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Mechanical properties and formability of EN AW-7075 in cold forming processes

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Abstract. Due to a low density and high tensile strength, the aluminum alloy EN AW 7075 T6 offers a high lightweight potential for structural components. Since its formability is limited at room temperature in the T6 temper state, the potential of this alloy for automotive bodies is only utilizable by adapted deep drawing processes. In recent years, process chains suited for warm and hot forming have been researched and developed. However, warm and hot forming solutions require additional process steps and a complex tooling system in comparison to cold forming processes. Alternatively, the forming of such blanks at room temperature in the W temper state is favorable since conventional tools can be used. The W temper state is a heat treatment condition achieved after solution heat treatment and subsequent quenching, which is characterized by an increased ductility. However, this condition is unstable, due to the onset of natural ageing. With increasing time after the quenching step, the strength of the material increases, which leads to a reduction of formability. Another phenomenon that occurs after quenching is the Portevin Le-Chatelier effect. This effect causes the formation of flow lines during cold forming and results in a decrease of ductility. Hence, the objective of the investigations was to determine the formability of EN AW 7075 as a function of the natural ageing time after solution heat treatment and quenching. Therefore, tensile tests of various aged samples were carried out. The results show a relation of the formability to the natural ageing time and a dependency on the quenching rate. Furthermore, a heat treatment strategy for EN AW-7075 was developed, that considers manufacturing processes like the cathodic dip coating. The influence of the quenching rate, ageing time and temperature as well as the influence of temperature of the paint baking process after the cathodic dip coating were considered. Therefore, a design of experiments and tensile tests were carried out. Thus, the deep drawing of EN AW-7075 at room temperature is particularly promoted.

1. Introduction

In car bodies aluminium is mainly used as lightweight material. The highest strength and therefore the highest lightweight potential belong to the 7000 series aluminum alloys. These materials have the same specific strength like hot-stamped steels and additionally feature an increased elongation at break [1]. In particular, the substitution of hot-stamped steel components by parts manufactured with 7000 aluminum alloys can lead to a significant reduction in body weight. However, these alloys have so far rarely been used in car body construction. The reason for this is the low formability of the materials at room temperature in the highest strength state. Therefore, various approaches are currently being investigated to improve the formability of the alloys.

One approach is the hot forming process route. Therefore, the aluminum blanks are heated to temperatures above the recrystallization temperature. The sheet material is subsequently transferred into a water-cooled press tool and simultaneously formed and quenched [2]. Argandoña et al. [3] have used this process route to form defect-free B-pillars. Another approach is the warm forming of the high strength material after quenching and artificial ageing. The improved formability of this process is based on the dissolution of η' precipitations and dynamic recovery effects at elevated temperatures [4]. Sotirov et al. [1] and Behrens et al. [5] have determined the increased formability for this process route for the alloy EN AW-7075. Noder et al. have also investigated a process variant for non-isothermal forming [6]. However, warm and hot forming solutions require additional process steps and a complex tooling system in comparison to cold forming processes. Alternatively, the forming of such blanks at room temperature in the W temper state is favourable since conventional tools can be used. Therefore, in this paper a cold forming process route is investigated.

2. Cold forming and heat treatment process route

To increase the formability of 7000 aluminum alloys, approaches like the W temper process are examined. This process is named after the W heat treatment state. This condition is achieved after solution heat treatment and quenching of the material. The alloying elements remain dissolved and a supersaturated state with a high number of solute atoms and vacancies is formed. Due to its high ductility, this heat treatment state allows cold forming. However, the blanks must be formed as soon as possible after quenching, otherwise the material will age naturally. As a result, the strength of the material increases and thus its formability is reduced. Argandoña [7] investigated the formability of EN AW-7075 at room temperature in the ductile W condition. However, due to the solution heat treatment process, the formed components have no usable mechanical properties. Therefore, an artificial ageing step must be carried out afterwards. The increase in strength bases on the forming of finely dispersed metastable precipitations [2]. The precipitation sequence determined by Degischer [8] and Löffler [9] describes partially coherent η' precipitations as the main hardening phase for 7000 aluminum alloys. The heat treatment can be combined by the artificial ageing process and the cathodic dip coating (cdc) process, see Figure 1. Another influence on the mechanical properties is the quenching rate after the solution heat treatment. For the alloy EN AW-7075, Behrens et al. [10] have investigated a dependency of the mechanical properties on the copper content of the alloy. Thereby, an extension of the W temper process route is possible. By partial quenching of the blanks it is possible to produce components with load-optimised tailored properties. For example, a spray-field can be used to quench certain areas of the blank rapidly, while the remaining areas cool down slowly [11, 12, 13]. Following artificial ageing, high strengths are achieved in the rapidly quenched areas. In the slowly cooled areas the strength is lower, but the ductility increases. However, in order to be able to adjust these partial properties, the heat treatment parameters of the complete process chain have to be adapted to each other.

