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Influence of a short-term heat treatment on the formability and ageing characteristics of aluminum profiles

Marion Merklein[a], Michael Lechner[a], Matthias Graser[a,*]

[a]*Institute of Manufacturing Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Egerlandstraße 11-13, 91058 Erlangen, Germany*

Abstract

Aluminum and its corresponding semi-finished products are widely used in the automotive industry. However, their formability is low in comparison to conventional steel materials. At the LFT a new approach to enhance the forming limits of precipitation hardenable aluminum alloys was invented. By performing a partial short term heat treatment a local softening of the material and the adaption of the material flow is possible. Due to this, critical forming areas are relieved and premature failure is prevented. After already been investigated in detail for blank material the adaption to aluminum profiles is preferable, because they are increasingly used in car space frames. For a better understanding of the mechanisms of this technology a comprehensive material characterization will be induced. Furthermore, the influence on the different subsequent aging processes (natural, artificial) is analysed. Based on the results, a process window and design rules for the implementation of a local short-term heat treatment on profiles of the precipitation hardenable aluminum alloy EN AW 6060 will be derived.

Keywords: Aluminum profiles; tailored properties; laser heat treatment, ageing process

1. Introduction

Since the 1990's a rethinking process regarding environmental issues has been taking place in the automotive industry. As a consequence, laws have been tightened up to reduce CO_2-emission. One possibility to comply with these legal requirements is the reduction of vehicle weight by the application of

* Matthias Graser. Tel.: +49 9131 85 28310; fax: +49 9131 85 27141.
E-mail address: matthias.graser@fau.de.

lightweight materials. In this context aluminum is utilised because of its low density, high stiffness and corrosion resistance. One application of this approach is for example the aluminum space frame of the Audi A8 which is almost entirely made out of different aluminum semi-finished products. A large percentage of these semi-finished products are aluminum profiles, which are frequently used due to their high stiffness and efficient producibility. However, profiles possess only limited formability. This disadvantageous forming behavior is expressed by premature failure during forming processes as well as geometrical defects such as warping, buckling, wrinkling and cross section reductions (Fig. 1a), which results in decreased accuracy and quality. (Vollertsen et al., 1999)

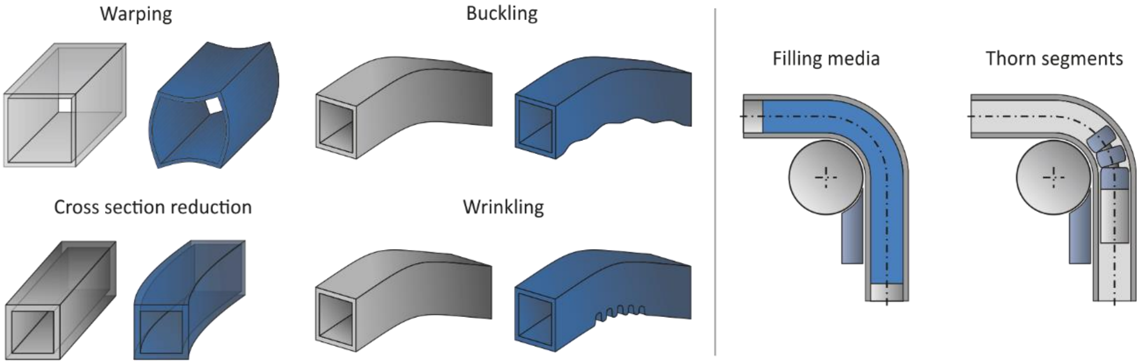

Fig. 1. (a) Types of failure in profile bending processes, (b) Countermeasures for bending failure

Various technologies were investigated to overcome these negative effects. One strategy is the adaptation of the bending process regarding the tool geometry, movement as well as the introduced moments and forces. The superposition of forces for instance in stretch bending leads to a stabilization of the cross section (Geiger and Sprenger, 1998). For reducing cross section deformations mandrels (Welo and Paulsen, 1996) and fillings (Duartea et al., 2014) are applied to support the extrusion wall from the inside and to prevent a buckling of the profile (Fig 1b). In a further approach investigated by Kleiner and Arendes (Kleiner and Arendes, 1996), the profiles are directly bended after the extrusion process.

