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Tailoring material properties of aluminum by local laser heat treatment

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- Invited Paper -

Abstract

The local laser heat treatment of precipitation hardenable aluminum alloys enables the tailoring of the materials properties and the manufacturing of lightweight and crash-proof components for the body in white. For conventional aluminum sheet metals and profiles the formability is enhanced by an indirect approach. Thereby specific parts of the products are softened in order to improve the material flow towards crack critical areas during the forming operation. For innovative high-strength aluminum sheet metal with nanocrystalline grain structure produced in the Accumulative Roll Bonding process in addition to the indirect approach a direct enhancement of the formability by recrystallization effects is possible.

Keywords: Aluminum alloys; Tailored Blanks; Tailored Heat Treated Profiles; Accumulative Roll Bonding; Heat Treatment

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1. Motivation / State of the art

The weight of cars has increased within the last 40 years up to 50% [1]. This is mainly a result of the customers demand to more comfort, performance and safety standards. The growing mass is however a big problem concerning the consumption and the environmental compatibility of the vehicle. The European lawmaker have identified that trend and set target emissions for new cars to 95 gCO_2/km for 2020 compared to a current average emission of 145 gCO_2/km [1]. New developments of engines and drivetrains alone will not be sufficient to fulfill the regulations of the government. Furthermore, a rising

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weight is not only a problem for the automotive industry, but nearly for the complete transportation sector as well. For example also trains became a quarter heavier in last decades. An auspicious possibility to solve these problems is the use of modern lightweight materials. At the moment an average car contains 960 kg of steel. Most of it is used in the body in white, which contributes with nearly 34% to the complete mass. The substitution of this conventional material by aluminum alloys is a success promising contribution for weight savings [2]. Based on their good mechanical properties precipitation hardenable aluminum alloys are used for that approach. However, these materials have in comparison to deep drawing steel a low formability. To overcome this, new technologies have to be developed in order to achieve lightweight constructions with aluminum.

A possible approach to enhance the formability is the partial tailoring of the mechanical properties. The strength distribution is obtained by a short term heat treatment before actual forming process. Based on the new strength distribution the material flow during the forming can be influenced and the formability can be enhanced. The forming process is performed in cold conditions. The first investigations were performed by Siebel and Beiswänger in 1953 [3], who already showed that a significant enhancement of the formability is possible.

However, the breakthrough of the technology is a result of two developments. On the one hand aluminum alloys are getting more and more important for the transportation sector, on the other hand new lasers for metal processing were developed, which allow a flexible and local heat treatment. In principal, also technologies based on heat induction and heat conduction could be used for tailoring the mechanical properties. However, it is difficult to test different heat treatment layouts and therefore is not suitable for scientific investigations. Especially in the last 15 years a lot of research work in this field was done and the technology is today known under the generic term “Tailored Heat Treated Blanks (THTB)” [4]. Although results are known for steel and copper materials, it turned out that, in particular, aluminum alloys of the 6000-series are suitable for the THTB technology [4]. Hardening of aluminum alloys of the 6000-series can be achieved by a heat treatment and the consequential formation of microstructural precipitates based on the alloying elements Mg and Si. In this context, the solution annealed state W and the naturally aged state T4 have to be distinguished. A short term heat treatment of hardenable aluminum by laser radiation leads to a significant softening of the aluminum blanks [4]. The particles that cause precipitation hardening are locally dissolved during the heat treatment and a quasi-solution annealed state appears. The technology was successful applied to conventional blanks, blanks produced with the Accumulative Roll Bonding process, for multistage forming operations and for profiles (Fig. 1)