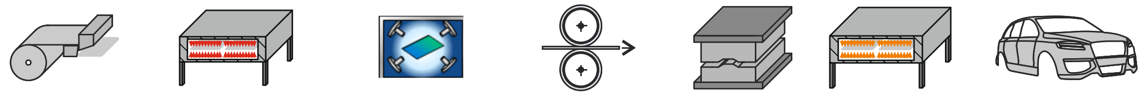


Figure 1. Process route for cold forming and heat treatment of 7000 aluminum alloys.

3. Experimental setup

The material used for the investigations is the copper-containing alloy EN AW-7075. The copper content is essential, due to its significant influence on the quenching sensitivity of this alloy. The chemical composition of the investigated material is listed in Table 1. The delivery state of the material was T6.

Table 1. Chemical composition of the investigated aluminum sheet metal material in ma.-% determined by spark spectroscopy.

Alloy	Zn	Mg	Cu	Mn	Si	Cr	Fe	Ti
EN AW-7075	6.1	2.35	1.63	0.05	0.08	0.19	0.17	0.02

3.1. Influences on tensile properties after quenching

Tensile tests were carried out to determine the influence of the quenching method and the natural ageing time after quenching on the formability of the material. For this purpose, samples of the test material were first heated at a solution heat treatment temperature T_{SHT} of 475 °C for a duration t_{SHT} of 10 min. Subsequently, a share of the specimens were rapidly quenched in a pneumatically operated plate tool. The quenching rate was 250 K/s. The other share of the samples was slowly cooled at air. In this case a quenching rate of 1 K/s was obtained. The quenching rate was determined by a type K thermocouple. After quenching, the specimens were aged naturally for various times. The aging duration was varied between 5 min and 30 d after quenching. However, the aging period was not started until the temperature of the blanks dropped below 50 °C during quenching, so that forming at room temperature could be ensured for the samples cooled at air. The different aging durations were chosen according to data of Ostermann et al. as it shown in Figure 2. This is based on the increasing hardness of the material with increasing natural ageing time.

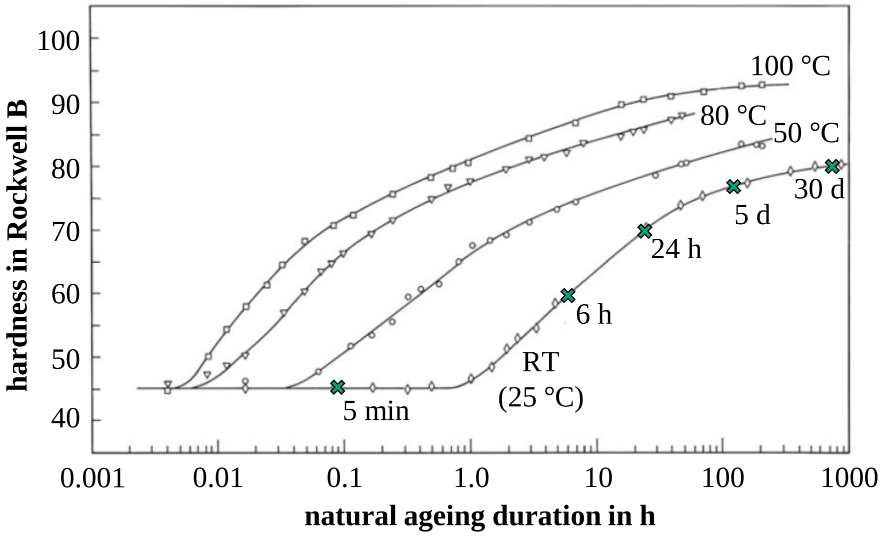


Figure 2. Hardness development in dependence of the natural ageing time according to [14] and selected natural ageing times according to the hardness evolution.

