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# Influences on the formability and mechanical properties of 7000-aluminum alloys in hot and warm forming

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**Abstract.** Aluminum alloys of the 7000 series possess high lightweight potential due to their high specific tensile strength combined with a good ultimate elongation. For this reason, hot-formed boron-manganese-steel parts can be substituted by these alloys. Therefore, the application of these aluminum alloys for structural car body components is desired to decrease the weight of the body in white and consequently CO<sub>2</sub> emissions during vehicle operation. These days, the limited formability at room temperature limits an application in the automobile industry. By increasing the deformation temperature, formability can be improved. In this study, two different approaches to increase the formability of these alloys by means of higher temperatures were investigated. The first approach is a warm forming route to form sheets in T6 temper state with high tensile strength at temperatures between 150 °C and 300 °C. The second approach is a hot forming route. Here, the material is annealed at solution heat treatment temperature and formed directly after the annealing step. Additionally, a quench step is included in the forming stage. After the forming and quenching step, the sheets have to be artificially aged to achieve the high specific tensile strength. In this study, several parameters in the presented process routes, which influence the formability and the mechanical properties, have been investigated for the aluminum alloys EN AW7022 and EN AW7075.

## 1. Introduction

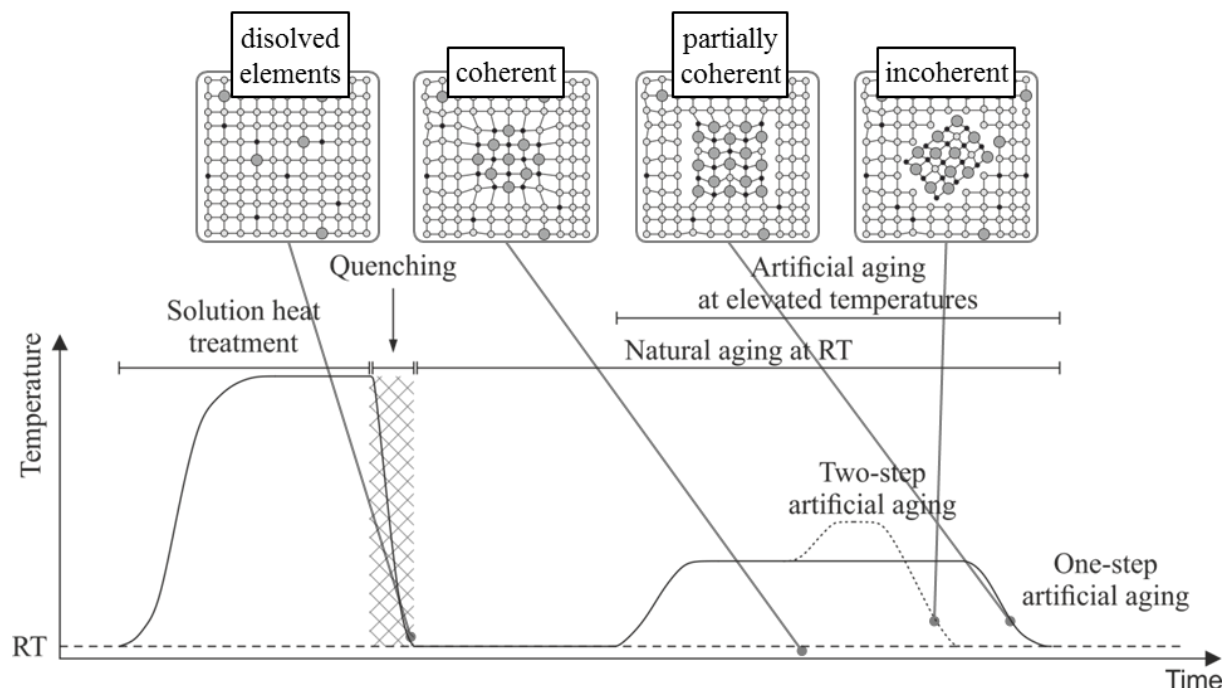
In automobile industry several approaches are pursued to reduce the weight of the body structure due to the requirements regarding exhaust emissions with the objective to reach equal or higher crash safety. Therefore, a use of ultra-high-strength steels [1] or high-manganese steels [2] or load adjusted parts [3] is possible. Aluminum alloys of the 7000 series combine the specific strength of press-hardened manganese boron-steel with ultimate elongations above 10 % [4]. Therefore, these alloys have a high lightweight potential. For this reason these materials can be used to decrease the weight of the automobile chassis and therefore to reduce the exhaust emissions by equal performance in crash situations. So far, an implementation of these alloys in body structure has been restricted because of the limited formability [4]. To increase the formability it is possible to form parts at elevated temperatures. For this, the warm forming at temperatures between 150 °C and 300 °C [5] and the hot forming above the recrystallization temperature [6] can be used. Therefore, a use of aluminium is promoted in modern lightweight construction together with other lower density materials such as fibre-reinforced plastics [7] or magnesium [8].



