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LOCALIZED STRENGTHENING OF AL-BASED CASTING ALLOYS BY AUTOMATIZED OPTIMIZATION OF LASER HEAT TREATMENT

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Abstract

The mechanic properties of many Aluminum alloys can be changed by a heat treatment and quenching procedure. If locally a strengthening of the alloy is needed, a localized heat treatment and quenching procedure may be an alternative to the energy intensive and costly treatment of the whole part. However, it is not obvious which process parameters are required in order to achieve the desired local strengthening. Thus, a numerical simulation of local heating and cooling in combination with predictions of the material constitution and thus local property changes is used for a multicriteria optimization approach where the desired local strengthening is defined as target function. The optimization scheme performs a series of process simulations where laser power and exposure time are varied automatically until the effective process is found which ensures sufficient local strengthening of the alloy.

Introduction

Castings made of Al-based alloys are often heat treated in order to improve their mechanical properties. This heat treatment happens in two steps. First, a supersaturated solid solution is obtained by heating up the casting to a certain temperature and then this state is conserved by rapid quenching back to room temperature. When this supersaturated solid solution is again heated up, but now mildly (if ever), different precipitations occur which hardens the material. In case of the AlSi7Mg0.5 alloy, which is focused on in the present work, the following precipitation sequence occurs from the quenched-in supersaturated solid solution upon heating: clusters with varying Mg and Si content, Guinier-Preston Zones (GP-Zones), beta'- and U1/U2-phases and the B-phase [1, 2, 3].

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

In this paper, an automatized 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.

Numerical Approach

Case of Loading

As starting point of this work, we have considered a simple rhombus-like plate casting with a centered hole. As case of loading the plate casting is considered to be fixed with a screwing connection at the center hole that is loaded with a prescribed mass, here of 360 kg that is acting on a ring area of 300 mm². 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 behavior is assumed and the local yield strength is given as $R_{p0.2}$, and the van Mises equivalent stress as σ^{eq}, then 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. Condition Eq. (1) must be fulfilled at all positions, $\vec{r}$, in the whole casting, especially in the vicinity of the loaded area at the center hole. Due to the axis-symmetry of the case of loading we have considered only a segment of the plate casting for the stress analysis (and the heat treatment described later). The segment was chosen long enough so that the outer boundary conditions do not affect the stress evolution close to the center hole. Fig. 1 shows the considered segment together with the assume boundary conditions for the stress analysis. The stress analysis was done with OpenFOAM [4] solving for the divergence of the Cauchy stress tensor to be zero. The position-dependent yield stress and also the Young's modulus were taken from a MatCalc simulation as explained below.

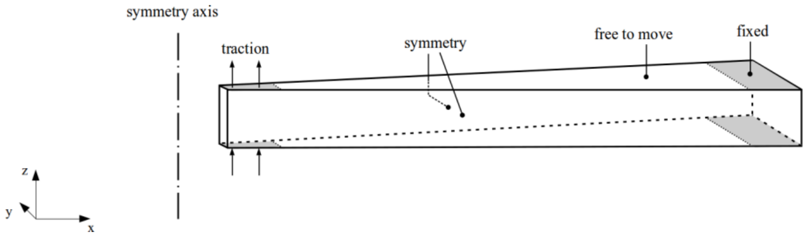

Figure 1. Wedge-shaped segment considered for the stress analysis. For the center hole a radius of 4 mm, for the segment a length of 200 mm and for the casting thickness 8 mm were chosen. An area at the outer fringe of the casting of 0.01285 m² was taken as fixed.

