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Inverse Approach to the Forming Simulation of Tailored Heat Treated Blanks

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ABSTRACT: While climate protection and environmental conservation gain an increasingly significant role, the weight reduction of car body parts is a consequence of the need for efficient fuel consumption and for reduced CO_2-emissions. Therefore advanced material and production methods have to be developed to meet this requirement. Since steel sheet metal parts cannot be substituted directly with lightweight aluminium parts, due to its minor formability, so called Tailored Heat Treated Blanks (THTB) are presented in this work. THTB are locally heat treated aluminium blanks from the 6000-series alloy, leading to a significantly improved formability for the manufacturing of complex aluminium car body parts. The enhancement of formability is reached by a local laser heat treatment before the forming operation. Since there is a strong influence of the heating on the forming process, a finite-element simulation of the process sequence is a prerequisite for the cost-effective usage of the THTB. The presented inverse approach considers first the desired forming result and enables the precise determination of heat treatment areas including the specific heat treatment temperatures. In conclusion the numerical solved appropriate strength pattern is verified with experimental test results of THTB.

Key words: finite element simulation, parameter identification, aluminium

1 INTRODUCTION

Compared with the conventional manufacturing of aluminum sheet metal, the forming of so called Tailored Heat Treated Blanks (THTB) enables the production of complex aluminum sheet metal parts [1], [2]. The reasons for the lower forming behavior of aluminum alloys are well founded in the material properties. Especially smaller values for uniform elongation (< 30 %) and vertical anisotropy (< 1) limit the attainable forming result.
Within the THTB process sequence a local heat treatment lowers the initial yield stress of the aluminum sheet and the altered material condition is preserved for about six hours. In this time-frame a cold forming operation has to be carried out. While using the precipitation hardenable aluminum alloys from the AA6xxx-series, the local heat treatment gives the possibility of a specific strength pattern adapted to the forming operation, thus reducing necessary process forces. Different heat sources can be used for the heat treatment, e.g. a Nd:YAG-Laser [3] or heat conduction [4].

2 INVERSE APPROACH

2.1 *Basic principle*

In the simplest case the heat treatment is applied in the later deformation area of the aluminum sheet and a loading decrement in the force transferring zone of the drawing part is obtained.
An enhancement considers also the later force transferring areas. But failure can occur in areas with lowered strength, because the stability under load can not sustain the respective process forces. An improvement to the process design of THTB is therefore the finite element (FE) simulation based identification of feasible heat treatment areas and respective heating process parameters. Because of the interdependence between heat treatment and

forming operation an inverse approach to the process design improves reliability and efficiency of the simulation of the process sequence. Within the inverse approach the process parameters and a prediction of the feasibility of a THTB forming process can be done in one step. In fig. 1 the basic principle of the inverse approach to the forming simulation of THTB presented in this work is illustrated.

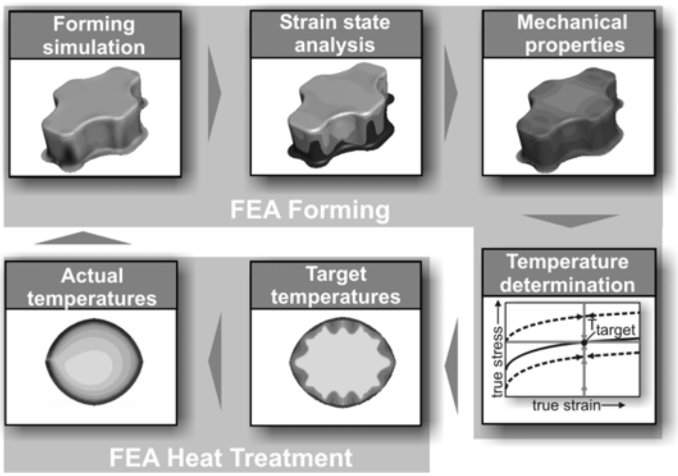

Fig. 1: Principle of the inverse approach to the process design of THTB - within the forming simulation the temperatures for the heat treatment are determined

In order to get the information how the mechanical properties have to be arranged for a drawable part, first the forming operation is considered. The information about a feasible strength pattern gives also the distribution of the maximum temperatures, which have to be applied by the heat treatment. It is important to emphasize, that the maximum temperatures are correlated to the final mechanical properties before the forming process. This has been already investigated in previous works [3].

After determining the maximum temperature distribution, the input parameters for the heat treatment are identified by simulation based optimization since the desired maximum temperature distribution is provided by the preceding FE analysis of the forming process. In turn, as a laser irradiates the material in the presented work, those input parameters are namely the feed rate and the laser power. In order to verify the inverse approach a forward simulation of the process sequence heat treatment and forming is conducted.

In the presented work the investigated material is the AA6016PX alloy in a thickness of 1 mm. The forming simulations were carried out using the ABAQUS/Explicit 6.6 solver, utilizing deformable S4R shell elements with 5 integration points. The heat transfer analysis uses the ABAQUS/Implicit 6.6 solver, while DS4 shell elements, capable to simulate heat transfer, heat capacity and thermal radiation, represent the blank in this process step.

