Yield Strength Prediction in 3D During Local Heat Treatment of Structural A356 Alloy Components in Combination with Thermal-Stress Analysis

Tobias Holzmann, Andreas Ludwig and Peter Raninger

Abstract The numerical investigation of common heat treated A356 as-cast parts was successfully exhibited by several authors for T4, T6 and T7 tempers. However, for non-uniform or local heat treatments (e.g. welding) the common procedure of estimating the material properties cannot be used. Therefore, a new methodology was developed in order to overcome the weak point in the kinetic calculation and to enable the prediction of the material properties in 3D. The single steps of the methods are described while mentioning interesting aspects briefly. Subsequently, a local heat treated structural A356 component case is presented while taking care about remelting and yielding. At the end possible areas of applications are given in which the new method can be applied.

Keywords Local heat treatment · Thermal-stress analysis · Yield strength prediction in 3D · Aluminum alloy

Introduction

Aluminum alloys are widely used in different industry sectors such as the automotive or aerospace ones. This is related to the excellent cast ability, high thermal and electric conductivity and corrosion resistance of aluminum alloys such as the A356 (AlSi7Mg0.3) alloy [1, 2]. The characteristic that these alloys can further be age hardened, which is mainly based on forming precipitates—typically magnesium included phases such as β or Θ and similar ones as the metastable β''—, during

T. Holzmann (✉) · A. Ludwig
Department of Metallurgy, Montanuniversitaet Leoben, Franz-Josef-Strae 18, A-8700 Leoben, Austria
e-mail: Tobias.Holzmann@unileoben.ac.at

P. Raninger
Material Center Leoben Forschung GmbH, Roseggerstrae 12, A-8700 Leoben, Austria

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natural or artificial aging and thus be controlled in terms of material properties, support these alloys even more while offering an excellent strength to weight ratio [3]. In the past numerous experimental investigations were made to analyze the influence of different parameters onto the microstructure and mechanical properties of aluminum alloy. For example Wang et al. [4] analyzed the dependency of the pouring temperature and cooling condition during solidification on the as-cast microstructure and the behavior during remelting the eutectic regime. Prasada Rao et al. [5] used strontium and antimony modifier in combination with the Al5Ti2C grain modifier in order to manipulate the eutectic structure for short and long melt treatment time. This particular topic of modifying the eutectic using different modifier elements to influence the nucleation and therefore the microstructure was discovered by various authors [6–8]. Other scientists such as Salleh et al. [9] and Caceres et al. [10] analyzed the influence of the amount of different elements—e.g. magnesium—on the microstructure and mechanical properties of aluminum alloys. Borodianskiy et al. [3] proposed a new method to refine the eutectic regime using ceramic nanoparticles in combination of a gas-dynamic treatment. In addition, the precipitation sequence during aging is well known based on investigations of several authors such as Dutta et al. [11] or Edwards et al. [12] and is nowadays almost completely understood. Despite experimental investigations, numerical models were developed simultaneously to capture the kinetic phenomena during annealing and aging in order to estimate the material properties numerically. The models discover a wide range of fields e.g. nucleation, grain growth, precipitation hardening etc. and are published elsewhere [13–15]. Falahati et al. [17] compared numerical simulations and measurements for arbitrary heat treatment—natural and artificial aging of aluminum. The work of Wu et al. [15] compared a set of experimental data of an A356 alloy with numerical simulations too. Both were found in good agreement.

However, the numerical investigations are generally done using the common T4, T6 or T7 heat treatment sequences. Especially the analyze of the T6 pattern is widely presented. Referring to local heat treatments—welding included—the common numerical procedure to evaluate the material properties cannot be used.

One possible approach was already suggested by Ludwig and Holzmann [18]. However, this method does only give a rough estimation of the material properties and cannot be applied for complex geometries based on the high non-linear yield strength evolution during local heat treatments. Furthermore, the applied area-weighted interpolation method can only be used for simple 2D geometries. Therefore, a new framework is presented here allowing to calculate the material properties in 3D for either an approximation or a highly accurate solution. Additionally, there is no limitation in the choice of the alloy one wants to investigate or the application field, e.g. a short local heat treatment with or without subsequent quenching and aging or analyzing the material behavior during welding around the welding seam. The presented method also includes thermal-stress calculation in order to avoid yielding or remelting of the material during a local heat treatment.