Heat Treatment

We have considered a Gaussian-shaped heat input of total power, P, for a certain time, t. Both, P and t are parameters which are subject to variations during the optimization procedure. P is varied between 500 and 8000 W and t between 1 and 105 s. Although a possible additional parameter to be varied, we have used a fix beam radius of $R = 15$ mm in this work. 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 [5]. For the heating period, we took $h = 50$ W/m^2/K with $T_{\mathrm{amb}} = 293$ K, and for the quenching period $h = 15.000$ W/m^2/K with $T_{\mathrm{amb}} = 283$ K. As quenching period we always took 20 s. Fig. 2 shows a schematic draft of the heat source acting on the area around the center hole of the plate casting. Note that the segment was chosen long enough so that the local heat treatment at the center never affects the outer boundary. For the time-depending temperature evolution in the plate we have solved the heat conductivity equation with OpenFOAM [4] using a heat conductivity of λ = 156 W/m/K, a heat capacity of c_p = 778 J/kg/K and a density of ρ = 2560 kg/m^3 for the considered AlSi7Mg0.5 alloy [6]. Note that the temperature-time curves at the six marked positions, which we call testing probes, were further used for the phase constitutive simulation.

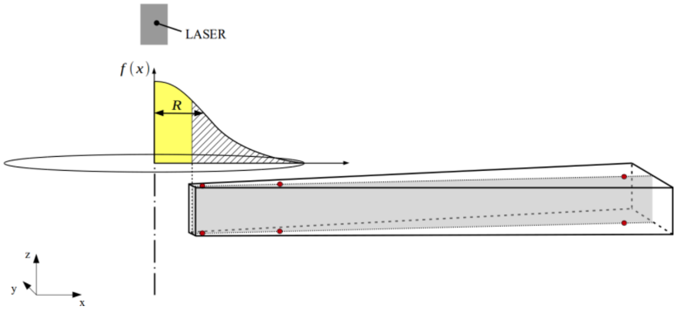

Figure 2. Schematic draft of the heat source. The non-hatched area below the Gauss-function defines the amount of energy being lost through the center hole.

The fact that a Gaussian-shaped laser beam at the center hole of the casting radiates most of its energy into the center hole could be avoided by using a ring-shaped laser beam. However, for the present investigation the exact shape of the laser beam is not of great importance as we are focusing on the strategy for the automatized optimization rather than on specific process details.

High laser power and long exposure time might lead to melting of the material. This has to be avoided. In the automatized optimization routine, parameter combinations where this happens are forbidden and excluded from the set of trials. A more sophisticated treatment of the melting problem is the introduction of two specific temperatures. At T_{off} the laser source is switched off and at T_{on} it is again switched on. The result of such an alternative off/on procedure is shown in Fig. 3. In the present numerical heat treatment this procedure is easy to implement. In practice, an empirical shutter or guided power-down technique applied at the laser control unit would be more adequate.

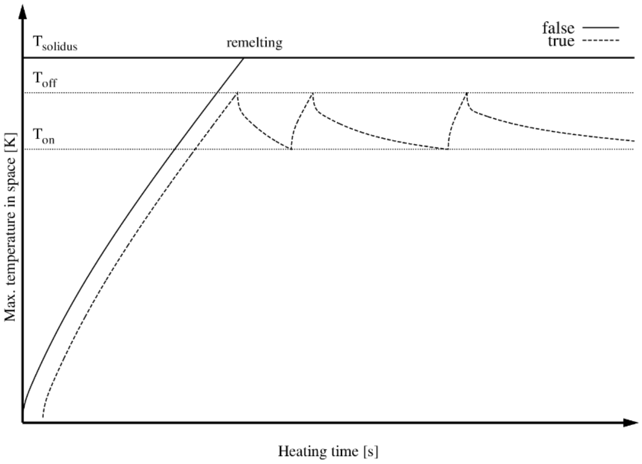

Figure 3. Possible temperature evolution at a surface position of the heated part. To avoid melting a temperature-guided shutter technique for the laser beam is tested.