Concededly these methods are quite costly and inflexible, why there is a need for an innovative method to enhance the formability of extrusion profiles. One application which has already been investigated in detail to enhance the formability of precipitation hardenable aluminum blanks - especially for the 6000 series - is the so called Tailored Heat Treatment (Geiger et al., 2009). By performing a short-term heat treatment the precipitations in the aluminum matrix are dissolved, resulting in an oversaturated solid solution with magnesium and silicon atoms. Due to this less obstacles hinder the dislocation movement and the material is softened. The process itself starts with a local short term heat treatment for example by laser radiation, resulting in a tailored blank with a controlled material distribution. Thus the material flow in a subsequent forming process can be controlled leading to an improved formability.

Because of its flexibility the adaptation of this technology for extending the forming limits of aluminum extrusion profiles in bending processes is targeted. Prerequisite for a successful application of the technology is the definition of a process window identifying the heat treatment parameters, which lead to an improved forming behavior. In this context, in particular the temporal stability of the material softening has to be taken into account. Immediately after the short term heat treatment a natural hardening process starts until the original mechanical properties are reached once more. With regard to the later industrial application and varying transport and storage times, the influence of the ageing process is of high interest for the process management.

Therefore, the influence of the natural ageing process at room temperature was investigated. Furthermore, the artificial ageing process at elevated temperatures and its dependency on the forming history as well as the preceding short term heat treatment was analysed.

2. Material and experimental setup

In the investigations the precipitation hardenable aluminum alloy EN AW 6060 was tested. The concentrations of Si and Mg for the analysed batch are 0.399% and 0.561% (Table 1). The percentage as well as the proportion of these two alloy components are the main influential factors for the mechanical properties of the material (Ostermann, 2007).

Table 1: Chemical composition of EN AW 6060 (in weight percentage)

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
0.399	0.223	0.0736	0.139	0.561	0.0222	0.0092	0.0173	0.0156

The tensile specimens were produced from aluminum extrusion profiles with dimensions 20x20x1200 and 2 mm material thickness. Due to this, the standard dimensions for tensile specimens according to DIN EN 10002 had to be modified to fit the geometry of the profiles. This lead to a reduction of both the clamping width from 20 mm to 14 mm and the measuring width from 12.5 mm to 8.75 mm (Fig. 2).

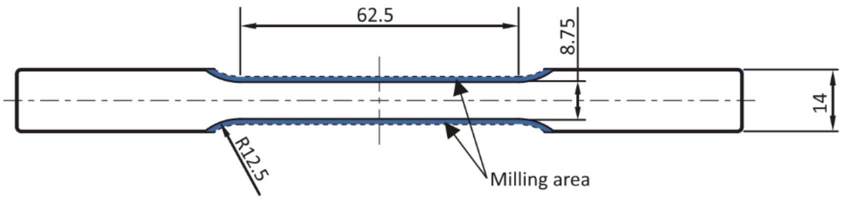

Fig. 2. Modified specimen dimensions

In the production process the specimens are initially laser cutted with a material allowance of 1 mm in the measuring zone by a Trumpf CO_2-Laser (TruLaser Cell 7020) with a three-dimensional movable laser head. Consecutively, the specimens are milled to their final dimensions, negating the influence of the thermal cutting process on the mechanical properties of the material.

For the radiation heat treatment a robot-mounted Nd:YAG laser with a maximum output power of 4 kW and a Gaussian intensity distribution was used. Thereby the focus diameter was set to 16 mm to increase the homogeneity of the temperature distribution over the specimens' width. The wave length of 1064 nm allows a laser beam guidance by optical fibers as well as a good absorption of the laser irradiation [Hügel and Graf, 2009]. Due to the high thermal conductivity of aluminum, the laser head velocity was set to 50 mm/s to limit the heat affected zone with regard to the later industrial application.

2.1. Temperature measurement

Temperature measurements (Fig. 3a) were conducted on the lower side of the specimen by a pyrometer, inside by a thermocouple element (Fig. 3b) and on the upper side by a thermal camera. Based on three measurement points the temperature distribution over the specimen thickness can be identified and subsequently utilized to compare radiation with other heating technologies for example double sided conduction heating. The thermocouple with a diameter of 0.5 mm and a measuring range from -100°C to

700°C was positioned inside the specimen through a hole which was produced by a micro electrical discharge machine SARIX SX-200-HPM. To achieve a homogenous absorption of the laser radiation as well as a homogenous emissivity for the thermal measurement the specimens were coated with a graphite layer, which has a constant emissivity of 0.95.