General Model Description

For analyzing the influence of a local heat treated structural aluminum alloy onto the material properties, a new simulation framework has been developed in order to simulate the energy insertion and its diffusion into a structural part as well as the resulting thermal stresses. Both quantities are used to limit the energy insertion based on user defined functions prohibiting yielding and remelting of the structural as-cast part. This is done by evaluating permanently the maximum occurring Von Mises equivalent stress and temperature—in the structural part—against the basic yield strength and the solidus of the alloy. Reducing the energy insertion is done after a trigger value is exceeded either for the maximum Von Mises stress or the maximum temperature. During the heat treatment and to evaluate the material properties in 3D, temperature curves at random positions are tracked, stored and used in the kinetic calculations afterwards. Thus, the material properties of each tracked position is available and can be used to get the 3D yield strength distribution in the structural part. Figure 1 shows an overview of the model with an additional optimization procedure.

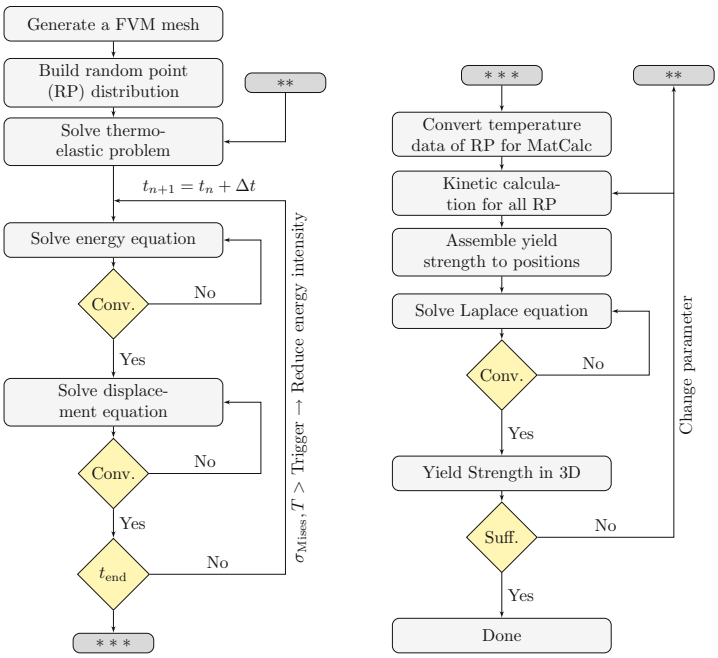

Fig. 1 General sequence of the new developed method for investigating into local heat treatments in combination with thermal-stress calculation and yield strength prediction in 3D. " Conv." stands for converged; " Suff." stands for sufficient

Energy and Stress Equations

The calculation of the energy distribution and the resulting thermal stresses during the local heat treatment are calculated using the finite volume method (FVM) approach. The general equations for the energy and displacements (for the stresses) are derived and implemented in the open source toolbox OpenFOAM® version 5 [19]. For reference, the equations are reported elsewhere [20–22]. The energy insertion is modeled as a boundary condition by using the multi-dimension Gaussian probability distribution [23]. Additional features of the boundary condition such as modeling convective heat transfer, moving heat sources (welding) etc. are explained in [24]. It is worth to mention that the displacement equation is calculated in a segregated manner without time derivative based on assumptions given in [20] and is not coupled with the energy equation due to small strains.

Kinetic Calculation

The evaluation of the material properties is done by using the scientific toolbox MatCalc [13, 16]. For the correct modeling approach, the numerical treatment is as follows: (i) estimate the phase fractions after solidification by using the Scheil approach; (ii) using the silicon phase fraction in combination of a log-normal function to initialize the grain distribution of the silicon in the eutectic—the log normal parameters were evaluated by analyzing the microstructure of the alloy; (iii) further cooling from liquidus temperature to room temperature by performing a kinetic calculation; (iv) using the phase compositions of (iii) for the subsequent kinetic evaluation for each random location; (v) extract the yield strength and store the result with the Cartesian coordinates. It is worth to mention that step (i) to (iii) is done only once and used for the repeated steps (iv) and (v).