2.2 *Specification of heat treatment areas*

In general a THTB can be subdivided into three sections as it is displayed in fig. 2-a in a FE forming analysis: the first section would be the non heat treated area, which should reflect the base material condition T4 of the used aluminum alloy. The second section is the so called W area, in which maximum temperatures fully soften the material. Between the T4 section and the W section there is the so called W-T4 transition zone. In this zone the mechanical properties have to be adapted in order to reflect the areas' force transferring capacities.

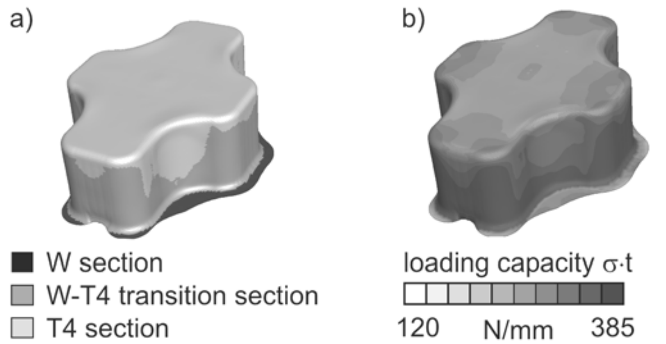

Fig. 2: Subdivision of heat treatment areas (a) and homogenous loading capacity for the cross part (b)

The areas T4, W and the W-T4 transition are identified due to the materials' strain state after the forming operation. Therefore it is necessary to conduct a first forming simulation in the T4 material state, neglecting an influence onto the material flow because of the heat treatment. Within the forming limit diagram the T4 section comprises the strain states between the tensile loading condition and the biaxial strain condition, because excessive thinning could occur as a consequence of the heat treatment. Therefore the material must preserve its initial condition in the T4 section. In any case the W section is the remaining flange which never transmits any process forces and it is dominated by a tensile and compressive loading condition in the deformation zone. The W-T4 transition section is the remainder between the W and T4 sections and it is thus characterized by a strain state below the tensile loading condition.

2.3 Adaptation of mechanical properties in W-T4

After determining the heat treatment areas, the so called homogenous loading capacity strategy is applied to specify the target mechanical properties of the W-T4 transition section as it displayed in fig. 2-b for the cross part. Basically there are two mechanisms in forming operations which influence the force transferring capability: Firstly during the forming process strength is regained due to work hardening and secondly the acting cross section determines the amount of transferable force. Therefore the homogenous loading capacity strategy takes into account the equivalent stress state and the thickness change of a deformed finite element with

$$\sigma_{\text{target}} \cdot t = (\sigma \cdot t)_{\max}^{T4} = const\ , \qquad (1)$$

where $(\sigma \cdot t)_{\max}^{T4}$ is the maximum of the product of the yield stress σ and its corresponding thickness t of all elements within the T4 section. The product between σ_{target} and the actual thickness t of a finite element in the W-T4 section is set to be constant to $(\sigma \cdot t)_{\max}^{T4}$. As a result fig. 2-b shows up an almost homogenous loading capacity distribution especially in the W-T4 transition zone. It is assumed that this homogeneous distribution leads to a strength pattern which guarantees a suitable force transferring capability within the force transferring areas during the forming process.

Taking from every finite element within the W-T4 section the current equivalent plastic strain $\varepsilon_{current}$ and the computed σ_{target} value according to (1), a bilinear interpolation between experimental derived true strain-stress curves gives the information about the necessary temperatures as it is shown in fig. 3.

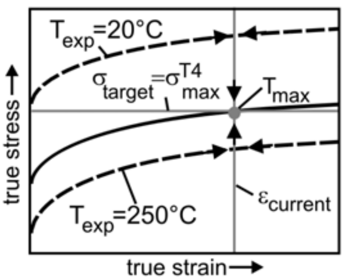

Fig. 3: Principle of temperature determination

The intercept point of σ_{target} and $\varepsilon_{current}$ gives with a bilinear interpolation a true stress-strain curve which belongs to a specific maximum temperature. In this way the heat treatment layout is derived as it is demonstrated for the cross die part in fig. 4 for the three sections T4, W-T4 and W. As it is shown within the W-T4 section, elements which are exposed to thicken, in conjunction with a localization of equivalent stress, are exhibited to higher heat treatment temperatures, whereas elements which tend to thinning, in conjunction with a lower stress state, are exhibited to lower heat treatment temperatures. In particular the outer corner radii show up the highest heat treatment temperatures within the W-T4 transition.