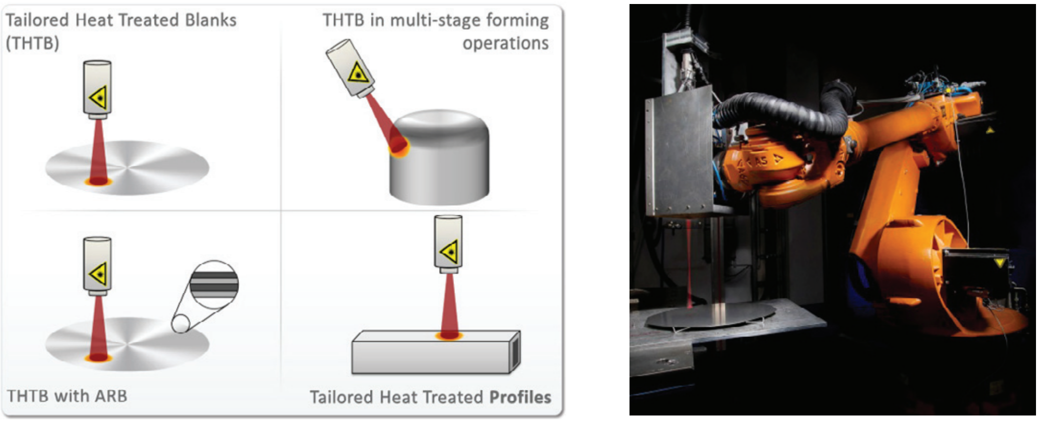

Fig. 1. Tailoring methods and experimental setup

2. Experimental procedure

The heat treatment is carried out using a Nd:YAG laser with a maximum power of 4000 W and a Gaussian beam profile (Fig. 1). For the irradiation of the specimens in defined areas, a 6 DOF articulated arm robot is used. During the heat treatment process the surface temperature of the specimen is measured by a pyrometer. The emission coefficient for uncoated aluminum was determined with a reconciliation method to e = 0.23, for graphite coated material to e = 0.95. Representative process parameters for the heat treatment of hardenable aluminum alloys are a maximum temperature of 400 °C and a holding time of less than 5 s.

3. Tailored Heat Treated Blanks

The enhancement of formability of aluminum blanks is mainly a result of an indirect approach. A short term heat treatment improves the formability of the material not directly. For some maximum temperatures the uniform elongation within tensile test is in fact lower. Therefore crack critical areas should not be heat treated, because the part would then be more susceptible to failure. Rather the material flow to the crack critical area should be improved. Consequently the definition of suitable heat treatment layouts is the biggest challenge for the successful production of Tailored Heat Treated Blanks. For drawing of a simple cup an analytical approach was developed [5]. For more complex geometries a thermo-mechanical simulation was built up at the Chair of Manufacturing Technology, which allows to determine the mechanical properties obtained by the short-term heat treatment and use them as input parameter for the numerical calculation of the forming operation [5]. Universal design principles were derived to determine which area of a blank have to be heat treated in order to get a better drawing depth [4]. Moreover, an inverse method for the definition of an appropriate laser path was developed [6].

4. Tailoring material properties in multistage forming operations.

New investigations show that local laser heat treatment can not only be used before, but also between two forming operations. Within the fundamental research work at first material characterization was performed. Aluminum tensile specimens were prestrained to a plastic strain of 10%. Fig. 2 shows the corresponding flow curves. As a result of hardening effects the yield strength increases by 40% from 139 MPa to 235 MPa. Moreover, the uniform elongation, which is an indicator of the remaining formability, is reduced by 35%. After the pre-straining the specimens were heat treated with laser radiation. For that the robot controlled laser moves over the tensile specimen with a speed of 20 mm/s and focus diameter of 30 mm. The high heat conductivity guarantees a homogeneous heat treatment. The laser power was varied between 400 W and 1200 W to achieve temperatures between 200 °C and 450 °C. After the heat treatment tensile tests were performed. Fig. 1 shows the corresponding flow curve for 400 °C. As a result of the dissolution of the magnesium-silicon-clusters and the recovery effects, there is a strong softening of the material. The yield strength was reduced by 56% to 103 MPa. The softening of prestrained material by a short term heat treatment was used to improve a multi-stage forming process. The process consists of a deep drawing operation combined with a subsequent hydroforming operation to form side shapes. Fig. 2 shows that within the conventional procedure the side shapes cannot be produced without failure. To overcome this, numerical simulation was used to find appropriate intermediate laser heat treatment layouts. In particular, the softening of the flange area show promising results. Caused by the lower yield strength of the heat treated area, these zones begin earlier to plastifiy during the forming operation. As a consequence the material flow to the critical areas can be improved. The results were validated by experimental results (Fig. 2). The part can now be produced without failure.

