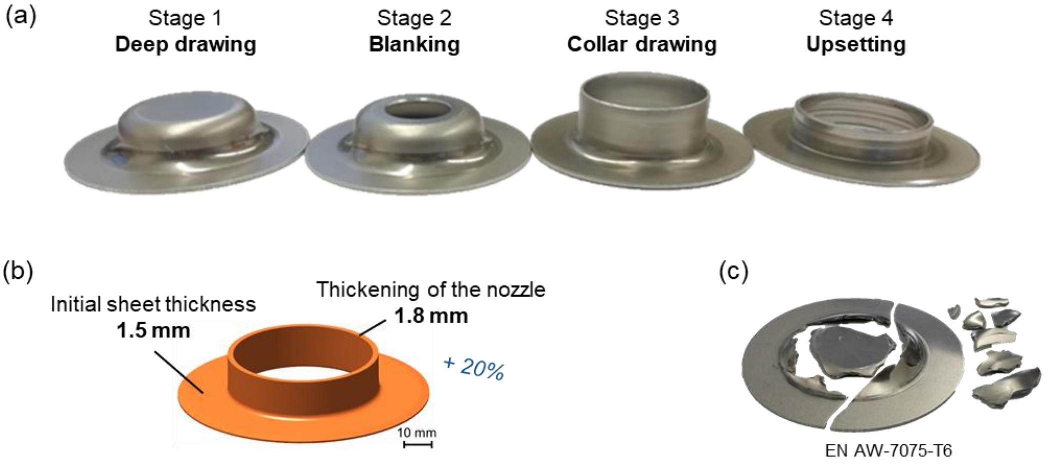


Figure 1. Multi-stage forming process: stadium sequence (a), demonstrator geometry with adapted wall thicknesses (b) and result of cold forming of EN AW-7075-T6 in stage 1 (c).

2. Materials and experimental setup

The high-strength aluminium alloys EN AW-6082 and -7075 and the experimental setup used to study their temperature-dependent process limits and to develop a feasible overall process route are described below.

2.1. High-strength aluminium alloys EN AW-6082 and -7075

The two materials investigated in this study are the high-strength aluminium alloys EN AW-6082 and -7075. Both belong to the heat-treatable alloy classes and are present in the high-strength T6 state (solution heat treated, quenched and artificially aged) with a thickness of 1.5 mm. Characteristic of the 6xxx alloy is the magnesium and silicon content, while zinc and copper are the main alloying elements in 7075. The exact chemical composition of the alloys can be found in Table 1.

Table 1. Chemical composition of EN AW-6082 and -7075.

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

Depending on the existing heat treatment condition or temperature, the sheets have very different mechanical properties. To quantify these in more detail, tensile tests are carried out with tensile specimens of shape H longitudinally to the rolling direction at a tensile speed of 0.2 mm/s. Table 2 shows that ultimate tensile strength of 316 MPa and 588 MPa can be achieved in the high-strength T6 state, for the 6082 and 7075, respectively. However, the elongation at break shows only low values of around 12 % each. Preconditioning to the unstable W-Temper- (solution heat treated and quenched) or soft annealed O-state can significantly reduce the strength while increasing the elongation at break, thus extending the formability.

Table 2. Mechanical properties of EN AW-6082 and -7075 in different heat treatment conditions.

Alloy – condition	R_m [MPa]		$R_{p0,2}$ [MPa]		A [%]	
EN AW-6082 – T6	316.1		289.1		12.0	
EN AW-6082 – W	183.7	*-42 %*	59.5	*-79 %*	24.5	*+103 %*
EN AW-6082 – O	115.9	*-63 %*	38.8	*-87 %*	32.4	*+169 %*
EN AW-7075 – T6	587.6		531.3		11.8	
EN AW-7075 – W	374.3	*-36 %*	164.9	*-69 %*	21.8	*+85 %*
EN AW-7075 – O	218.4	*-63 %*	104.8	*-80 %*	15.0	*+27 %*