## 2. Hot and warm forming and heat treatment of 7000 aluminum alloys

Due to the highest reachable strength, the sheet material in the warm forming is in T6 temper state. For this reason the formability is limited. The expansion of formability in warm forming bases on the dissolution of  $\eta'$  precipitations and dynamic recovery processes [6]. Kumar et al. [9] found that the formability at 250 °C is improved for tubes consisting of EN AW7020. Furthermore, Kumar et al. [6] and Wang et al. [5] also found that warm forming and paint bake lead to a loss in strength. The hot forming of aluminum is also known as hot form quench (HFQ) process. In the first step the sheet material is heated up to solution annealing temperature. Subsequently the sheets were transferred into a forming machine and has been simultaneously formed and quenched [10]. Argandoña [11] investigated the forming behavior of the alloy EN AW7075 in HFQ-process. With this process it was possible to form b-pillars without defects.

After the hot forming process the formed parts have to be artificial aged. By this heat treatment the final mechanical properties of the part can be adjusted. In the artificial aging step finely dispersed metastable precipitations are formed which increase the strength of the material [10]. A schematic temperature profile for the heat treatment of a 7000 aluminum alloy is shown in Figure 1. Also the crystal lattice structure for the individual forming steps is shown. After solution heat treatment the alloy elements are dissolved in the crystal lattice of the aluminum. This microstructure condition is maintained by the quenching step. In case of natural aging coherent precipitations are formed as clusters or as Guinier-Preston (GP) zones. In case of artificial aging, first partially coherent  $\eta'$  precipitations are formed. Then incoherent precipitations in form of  $\eta$ -MgZn<sub>2</sub> are formed. This precipitation sequence was described by Degischer [12] and Löffler [13]. The main hardening phase is the partially coherent  $\eta'$  phase [14].