The quenched samples were used subsequently to determine a stress-strain curve for each quenching rate and natural ageing duration. A tensile test machine S100/ZD by DYNA-MESS was used for this purpose. The tests were carried out according to DIN EN ISO 6892-1. The specimens were prepared according to DIN 50125. The shape H with an initial gauge length of 50 mm was used. The investigated alignment of the specimens to the rolling direction were 0°, 45° and 90°.

3.2. Influence of heat treatment parameters on the mechanical properties of the components

The mechanical properties of the components produced by the process route described in chapter 2 depend mainly on four different process parameters. These are, on the one hand, the quenching method selected after solution heat treatment, the artificial ageing temperature and duration and whether cathodic dip coating is carried out at the end of the process or not. The influence and significance of the influence of these parameters on the ultimate tensile strength as well as the elongation at break was tested within a design of experiments. In order to be able to determine the quadratic influence of individual parameters, a response surface design was selected as the experimental plan. Figure 3 shows the structure of the design. The artificial ageing time and temperature were varied in five stages between 2 h and 24 h, respectively 100 °C and 180 °C. For each temperature and time combination three tensile tests were carried out. The central point was tested a total of fifteen times to investigate a scattering of the results.

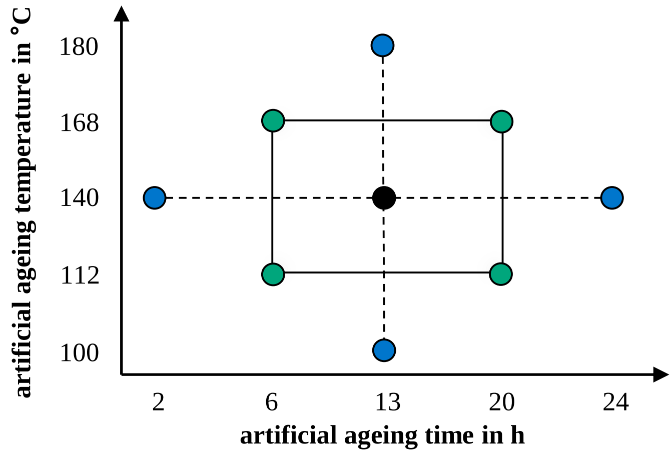


Figure 3. Response surface design to investigate the influence of the process parameters on the mechanical properties.

The influence of the quenching method was investigated in two levels. First a rapid cooling in the plate tool mentioned in chapter 3.1 and second a slow cooling at air. For the investigations regarding the influence of the cathodic dip coating, its heat treatment process was reproduced in a furnace. A two-level factor was therefore also applied in the response surface design. The first level includes a final heat treatment by means of cdc. In the second level, no further heat treatment is carried out after artificial ageing. Thus the response surface design shown in Figure 3 is repeated four times for the different combinations of quenching method and cdc. The complete heat treatment sequence is shown in Figure 4. After quenching in the tool or at air, a five-day natural ageing at room temperature was carried out. The final cdc process is based on Kumar et al. [15]. This five-step heat treatment considers not only the paint baking process but also further drying steps in the cdc-process.