To set these conditions, defined heat treatment routes are necessary. In the W-Temper, a short solution annealing of 3 minutes is carried out at alloy-dependent temperatures of 530 °C (6082) or 480 °C (7075). Afterwards, the blanks are rapidly quenched in a 15 % polymer solution to maintain the supersaturation state. The polymer quenchant Serviscol 98-AL from Burgdorf leads to a reduction in distortion [17]. To produce the soft-annealed O-state, rapid heating to 410 °C is carried out in accordance with the recommendation of DIN 29 850, including a 2-hour holding time. Subsequently, the sheets are cooled down to 260 °C (6082) or 230 °C (7075) at a controlled rate of 30 °C/h and held for further 2 hours before cooling in air. [18]

2.2. *Experimental setup*

The forming tests are carried out on the specially developed four-stage forming tool which can be seen in Figure 2 (a). Special features are the heatable active parts (die, blankholder and punch) which allow precise temperature-control to ensure the necessary forming temperature or maintain temperatures in the individual stages. The heated active parts made of Uddeholm's hot-work tool steel Unimax® are realized by means of inserted heating cartridges or tubular heaters as well as thermocouples type K for the extraction of the controlled variable. To reduce the heat flow into the adjacent tool components, isolation plates made of AGK's K-Therm® AS 600M and a water cooling are integrated. To ensure high reproducibility with regard to the cycle time and the accuracy of the component alignment, an electro-pneumatic transfer system (not shown in Figure 2) was also implemented.

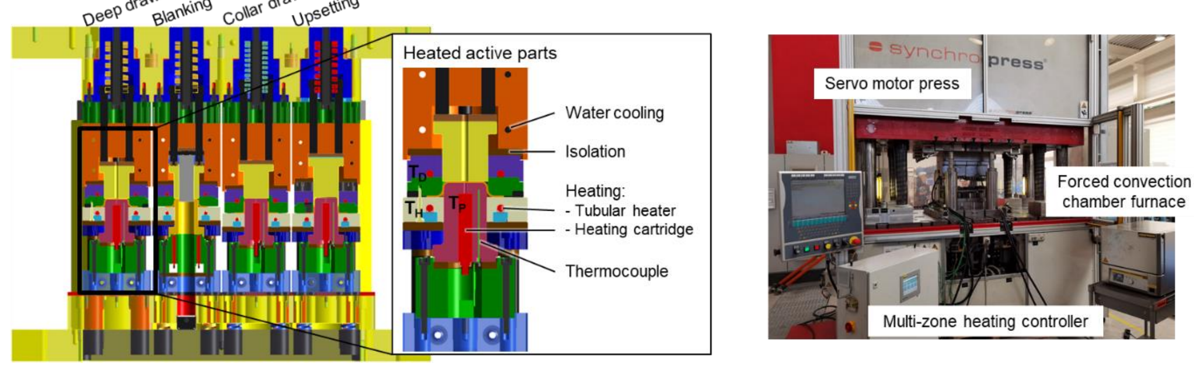


Figure 2. Experimental setup: four-stage forming tool with heated components (a) and used plants (b).

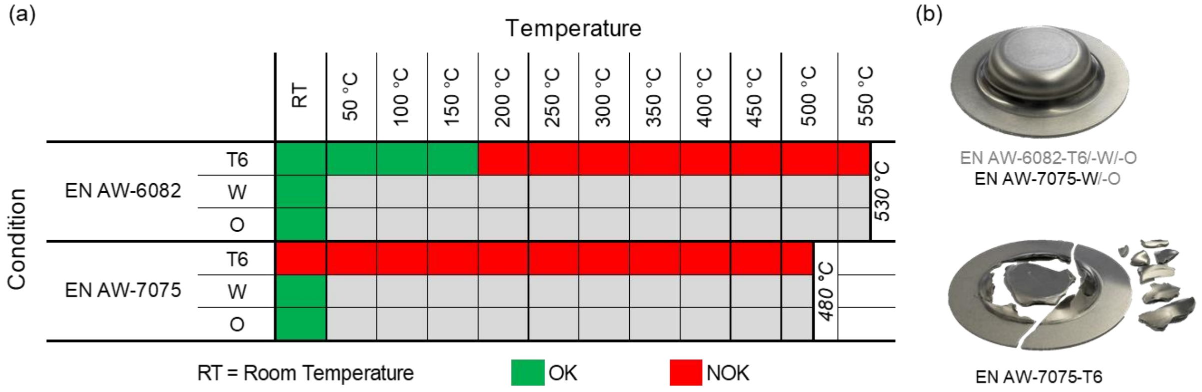
The entire experimental setup with all further equipment is shown in Figure 2 (b). The tool is mounted on the servo motor press Synchropress SWP 2500 with a maximum press force of 2 500 kN. Furthermore, a multi-zone heating controller with a maximum power of 20 kW and 16 individually regulated heating zones is used to control the 12 active parts, as well as the forced convection chamber furnace N 15/65 from Nabertherm for heat treatment or heating the components.

