# Influence of the Quenching Rate and Natural Ageing Duration on the Formability and Mechanical Properties of EN AW-7075

**B.-A. Behrens, S. Hübner, H. Vogt, O. Golovko, S. Behrens, and F. Nürnberger**

**Abstract** Due to the low density and high tensile strength, the aluminium alloy EN AW-7075 offers a high lightweight potential for structural components. In recent years, 7xxx-aluminium alloys have been the subject of numerous investigations in the field of warm and hot forming and suitable heat treatments to fully use their potential for applications in automotive bodies. Alternatively, forming blanks of these alloys at room temperature in the W-temper state is favourable since conventional tools can be used. However, this condition is unstable. As the ageing duration after quenching increases, the formability decreases due to natural ageing. Hence, the objective of this investigation was to determine the formability of EN AW-7075 as a function of the ageing time. Furthermore, since the quenching rate after solution heat treatment influences the resulting mechanical properties, an adapted process route to manufacture components with tailored properties was explored. For this purpose, samples were partially quenched after solution heat treatment and then artificially aged. To determine the influence of the quenching rate, hardness tests were carried out.

**Keywords** 7xxx-aluminium alloys · Cold forming · Formability · Tailored tempering

## 1 Introduction

Nowadays, the most common lightweight material in the automobile industry is aluminium. In car bodies mainly the alloy series 5000 and 6000 are used for structural or shell parts, respectively. However, the highest strength aluminium alloys belong to the 7000 series. These materials have the same specific strength as hot-stamped

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steels and an additional feature of increased elongation at break [1]. In particular, the substitution of hot-stamped steel components by components made of 7000 series aluminium alloys can lead to a significant reduction in body weight. However, these alloys have so far been rarely 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 warm forming of the high strength material after quenching and artificial ageing (in T6 condition according to EN 515). The improved formability of this process is based on the dissolution of $\eta$' precipitations and dynamic recovery effects at elevated temperatures [2]. Sotirov et al. [1] and Behrens et al. [3] have determined the increased formability for this process route for the alloy EN AW-7075. The influence of the heat treatment condition of the initial material on the formability has also been examined by Kumar et al. [4]. Noder et al. have investigated a process variant for non-isothermal forming [5]. They and Behrens et al. [6] have determined an over-ageing of the aluminium alloys. This is caused by the additional heat treatment for warm forming.

Another approach is the hot forming process route. Therefore, the aluminium blanks are heated to temperatures above the recrystallisation temperature. The sheet material is subsequently transferred into a water-cooled press tool and simultaneously formed and quenched [7]. Argandoña et al. [8] have used this process route to form defect-free B-pillars. 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 is based on the forming of finely dispersed metastable precipitations [7]. The precipitation sequence determined by Degischer [9] and Löffler [10] describes partially coherent $\eta$' precipitations as the main hardening phase for 7000 series aluminium alloys. For the alloy EN AW-7075, Behrens et al. [11] have additionally investigated the influence of the quenching rate on the mechanical properties, which should be chosen according to the copper content of the alloy.

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 Process Route

The high strength of the 7000 series aluminium alloys results in a limited formability in T6 condition at room temperature. Therefore, different approaches like the W-temper process are examined to increase the formability. This process is named after the W-temper heat treatment state. This condition is achieved after solution heat treatment and quenching of the material. The alloying elements remain dissolved and

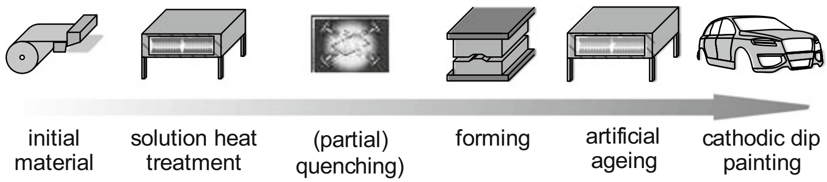



**Fig. 1** Cold forming and heat treatment process route for the 7000 series aluminium alloy

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 [12] investigated the formability of EN AW-7075 at room temperature in the ductile W condition. To set the final mechanical properties of the components, a subsequent heat treatment is necessary [13] which can be a combination of artificial ageing and the cathodic dip painting process, see Fig. 1. An extension of the process route is possible by controlled cooling of the blanks. Since copper-containing alloys of the 7000 series have a sensitivity to the quenching rate, 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 [14, 15]. 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.

