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Physics Procedia 56 (2014) 1400 – 1409

Physics Procedia

8th International Conference on Photonic Technologies LANE 2014

Influence of pre-straining and heat treatment on the yield surface of precipitation hardenable aluminum alloys

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Abstract

Precipitation hardenable aluminum alloys are some of the most important lightweight materials. However, their range of applications in comparison to conventional deep drawing steels is limited by the low formability. Therefore, a new and innovative approach to enhance the formability of aluminum alloys in multistage forming operations was invented at the Institute of Manufacturing Technology, called intermediate heat treatment (IHT). Based on a short-term, laser-assisted heat treatment between two forming steps, it is possible to locally adapt the mechanical properties and realize an optimized strength distribution. For the successful application of the technology, the influence of the heat treatment on the mechanical properties has to be analyzed. Concerning the simulation of a multistage forming process, in particular, the yield surface of the material is very important. Within this paper, the influence of a combined pre-straining and a subsequent short-term, laser-assisted heat treatment on the yield surface will be presented.

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH

Keywords: intermediate heat treatment; aluminum; yield surface

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1. Introduction

Due to their relative high strength, good weldability and corrosion resistance precipitation hardenable aluminum alloys of the 6000 series are the most important lightweight material and are used in many industrial products, especially in the automotive and aerospace sector [1]. However, the processability of aluminum alloys is limited by the low formability in comparison to conventional deep drawing steel. In [2] the authors presented a new and

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Peer-review under responsibility of the Bayerisches Laserzentrum GmbH
doi:10.1016/j.phpro.2014.08.070

innovative approach to enhance the formability of aluminum called intermediate heat treatment. Key idea of the new technology is the use of a local short term intermediate heat treatment between two forming operations for tailoring the material properties and improving the material flow [3].

2. State of the art

Within the production process, precipitation hardenable aluminum alloys are just solution heat treated (500°C to 550°, 60 min) and subsequently quenched to room temperature. Afterwards a precipitation hardening process starts due to the high weight percentage of the main alloying elements magnesium (Mg) and silicon (Si). The resulting MgSi-clusters lead to a deformation of the lattice and hinder dislocations in their movement [4]. Consequently, the strength of the material increases. Already in 1941 Haase found out that a short term heat treatment can be used to soften precipitation hardenable aluminum alloys again [5]. Thereby the strength increasing MgSi-clusters are dissolved. It took, however, more than 40 years until in 1998 Vollertsen und Lange used the effect for tailoring material properties and thereby improving forming processes [6]. Key idea of the approach is a local adaption of the mechanical properties of aluminum blanks by a local laser heat treatment. Caused by the new strength distribution, the material flow during the forming operation can be improved. The technology was subject of several scientific investigations and is today known under the generic term "Tailor Heat Treated Blanks" [7]. Main advantage in comparison to conventional temperature assisted processes is that the heat treatment is performed before the forming process itself. Consequently, standard cold forming tools can be used, which is in particular important for the implementation into series productions [8]. In the last 5 years several publications proved that the involved mechanism of the approach can be transferred to other applications. It is for example not only possible to heat treat conventional blanks, but also high strength aluminum alloys produced by the so called accumulative roll bonding process [9]. Furthermore, Nguyen et al. [10] indicated that precipitation hardenable aluminum alloys can not only be softened, but also hardened by using artificial ageing effects. Thereby longer holding times and lower temperatures are necessary. Finally, the technology is not only suitable for deep drawing operations but also for bending or hammering applications [11]. Whereas all investigations so far used the heat treatment before the forming process, the authors proved that the effects can also be applied between two forming operations. In comparison to the well-known recrystallization annealing, for this approach only a local and very short (≤ 2 sec.) heat treatment is necessary and therefore the procedure is very resource and time efficient. It turned out that the main challenge for the successful application of the technology is the design of the heat treatment layout, because not every heat treatment leads to an enhancement of the formability. In order to develop transferable design guidelines and perform a numerical simulation of the process, the influence of the short heat treatment on the mechanical properties has to be identified.