3. Experimental determination of the process limits in the individual tool stages

In order to determine an industrially feasible and economical overall process chain, it is necessary to investigate the process boundaries in the single stages. Accordingly, the four individual stages are examined in more detail below and their process limits and influences are outlined. This also includes factors such as springback, thermal expansion/shrinkage or accuracy.

3.1. Stage 1: Deep drawing

In the first stage, a cup with an internal diameter of 50 mm and a remaining flange is deep drawn from a circular blank with a diameter of 102 mm. The process window shown in Figure 3 demonstrates that EN AW-6082 can be formed in all three initial states, whereas EN AW-7075 necessarily requires preconditioning, because it breaks into several pieces during cold forming. With increasing forming temperatures, the sheet begins to tear in the radius of the bottom before breaking off completely during hot forming. The process limits can be extended by using a distance ring at higher temperatures, but this leads to the formation of wrinkles in the flange, which also remain in the subsequent stages and thus represent rejects.


(a)

Condition		Temperature: RT	50 °C	100 °C	150 °C	200 °C	250 °C	300 °C	350 °C	400 °C	450 °C	500 °C	550 °C	
EN AW-6082	T6	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	530 °C
	W	🟩												
	O	🟩												
EN AW-7075	T6	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥 480 °C		
	W	🟩												
	O	🟩												

RT = Room Temperature 🟩 OK 🟥 NOK

Figure 3. Process window of the 1st stage for EN AW-6082 and -7075 in different heat treatment conditions and temperatures (a) and exemplary presentation of a good and bad part (b).

Forming in the five material-condition combinations (EN AW-6082-T6, -W and -O as well as EN AW-7075-W and -O) shown in green provides good and robust process conditions due to the cold forming. An essential point for the further process route is the wall thickness distribution shown in Figure 4 (b). Therefore, the components were cut through in the respective stages using wire cutting and then measured at significant points using an optical measuring system. In all conditions, thickening occurs in the area of the flange, while the cup wall and, in particular, the radius of the cup bottom become significantly thinner. For the example shown in Figure 4, made of EN AW-6082 in the high-strength T6 condition, the maximum thinning amounts to 10.1 % on the initial sheet thickness of 1.5 mm.

3.2. Stage 2: Blanking

In the second stage, a hole with a diameter of 32 mm is blanked in the bottom of the cup. Blanking proves to be uncritical, as no component failure occurs for any combination, which is why this process step is not considered in more detail below. However, the shape of the cut edge shown in Figure 4 (a) is influenced by the mechanical properties of the material. At low temperatures, strain hardening occurs near the cut surface [19], while at elevated temperatures the microstructure of the materials is influenced by the temperature input.