## 3 Experimental Setup

For the experimental investigations, the aluminium alloy EN AW-7075 in T6 state was examined. This alloy contains copper and is thus sensible for quench processes [13]. The mechanical properties are listed in Table 1.

**Table 1** Investigated aluminium sheet metal material

| | Sheet thickness (mm) | Ultimate tensile strength *UTS* (MPa) | Elongation at break *A* (%) | Copper content (wt.%) |
|---|---|---|---|---|
| EN AW-7075 T6 | 2.0 | 569 | 14.1 | 1.63 |

### *3.1 Formability in W-Temper State*

A Nakajima test was carried out to investigate the formability of alloy EN AW-7075 in the W-temper state. This test was used to determine forming limit curves for various heat treatment conditions. Both the influence of the quenching rate and of the natural ageing time between solution heat treatment and the Nakajima test were investigated. For sample preparation, the Nakajima samples were, therefore, first solution heat-treated and then quenched. The solution annealing temperature ($T_{SHT}$) was 480 °C and was maintained for 10 min ($t_{SHT}$). For rapid quenching, the blanks were subsequently cooled in a pneumatically operated plate tool. This is shown in Fig. 2 on the left. To ensure uniform cooling of the blanks, the plates of the tool were water-cooled. In addition, and to simulate low cooling rates, the blanks were placed on spacers in the tool to prevent premature cooling. For this slow cooling of the samples, they were cooled down at air. The time–temperature curves for both quenching methods are shown in Fig. 2 on the right. In the pneumatic tool, a quenching rate of 250 K/s is reached in the temperature range of 400 °C–200 °C, at air of 1.11 K/s.

After quenching, the blanks were aged naturally for various times. The ageing duration was varied between 5 min and 30 days after quenching. However, the ageing 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 ageing durations were chosen according to the data of Ostermann et al., as shown in Fig. 3. This is based on the increasing hardness of the material with increasing natural ageing time.

The quenched samples were used subsequently to determine a forming limit curve for each quenching rate and ageing duration. A universal testing machine from the Erichsen company was used for this purpose, see Fig. 4 on the left. The tests were

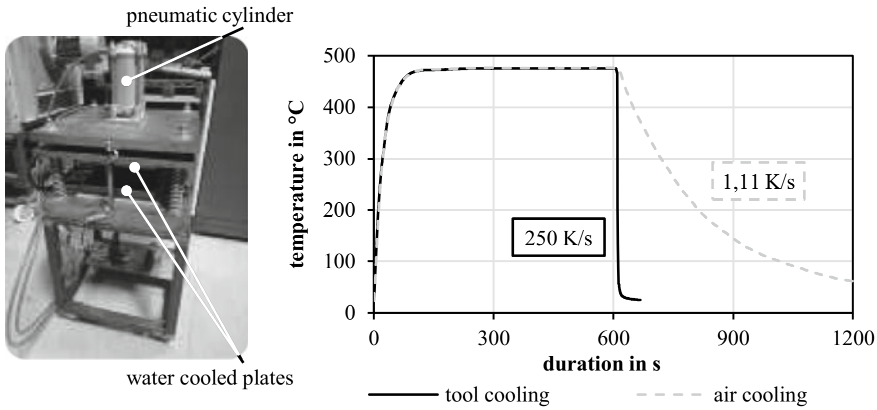



**Fig. 2** Pneumatically operated tool (left) and time–temperature diagram of the quenching step for high and low cooling rates (right)