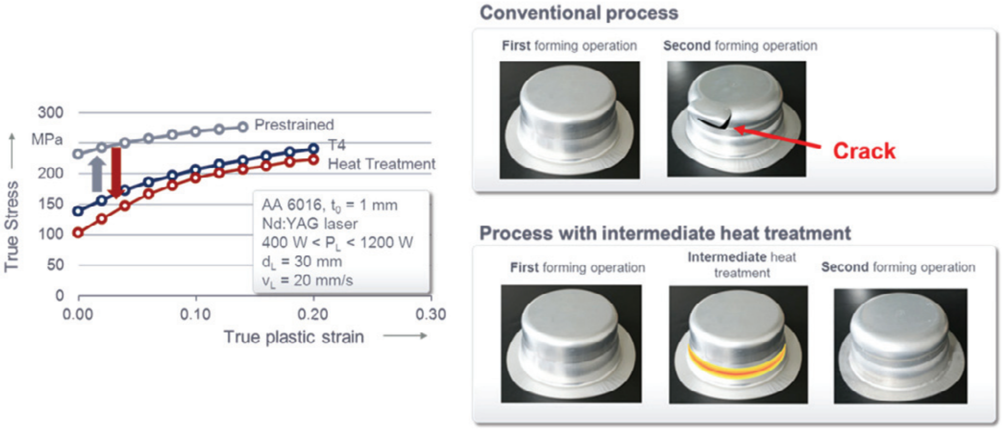

Fig. 2. Intermediate heat treatment – Material characterization and forming results

5. Tailored Heat Treated Profiles

The local laser heat treatment can be applied for profiles as well. Similar to aluminum sheet material also typical precipitation hardenable aluminum alloys used for profiles can be softened by a short term heat treatment. Tensile specimens were cut out of the profile and subsequently laser heat treated. It can be seen that there is a very strong softening effect. The yield strength decreases by 80% from 240 MPa to 48 MPa. The effect was used to enhance the formability of profiles. Similar to the THTB technology the crack critical areas should not be heat treated directly. Due to the lower yield strength the specimen would be more susceptible to failure. However, by softening upper parts of the profile the material flow during the bending operation can be improved. The procedure was validated with experimental results. Thereby a universal testing machine walter + bai FS-300 was used to perform a conventional three point bending test.

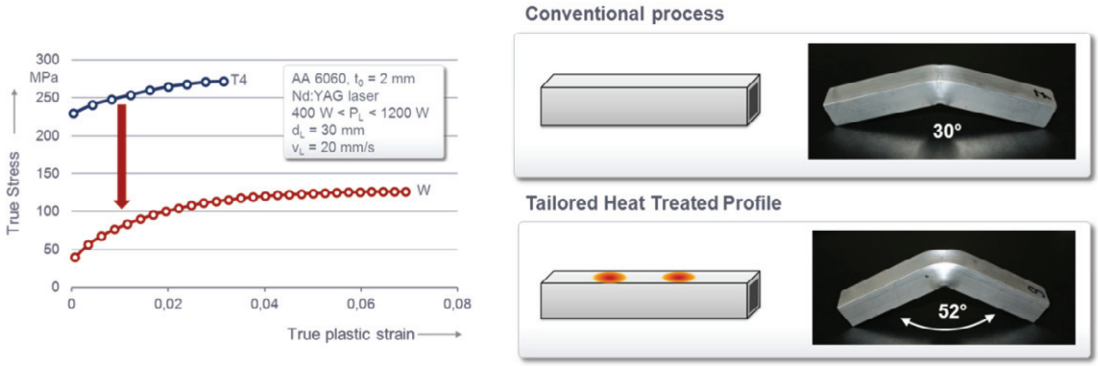

Fig. 3. Tailored Heat Treated Profiles – Material characterization and forming results