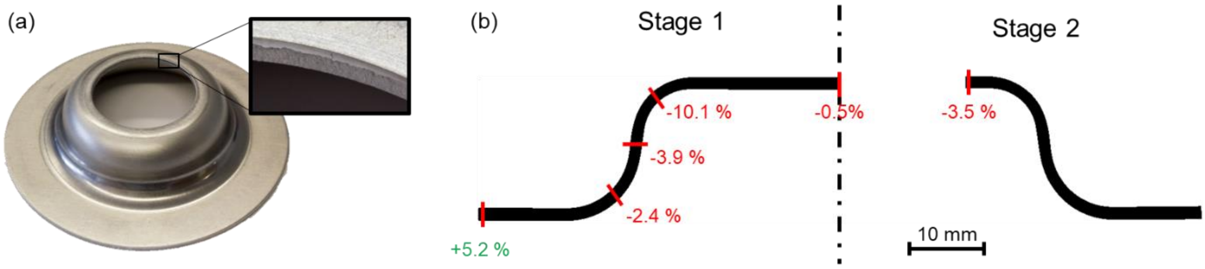
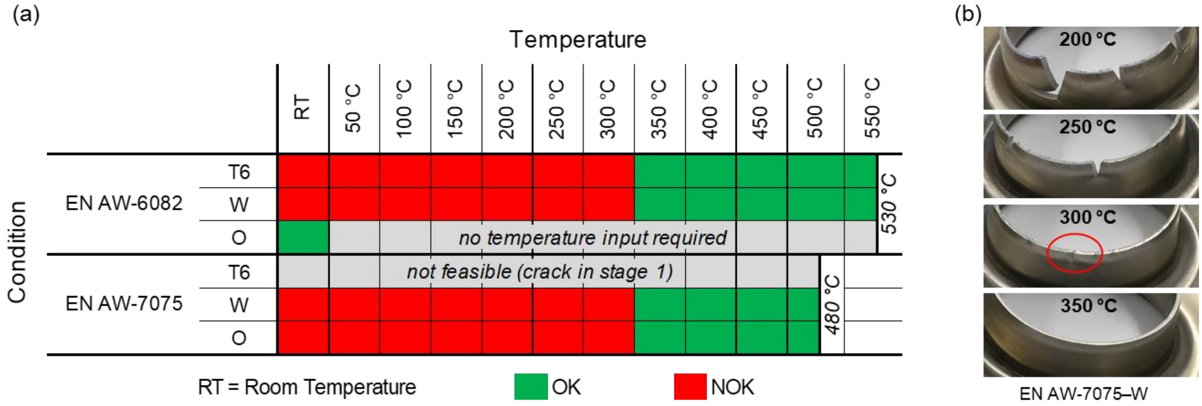


Figure 4. Blanked cup from the 2nd stage incl. enlarged cut edge view (a) and wall thickness profiles of the stages 1 and 2 with the percentage deviation from the initial sheet thickness of 1.5 mm, made of EN AW-6082-T6 (b).

3.3. Stage 3: Collar drawing

In the third stage, the remaining bottom is set up by means of collar drawing. In contrast to the first stage, the process window (cf. Figure 5 (a)) clearly shows that only the soft annealed state of EN AW-6082 can be formed successfully at room temperature. All other conditions need forming temperatures above 350 °C. The exact influence of the temperature can be seen in Figure 5 (b). It shows a temperature variation from 200 to 350 °C for the W-Temper state of EN AW-7075. The temperature increase leads to an extended formability and thus also larger expansion ratios. The exact shape of the cut edge and its influences on the later collar geometry under variation of the materials, temperatures and heat treatment conditions are part of current investigations.


(a)

Condition			Temperature												
			RT	50 °C	100 °C	150 °C	200 °C	250 °C	300 °C	350 °C	400 °C	450 °C	500 °C	550 °C	
	EN AW-6082	T6	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	530 °C
		W	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	
		O	🟩	no temperature input required											
	EN AW-7075	T6	not feasible (crack in stage 1)											480 °C	
		W	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩		
		O	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩		

RT = Room Temperature 🟩 OK 🟥 NOK

Figure 5. Process window of the 3rd stage for EN AW-6082 and -7075 in different heat treatment conditions and temperatures (a) and temperature influence during collar drawing of EN AW-7075 in the W-Temper condition (b).

During collar drawing and the associated widening of the 32 mm hole to the punch diameter of 50 mm, there is a strong thinning of the collar. The initial sheet consequently becomes up to 31.6 % thinner at the tip, as Figure 6 shows. This leaves a wall thickness of 1.026 mm in the zone with the highest strain hardening through blanking and forming.

3.4. Stage 4: Upsetting

And finally, in the fourth stage, an upsetting takes place to increase the initial wall thickness from 1.5 mm to 1.8 mm. The cross-section of the component geometry in Figure 6 shows that the preceding forming stages and the associated strain hardening and thinning effects lead to buckling of the collar. In these notches, the desired sheet thickness is not achieved, but there is a thickening of the previously heavily thinned material so that it is stronger than the initial sheet. In the areas in between, the wall thickness of 1.8 mm is achieved. Consequently, a material thickening of well over 20 % is achieved.