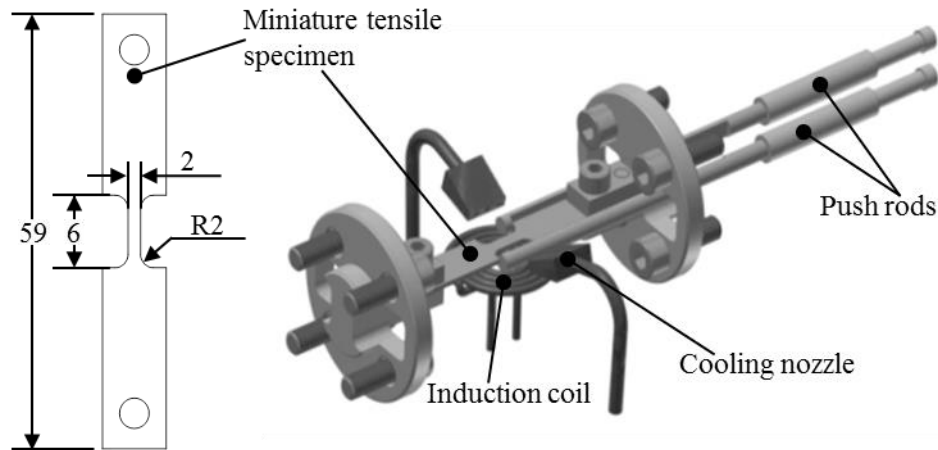


**Figure 1.** Schematic time temperature profile for the heat treatment of 7000 aluminum alloys [15].

## 3. Experimental setup

The influence of the forming parameters on the formability and the mechanical properties of the specimens were investigated by miniature uniaxial tensile tests. Therefore, a quenching and forming dilatometer was used. The specimens were heated up to the desired temperature via an induction coil and their temperature was measured by a fine-wire thermocouple. Cooling nozzles were used to regulate the temperature during the test. The elongation was measured by push rods during the tensile

test. The miniature specimen and the experimental setup in the measuring chamber of the quenching and forming dilatometer are shown in Figure 2.



**Figure 2.** Miniature tensile test specimen and experimental setup within the measuring chamber of the quench and forming dilatometer.

For the experimental investigations two different aluminum alloys of the 7000 series were examined. Both alloys contain copper and are thus sensible for quench processes [15]. The mechanical properties for both alloys and their different heat treatment states are listed in Table 1.

**Table 1.** Investigated aluminum sheet metal materials.

	Sheet thickness (mm)	Ultimate tensile strength $R_m$ (MPa)	Elongation at break $A$ (%)	Copper content (wt%)
<b>EN AW7022-F</b>	2	338	6.0	0.5 – 1.0
<b>EN AW7022-T6</b>	2	498	10.1	0.5 – 1.0
<b>EN AW7075-T6</b>	2	549	12.3	1.2 – 2.0

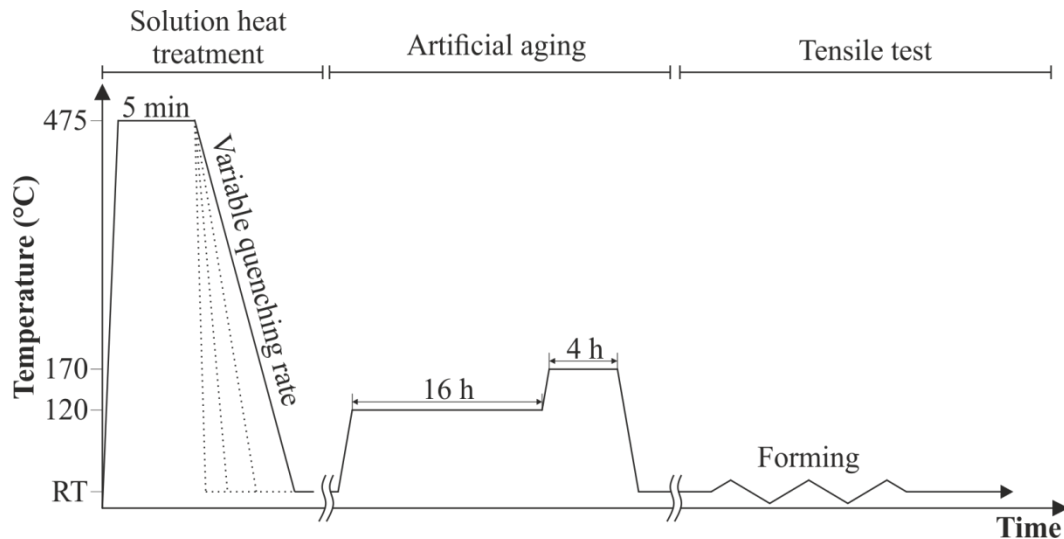
To determine the influence of the forming temperature on the formability, five different temperatures were investigated as listed in Table 2. The temperatures between 150 °C and 300 °C belong to the warm forming of 7000-aluminum. As hot forming temperature 475 °C was used, which corresponds to the solution annealing temperature of 7000-aluminum alloys [16].

