Automatic optimization of localized heat treatment for Al-Si-Mg alloys

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Automatic optimization of localized heat treatment for Al-Si-Mg alloys

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Abstract. Material properties of aluminium alloys can usually be achieved by a heat treatment and quenching procedure. In case that only local strengthening is needed, a local heat treatment and quenching strategy could be an option to the energy intensive, time consuming and costly treatment of the whole part. One of the essential problem using a local strengthening procedure is the lack of knowledge about suitable process parameters. Therefore, a multiple criteria optimization approach with local strengthening as target function was set up, whereby the material constitution was calculated based on the precipitation evolution during local heat treatment and cooling. By automatically varying the exposure time and laser power, a series of process simulations was performed to find adequate process parameters for the sufficient local strengthening of the alloy.

1. Introduction

Aluminum alloy castings are often heat treated in order to improve its mechanical properties. The heat treatment is done in two steps. First, a supersaturated solid solution is obtained by heating up the casting to a certain temperature. This state is conserved by rapid quenching back to room temperature. While the supersaturated solid solution is heated up again, but now slightly (if ever), different precipitations can occur which hardens the material. In case of the AlSi7Mg0.5 alloy, which is focused on in the present work, the following precipitation sequence appears from the quenched-in supersaturated solid solution during heating: clusters with varying Mg and Si content, Guinier-Preston Zones (GP-Zones), beta'- and U1/U2-phases and the B-phase [1-3].

If only local strengthening is needed, time and energy could be saved by performing a local heat treatment. This might be quite efficient, if only one heating cycle combined with self-quenching is sufficient. Such a heat treatment is conceivable with different heat sources of which the laser is the most elegant, flexible and precise. However, when defined material improvements are desired, the power input, the beam diameter, the duration of heating and the necessary quenching strength are a priori unknown parameters.

In this paper, an automatic optimization procedure is suggested that focus on short time local laser heating with quenching of an as-cast AlSi7Mg0.5 alloy in order to improve the strength of the material so that it can resist a prescribed loading.

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2. Numerical Approach

2.1 Case of loading

The starting point of this work is a simple rhombus-like plate casting with a centred hole. In case of loading the plate casting stresses occur in the material. Exemplary a traction around the centred hole with a load of 360 kg (area 300 mm²) is applied in this work. The task of the optimization procedure is that the material property, namely the yield strength, should locally be improved by a laser heat treatment with subsequent quenching so that plastic deformation of the material can be avoided. If ideal elasto-plastic behaviour is assumed the condition of no plastic deformation can be written as

$$\Delta = R_{p0.2}(\vec{r}) - \sigma^{eq}(\vec{r}) \cdot S \geq 0\,, \tag{1}$$

where S represents a security factor, $R_{p0.2}$ the local yield strength and σ^{eq} the van Mises equivalent stress. For all positions, $\vec{r}$, in the whole casting, the condition equation (1) has to be fulfilled, especially in the vicinity of the loaded area at the centre hole. Using the rotational-symmetry condition for the considered case of loading, it is possible to consider only a segment of the plate casting for the stress analysis (and the heat treatment described later). The length of the segment was chosen in a way that the heat treatment does not affect the outer plate casting regions and therefore only local strengthening around the center hole is obtained. In Figure 1 the considered segment together with the assumed boundary conditions for the stress analysis is shown. The stress calculation is done using OpenFOAM [4], solving for the divergence of the Cauchy stress tensor to be zero [5]. The position dependent Young's modulus and yield strength were computed by a MatCalc simulation as explained below.

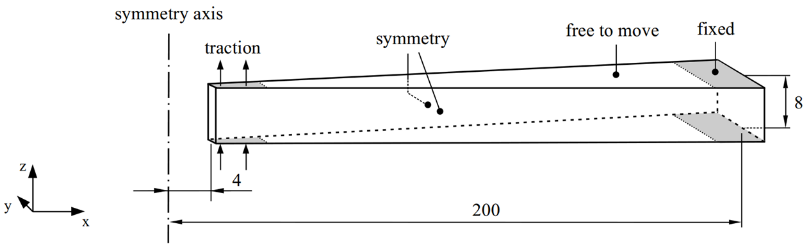

Figure 1. Wedge-shaped segment considered in the stress analysis. For the center hole a radius of 4 mm, for the segment a length of 200 mm and for the casting thickness 8 mm were chosen. The grey fixed area on the right side where no motion is allowed is 0.01285 m².