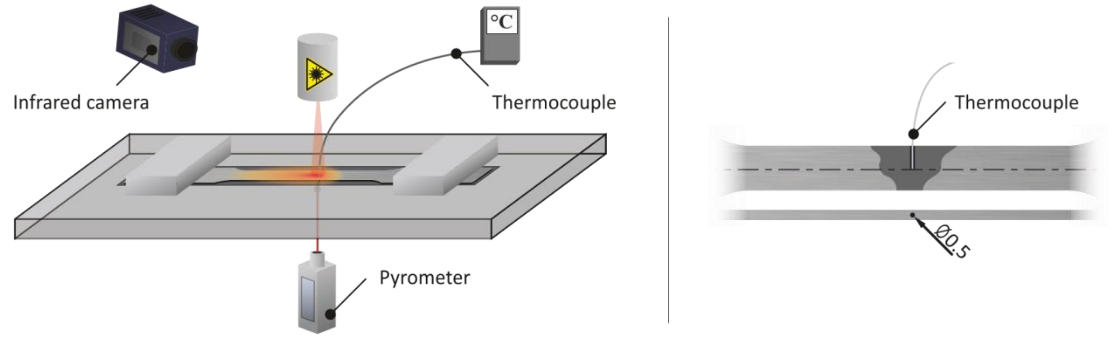

Fig. 3. (a) Overview of temperature measurement setup, (b) Placement of thermocouple

After the heat treatment the mechanical properties of the material were identified by tensile tests as well as Brinell hardness measurements. The tensile tests were performed with a Zwick 100 testing machine according to the parameters of the testing and documentation guideline for mechanical properties of aluminum materials in the automotive industry, which was developed by Stahlinstitut VEDh et al., 2005. Additionally, the Brinell hardness was measured with a universal testing machine, a wolfram indenter with a diameter of 2.5 mm and a testing force of 62.5 kilopond.

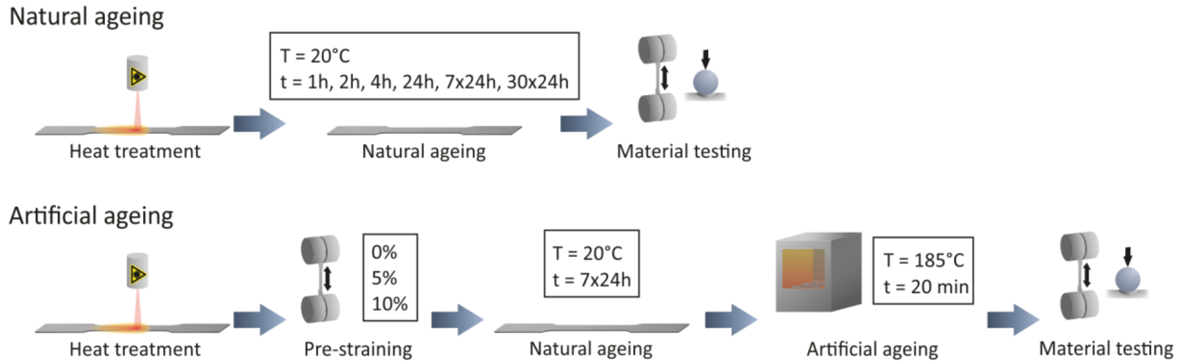

Fig. 4. Overview of testing procedure

Furthermore, the effects of the natural and artificial aging process were analysed (Fig 4). The influence of the natural ageing on the mechanical properties depending on the preceding short term heat treatment as well as the ageing period which was varied from 1 hour to 1 month was investigated. The artificial ageing process was simulated according to the industrial process in the automotive production. In order to identify the influence of the forming history on the later artificial aging process the specimens were heat treated and immediately afterwards pre-strained to 0%, 5% and 10% plastic strain. After one week of natural ageing, which represents potential storage or transport intervals, the specimens were artificially aged in a convection oven at 185°C for 20 minutes. Finally the mechanical properties were measured by uniaxial tensile tests and the hardening effect achieved by the heat treatment was documented.

3. Experimental results

The experimental results stated in the following paragraphs comprise on the one hand the temperature distribution over the material thickness. On the other hand the effects of a natural as well as artificial ageing process are constituted. In this context, the investigations focus on the influence of the preceding heat treatment, the forming history and the parameters of the ageing processes.