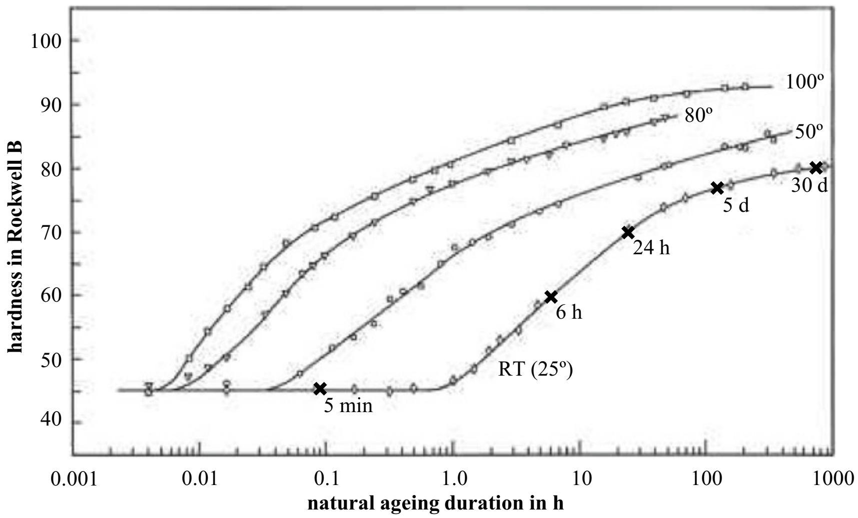



**Fig. 3** Hardness development depending on the natural ageing time according to [13] and the selected ageing times according to the hardness evolution

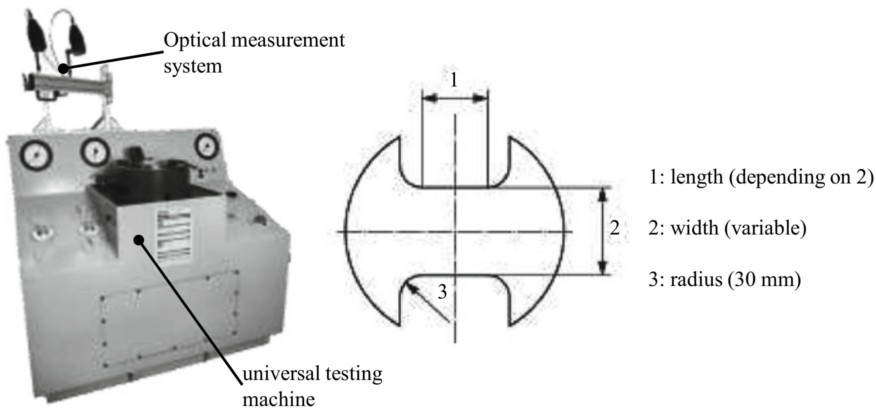



**Fig. 4** Nakajima testing rig (left) and shape of the sheet metal samples (right)

carried out according to DIN EN ISO 12004-2. The hemispherical punch had a diameter of 100 mm. The clamping force to prevent the material from flowing was set to 300 kN and the punch speed during the test was 1.5 mm/s. The specimens were prepared according to DIN EN ISO 12004-2. The shape shown in Fig. 4 on the right was used. The rolling direction of the blanks was parallel to the orientation of the crossbar. The width of the crossbar was varied to set different stress states in the sample. A total of five crossbar widths were used, ranging from 30 to 160 mm.

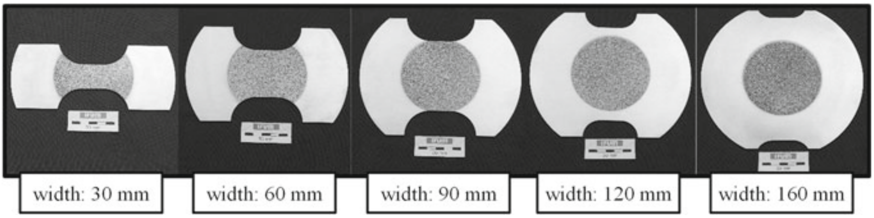



**Fig. 5** Overview of the used test samples and the varied width of the crossbar

The optical measuring system Aramis from the company GOM mbH was used to evaluate the samples. For this purpose, a stochastic pattern was applied to the samples, which can be detected by the measuring system. The prepared samples with the varied crossbar widths are shown in Fig. 5. The evaluation of the samples was carried out according to the online method AM3 described in DIN EN ISO 12004-2. The maximum major and minor strain were determined immediately before the crack.