The profiles were filled with sand to avoid cross section deformation and were bend until a crack on the upper side occurred. Without heat treatment a maximum bending angle of 30° is possible. However, by tailoring the mechanical properties with a local laser heat treatment before the forming operation the bending angle can be increased by 73% to 52° until crack occurs.

6. Local heat treatment of high strength aluminum produced by Accumulative Roll Bonding

6.1. Accumulative Roll Bonding

The Accumulative Roll Bonding (ARB) process enables the production of high strength aluminum sheet metal with nanocrystalline grain structure [7]. It belongs to the group of severe plastic deformation (SPD) processes. It can be applied to many different materials, whereas hardenable aluminum AA6016 is considered in this work. The ARB process consists of three main process steps: at first, surface treatment is carried out by wire-brushing at which the oxide layer is removed and the surfaces of the sheets are roughened. In the next step, two sheets are stacked in a sandwich manner. Finally, the sheets are joined in a rolling operation with 50 % thickness reduction. These process steps can be repeated several times until the desired number of layers and mechanical properties, respectively, are obtained.

The induced high shear strains lead to transformation of the coarse grains of the initial state to an ultrafine-grained microstructure. The change of the grain size leads to completely different material properties. Considering the tensile strength, sheets from AA1050 with 256 layers after eight rolling cycles show about 70% higher values in comparison to the initial state [8]. Regarding technical alloys such as AA6016 the ductility decreases drastically compared to the as-received condition. As a consequence, the formability has to be enhanced for the production of components out of nanocrystalline high-strength sheet metal. In this context, the THTB technology is a possibility to increase the ductility of the nanocrystalline aluminum using the same infrastructure and process parameters than for the heat treatment of single layer AA6016 [9]. In addition to the dissolution of the precipitates, the local recrystallization of the ultrafine grain structure is another relevant effect concerning ARB processed sheets [10]. The combination of the ARB process and the THTB technology permits the realization of multilayered aluminum blanks with functional gradients over the plane and in thickness direction regarding the mechanical properties. As a consequence, the production of formed lightweight components with the outstanding material properties of the nanocrystalline aluminum in the load-bearing areas of parts for the body in white can be enabled. In this work, the air bending test is used for studying the effect of the ARB process and a subsequent local short term heat treatment by laser radiation.

6.2. Experimental procedure: Accumulative Roll Bonding, local heat treatment and bending tests

The nanocrystalline sheet metal was produced using the laboratory rolling mill of the Institute of General Materials Properties as described in [10]. The experiments were carried out with AA6016 in the naturally aged state T4 with an initial thickness of 1.0 mm. Prior to the ARB process, the sheets were solutionized in a furnace at 540 °C for one hour and water quenched. The surface treatment of the sheets was done using a manually operated wire-brushing machine with a stainless steel wire wheel. The rolling process was carried out at 230 °C and with a thickness reduction of the sheets of 50%. It was repeated four and eight times in order to get so-called N4 sheets with 16 single layers and N8 sheets with 256 layers. As a reference N0 sheets in the as-received state T4 were used. Additionally, heat treated and non-heat treated specimens of the N0, N4 and N8 state were considered. For the air bending tests specimens with a size of 56 x 20 mm and an orientation with rolling direction parallel to the bending edge were cut from the rolled sheets with a thickness of 1.0 mm (see Fig. 4a).