3.1. Temperature distribution

The temperature distribution caused by laser radiation heating mainly depends on the thermal input, the thermal conductivity and the thickness of the material. Thus, the influence of the laser power on the temperature distribution was identified by measuring the resulting temperatures for laser powers in the range between 0.48 kW to 1.2 kW, whereby standard deviations were not exceeding 6°C (Fig 5). A laser power of 0.48 kW results in a temperature of 202°C on the upper side, 136°C in the middle and 107°C on the lower side. This disparity can be explained by the high laser power and velocity in combination with the material thickness of 2 mm. With rising thermal input due to the higher laser power, the temperature deviation between the upper and the lower side increases. For a laser power of 0.92 kW the temperature on the upper side is about 340°C and the temperature on the lower side is only 179°C. For the highest laser power tested the temperatures rises to 450°C on the upper side, 309°C in the middle and 241°C on the lower side. As a consequence the difference between the upper and the lower side is doubled from the lowest to the highest investigated laser power. The result is a non-uniform material structure, which leads to different mechanical properties over the cross section of the aluminum extrusion alloy, which has to be taken into account for the future and the numerical design of heat treatment layouts.

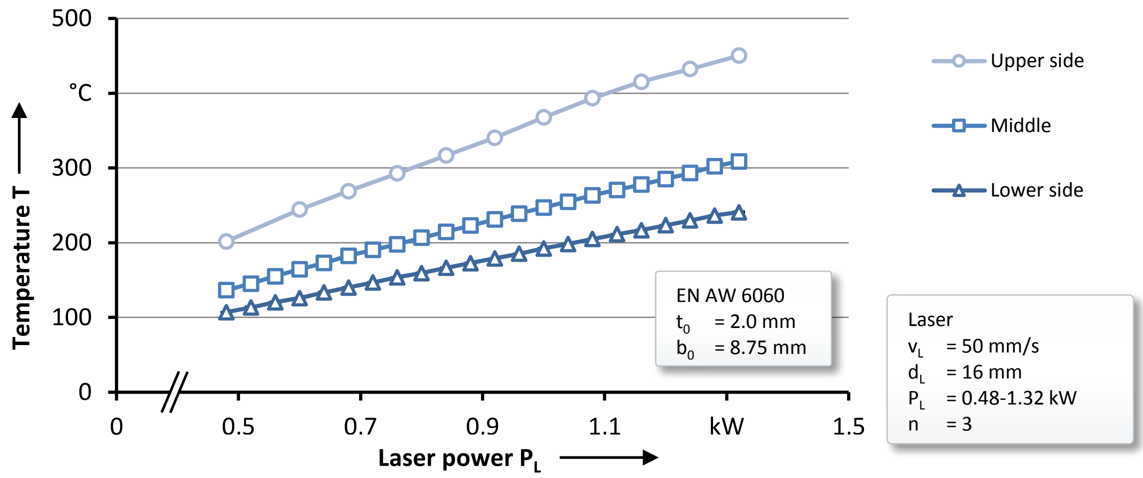

Fig. 5. Temperature distribution over the material thickness

For the ongoing investigations the scope of experiments was reduced with regard to the laser power. For this purpose tensile tests were conducted 15 minutes after the heat treatment and the resulting yield strengths were compared with already existing values received from double sided conduction heating. Subsequently the laser powers to achieve the mechanical properties according to 200°C, 250°C, 300°C and 400°C were derived and utilised in the following material characterization, whereby a high reproducability of the experimental results could be achieved.

3.2. Natural ageing

During the natural ageing process precipitations are formed from the dissolved Mg and Si clusters, which act as hindrances to the dislocation movement resulting in a higher strength of the material. As a first step the influence of the laser power on the mechanical properties was investigated after a natural ageing time of 1 hour (Fig. 6). In this context a softening of the material was detected beyond 200°C, reaching its maximum at 400°C. Hence, it can be concluded that all the magnesium and silicon atoms are dissolved in the aluminum matrix, leading to a yield strength decrease of 50% in comparison with the T4 condition.