## *3.2 Tailored Tempering of EN AW-7075*

In order to obtain areas with different mechanical properties in one part, the alloy EN AW-7075 was partially quenched after solution heat treatment. An adjustable compressed air-quenching facility as shown in Fig. 6 on the left was used for this purpose. By means of cooling nozzles, it is possible to cool down certain areas of the blank with different quenching rates. These areas achieve a higher strength after the heat treatment. To change the quenching rate, various parameters can be set. On the one hand, these are the number and arrangement of the cooling nozzles. It is either possible to use three nozzles arranged below the blank or a total of six nozzles.

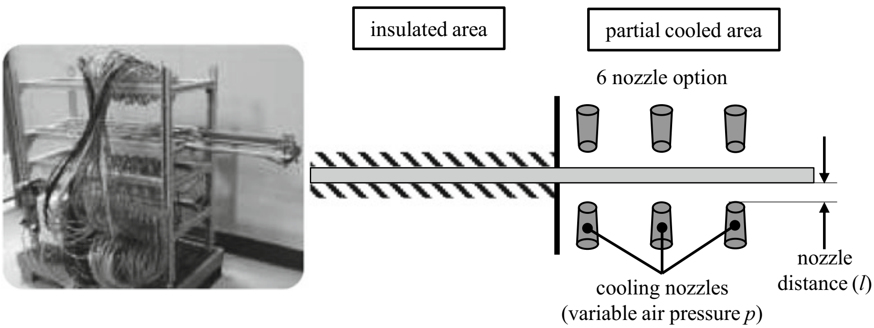



**Fig. 6** **C**ompressed air-quenching facility for partial quenching (left) and schematic overview of the adjustable compressed air-quenching facility parameters

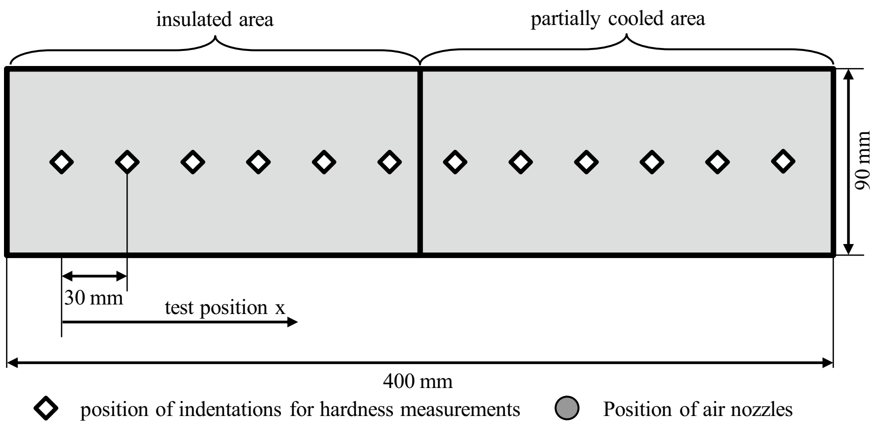



**Fig. 7** Indentation positions for the hardness measurements of the partially quenched sheets

Furthermore, the distance ($l$) between the nozzles and the blank can be either 100 mm or 150 mm. In addition, the air pressure ($p$) can be adjusted between 1 and 6 bar. On the other hand, a low quenching rate is required for areas where low strength is to be achieved. This can be reached in the test setup used by insulation. A schematic layout of the compressed air-quenching facility is shown in Fig. 6 on the right. The solution heat treatment before quenching was performed at 480 °C for a duration of 10 min.

After solution heat treatment and partial quenching, the heat treatment was continued by artificial ageing of the sheet metal strips at 120 °C for 24 h. A Vickers hardness test was then carried out on the surface of the samples. A ZwickRoell ZHU250 hardness testing machine was used for this purpose. The test was equivalent to the HV10 hardness test. The positions of the hardness test are shown in Fig. 7. Five hardness indentations were made in each of the insulated and quenched areas. The tests were performed at a distance of 30 mm from each other.

The evaluation method shown in Fig. 8 was used to determine the hardness gradient and the transition zone length as a function of the quenching parameters. First of all, the mean value of the hardness of the first four hardness indentations and the last four hardness indentations was determined. These mean values are entered as lines 1 and 2 in the hardness profile. The distance between the intersection points of lines 1 and 2 with the hardness curve describes the transition zone. In addition, the difference between the two mean values along the transition zone is the hardness gradient. The hardness gradient and the transition zone are used as evaluation criteria.