2.2 Heat treatment

A Gaussian-shaped heat input of total power, P , was considered perpendicular to the plate casting for a certain time, t . Both, P and t are parameters which subject to variations during the optimization procedure. P is varied between 500 and 8000 W and t between 1 and 105 s. The beam diameter, also known as variance of the Gaussian shape, was taken constant with a value of 0.03 m. As initial condition, we started with the material at room temperature, used symmetry conditions at the wedge side faces and a heat transfer coefficient, h, with an ambient temperature, T_{amb} at top, bottom, left and right surface were used [6]. During the heating period the value of the heat transfer coefficient h was taken as 50 W/m²/K with T_{amb} = 293 K. For the quenching period h was chosen to be 15000 W/m²/K with T_{amb} = 283 K. In addition the quenching period was fixed to 20 s for each simulation. A schematic draft of the heat source that is acting on the area around the center hole of the plate casting is shown in Fig. 2. For the time depending temperature evolution, the heat conductivity equation is solved with OpenFOAM [4]. The material parameters and values for the considered AlSi7Mg0.5 alloy [7] are the heat

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conductivity, λ = 156 W/m/K, the heat capacity, c_p = 778 J/kg/K and the density ρ = 2560 kg/m³. For each of the six marked positions, which are called testing probes, the temperature history curve was further used for the phase constitutive simulation.

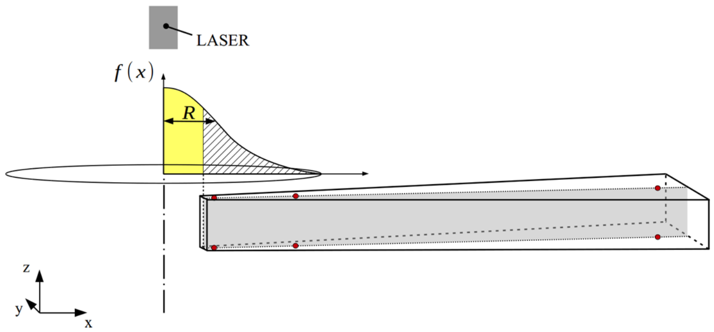


Figure 2. Schematic draft of the heat source. The non-hatched area below the Gauss-function defines the amount of lost energy through the centre hole. R denotes half of the beam diameter.

Note that the Gaussian-shaped laser beam radiates most of its energy into the centre of the hole. That can be avoided using a ring-shaped laser. Indeed, in the present work the exact shape of the laser beam is not of significant importance as the focus of the work lies on the strategy for the automated optimization rather than on specific process details.

In case of high laser power and long exposure time melting of the material can occur. This has to be avoided. If a combination of parameters leads to melting, the optimization routine will exclude the corresponding parameter set from the trials. A smarter way to prevent melting is to introduce two specific temperatures where the laser is powered off (T_{off}) or on (T_{on}). Fig. 3 shows a result of such an alternating off/on strategy. In the present numerical heat treatment this procedure is easy to implement, whereas in practice, an empirical shutter or guided power-down technique would be applied to the laser control unit.

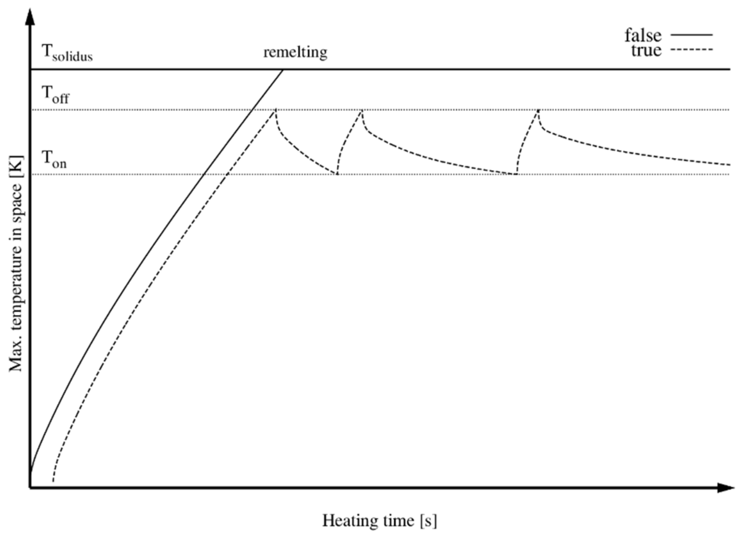


Figure 3. Possible temperature evolution at a surface position of the heated parted. To avoid melting an alternating off/on strategy for the laser beam was tested.