Similar to stage 2, any temperature control can also be implemented for upsetting, but the final geometries differ from each other. A comparison between a cold- and a hot-formed sample at 400 °C shows an improved accuracy in the wall thickness and the springback due to the temperature input, but the overall component shrinks so that the diameter d, shown in Figure 6, falls below the target dimension of 50.0 mm.

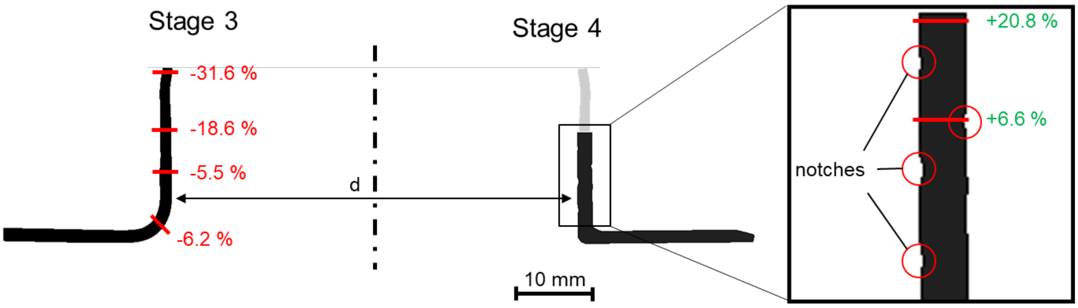


Figure 6. Wall thickness profiles of the stages 3 and 4 with the percentage deviation from the initial sheet thickness of 1.5 mm, made of EN AW-6082-T6 with intermediate heating.

In the example of EN AW-6082-T6 shown above, the diameter d shrinks from 50.09 to 49.80 mm at a measurement height of 7 mm, whereas the wall thickness increases at the same point from 1.77 to 1.79 mm due to the previous temperature input.

4. Possible process routes and industrial implementation

Based on the investigations of the individual forming stages, it becomes apparent that apart from the alloy EN AW-6082 in the soft annealed O-state, no overall process chain can be realized without intermediate heating. For this reason, a new temperature control to realize a coherent overall process chain is developed before its industrial feasibility is demonstrated.

4.1. Possible process routes

The desired demonstrator geometry made of EN AW-6082 can be produced by cold forming in the soft annealed O-state. This has the advantage of not requiring temperature-controlled tools, but subsequent heat treatment to achieve the high-strength material properties.

For the highest-strength alloy EN AW-7075, preliminary investigations indicate that, regardless of preconditioning, heating of the component before stage 3 is indispensable. There are two basic ways to realize this. The first is external heating in the furnace, but this requires extensive peripherals to handle the components. The second possibility is internal heating in the second stage of the temperature-controlled forming tool. This allows the temperature control shown in Figure 7 (a) to be realized.

Due to the heating during the punching process, inline heating within seconds is possible in the case of a two-sided contact under pressure [20]. The influence of holding time and tool temperature on the sheet temperature is shown in Figure 7 (b). The graph illustrates that at a tool temperature of 400 °C, a heating up to 350 °C is possible in about 3 seconds [9]. To determine the heating behaviour, the blanks are prepared with longitudinal notches of 1 mm deep, into which thermocouples type K are inserted. The prepared sheet is then placed on the blank holder and the press is moved so that it is heated under the pressure of the blank holder springs.

However, the parallel stroke of all tool stages must be taken into account. A dwell time at bottom dead centre will inevitably also occur within the other stages, so that shrinkage can occur with hot components and cooler tools. This could be avoided or optimized with a specially developed heating stage.