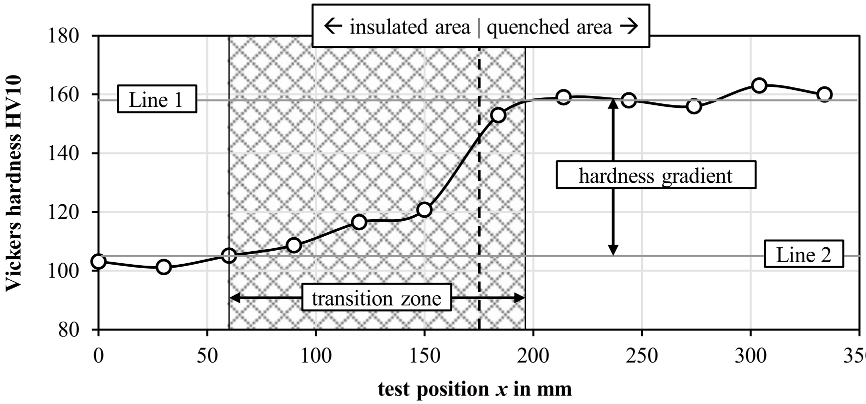



**Fig. 8** Analysis method for the partially quenched sheets

# 4 Results of the Experimental Investigations

## *4.1 Formability in W Temper State*

First, the influence of the natural ageing time on the formability of the alloy EN AW-7075 after quenching was investigated. For this purpose, the Nakajima specimens were either quenched quickly in the pneumatic press or cooled slowly at air. As an example for natural ageing durations of 6 h and 30 days, the forming limit curves of the slowly cooled samples are shown in Fig. 9. As a reference, a forming limit curve for the investigated material in the T6 condition was also determined. The

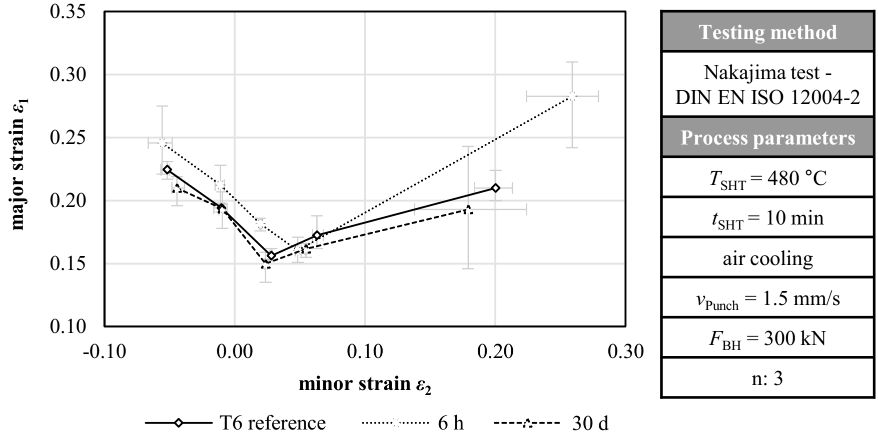
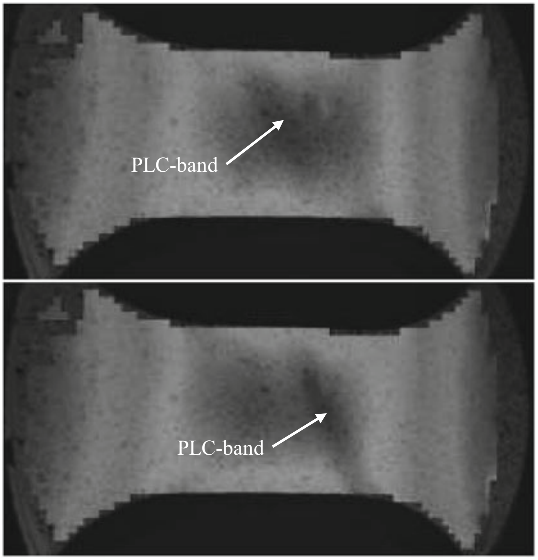



**Fig. 9** Influence of the natural ageing time on the formability of EN AW-7075

lowest formability was found for all material states between a major strain degree of 0.14 and 0.16. The minor strain varies between 0.025 and 0.05. For strain states that remain within the range of uniaxial tension, the formability for the natural-aged samples are slightly higher than for the reference state. The highest formability is achieved with decreasing ageing time. The same behaviour can be observed for the biaxial stress state. Only the formability of the samples aged for 30 days is below the reference level. As before, the samples that have been aged naturally for the shortest time have the highest forming capacity. The same behaviour was determined for the rapidly quenched samples.