3. Experimental set up

3.1. Material characterization

For the scientific investigation, the aluminum alloy AA6016 with a sheet thickness of t_0 = 1 mm in the natural aged condition T4 was used. The tensile tests were performed according to DIN 6892-1. In order to evaluate the yield surface, in addition biaxial tension tests were performed (fig.1). However, the biaxial tension test is not standardized yet.

Fig. 1. Biaxial tension test according to Merklein and Biasutti [12].

In the past, several scientific groups presented different testing devices and specimens geometries. Within this research project, the experimental set up of Merklein and Biasutti (fig. 1) [12], developed at the Institute of Manufacturing Technology, was used. Both the uniaxial and the biaxial testing machine were used for the pre-straining and the material characterization. The homogeneousness of the pre-straining was analyzed with the optical strain measurement system Aramis, Gom company (Braunschweig).

3.2. Heat treatment

In principle, different technologies, based on heat induction, heat conduction and laser radiation can be used for the heat treatment. Whereas the conductive heat technologies are more suitable for mass production, within scientific investigations and prototype series the flexible robot controlled laser is an appropriate tool. In particular, different heat treatment layouts can be tested easily. For the laser active medium a Nd:YAG crystal was chosen because the wavelength of λ=1064 ensures are good absorption of the laser energy by the aluminum alloy [13]. The laser has a Gaußian profile, a maximum power of P_L = 4 kW and the beam guidance is realized by optical fibers. For the measurement of the temperature thermocouples and non-contact measuring systems like a pyrometer and a thermographic camera are used. The emission coefficient for uncoated aluminum was determined with a reconciliation method to e = 0.23, for graphite coated material to e = 0.95. All measurements were carried out at the side of the blank opposite to the laser beam to avoid the influence of interfering radiation. The laser is also illustrated in fig 2.

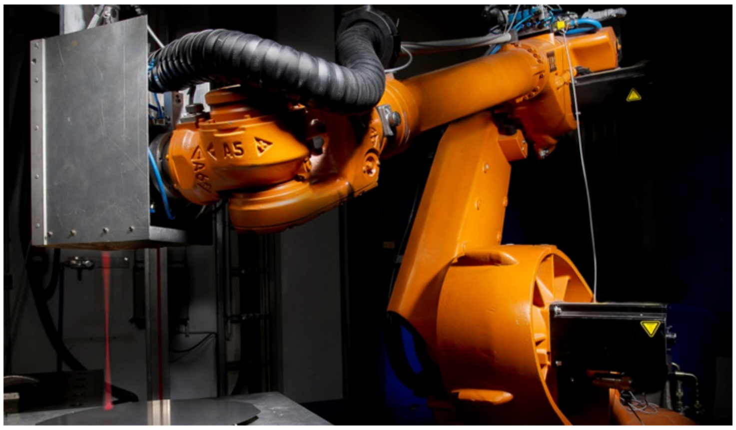

Fig. 2. Robot controlled laser system with acitve pilot laser.

4. Results

4.1. Material modelling and time-temperature-profile

Important for the numerical design of a multistage forming process is the yield surface of the material. It describes when yielding of the material starts in dependency of the principal stresses σ_1 and σ_2. In the past, several mathematical approaches were developed in order to predict the mechanical properties [14]. For aluminum alloys, in particular, the scientific approaches of Barlat [15] and Banabic [16] show good confirmation between approximation and experimental results. For the determination of the yield surface seven parameters are necessary, the yield strength and Lankford coefficient of uniaxial tension in 0°, 45° and 90° to the rolling direction and the yield strength for biaxial tension. All seven parameters were determined in dependency of pre-straining and different heat treatments. For the identification, a Lebenberg-Marquart algorithm in the software Matlab was used.