2.3 Material constitution simulation

During the heat treatment and quenching procedure the evolution of the material constitution of the AlSi7Mg0.5 alloy was calculated at the six testing probes shown in Fig. 2 by using the commercial software MatCalc [8]. Based on a thermodynamic database and corresponding precipitation calculations, MatCalc also provide data on the yield strength and Young's modulus. However, for the heat treatment and quenching simulation the constitution of the as-cast material has to be known as initial state. Therefore, we have performed a multicomponent Scheil solidification simulation [9] whereby MatCalc calculated the evolution of phases and precipitations together with concentration profiles. Based on these results, the temperature-time history at the six testing probes was used to calculate the evolution of the material constitution during the heat treatment and quenching step. The final Young's moduli and yield strength are then area-weighted interpolated, respectively extrapolated, onto the whole wedge-shaped segment. These position-dependent mechanical properties were then used in the stress analysis mentioned above.

2.4 Automated optimization scheme

The subject for the automatic optimization algorithm is finding a proper laser power and exposure time combination so that no yielding occurs. In other words, for any point in the casting, the yield strength has to be larger than the von Mises equivalent stress which occurs during loading (Eq. (1) has to be fulfilled). The requirement for this condition is that the difference between yield strength and von Mises equivalent stress is larger or equal to zero at each space point and can be expressed as

$$\delta_{\text{out}} = \min\{\Delta(\vec{r})\} \geq 0\,. \tag{2}$$

From eq. (1) and (2) it is obvious that if δ_{out} is larger than zero the local strengthening of the material is stronger than necessary. Therefore, we chose $\delta_{\text{out}} = 0$ as criterion for the optimization as target function, so that a minimum of heat treatment effort results in no plastic deformation during loading.

The present study uses a gradient scheme based on the Fletcher-Reeves formula from the open source optimization toolkit Dakota [10, 11]. The optimization procedure is shown in Fig. 4. The process chain that is addressed here consists of (a) casting and solidification; (b) local heat treatment and quenching; and (c) the case of loading. Referring to the modelling point of view, the process chain has to be treated more detailed: (i) material constitution during solidification; (ii) material constitution during cooling to room temperature; (iii) temperature evolution during heat treatment and quenching; (iv) material constitution during heat treatment and cooling; (v) extraction of yield strength and Young's modulus; (vi) inter/extrapolation onto the 3D grid for stress analysis; (vii) 3D analysis in the case of loading. The steps (i) to (v) have to be executed point-wise e.g. at the selected testing probes shown in Fig. 2. All three dimensions are involved (3D) for step (vi) and (vii). If the load analysis responds $\delta_{\text{out}} = 0$, an optimum is found and the optimization procedure stops. Otherwise the process chain starts all over again using a new set of input parameters (for now the laser power, P, and the exposure time, t). The next set is suggested by Dakota based on the above mentioned gradient-based scheme.

At the moment, part (i) and (ii) could be neglected within the optimization loop because the as-cast material is the base for the local heat treatment and is identical for each loop. Currently, we are working at a process chain where the solidification conditions will influence the local material constitution. This extension will lead to new input parameters for the automated optimization toolbox like the casting temperature or cooling conditions during solidification. For this more general case, part (i) and (ii) must be considered inside the optimization loop.