Material Constitution Simulation

The evolution of the material constitution for the AlSi7Mg0.5 alloy during heat treatment and quenching was calculated at the six testing probes shown in Fig. 2 by using the commercial code MatCalc [7]. 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. That's why we have performed a multicomponent Scheil solidification simulation [8] while MatCalc already calculates phase and precipitation evolution together with concentration profiles. Based on these results, the evolution of the material constitution during heat treatment and quenching is calculated using the temperature/time history at the before mentioned six testing probes. The final yield stresses and Young's moduli are then area-weighted interpolated, respectively extrapolated, onto the whole wedge-shaped segment. Such position-dependent mechanical properties are used in the stress analysis mentioned above.

Automatized Optimization Scheme

The task the automatized optimization should solve is to find a proper laser power and exposure time combination which is suitable to reach, at any point in the casting, a yield strength larger than the von Mises equivalent stress occurring during loading (Eq. (1)). This condition is fulfilled if the minimum difference between yield strength and von Mises equivalent is larger or equal to zero, that's

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

If δ_{out} is larger than zero the local strengthening of the material by heat treatment and quenching is stronger than necessary. We thus chose $\delta_{\text{out}} = 0$ as target function for the optimization. That implies that no plastic deformation occurs with a minimum of heat treatment effort.

In the present study, we have used a gradient-based scheme from the open source optimization platform Dakota [9]. Fig. 4 shows the flow chart for the optimization scheme. As described above the process chain being addresses here consists of (a) casting and solidification; (b) local heat treatment and quenching; and (c) the case of loading. However, from a modelling point of view the 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 of the case of loading. Steps (i) to (v) have to be done point-wise e.q. at the selected testing probes shown in Fig. 2. For points (vi) and (vii) all three dimensions are involved (3D). If the load analysis reveals $\delta_{\text{out}} = 0$ the optimum is found and the procedure stops. If not the procedure starts all over again with a new set of input parameter (for now laser power, *P*, and exposure time, *t*). The next (*P*, *t*)-input set is suggested by Dakota based on the above mentioned gradient-based scheme.

Actually, part (i) and (ii) could be placed out of the optimization loop, as the as-cast material is the bases for the local heat treatment procedure. However, we are currently working at a scheme where the solidification conditions will affect the local material constitution. Then casting temperature or cooling conditions during solidification might also be possible inputs for an extended input set. In this more general case, part (i) and (ii) must be considered inside the optimization loop.