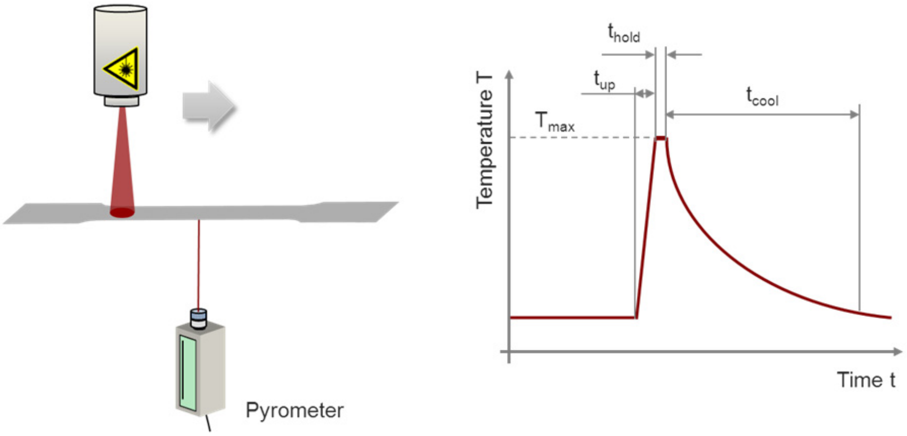

Fig 3.: Principle of the heat treatment

The procedure of the heat treatment together with a schematic time-temperature-profile is presented in Fig. 3. It can be characterized by a heating time t_{up}, a holding time t_{hold}, a cooling time t_{cool} and the maximum temperature T_{Max}. Former investigations proved that the main influencing parameter on the mechanical properties is the maximum temperature. However, keeping in mind the necessary localization of the heat treatment the heating and holding time should be very short. Moreover, no active cooling should be used. These criteria lead to time-temperature profiles characterized by a heating time of 1.5 s and a holding time of 0.3 s. The self-quenching effect leads depending on the maximum temperature to cooling times between 30 to 120 s.

4.2. Influence of short-term heat treatment without pre-straining

At first, the influence of the heat treatment without pre-straining will be presented. The result of the yield strength and the r-value in uniaxial tension depending on the maximum temperature can be seen in fig. 4 and fig. 5. The diagram shows that the softening of the material starts at a temperature of about 200°C. Between 200°C and 350°C there is strong reduction of the mechanical properties from 126 MPa to 75 Mpa. This effect can be explained by the dissolution of MgSi-Clusters. For higher temperatures above 350°C no further softening of the material can be identified. The results indicate that there is no significant influence of the rolling direction on the softening of the material. Evaluating the r-value, which is a criterion for the anisotropy of the material, it can be seen that there is no influence of the heat treatment. The anisotropy is mainly a result of the crystallographic orientation and the rolling process. However, both are not influenced by the heat treatment und therefore no significant repercussions on the anisotropy can be identified. The r-values are in principal low, but usual for aluminum alloys of the 6000 Series.

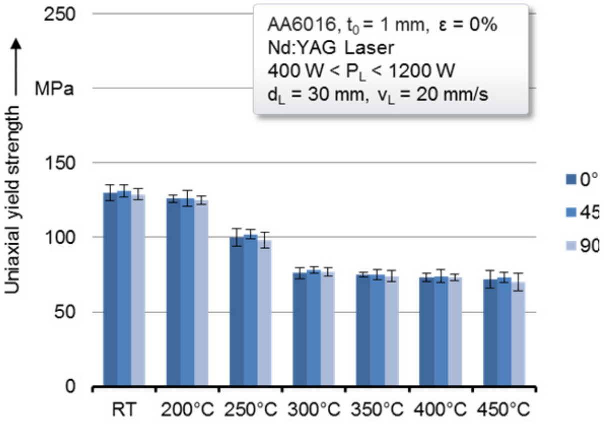

Fig. 4. Influence of the heat treatment on the uniaxial yield strength without pre-straining.