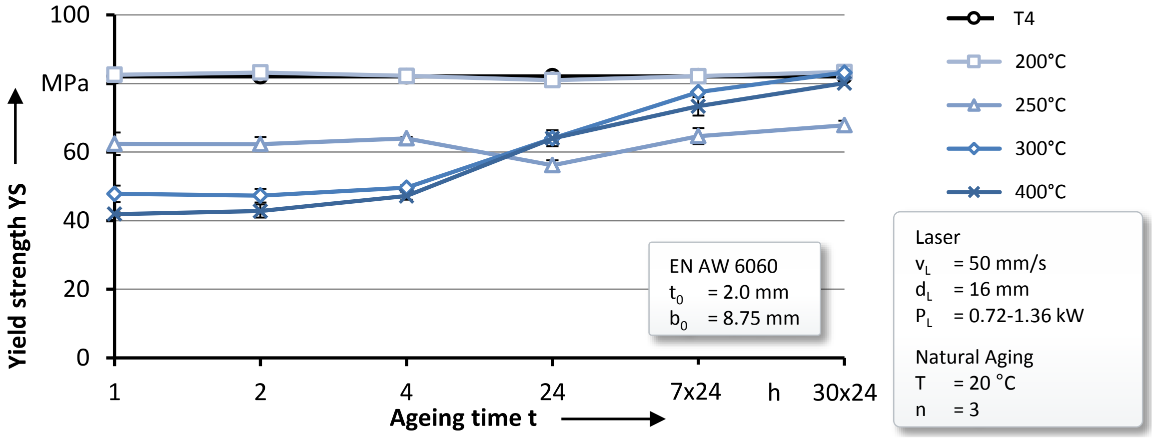

Fig. 6. Influence of the natural ageing time on yield strength

For further investigations the ageing time was varied from one hour to one month after the heat treatment. For 200°C no influence of the aging time on the mechanical properties could be detected. An explanation is that no Mg and Si atoms are dissolved at this temperature, whereby no precipitations can be formed during the aging process. The specimens which were heat treated at 300°C and 400°C show a constant increase of the yield strength until the original yield strength of the T4 material is almost reached after one month. In contrast to this an interesting effect was identified for the heat treatment at 250°C. It leads to a softening of only about 25% but shows no hardening behavior over the whole ageing time.

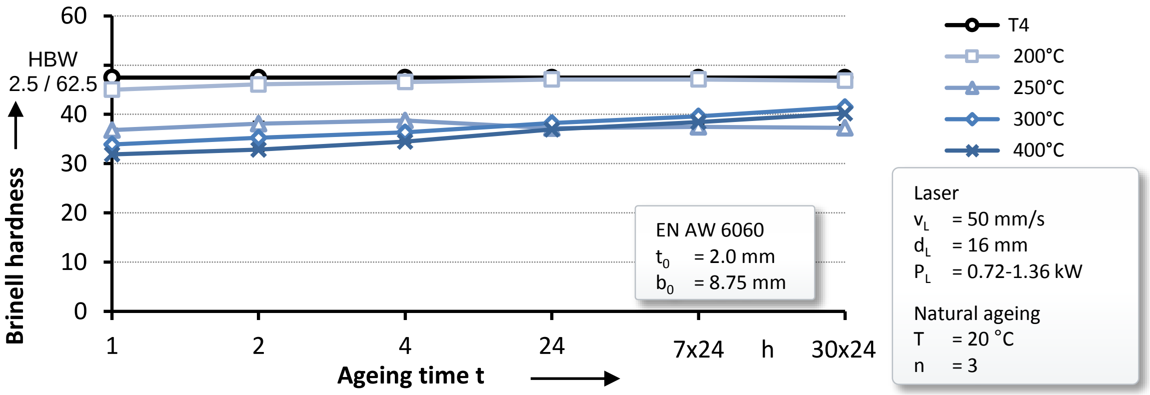

Fig. 7. Influence of the natural ageing time on Brinell hardness

In general, only a small standard deviation of the mechanical properties could be detected. The experimental results were double checked using Brinell hardness measurements after the preassigned ageing intervals (Fig 7). The original material in T4 state has a hardness of 47.5 HBW. Just as in the tensile tests initially a decrease of the hardness for a heat treatment of 300°C and 400°C to 33.9 and 31.9 HBW was identified after which a constant hardening could be stated. Whereas the specimens heat treated at 250°C stayed at a Brinell hardness value of around 35 HBW.