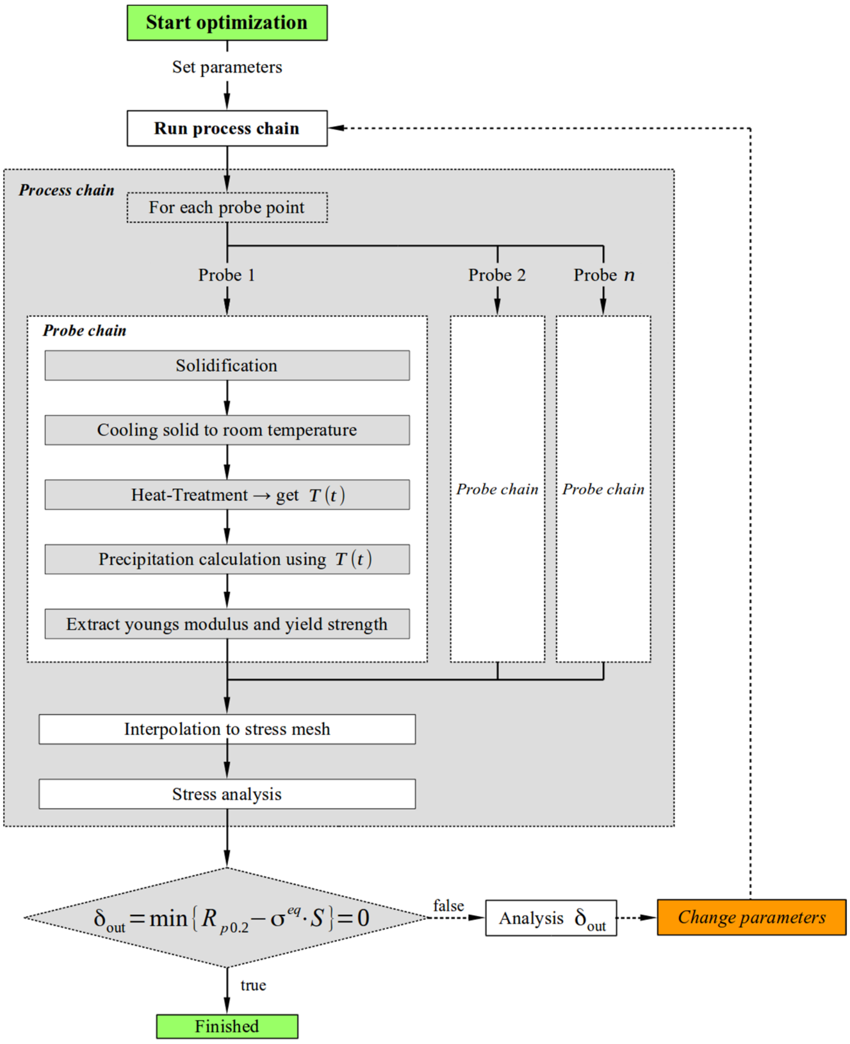


Figure 4. Flow chart of the automated optimization scheme.

3. Results and Discussion

The procedure of local heat treatment and quenching leads to the formation and growth of particular precipitations. As a results the material is strengthened by increasing the yield strength. Details on the mechanisms that cause this increase is beyond the scope of this paper and is therefore not discussed here. Fig. 5 shows the obtained yield strength (here $Rp_{0.2}$) at a position close to the surface near the centre as a function of exposure time and laser power. Lower laser power results in insufficient local strengthening because the local heating is not strong enough to reach a temperature level that favours the occurrence and growth of precipitations. Thus, the yield strength after heat treatment is the same as for the as-cast one (around 104 MPa). For higher laser powers the obtained yield strength increases rapidly to more than 130 MPa, whereby the shorter the exposure time the larger the power has to be to reach this increase. For high laser powers and longer shutter speed melting is predicted. The corresponding set of data points are not considered for the automated optimization and are thus not shown in Fig. 5.

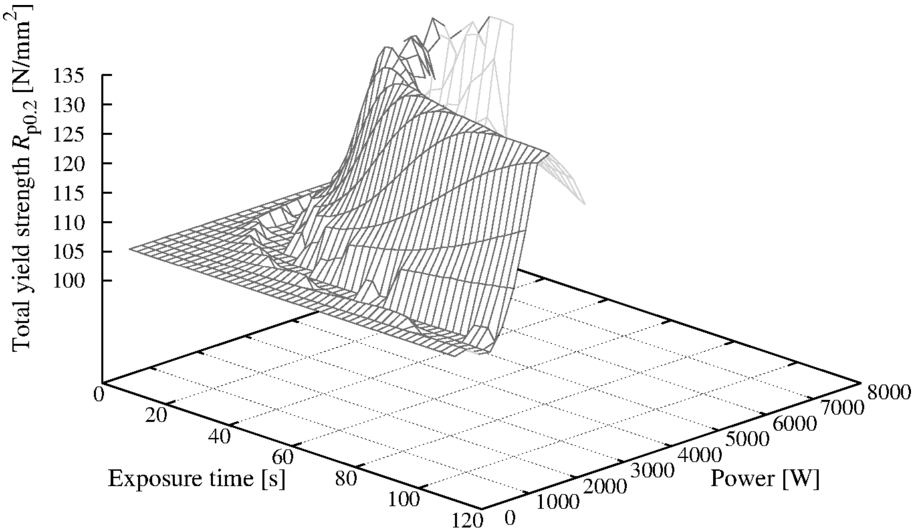


Figure 5. Strengthening of the material as function of laser power and heating time at the position close to the surface near the centre. For higher power values melting is predicted and therefore the corresponding power-time data set is not shown.