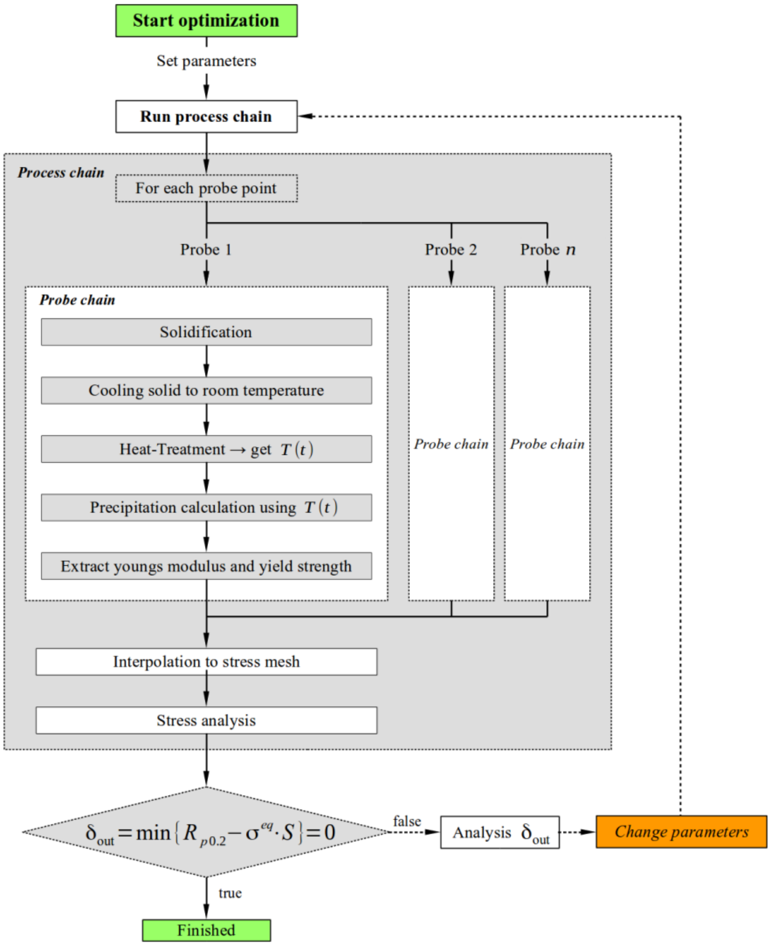

Figure 4. Flow chart of the automatized optimisation scheme.

Results and Discussion

The local heat treatment with quenching procedure results in the occurrence and growth of particular precipitations, which strengthen the material by increasing the yield strength. It is beyond the scope of this paper, to give further details on the mechanisms causing this increase. Fig. 5 shows the yield strength (here $R_{p0.2}$) depending on laser power and exposure time at the position where the maximum von Mises stresses occur. For lower laser power the local heating is not strong enough to reach a temperature level that favors the occurrence and growth of precipitations. Thus, the yield strength is the as-cast one (around 104 MPa). For higher laser power the yield strength increases to more than 130 MPa, whereby the shorter the exposer time the larger the power necessary to reach this increase. However, shortly after reaching the maximal level melting occurs and thus no data points are given any more.

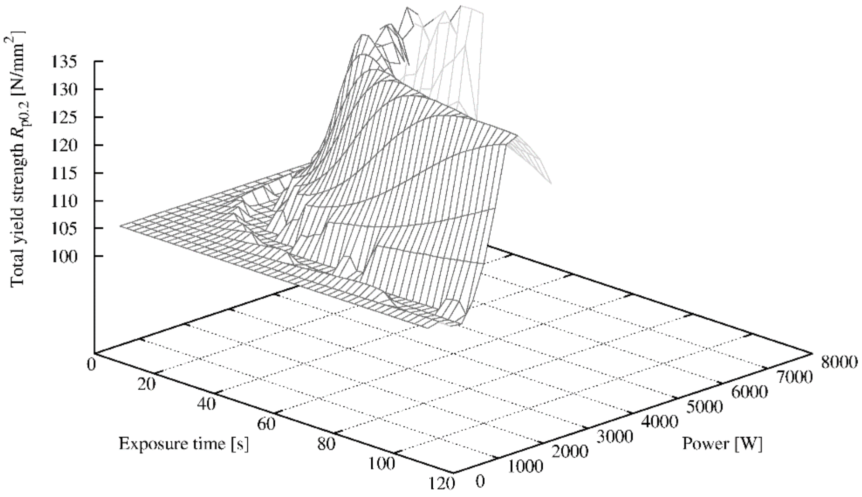

Figure 5. Strengthening of the material as function of laser power and heating time. For larger powers melting occurs and thus the power-time data set is cancelled.

In order to avoid melting at the casting surface, the shutter technique mentioned above with T_{off} = 793 K and T_{on} = 773 K was applied. Fig. 6 shows the corresponding yield strength surface. Now even higher laser powers for longer heating times are allowed without melting the material.