Random Point Generation

The main part in the new approach is the generation of random positions in the structural component in combination with the subsequent solution of a Poisson equation. The random locations are used to track and store the temperature profiles during the heat treatment. Therefore, a new application was developed in the OpenFOAM® environment in order to use all in house classes and combine the outcome of the application directly to the thermal-stress solver. This also enables an easy procedure to solve the Poisson equation afterwards. The application itself determines the bounding box of the geometry in use and generates arbitrary locations within the numerical mesh automatically.

Two main strategies are developed right now. The user can either specify if the whole geometry or an own region is considered during the point generation. In addition, both variants can be combined while different point densities can be specified. This feature comes in handy if a more accurate solution of the yield strength is required locally.

The application itself generates a file containing cell IDs and the corresponding Cartesian positions of all points which are used in the local heat treatment step, and for manipulating the Poisson equation later on.

It should be noted that the application has the possibility to set a true random mode or not. Running the application in true random mode will produce a non-reproducible random point distribution while the alternative mode outputs a random distribution that can be re-generated by executing the application with the same settings again.

Yield Strength Distribution in 3D

Knowing the yield strength quantity at all random locations in combination with the position information allows one to calculate the yield strength distribution in 3D by solving a Poisson equation. The equation is solved for steady-state condition while the diffusion coefficient does not have a physical meaning and can be set arbitrarily —it influences only the amount of re-calculations. The source term on the right hand side of the equation (**Ax = b**) contains the known yield strength values at the corresponding positions. The numerical approach is implemented in OpenFOAM®.

It is worth to mention that instead solving the Poisson equation, FOAM offers the manipulation of the matrix system while adding explicit sources. Therefore, the Poisson equation can be replaced by the Laplace one. Based on the structure of the applications which were developed, the latter method is used.

Results and Discussion

An example of a local heat treatment is given now. A structural design, partly depicted in Fig. 2, is local heat treated around the bore hole by using the boundary condition mentioned previously. Before the thermal-stress calculation is performed, a random point distribution is generated. A possible outcome is shown in Fig. 4. Those points are used to track and store the individual temperature profiles.

During the simulation, the inserted energy is controlled in order to prevent yielding and remelting of the material; c.f. Figure 3. At the early stage (0–5 s) the energy insertion is controlled by using a parabola function in order to limit the maximal appearing Von Mises stress. The influence of the function is clearly visible in Fig. 3; the inserted energy profile follows the parabola function from 0 to 5 s. As the intensity of the LASER increases, the thermal stresses gain as well. After a

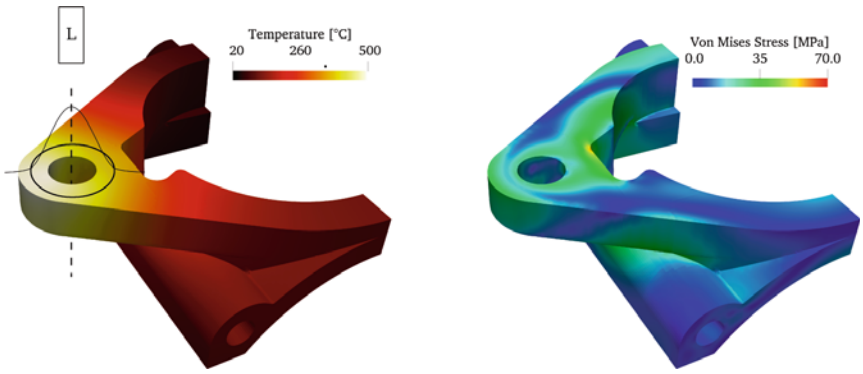

Fig. 2 Local heat treated structural part after 10 s. Left: Temperature profile and energy insertion; Right: Von Mises stress profile