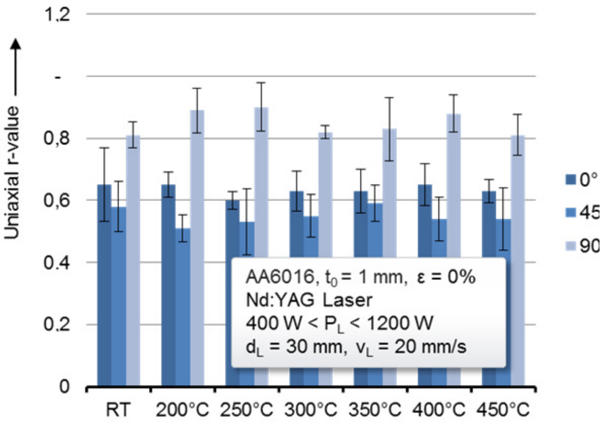

Fig. 5. Influence of the heat treatment on the uniaxial r-value without pre-straining.

In fig. 6 the influence of the maximum temperature on the biaxial yield strength is presented. Similar to the uniaxial yield strength, also the reduction of the biaxial yield strength starts at a temperature of about 200°C and the maximum softening is reached at temperature of 350°C. Higher maximum temperatures do not lead to a further softening of the material.

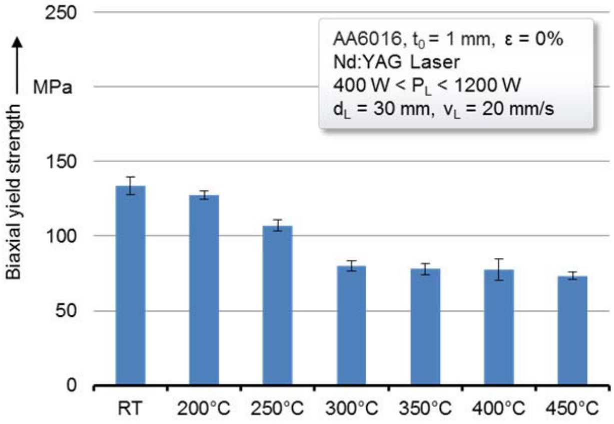

Fig. 6. Influence of the heat treatment on the biaxial yield strength without pre-straining.

Fig. 7 shows the yield surface according to the mathematical model of Banabic based on the experimental material characterization. There is a very good confirmation between the approximation by the model and der experimental data. The results indicate that the size of the yield surface reduces, however the shape hardly changes. The phenomena can be explained by two effects. On the one hand the heat treatment has no influence on the r-values of the material. On the other hand it can be discovered that the ratio of uniaxial and biaxial tension is nearly the same for all heat treatment processes (table 1). This implies that the softening is independent form the stress condition. Keeping also in mind that the heat treatment has no influence on the anisotropy, the effort for the material characterization can be reduced by 67% from 175 tests to 55 by using a scaling model. Consequently, it is sufficient to do a complete evaluation of the material at room temperature and a characterization under uniaxial tension in rolling direction for elevated temperatures. In addition, the presented modeling shows that the size of the yield surface reduces due to the heat treatment, however, the shape is nearly the same. For forming operations, in principal, an elongated elliptical yield surface is favorable, like it is known from deep drawing steels. Such a shape is a criterion for a good formability. The results indicate that the material only gets softer by the heat treatment and there is no direct enhancement of the formability. At a first glance, this seems to be opposed to the goal of the research project, because actually the formability should be enhanced. The solution of the supposed contradiction is that the enhancement of the forming limit can be realized by interaction of soft and hard areas. Therefore, it is not a direct but an indirect approach.

Table 1. Ratio of biaxial and uniaxial yield strength without pre-straining.