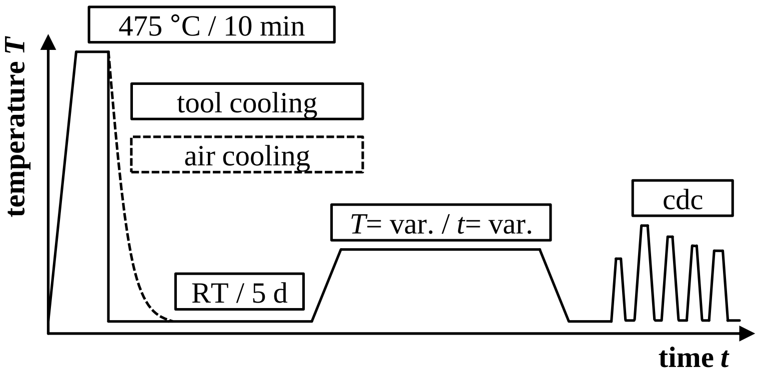
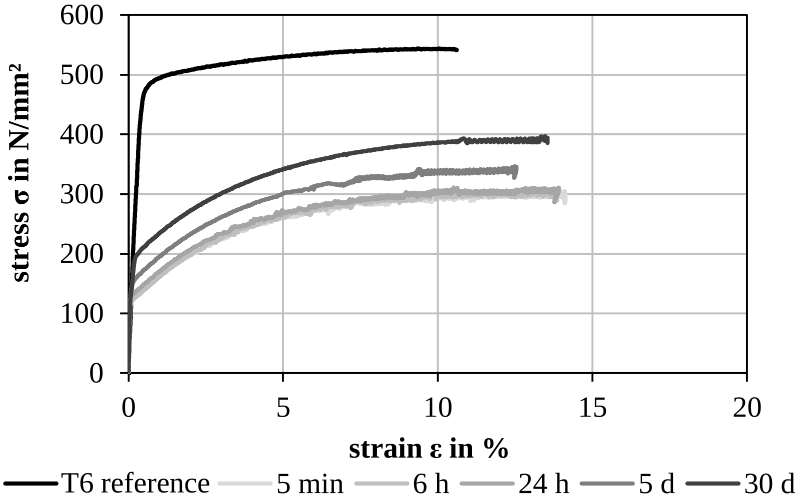


Figure 4. Sequence of the heat treatment process to adjust the mechanical properties.

4. Results of the experiments

4.1. Influences on tensile properties after quenching

First, the influence of slow cooling at air and the natural ageing duration on the stress-strain curves was determined. The results are shown in Figure 5 for an alignment of the tensile test samples 90° to the rolling direction. As a reference, the stress-strain curve of EN AW-7075 in T6 condition is also shown. As can be seen, after solution heat treatment and air cooling, a significantly lower stress level is achieved. With decreasing natural ageing time, the stress also decreases until a minimum stress level is reached for 24 h. Although an increase of the elongation with decreasing ageing time, was not determined. The same behavior was also investigated for the other rolling directions.



Testing method
Tensile test - DIN EN ISO 6892-1
Process parameters
T_{SHT} = 480 °C
t_{SHT} = 10 min
air cooling
$\dot{\varphi}$ = 0.1 s^{-1}
90° to RD

Figure 5. Stress-strain-curves for EN AW-7075 after solution heat treatment and subsequent air cooling depending on the natural ageing time.

A different behavior was determined for the samples quenched rapidly in the plate tool. The results are shown in Figure 6. Due to the high quenching rate, a similar stress level as in the T6 condition was obtained after a natural ageing time of 30 d. The elongation, however, was significantly increased compared to air cooling and the T6 reference. As the natural ageing time decreases, the yield and tensile strength decreases like for the slowly cooled samples. The reachable elongation at break also decreases with decreasing natural ageing time. A further phenomenon can be observed in this case. With decreasing natural ageing time, dynamic strain ageing occurs increasingly. This phenomenon is also known as Portevin-Le Chatelier effect. The effect appears for slowly and rapid quenched samples but is more pronounced in samples quenched quickly and exposed to a short natural ageing time. This can be explained by the higher amount of solute atoms immediately after quenching. With a natural aging time of 5 min, this effect is pronounced to such an extent it causes the stress-strain curve to leave its typical path and break at about an elongation of only 7.5 %.