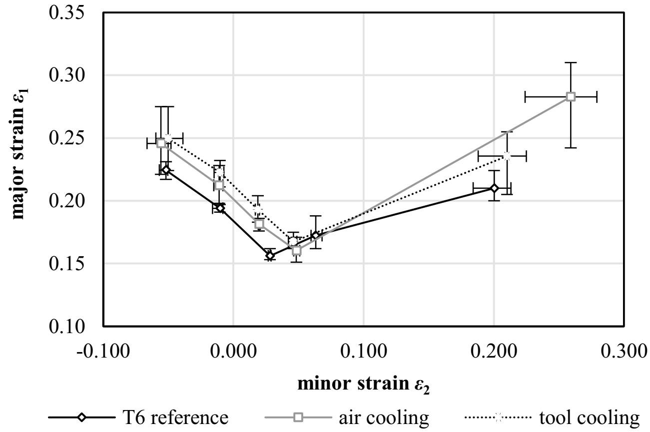
During the Nakajima experiments, a dynamic strain ageing was determined in the samples. This phenomenon is also known as Portevin–Le Chatelier effect. The plastic deformation occurs unevenly across the formed area. The effect is more pronounced in samples quenched quickly and exposed to a short natural ageing time. This can be explained by the higher amount of solute atoms immediately after quenching. The formation of PLC bands during the Nakajima experiments is shown in Fig. 10. In this figure, the major strain is represented on the sample surface. The dark bands indicate a localised plastic strain in the sample.

In addition to the influence of the natural ageing time, the influence of the quenching rate on the formability was investigated. The results for an ageing duration of six hours are shown in Fig. 11. The obtained results are representative of all ageing durations. The T6 condition of the material EN AW-7075 is shown as a reference. For the area of uniaxial tension up to the lowest major strain, the rapidly quenched samples have a higher forming capacity. This is slightly higher than the reference




| Testing method |
| --- |
| Nakajima test - DIN EN ISO 12004-2 |
| **Process parameters** |
| $T_{SHT}$ = 480 °C |
| $t_{SHT}$ = 10 min |
| tool cooling |
| width= 30 mm |
| $v_{Punch}$ = 1.5 mm/s |
| $F_{BH}$ = 300 kN |
| n: 3 |

**Fig. 10** Portevin–Le Chatelier bands during the Nakajima test




| Testing method |
| --- |
| Nakajima test - DIN EN ISO 12004-2 |
| **Process parameters** |
| $T_{SHT}$ = 480 °C |
| $t_{SHT}$ = 10 min |
| $t_{ageing}$ = 6 h |
| $v_{Punch}$ = 1.5 mm/s |
| $F_{BH}$ = 300 kN |
| n: 3 |

**Fig. 11** Influence of the quenching rate on the formability of EN AW-7075

condition. In the biaxial stress state, on the other hand, the formability of the slowly cooled specimens is higher than that of the rapidly quenched.

## *4.2 Tailored Tempering of EN AW-7075*

To achieve partially different mechanical properties in sheet metal strips of the material EN AW-7075, these strips were quenched in a compressed air-quenching facility with varying parameters. In insulated areas with a low quenching rate, zones with reduced hardness should be tailored. In areas with a higher quenching rate, however, a higher hardness has to be obtained. In these areas, the sheet was quenched in the compressed air-quenching facility with varying air pressure, varying nozzle distance from the sheet, and either three or six nozzles. The influence of the number and arrangement of the nozzles is shown in Fig. 12. By quenching the sheet metal on both sides with six instead of three nozzles, the hardness level in the complete sheet metal increases. The quenching rate of the rapidly quenched zone is therefore so strong that the insulation is not fully suited to maintain the reduced hardness level in the insulated area. However, the hardness gradient and the width of the transition zone are only slightly affected by the number and arrangement of the nozzles.