**Table 2.** Investigated forming temperatures for warm and hot forming.

	Forming temperature (°C)
<b>EN AW7022-F</b>	
<b>EN AW7022-T6</b>	150; 200; 250; 300; 475
<b>EN AW7075-T6</b>	

Moreover the influence of the quenching rate and the paint bake on the mechanical properties was investigated. Therefore, both aluminum alloys were annealed for 5 min at solution heat temperature of 475 °C. To determine the influence of the quenching rate, the specimens were quenched with 1 K/s, 3 K/s, 30 K/s and 100 K/s after the solution heat treatment. Then the specimens were artificial aged in a climatic chamber. Therefore a two-step artificial aging process was used. The first step took 16 h at

120 °C and the second step 4 h at 170 °C. The schematic time-temperature profile is shown in Figure 3.

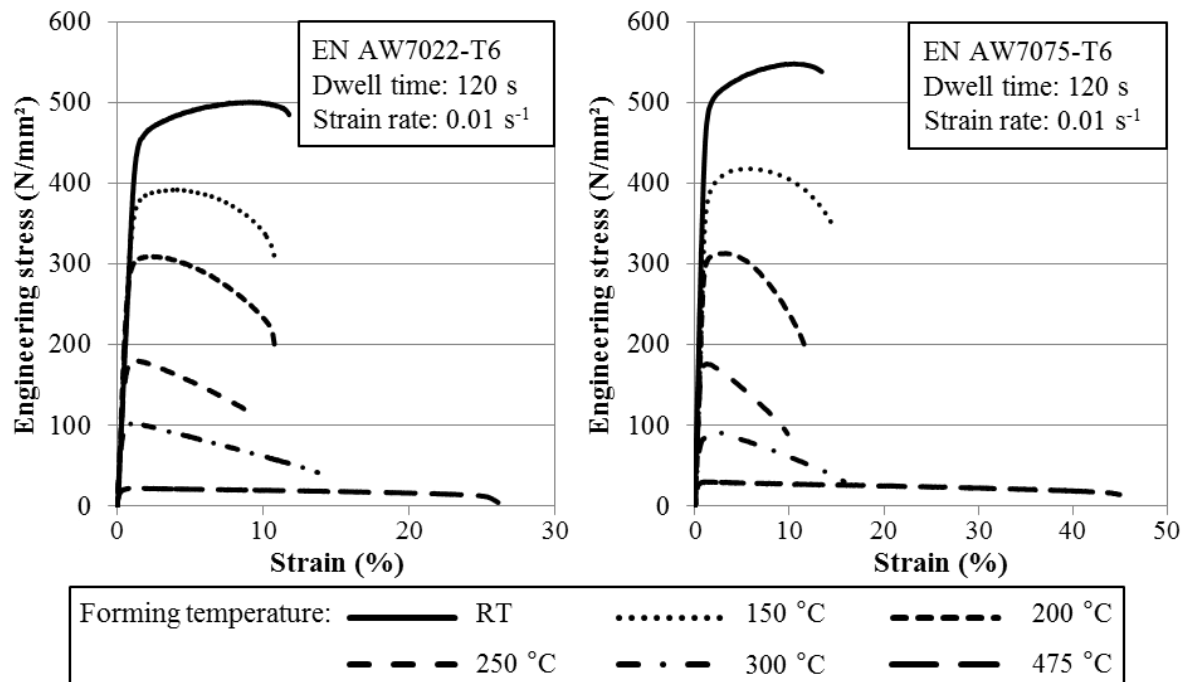


**Figure 3.** Schematic time-temperature profile for the solution heat treatment quenching investigation.

The cathodic dip-paint coating is a fix element in the process chain of car manufacturing. Therefore, it is important to know, how the aluminum alloys respond to the thermal load in paint bake. For this reason the influence of a simulated paint bake on the aluminum alloys in T6 heat treatment state was determined. Therefore, the specimens were heated to 180 °C for 20 min in a climatic chamber. Afterwards, a tensile test at room temperature in the quench and forming dilatometer was conducted.