Temperature	**RT**	**200°C**	**250°C**	**300°C**	**350°C**	**400°C**	**450°C**
σ_b / σ_0	1.03	1.01	1.07	1.05	1.04	1.06	1.02

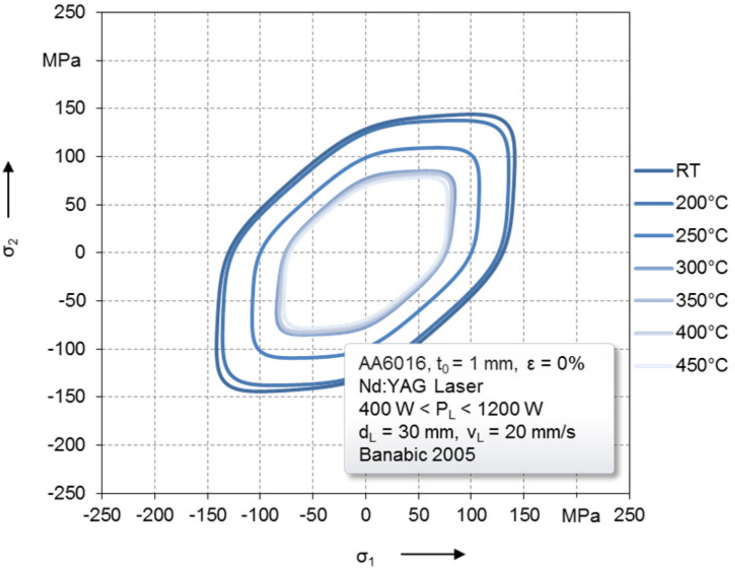

Fig. 7. Influence of the heat treatment on the yield surface without pre-straining.

4.3. Influence of short-term heat treatment after pre-straining

In order to “simulate” a multistage forming process, in addition the influence of the heat treatment after a pre-straining was investigated. The pre-straining itself leads to an increase of the yield strength under uniaxial tension by 53% to 205 MPa due to hardening effects (fig. 8). For temperatures of 200°C again nearly no influence of the heat treatment can be recognized. For temperatures above 200°C a significant softening of the material starts. However, compared to the above presented results the reduction of the yield strength does not stop at a temperature of 350°C. The highest softening can be identified for a maximum temperature of 450°C. There the yield strength with and without pre-straining are nearly at the same level. Consequently, the experimental characterization proved that in addition to the above mentioned dissolution of MgSi-Clusters further softening effects like annealing and recrystallization are present. Comparing the r-values of the different maximum temperatures, no significant influence of the heat treatment can be identified (fig. 9).

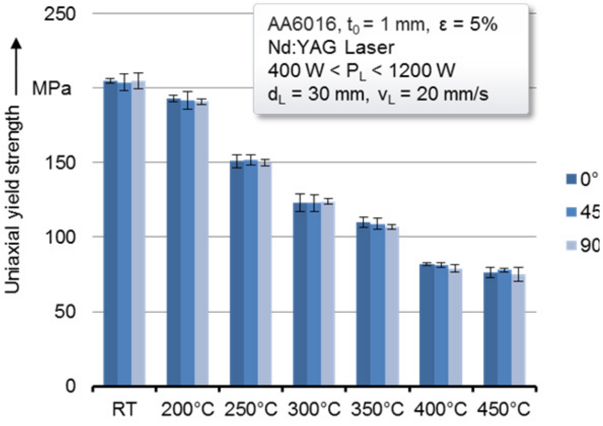

Fig. 8. Influence of the heat treatment on the uniaxial yield strength after pre-straining.