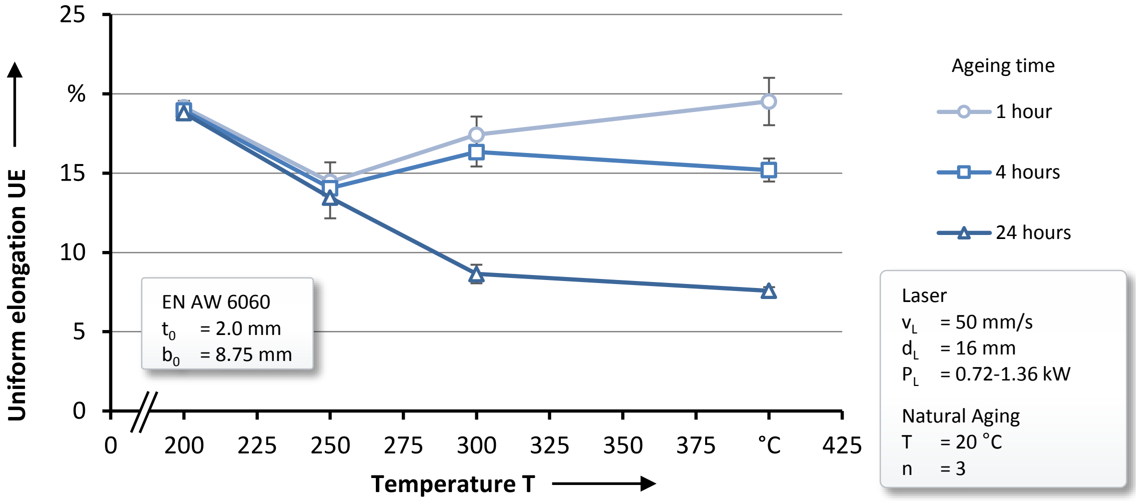

Fig. 8. Influence of the natural ageing time on uniform elongation

With regard to the uniform elongation (Fig. 8) there is almost no difference between the original state and the specimens, which were heat-treated at 400°C, with a value of 19%. For a heat treatment of 250°C a critical temperature zone was detected where the uniform elongation decreases to 14%. This effect has already been stated in numerous investigations regarding the tailor heat treatment for blank material and is assumedly connected to the formation of β' and β'' precipitations that lead to an inhomogeneous structure, resulting in a premature failure of the material (Geiger et al., 2004). In analysis concerning the influence of the ageing duration a decrease of the uniform elongation for heat treatment temperatures of 300°C and 400°C was detected. The values are reduced to 16.3% and 15.2% after one hour and decrease even more after 24 hours to 8.6% and 7.6%. This decline is most likely caused by an inhomogeneous precipitation formation, resulting from the temperature gradient over the material thickness. (Hofmann, 2004)

3.3. Artificial ageing

The influence of artificial ageing was tested including the impact of different pre-strains (Fig. 9). Therefore, after the heat treatment specimens were pre-strained to 5% and 10% plastic strain and the resulting mechanical properties after one week of natural ageing were compared to specimens with no pre-straining, before as well as after the artificial aging process.
As already demonstrated specimens which are heat treated at 250°C show no hardening during the natural ageing process. As a consequence, the yield strength of these specimens before the artificial ageing process was the lowest with 62 MPa, whereas a heat treatment of 300°C and 400°C led to values of 77 MPa and 74 MPa. After the artificial ageing process this relation is maintained although the highest increase of the yield strength of 12.5% could be detected for specimens heat treated at 250°C.

A pre-straining of the specimens after the heat treatment leads to higher yield strength in general. One reason given for this is the increased density of dislocations, which causes a higher strength of the material. This effect superposes the negative hardening behavior detected for a heat treatment of 250°C. Therefore a decrease of the yield strength from 200°C to 400°C was identified for 5% and 10% pre-straining. Furthermore, the dislocations act as germs for the formation of precipitations, which represent obstacles for the dislocation movement [Gottstein, 2014]. Due to this the influence of the artificial ageing process on the yield strength is increased in comparison between 0% and 5% pre-straining. For 10% pre-straining and a heat treatment of 200°C the highest yield strength after the artificial ageing process is reached with 198 MPa, whereas for 400°C only 159 MPa are achieved.