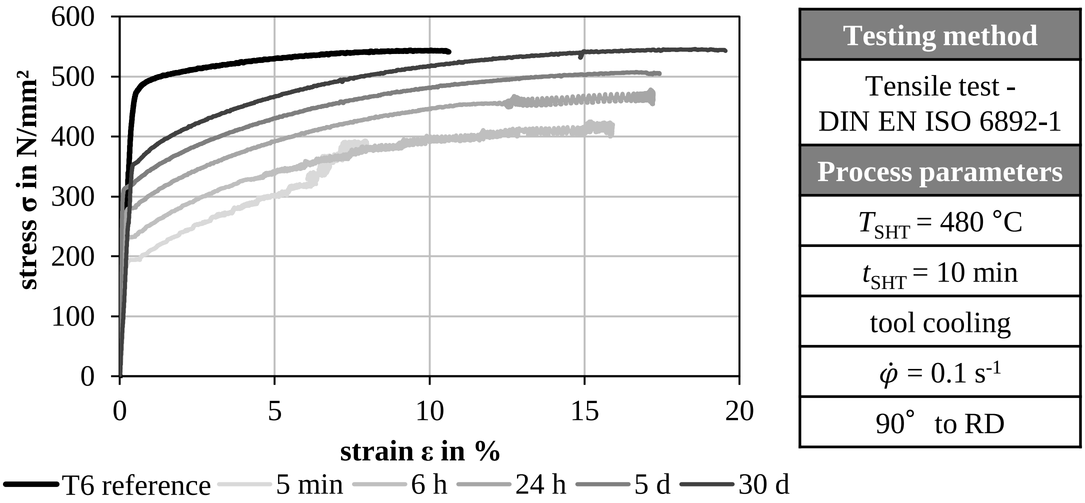


Figure 6. Stress-strain-curves for EN AW 7075 after solution heat treatment and subsequent tool cooling depending on the natural ageing time.

4.2. Influence of heat treatment parameters on the mechanical properties of the components

The results of the tensile tests carried out as a part of the design of experiments are shown in Figure 7. The increasing artificial ageing time has a negative influence on the ultimate tensile strength and elongation at break. The value of both properties decreases with increasing ageing time. The ageing temperature has a similar influence. With increasing temperature, the level of both mechanical properties decreases. In addition, the artificial ageing temperature also has a quadratic influence on the ultimate tensile strength and elongation at break, resulting in a maximum in the temperature range from 100 °C to 120 °C. For the two parameters investigated in two stages - quenching method and cathodic dip coating - only a linear dependency was observed. As expected, the quenching method has a great influence on the mechanical properties. At low quenching rates a low strength and a high elongation is ensured. For the rapid quenching method in the tool the trend is the opposite. The cdc influences only the elongation at break. If a cdc is carried out, it causes an overageing of the material and thus a reduction in elongation at break.

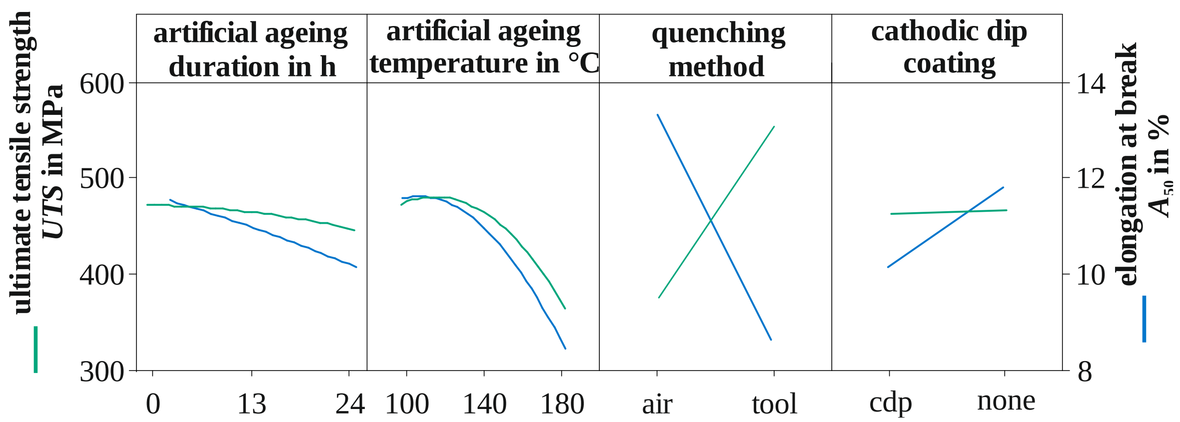


Figure 7. Influence of the investigated process parameters on the ultimate tensile strength and the elongation at break of EN AW-7075.

To determine the significance of the influence of the individual parameters and their interactions with each other, a Pareto-diagram was compiled regarding ultimate tensile strength and elongation at break (s. Figure 8). The significance limit was calculated for both parameters at a standardized effect of 2.02. This means that parameters or interactions of different parameters above this value have a significant effect on the respective property. The quenching method has the highest influence on both investigated mechanical properties. Other significant factors influencing the ultimate tensile strength are the artificial ageing temperature and duration and the interaction between these parameters. The cdc process, as well as the interactions with this parameter, have a high influence on the elongation at break.