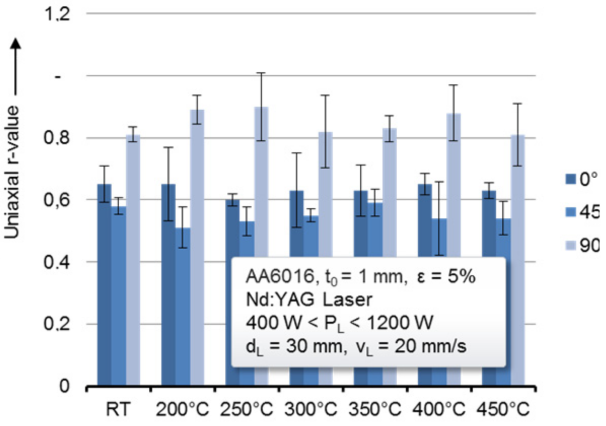

Fig. 9. Influence of the heat treatment on the uniaxial r-value after pre-straining.

In addition also a pre-straining on the biaxial yield strength was investigated (fig. 10). Without heat treatment the hardening effects lead to an increase of the yield strength from 133 MPa to 243 MPa. Already at a maximum temperature of 200°C a significant influence of the heat treatment on the mechanical properties can be identified. Similar to the yield strength under uniaxial tension the maximum softening is reached at a temperature of 450°C.

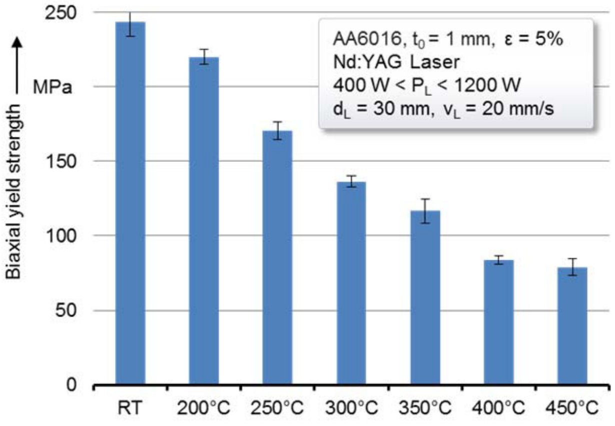

Fig. 10. Influence of the heat treatment on the biaxial yield strength after pre-straining.

Comparing the ratio of the biaxial and the uniaxial yield strength for different heat treatment temperatures, it can be seen that pre-straining leads to a stronger increase of the biaxial than the uniaxial yield strength (table 2). However, for maximum temperatures above 350°C the results with and without pre-straining are similar. That again confirms the consideration of further softening effects.

Table 2. Ratio of biaxial and uniaxial yield strength.

Temperature	**RT°C**	**200°C**	**250°C**	**300°C**	**350°C**	**400°C**	**450°C**
σ_b / σ_0	1.19	1.14	1.13	1.11	1.06	1.02	1.04

Based on the variations of the biaxial to uniaxial ratio also the shape of the yield surface changes (fig. 13). It looks more elongated because the increase under biaxial tension is higher than under uniaxial tension. However, by evaluating the influence of the heat treatment, it can be seen, that in particular with maximum temperatures above 350°C the “original” shape returns. In contrast to the results without pre-straining, the change of the shape does not allow the application of a scaling model for the approximation of the yield surface by a reduced material characterization. Again there is a very good confirmation between the approximation by the model of Banabic and der experimental results.