The results of the determined hardness gradients and transition zones are shown in Fig. 13. The air pressure and the distance between the nozzles and the sheet metal were varied. The six nozzle configuration was used for all parameter variations. It was observed that with increasing air pressure the hardness gradient increases. With a nozzle distance of 100 mm the hardness gradient increases from 43 HV10 at 1 bar air pressure to 54 HV10 at 6 bar. For a nozzle distance of 150 mm the determined difference is more distinct. In this case, the hardness gradient increases from 28 HV10 to 53 HV10 when the air pressure increases. For both nozzle distances of 100 mm

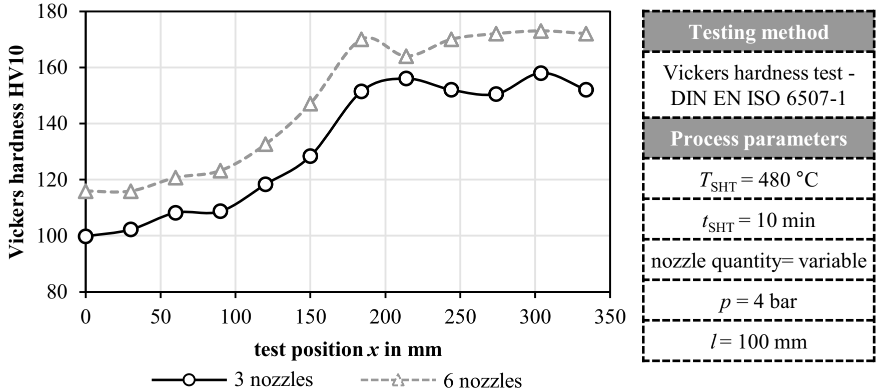



**Fig. 12** Hardness profiles of partially quenched sheet metal strips by varied nozzle quantity

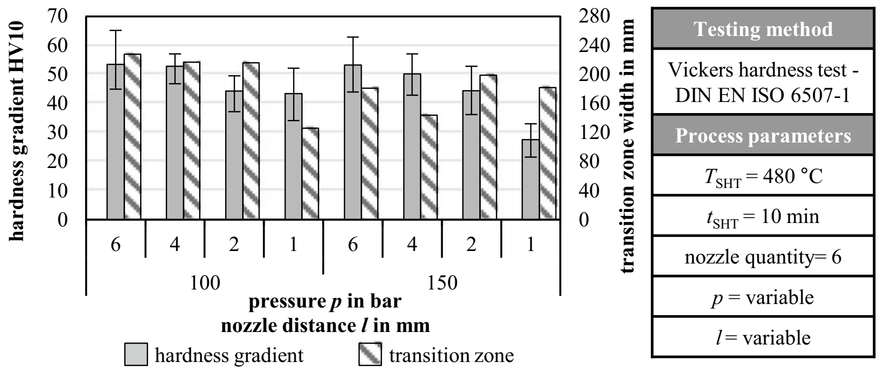



**Fig. 13** Results for the hardness gradient and transition zone of partially quenched EN AW-7075

and 150 mm the influence of the air pressure on the transition area is rather small. At 100 mm a reduction of the transition area with decreasing air pressure has been determined. At a distance of 150 mm, on the other hand, no clear influence can be identified.

## 5 Conclusions and Outlook

The influence of the quenching rate and the natural ageing duration after quenching on the formability of the alloy EN AW-7075 in the W-temper state was investigated. Furthermore, it was determined how a partial quenching process can be carried out to produce components with locally adjusted tailored mechanical properties. It was shown that the W-temper state reaches an increased formability compared to the T6 state. However, the formability decreases with increasing ageing time. For short ageing times after quenching, PLC bands are formed, which cause localisation of the strain and limit the formability. It has also been shown that in the stress state area of uniaxial tension, a rapid quenching rate after solution heat treatment is advantageous for formability. For the biaxial stress state, however, slow quenching rates are advantageous. In future experiments, the PLC effect will be investigated more closely by tensile tests. In addition, the process of solution heat treatment and quenching with subsequent forming will be transferred to a complex-forming geometry, and formability will be studied at the example of deep-drawing tests.