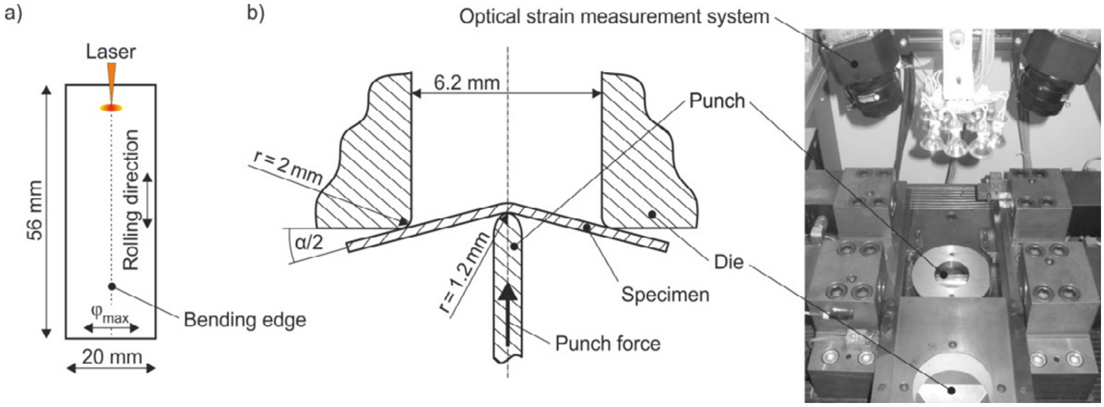

Fig. 4. (a) scheme of bending specimen; (b) bending test setup

The local heat treatment is done using the Nd:YAG laser described above. During the heat treatment process the surface temperature of the graphite coated specimens was measured with a pyrometer at the bottom side. The heat treatment along the bending edge was performed using a spot size of 5 mm, an output power of 850 W and a feed rate of 0.2 m/s. The temperature determined at the bottom side was within a range of 318 to 356 °C. In all cases, the maximum holding time was less than 5 s referring to the temperature of 200 °C below which no significant changes occur concerning the mechanical properties [9]. In order to eliminate the influence of the beginning precipitation process, all heat treated specimens were tested within a time period of one hour after the heat treatment.

The air bending tests were carried out according to DIN EN ISO 7438 and the experimental setup shown in Fig. 4b was used. The applied die had a clearance of 6.2 mm and radii of 2 mm. The specimens were oriented in such a way that the maximum tensile stresses during bending occurred at the side of the specimens, which was faced to the laser beam and the compression zone was faced to the punch. The punch with a radius of 1.2 mm was moved with a velocity of 1.2 mm/s up to a maximum bending angle α of 80°. When cracking appeared, the tests were stopped at 90% of the maximum punch force. For the determination of the occurring strains the optical strain measurement system ARAMIS with two CCD cameras was used. A stochastic pattern was applied to the specimens along the bending edge. The tests were carried out at room temperature and every test was performed three times.

6.3. Results of the bending tests

The punch force vs. bending angle curves from the air bending tests of heat treated and non-heat treated specimens of AA6016 in the as-received state and after four and eight rolling cycles are shown in Fig. 5. In the as-received state with and without heat treatment bending angles of 80° could be reached without cracking. According to the principle of the THTB technology, the short term laser heat treatment of the bending edge of the as-received AA6016-T4 leads to significant reduction of the punch force of about 40% due to the dissolution of the hardening precipitates. Compared to the initial condition, the non-heat treated aluminum with 16 and 256 layers, respectively, shows significantly higher punch forces due to the strengthening effect of the nanocrystalline grain structure. However, these materials showed limited bendability that can be seen from the reduced maximum bending angles of about 50° when cracking appeared. In this context, the local heat treatment of the ultrafine grained AA6016 is able to decrease the forming forces by about 50% and to enhance the bendability that can be seen from the increased maximum bending angle of 80°.