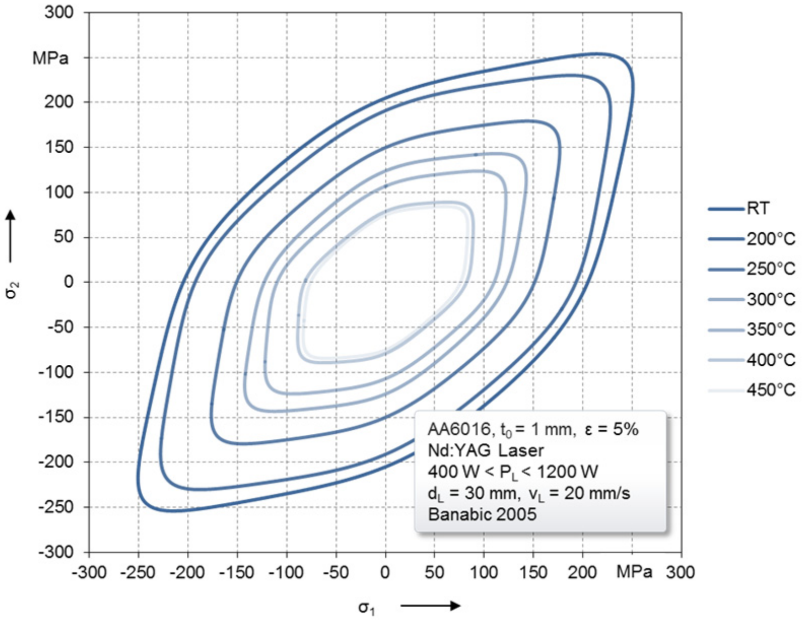

Fig. 11. Influence of the heat treatment on the yield surface after pre-straining.

4.4. Validation of the material model

The presented results were finally used for the design of heat treatment layouts for a multistage forming process. The process consists of a first forming operation where a deep drawing cup is produced. Subsequently, a hydroforming process is used to realize side elements. Without heat treatment, it is not possible to form the side elements without failure (fig. 14). However, by using a short term intermediate heat treatment (400°C), the area beneath the crack can be softened. Due to the lower yield surface the material flow to the crack critical area can be improved. The comparison between simulation and experimental result shows good conformity.

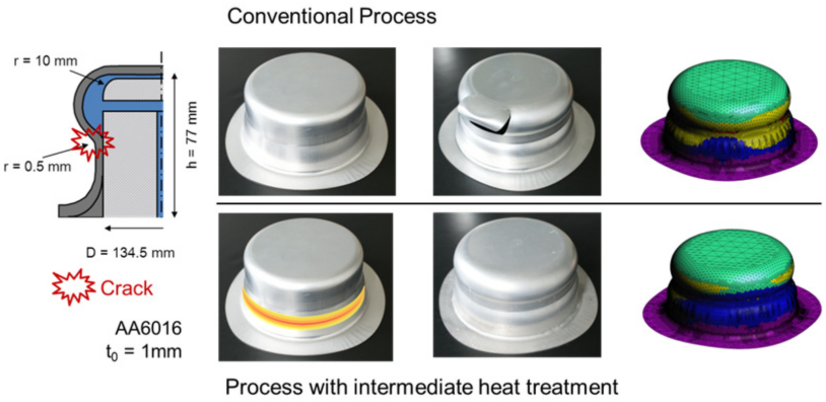

Fig. 12. Numerical desin of the short-term intermediate heat treatment to imporve the formability within multistage forming operations [2].

5. Summary and Outlook

An auspicious possibility to realize lightweight constructions is the substitution of conventional material, e.g. steel, by a lighter material, e.g. aluminum. However, the formability of aluminum is limited and therefore the application is often challenging. The short-term intermediate laser heat treatment (IHT) has a great potential to improve the formability of precipitation hardenable aluminum alloys in multistage forming processes. Idea of the technology is the tailoring of the mechanical properties by laser heat treatment. It is thereby very resource and time efficient. For the design of the appropriate heat treatment the influence of a short-term heat treatment after pre-straining on the mechanical properties were investigated. The experimental results proved that a softening of the material after pre-straining is possible. Moreover, the influence of pre-straining and short-term heat treatment on the yield surface were presented. Within further scientific investigations the influence of pre-straining and heat treatment will be determined for additional aluminum alloys of the 6000 and 7000 series.

Acknowledgements

The authors gratefully acknowledge funding of the Erlangen Graduate School in Advanced Optical Technologies (SAOT) by the German Research Foundation (DFG) in the framework of the German excellence initiative. Moreover, the authors are grateful to the German Research Foundation (DFG) for supporting the investigations in the research project Enhancement of formability of aluminum alloys in multi-stage forming operations by a local intermediate heat treatment (Me 2043/25-1).

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