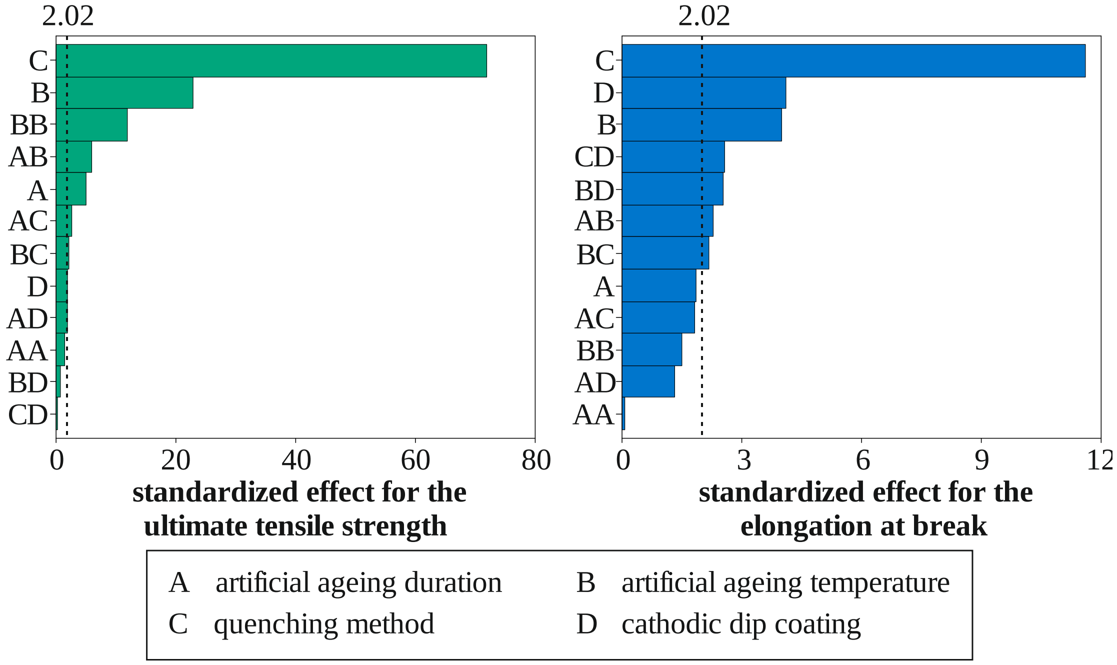


Figure 8. Pareto chart of the standardized effects for the ultimate tensile strength (left) and the elongation at break (right)

5. Summary and Outlook

The influence of the quenching rate and the natural ageing time after solution heat treatment on the formability of the alloy EN AW-7075 were investigated by tensile tests. It was shown that the quenching rate has an influence on the flow stress necessary for deformation and the achievable elongation at break. Low quenching rates tend to result in lower flow stresses compared to rapid rates. However, the ductility is influenced positively at higher quenching rates. In the case of rapid cooling, an increase in ductility compared to the T6 reference state was determined for ageing times above 6 h and an increasing dynamic strain ageing observed. At a short ageing time of only 5 min, the strain ageing is so pronounced that the ductility of the material is reduced significantly. This behavior is uncommon for the alloys of the 7000 series and shall be explored in future examinations by Nakajima tests.

In further experiments the influence of the different heat treatment parameters of the cold forming process route on the mechanical properties was investigated at the example of tensile tests. A significant influence of the quenching rate after solution heat treatment and the artificial ageing temperature was determined. As expected, the strength increases with increasing quenching rates, whereas high elongation at break is achieved with low quenching rates. An increasing ageing temperature above 120 °C has a negative influence on the mechanical properties. It has also been observed that the cdc-process, which is obligatory in the automotive industry, has a negative influence on the elongation at break for the examined material. In future investigations, heat treatment parameters shall be determined which, in the case of a partially quenched component, lead to maximum ductility in the slowly quenched area and to a strength level that is comparable to the T6 condition in the rapidly quenched component area.

According to the obtained results, the presented W temper process route provides an alternative to established forming routes like warm or hot forming of high-strength aluminum alloys. The increased ductility of the alloy EN AW-7075 after quenching suggests an improvement in formability at room temperature. However, these results must be examined and verified in deep-drawing tests. Together with the possibility of manufacturing tailored parts, the W temper process route represents a good opportunity to promote lightweight design in modern car bodies.

Acknowledgements
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