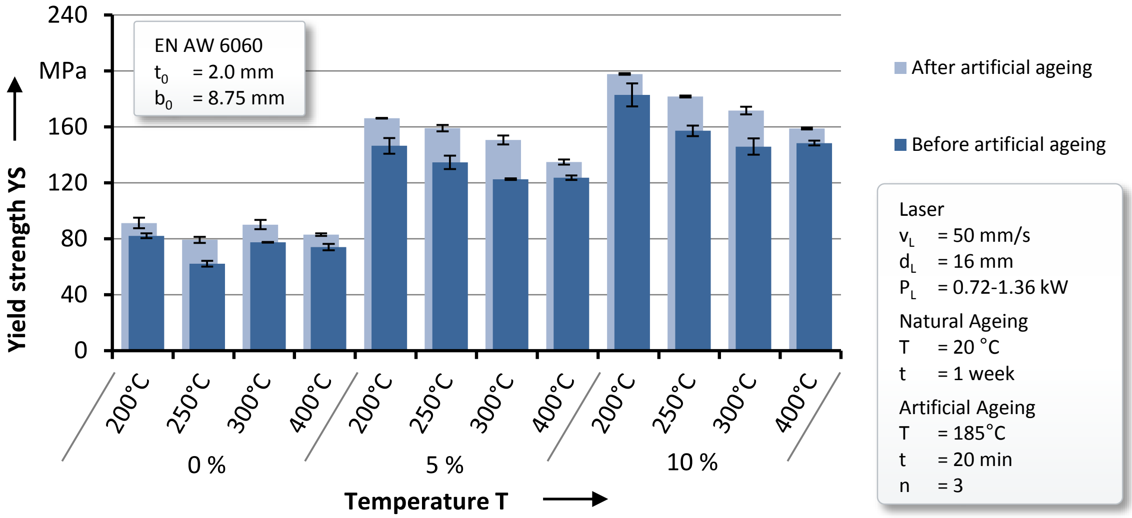

Fig. 9. Yield strength after artificial ageing depending on pre-straining

These results were verified by additional hardness measurements, whereby the increase of hardness depending on the pre-straining could be stated (Fig. 10). With 5% plastic strain and a heat treatment of 200°C a hardness of 68.9 HBW was reached, whereas with a heat treatment of 400°C the hardness is only 57.8 HBW. Using a higher pre-strain of 10% the difference between the 200°C and 400°C is even higher with values of 80.7 HBW and 64.9 HBW.