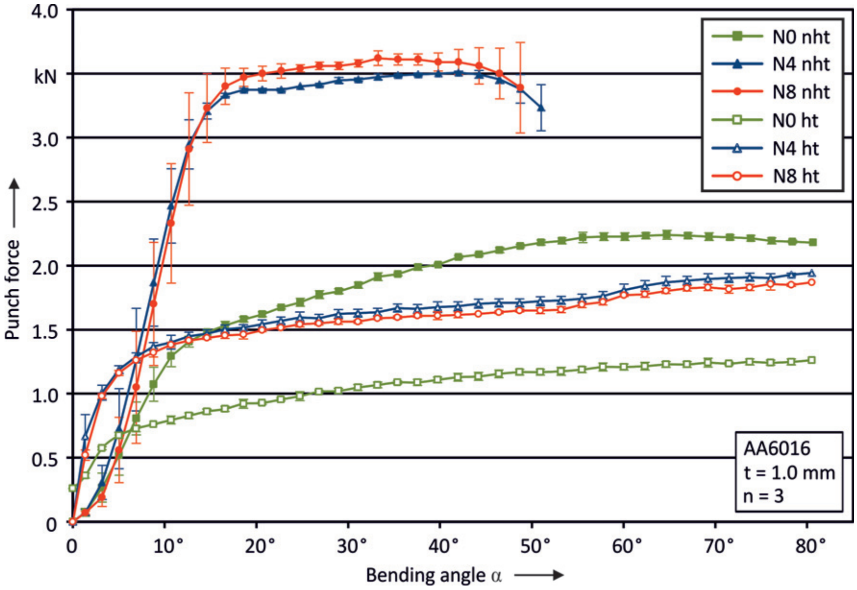

Fig. 5. Punch force vs. bending angle for non-heat treated (nht) and heat treated (ht) AA6016 with different number of layers

In Fig. 6 the major strain distributions at the maximum punch force detected by the optical strain measurement system are shown for heat treated and non-heat treated AA6016 with different numbers of rolling cycles. In the N0 condition the heat treated specimen shows only slightly higher strain values compared to the non-heat treated state. In contrast, significantly higher strains occured for the heat treated N4 and N8 specimens compared to the non-heat treated state. The local short term heat treatment leads to higher ductility of the multilayered aluminum, whereas the specimens without heat treatment crack at lower bending angles. Additionally, the ultrafine grained aluminum without heat treatment shows strain localization at the bending edge in comparison to the as-received sheet metal.

The investigation of the effect of the local laser heat treatment on the microstructure of nanocrystalline AA6016 and the characterization of the heat affected zone was done in [10] and is not considered in this work.

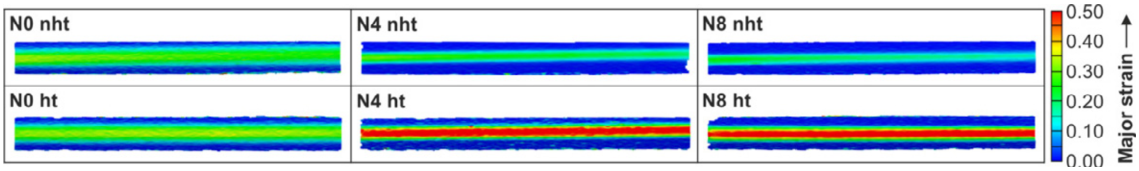

Fig. 6. Distribution of the major strain along the bending edge of N0, N4 and N8 specimens with and without heat treatment (ht/nht) at maximum punch force

7. Conclusion

The Tailored Heat Treated Blanks technology enables the enhancement of the forming limits of aluminum by the application of a short term heat treatment done by laser. This was proven by the realization of aluminum blanks and profiles with a tailored property distribution. Furthermore, a local laser heat treatment was successfully applied between two forming operations. In addition, the THTB technology works with nanocrystalline aluminum sheet metal produced by the Accumulative Roll Bonding process. In this context, the local heat treatment led to a significantly enhanced bendability.

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