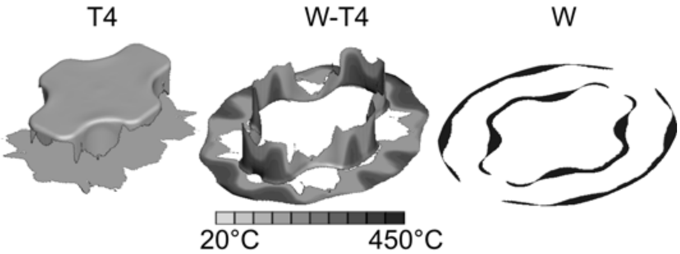

Fig. 4: Temperature distribution of the cross die part – displayed for the deformed and the initial blank (projection)

While the numerical investigation of the forming process constitutes the shown target temperatures in fig. 4, the laser heat treatment process parameters must meet the so called actual temperatures. This is achieved within the thermal finite element analysis of the laser heat treatment.

2.4 Optimization of heat treatment

For this purpose the global optimization algorithm simulated annealing for locating the global minimum of a given function is utilized within the ABAQUS/CAE environment [5]. This algorithm is provided by the scientific Python library SciPy [6]. With regard to the heat treatment process design the cost function E characterizes the overall temperature deviation between the target and actual temperatures T_i and θ_i summarizing its squared differences according to

$$E = \sum_i (T_i - \theta_i)^2\ . \qquad (2)$$

The actual temperatures θ_i are obtained by thermal finite element analyses of the irradiation process taking into account an input parameter set provided by the optimization algorithm. Since the laser irritation paths are spatially discrete modeled, the path definition itself must be provided by the user. The time dependent parameters of the laser heat source, the spot location and diameter, and the power density are linearly interpolated between the path nodes from discrete values by a Fortran user-subroutine during the thermal finite element simulation. Since the process parameter definition at the path nodes results in a large search space causing huge computational costs concerning the iterative

optimization algorithm, a function based distribution of the laser parameters to the path nodes is introduced. In such a manner the number of optimization parameters is reduced, although maintaining a high irradiation path complexity.
As a result the actual heat treatment temperatures provided by the optimization procedure are displayed in comparison to the calculated target temperatures in fig. 5. According to the proposed heat treatment layout nine laser paths were implemented and a good agreement between the target and actual temperatures was reached for a laser power of 4 kW.

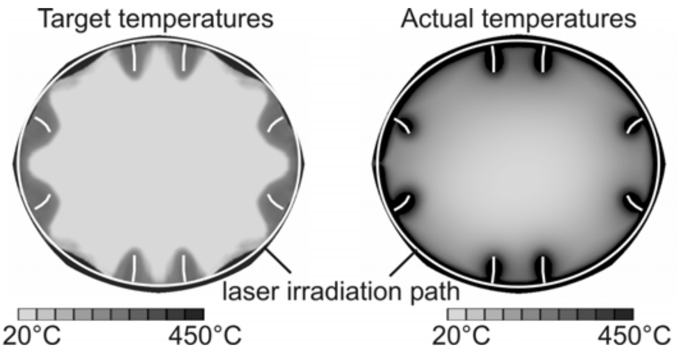

Fig. 5: Target and actual temperatures within the cross part

The solution of the function based distribution was achieved after about 500 optimization loops. The approximate minimum of the objective function (2) is obtained for v_0=25 mm/s and m_{lin}=0.35 as parameters for the distribution of the laser feed rate, i.e. the feed rate increases linearly from 25 mm/s at the start point of the laser path to 30 mm/s at the end. Within the border path a laser spot diameter of 20 mm was chosen, whereas the spot diameter of the inner paths was set up to 35 mm.

3 EXPERIMENTAL VALIDATION

In order to evaluate the proposed inverse approach an experimental testing of the drawing of THTB was conducted. A Nd:YAG-laser with a power of 4 kW was used for the heat treatment. It was guided by a industrial robot above the sheet. A pyrometer was guided by a second robot below the sheet to measure the current temperature. All process parameters were set up according to the proposed values derived from the inverse approach. The drawing results of the experiments are shown in fig. 6 for a sheet in the T4 condition and for a THTB. The formability enhancement is demonstrated with the increase of the drawing depth from 20 mm to 45 mm. Since the implementation and monitoring of the heat treatment process is difficult to handle, the proposed drawing depth of 70 mm could not be reached and will be the aim of future works.

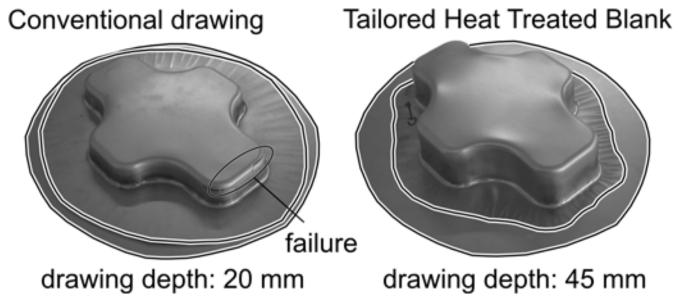

Fig. 6: Experimental validation of the inverse approach

4 CONCLUSIONS

In this work an inverse approach to the process design of THTB was used to determine a maximum temperature distribution which enhances the formability of precipitation hardenable aluminium alloys within the forming operation. Future improvements will have to deal with a better flexibility in the heat treatment process parameter determination.

ACKNOWLEDGEMENTS

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