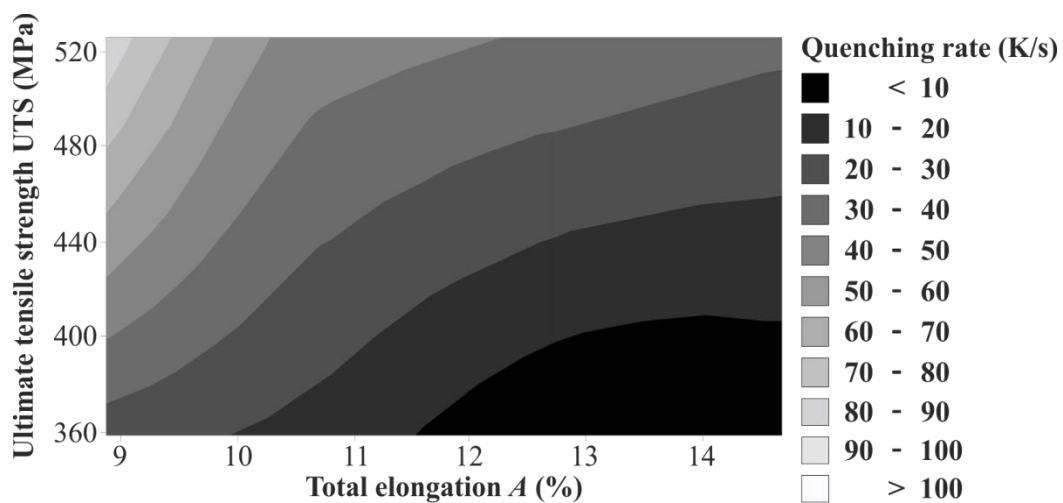
#### 4. Results of the experimental investigations

The influence of the forming temperature on the formability in miniature tensile test is discussed in the following. With an increasing forming temperature the stress needed to deform the specimen decreases, as illustrated for alloys EN AW7022-T6 and EN AW7075-T6 in Figure 4. At forming temperature of 150 °C the alloy EN AW7075-T6 has a higher engineering stress than alloy EN AW7022-T6 due to the higher initial tensile strength at room temperature. This difference decreases with increasing forming temperature. Until forming temperatures of 300 °C the maximal strain starts to increase for both alloys. The highest formability is reached in the hot forming at 475 °C for the alloys EN AW7022-T6 and EN AW7075-T6 with an engineering stress of 22 N/mm<sup>2</sup> respectively 30 N/mm<sup>2</sup> and a maximum strain of 26 % respectively 45 %.

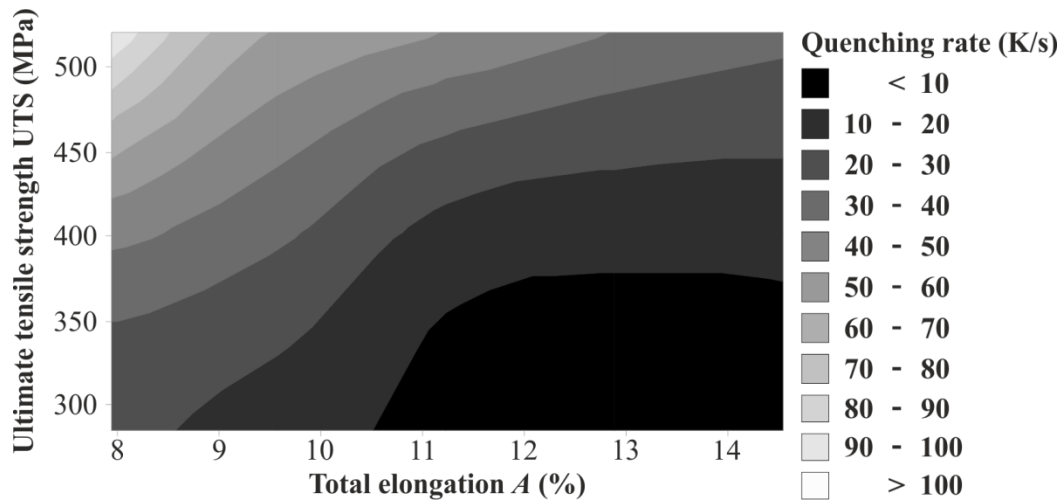


**Figure 4.** Influence of the forming temperature on the formability in the warm and hot forming of EN AW7022-T6 (left) and EN AW7075-T6 (right).