Additionally, the influence of the quenching conditions on the mechanical properties, particularly the hardness, was determined. By means of a compressed air-quenching facility setup, it was possible to produce sheet metal strips with locally adapted properties. A hardness gradient of up to 54 HV10 was obtained. For example, a transition zone of 144 mm at a hardness gradient of 50 HV10 was achieved. In future researches, the influence of alternative quenching media on others such as water–air mix shall be investigated. The aim will be to reduce the processing time while maintaining the hardness gradient and decreasing the width of the transition zone.

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## References

1. Sotirov N, Simon P, Waltenberger T, Uffelmann D, Melzer C (2011) Verbessertes Umformverhalten von höchstfesten 7xxx-Aluminiumblechen durch Halbwarmumformen. HTM J. Heat Treatm. Mat. 66(1):37–43
2. Kumar M, Sotirov N, Chimani CM (2014) Investigations on warm forming of AW-7020-T6 alloy sheet. JMatProTec 214(8):1769–1776. https://doi.org/10.1016/j.jmatprotec.2014.03.024
3. J Noder, S DiCecco, C Butcher, M Worswick 2017 Finite element simulation of non-isothermal warm forming of high-strength aluminum alloy sheet. AIP Conf Proc 1896:080017. https://doi.org/10.1063/1.5008097
4. Kumar M, Ross NG (2016) Influence of temper on the performance of a high-strength Al-Zn-Mg alloy sheet in the warm forming processing chain. JMatProTec 231:189–198. https://doi.org/10.1016/j.jmatprotec.2015.12.026
5. Behrens B-A, Hübner S, Vogt H (2018) Formability of 7000 aluminum alloys in warm and hot forming condition. IOP Conf Ser: Mater Sci Eng 418:012027. https://doi.org/10.1088/1757-899X/418/1/012027
6. Behrens B-A, Hübner S, Vogt H (2017) Forming of high-strength aluminum alloys – Influence of the forming temperature on the formability of 7xxx-aluminum alloys. WT Werkstatttechnik 107(10):695–699

7. El Fakir O, Wang L, Balint D, Dear JP, Lin J, Dean TA (2014) Numerical study of the solution heat treatment, forming, and in-die quenching (HFQ) process on AA5754. IJMachTools 87:39–48. https://doi.org/10.1016/j.ijmachtools.2014.07.008
8. Mendiguren J, Saenz de Argandoña E and Galdos L (2016) Hot stamping of AA7075 aluminum sheets. IOP Conf Ser: Mater Sci Eng 159:012026 https://doi.org/10.1088/1757-899X/159/1/012026
9. Degischer HP, Lacom W, Zahra A, Zahra CY (1980) Decomposition process in an Al-5%Zn-1%Mg alloy. Z Met 71(4):231–238
10. Löffler H, Kovács I, Lendvai J (1983) Review: Decomposition processes in Al-Zn-Mg alloys. J Mater Sci 18:2215–2240
11. Behrens B-A, Nürnberger F, Bonk C, Hübner S, Behrens S and Vogt H (2017) Influences on the formability and mechanical properties of 7000-aluminum alloys in hot and warm forming. J Phys: Conf Ser 896:012004 https://doi.org/10.1088/1742-6596/896/1/012004
12. Sáenz de Argandoña E, Galdos L, Ortubay R, Mendiguren J, Agirretxe X (2015) Room temperature forming of AA7075 aluminum alloys: W-temper process. KEM 651–653:199–204
13. Ostermann F (2014) Anwendungstechnologie aluminium, 3rd edn. Springer Vieweg, Berlin.
14. Nürnberger F, Diekamp M, Moritz J, Wolf L, Hübner S, Behrens B-A (2014) Spray cooling of early extracted hot stamped parts. Paper presented at the 143rd TMS Annual Meeting, San Diego, California, 16–20 February 2014, pp 983–990 https://doi.org/10.1002/9781118889879.ch116
15. L Wolf, M Diekamp, T Gretzki, F Nürnberger, F-W Bach, D Rodman, J Moritz, J Schrödter, S Hübner, B-A Behrens 2014 Hot stamping and subsequent spray cooling: A new manufacturing approach. In Plastic deformation of metals. Akzent, Dnipropetrovsk, UA, pp 36–55