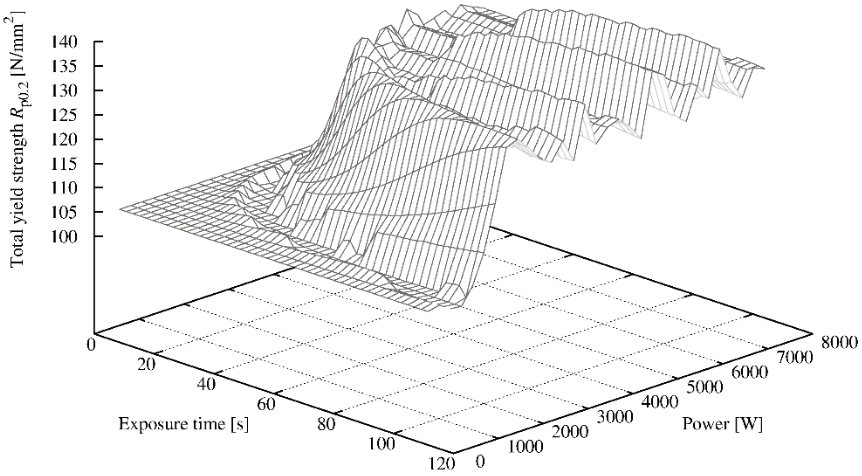

Figure 6. Strengthening of the material using the laser shutter technique according to Fig. 3.

As described above, in the present optimization scheme δ_{out} is the output quantity and P and t are the input quantities. The gradient-based optimization algorithm from Dakota suggests a new input data set (P, t) based on the actual value of δ_{out} and its gradient with respect to (P, t). Fig. 7 shows how the optimization scheme quite quickly finds the optimum, namely $\delta_{out} = 0$. Only 36 optimization loops were needed. Of course the scheme is generalizable and further variable parameter could be used as input data set.

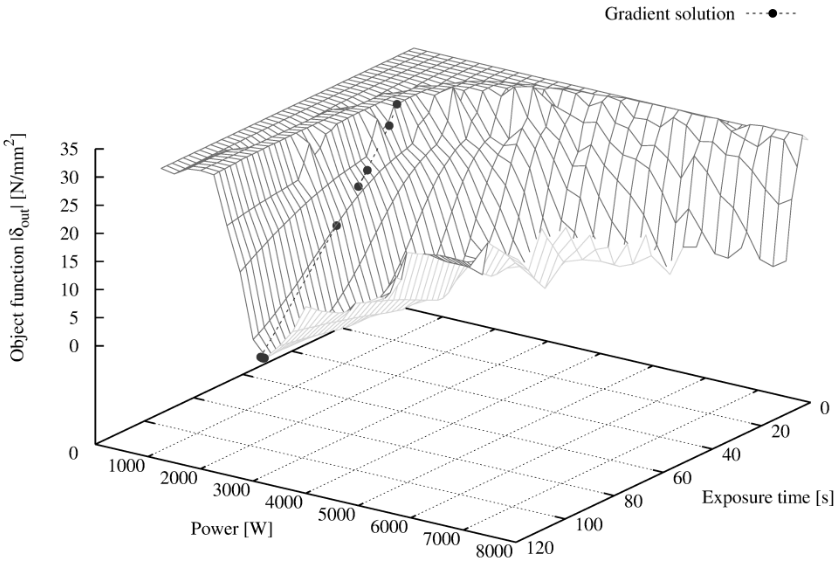

Figure 7. The target function, $|\delta_{out}\,(P, t)|$, evolves corresponding to the optimization strategy. For the presented case the minimum, $\delta_{out} = 0$, was found after 36 iterations.

Conclusion

In this paper, it was demonstrated that local strengthening of an as-cast AlSi7Mg0.5 alloy with a short time laser heat treatment might be possible. With an automatized optimization scheme the necessary laser power and exposure time was estimated to locally increase the yield strength so that the material can withstand a localized traction acting e.g. at a screwing connection without any plastic deformation. Beside a 3D heat transfer calculation and 3D stress analysis, the procedure uses predictions from the material calculator MatCalc, which are currently under validation. The proposed procedure has great potential as it might allow to account for casting features like casting temperature, cooling conditions, alloy composition, laser beam diameter and much more. Especially with the increased usage of robotics, it is conceivable that local laser heat treatment, preferable with self-quenching, might gain in importance. We think that the present paper is a significant step into that direction, as it shows 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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