Beside the influence of the forming temperature on the formability, also the effect of the quenching rate on the mechanical properties in the hot forming was investigated. Figure 5 shows the interpolated contour plot of the ultimate tensile strength and total elongation for the alloy EN AW7022-F. The ultimate tensile strength increases with increasing quenching rate, while the total elongation decreases. The same effect is shown in Figure 6 for alloy EN AW7075-T6. However, the sensitivity on the quenching rate of alloy EN AW7075-T6 is higher than the sensitivity of EN AW7022-F. The reason therefore is the difference of the chemical composition of the two alloys. The alloy EN AW7075-T6 contains a higher weight percentage of copper and with increasing contains of copper, the sensitivity on quenching rate also increases [15].

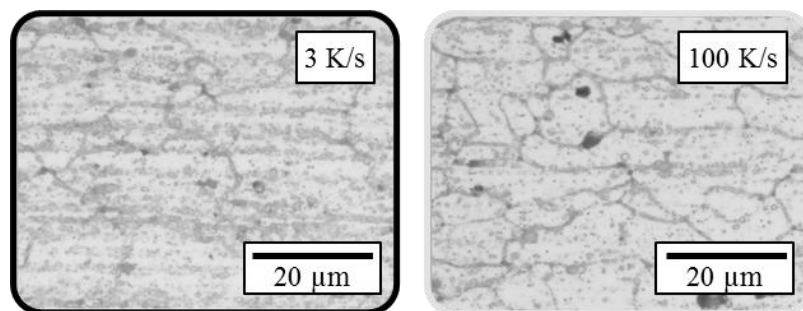


**Figure 5.** Contour plot of the mechanical properties for alloy EN AW7022-F quenched with various quenching rates.

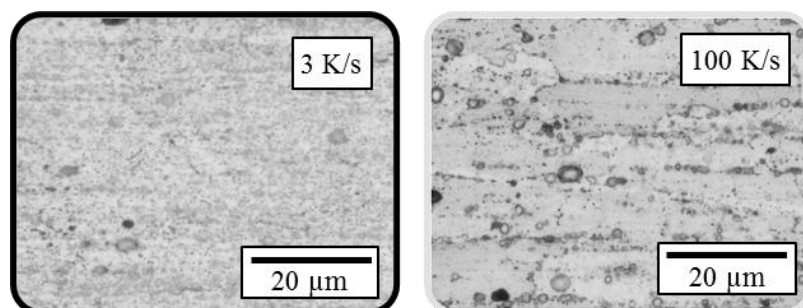


**Figure 6.** Contour plot of the mechanical properties for alloy EN AW7075-T6 quenched with various quenching rates.

Figure 7 and Figure 8 show microstructure images of both investigated alloys for different quenching rates. At quenching rates of 3 K/s most precipitations formed on the grain boundaries. Also, a high amount of precipitations with a size in micrometer range are formed at low quenching rates. At quenching rates of 100 K/s fewer precipitations have formed on the grain boundaries as well as in micrometer range within the grains. These effects are the reason for the increasing tensile strength with increasing quenching rate. The strength depends on the kind of precipitation that is formed while the heat treatment. The highest strength is achieved by  $\eta'$  precipitations in nanometer range within the grains. With a decreasing quenching rate the dissolution of the alloy elements increase and therefore the forming of precipitations on grain boundaries and in micrometer range is supported.