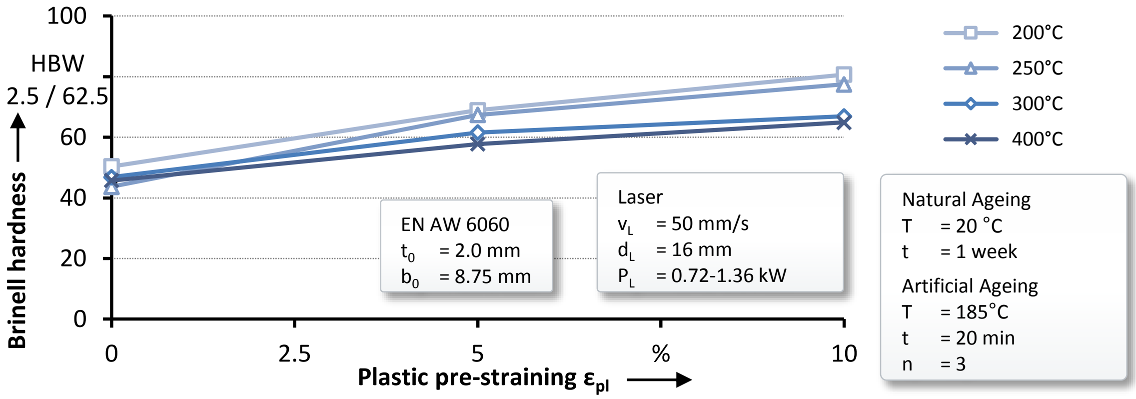

Fig. 10. Brinell hardness after artificial ageing depending on pre-straining

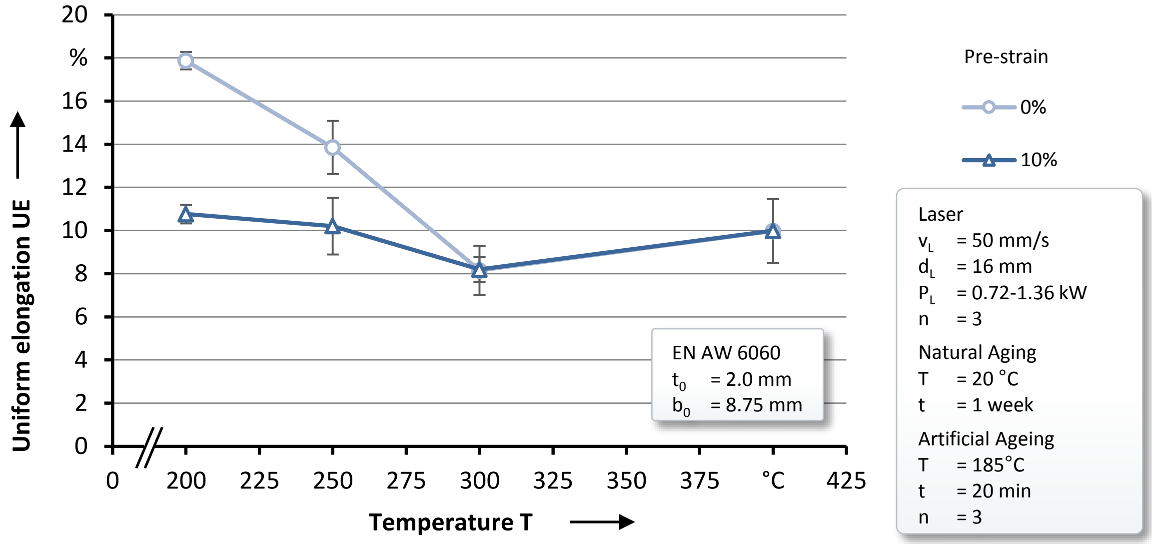

Fig. 11. Uniform elongation after artificial ageing depending on pre-straining

After pre-straining the increase of the yield strength is accompanied by a decrease of the uniform elongation. During the natural ageing process a further decline of the uniform elongation over time was detected for heat treatments of 300°C and 400°C. For the specimens with no pre-straining this effect is even visible after the artificial ageing process (Fig. 11). The uniform elongation decreases from 17.9% for 200°C to 8.2% for 300°C and 10% for 400°C. By adding a pre-straining of 10% the differences between the investigated temperatures are lower and the uniform elongation for specimens heat-treated with 200°C decreases to 10.8% whereas the values for higher temperatures stay nearly constant.

4. Discussion

By means of a short term laser heat treatment a softening of the aluminum alloy EN AW 6060 starts already at temperatures higher than 200°C. However, to achieve the best influence on the material flow a high softening is favorable. Due to this the laser heat treatment should reach temperatures from 300°C to 400°C. And with attention to the instability of the material softening proven by tensile test as well as hardness measurements the forming process should be performed in a time interval of 4 hours after heat treatment. Furthermore the results of the experiments after the natural and artificial ageing process have shown a decrease of the uniform elongation at higher temperatures, which has to be taken into account if high crash requirements have to be met.

5. Summary and Outlook

The investigations have identified the following results:

- A short term laser heat treatment with high laser head velocities results in an inhomogeneous temperature distribution over the material thickness.
- The maximum softening of 50% for the aluminum extrusion alloy EN AW 6060 is reached at 400°C.

- After the heat treatment a constant hardening during natural ageing was detected as well as a decrease of the uniform elongation. Therefore, the forming process should be within 4 hours after the short term heat treatment to use the tailor heat treatment technology to full capacity.
- For a heat treatment of 250°C a decrease of the uniform elongation as well as no natural ageing of the material is detectable.
- An improvement of the yield strength depending on the forming history of the material can be achieved by artificial ageing. However, heat treatment temperatures of 300°C and 400°C lead to a decrease of the uniform elongation.

In further investigations the influence of the heating as well as the cooling velocity resulting in different temperature distributions should be analyzed and its influence on the subsequent ageing processes identified. After the completion of the process window the mechanical properties are transferred to the numerical simulation. Different heat treatment layouts will be designed and afterwards validated by experimental tests. In a final step the general guidelines for the design of heat treatment layouts for aluminum profiles will be developed. Derived from this the design of heat treatment layouts will be optimized and used to improve an industry-oriented bending process.

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