To avoid melting of the surface of the casting, the alternating off/on strategy mentioned above was applied with two different sets of values for T_{off} and T_{on}. For the first set, T_{off} = 793 K and T_{on} = 773 K were chosen and for the second set T_{off} = 593 K and T_{on} = 573 K, respectively. Fig. 6 shows the corresponding obtained yield strength at the same position as for Fig. 5. As the off/on strategy avoids temperatures above the solidus temperature, higher laser powers and longer exposure times can now be accepted for the automated optimization without a risk of melting.

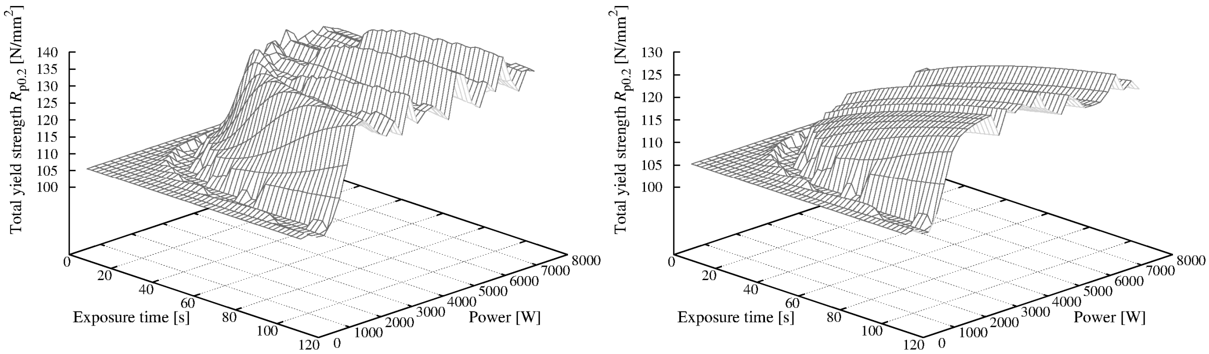
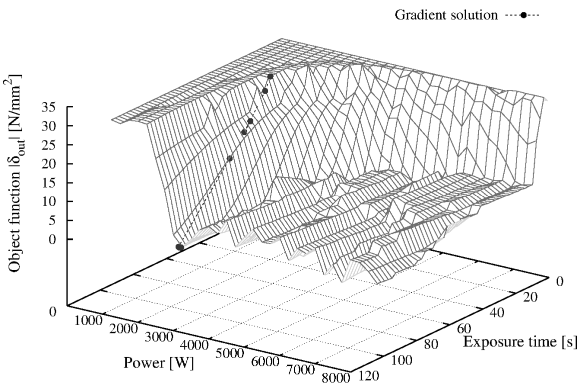


Figure 6. Strengthening of the material as function of laser power and heating time using the alternating off/on strategy with two different sets of values for T_{off} and T_{on}. The left plot corresponds to higher temperatures close to solidus and the right plot to temperatures 200 K lower

While using lower temperature bounds for the off/on strategy, the yield strength surface is smoothed out (less jagged) and the absolute values are lower compared to the higher temperature set. Formation and growth of precipitations which results in a yield strength increase is favored by using higher temperatures. Thus, it is clear that an off/on interval at higher temperatures leads to higher yield strengths. For the off/on interval which is 200 K lower even extreme high laser power and long exposer time do not lead to a yield strength increase comparable to the first case. This results demonstrate the importance of the right thermal treatment.