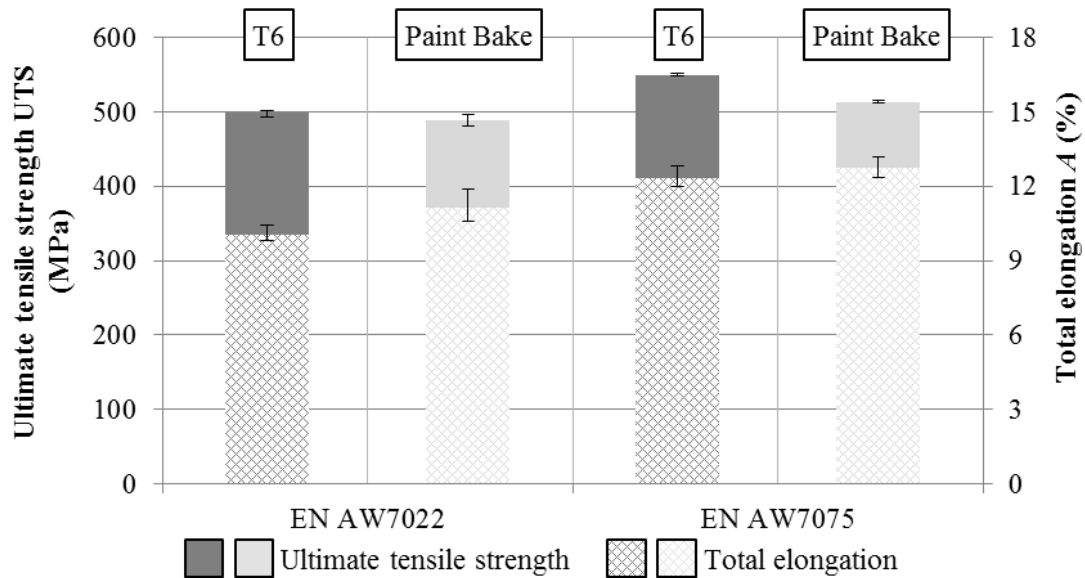


**Figure 7.** Microstructure of alloy EN AW7022-F with a quenching rate of 3 K/s (left) and 100 K/s (right).



**Figure 8.** Microstructure of alloy EN AW7075-T6 with a quenching rate of 3 K/s (left) and 100 K/s (right).

Moreover, the effect of simulated paint bake on the mechanical properties in T6 temper state was investigated. In Figure 9 the influence of the paint bake process is shown by comparison between the initial mechanical properties in T6 temper state and the heat treated specimen. By paint bake the ultimate tensile strength decreases for both alloys. A higher reduction takes place at alloy EN AW-7075 by 37 MPa from 550 MPa to 513 MPa. With decreasing strength the ductility increases, shown by the total elongation. Although, the strength reduction of EN AW7022-T6 is smaller, the increase in elongation is higher compared to EN AW7075-T6. The elongation increases from 10.1 % to 11.2 % respectively from 12.3 % to 12.7 %.



**Figure 9.** Influence of the paint bake on the mechanical properties in T6 temper state.

## 5. Summary and Outlook

In this paper, influences on the formability and the mechanical properties in warm and hot forming of the aluminum alloys EN AW7022 and EN AW7075 were investigated. It was shown that the temperature has a significant influence on the formability of 7000-aluminum alloys. With increasing forming temperature the required stress to deform the specimens decreases. Until temperatures of 300 °C also the maximum strain increases whereby the best formability is available at hot forming conditions. Furthermore the influence of the quenching rate on the mechanical properties was investigated. It was found that the quenching rate sensitivity is depending on the containing copper of the alloy. Also the mechanical properties are depending on the quenching rate. With decreasing quenching rate the dissolution of the alloy elements increase and therefore less strengthening precipitations are formed while the artificial aging step. Beside the influence of the quenching rate on the mechanical properties also the effect of paint bake was examined. It is shown that the paint bake heat treatment reduces the maximum strength in T6 temper state for both tested alloys. In further investigations, the influence of the warm forming on the mechanical properties will be examined as well as the influence of the heat treatment on the resistance against stress corrosion for 7000-aluminum alloys.

## 6. Acknowledgements

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