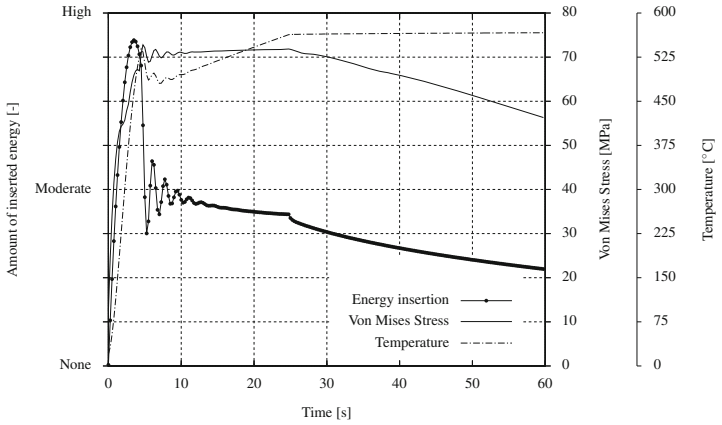

Fig. 3 Energy insertion control by the maximum occurring Von Mises stresses and temperature in the structural as-cast part. The energy control is based on user defined functions and are used after a trigger values is exceeded

defined Von Mises trigger value is reached the energy is reduced (5–25 s) by thermal stresses. Due to the high thermal conductivity—of the aluminum alloy—the temperature gradients get smoothed out rapidly and decrease the stresses respectively. In the meanwhile the temperature rises up to the temperature trigger value. Subsequently, the energy insertion is controlled by the temperature (25–60 s). A snap-shot of the temperature and stress profile at 10 s is depicted in Fig. 2 as well as a sketch of the laser direction. It is worth to mention that due to the reduced energy insertion, the highest temperature values are at the tail of the bore hole. This can be related to the high thermal conductivity and the accumulation of energy in that region. The Gaussian profile around the bore hole can only be observed in the first few seconds and is not shown here.

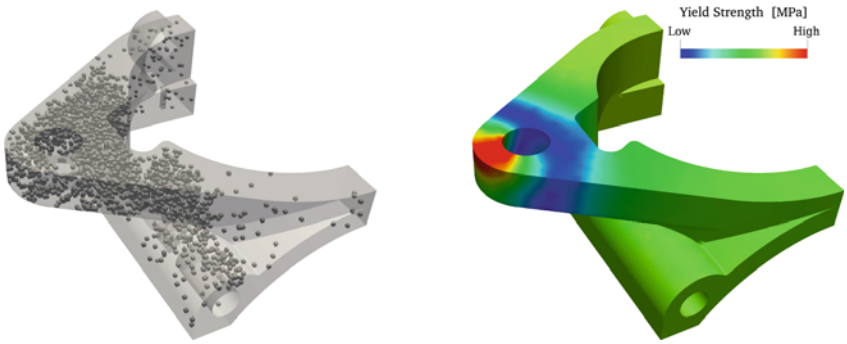

Fig. 4 Random point generation and yield strength distribution in 3D after the local heat treatment and artificial aging

After 60 s the whole part is water quenched (not shown in Fig. 3). The tracked temperature profiles of the random points are converted to a MatCalc readable file format and used for the kinetic calculations. After knowing the yield strength of the random points, the Poisson equation is solved and the predicted yield strength of the structural part is available in 3D cf. Figure 4.

Summary

The suggested method to estimate the yield strength distribution in 3D for structural aluminum parts can be used to investigate into local or non-uniform heat treatments while avoiding yielding and remelting. The intelligent connection between different software packages in combination with the new developed methodology allows further to investigate into different kinds of application field and alloys such as common heat treatment, local heat treatment and welding—investigating the behavior of the material around the welding seam.

Additionally, the 3D yield strength distribution can be used to optimize different areas of interest. E.g. one can calculate the volume averaged yield strength around the bore hole and using this quantity as an object function for an optimizing chain, c.f. Figure 1.

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