As described above, in the present optimization scheme δ_{out} is the output quantity and *P* and *t* are the input quantities. Fig. 7 shows how δ_{out} varies on changes in *P* and *t* for the two heat treatment cases mentioned above. Note that for each $\delta_{out}(P,t)$-surface 20x20 stress simulations in 3D had been performed. Using the Fletcher-Reeves gradient-based optimization algorithm, a new input data set for *P* and *t* is evaluated based on the gradients of the respond function δ_{out} with respect to (*P*, *t*). Fig. 7 shows the absolute values of the respond quantity δ_{out} of both cases including the evaluation of the optimization strategy (black points). The optimization scheme finds the minimum rather quickly. For the first case where the heat treatment is done at elevated temperatures, the automated optimization scheme needed only 36 iterations to find the optimum $\delta_{out} \approx 0$ (Fig. 7, left). For the second case only an object function of $\delta_{out} \approx 12$ was found. That means that no parameter set (*P*, *t*) is suitable for improving the yield strength of the aluminium alloy such that plastic deformation can be avoided.



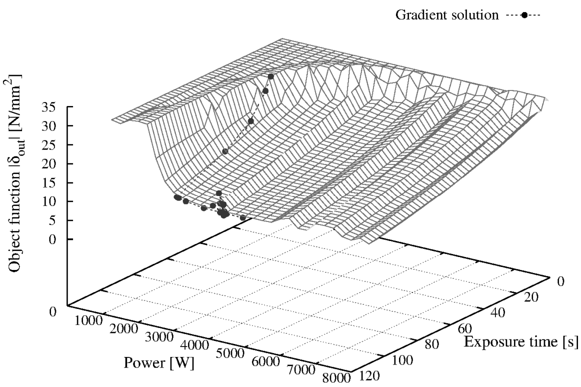


Figure 7. The absolute value of target function, $\delta_{out}(P,t)$, evolves corresponding to the optimization strategy. For the presented case the local minimum, $\delta_{out} \approx 0$, was found after 36 iterations in the left plot. The right plot has no set of input quantities to reach $\delta_{out} = 0$.

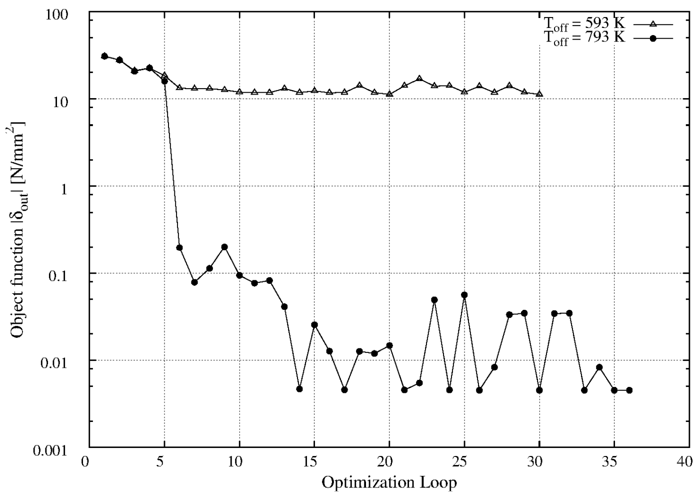


Figure 8. Gradient-based evolution of the target function, $|\delta_{out}(P,t)|$

Fig. 8 shows the absolute values of the target function for both cases in more detail (variations during optimization). It can be seen that for the first case after 14 iterations the minimum is already found but does not stop due to the abort criteria of the optimization. Comparing Fig. 7 and Fig. 8 it is obvious that the shape of the object function is essential for the correct choice of the optimization strategy (global or local search). Furthermore the object function and therefore the total yield strength development highly depend on the heat treatment parameters.

4. Summary

The paper demonstrates that a local strengthening of an as-cast AlSi7Mg0.5 alloy with a short laser heat treatment is possible. Taking the advantage of an automated optimization scheme, it is shown that the necessary laser power and exposure time could be estimated so that a local increase of the yield strength enables the material to withstand a localized traction acting without any plastic deformation. Beside a 3D heat transfer calculation and a 3D stress analysis, the procedure uses predictions from the material calculator MatCalc, which are currently under validation. The proposed procedure has great potential because it might allow to optimize features like casting temperature, cooling conditions, alloy composition, laser beam diameter and much more for the casting and heat treatment. Particularly with the increased usage of robotics, it is conceivable that local laser heat treatment, especially with self-quenching, might gain in importance. We think that the present paper is a significant step into that direction as it demonstrates how the suitable process parameters might be obtained. Energy and time saving might be the ultimate benefit of the proposed local strengthening of Al-based alloys.

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