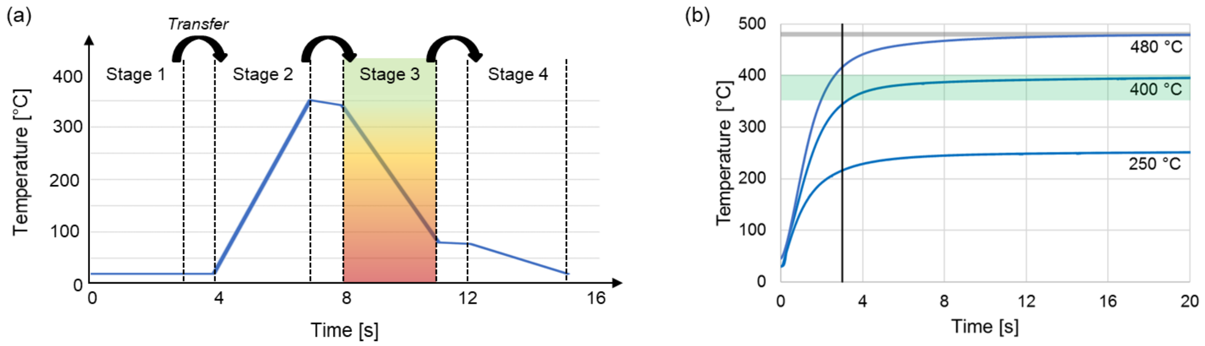


Figure 7. Developed temperature control for multi-stage forming of high-strength aluminium alloys (a) and heating behaviour of the sheet at conductive heating in the forming tool at tool temperatures of 250, 400 and 480 °C (b).

4.2. Industrial implementation

For the implementation of the multi-stage process chain in an industrial environment, a precisely designed process sequence is necessary. In addition to robustness, the economic aspects are of course also of high relevance, so that a high degree of automation is required. Only one employee is required for the provision of materials and process monitoring. An industrial process chain for the use case shown above could therefore look as shown in Figure 8.

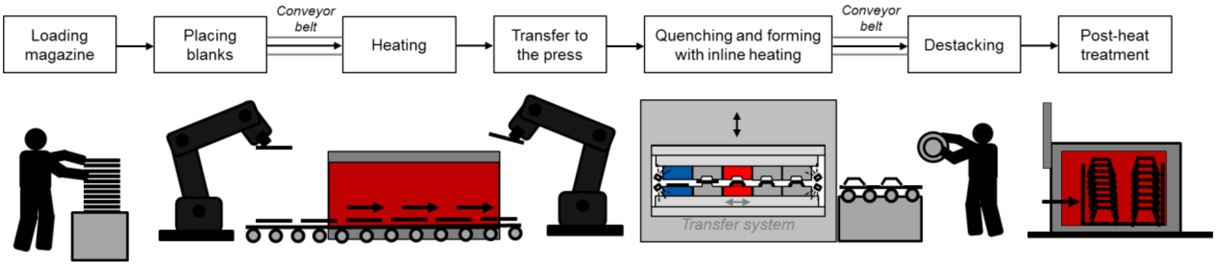


Figure 8. Industrially feasible process chain for the mass production of multi-stage formed components made of high-strength aluminium.

Starting with cut blanks, these are first loaded into a magazine and placed on a conveyer belt by a robot. This passes through a continuous furnace. The tempered sheets can then be removed and placed in a cooled tool within the transfer press. With inline quenching the distortion can be kept low and no drying is required as with external quenching. All subsequent stages are linked by means of the transfer system. The process chain includes a tempered stage for inline heating of the components. After the forming process, a post-heat treatment is required to achieve the high-strength material properties. For both, the soft-annealed alloy EN AW-6082 and the combined process route for the alloy EN AW-7075, the original T6 properties can be reached by means of a subsequent heat treatment (solution heat treated, quenched and artificially aged).

5. Summary and outlook

The paper shows that multi-stage forming operations of the high-strength aluminium alloys EN AW-6082 and -7075 are feasible, although not with the conventional process routes of warm or hot forming, which already fail in stage 1. Due to the different processes and their respective requirements, a precise temperature design and inline control is needed. But the temperature input affects the process and the final geometry of the component in many ways.

Related challenges that continue to be worked on are the tribology under continuous temperature load, the economic and ecological subsequent heat treatment to achieve the high-strength properties while maintaining dimensional accuracy and minimized cycle time through inline heating.

6. Acknowledgement

The project 'Productivity assurance of temperature-supported aluminium forming processes through dual research and training' (HA project no. 1269/21-170) is financed with funds of LOEWE – Landes-Offensive zur Entwicklung Wissenschaftlich-ökonomischer Exzellenz, Förderlinie 3: KMU-Verbundvorhaben (State Offensive for the Development of Scientific and Economic Excellence).

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