Integrated modelling of transitions in mechanical conditions during casting and heat treatment

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Abstract. The mechanical material behaviour of a cast component changes significantly during casting and heat treatment. The big difference in temperature levels during the different process steps causes different deformation mechanisms to be active. The thermal gradients promote transient stresses that can lead to inelastic deformations, residual stresses and in some cases to defects in the final part. It is a big challenge to make a reasonable transition in the mechanical model, and hence material data, when modelling several different coupled process steps. It is important to use an integrated approach where the transition is included in the full load history of the part. When industrial examples are considered, the sequence of process steps typically also changes the thermal and mechanical boundary conditions significantly e.g. going from being mechanically constrained during casting to being supported point-wise during the heat treatment process. This change includes mapping of results and obtaining equilibrium in a new global system, where the further reaction forces from the supports must be handled with contact conditions to e.g. predict deformations due to gravity during solution heat treatment. The work presented in this paper is focused on modelling the mechanical fields, taking into account the changes in the mechanical material model at different temperature levels, and the transition in mechanical behaviour when the microstructure is changing during the different steps of the heat treatment process. The approach used is based on a unified model where creep effects are considered at high temperature and rate effects are included in general during cooling. Proposals are made to include cooling rate sensitivity, annealing and precipitation hardening via modification of mechanical properties in the different process steps.

1. Introduction
Casting of aluminum parts for the automotive industry is often followed by a heat treatment process, where the mechanical properties are improved by modifying the as-cast microstructure in a sequence of thermal steps. In this way, it is possible to obtain a material with increased ductility and higher strength compared to the as-cast conditions. The process view of the casting and heat treatment processes can be used to illustrate the thermal history of the part, see figure 1, left. The different steps can have significant influence on the stress levels and the distortion that can build up during e.g. elevated temperatures.

The most widely used aluminum casting alloys are based on different contents of Si, Cu and Mg. For the hypoeutectic alloys, the microstructure consists of a primary $\alpha$-Al phase and Al-Si eutectic. The additional components Mg and Cu are either contained in the $\alpha$-Al in solid solution or
precipitated as intermetallic phases e.g. Mg\(_2\)Si or Al\(_2\)Cu. The content of Mg and Cu in solid solution is temperature dependent according to the phase diagram. This temperature dependency is exploited during solution treatment to form a super-saturated solution of Mg and Cu, which is maintained during quenching to allow a controlled precipitation of intermetallic phases during artificial aging.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Left: Process view showing the thermal history of the casting and heat treatment processes. Right: The phase diagram indicating the path for generating the super-saturated solid solution.

During the casting and the heat treatment process steps, stresses and deformations develop depending on the thermo-mechanical loading of the material. High thermal gradients can lead to significant stresses that promote the risk of cracks and cause inelastic strains, which can lead to residual stresses in the final part. To get an assessment of the thermo-mechanical loading of the material it is important to perform a numerical simulation where the different process steps are modeled. However, when these process steps are analyzed using numerical simulation, the mechanical properties are typically only assumed to be temperature dependent and at elevated temperature also strain rate dependent, [1]. Hence, the evolution of the mechanical properties with respect to microstructure is in general not taken into account. Nevertheless, the reason for doing heat treatment is to improve the performance of the material, which will also affect the numerical analysis. It is the purpose of this paper to include the evolution of the mechanical properties in the numerical modeling of the casting and heat treatment processes. In this paper it has not been the intention to model the microstructure and relate this to the mechanical properties, but rather to identify what is important to include in order to make the first steps in having local properties that depend on the thermal history, i.e. temperature level and cooling rate.

2. **Modelling the evolution of mechanical properties**

Thermo-mechanical modeling of the casting and heat treatment process is a challenge even without considering the evolution of the material data. The main concern is to model the response of the material at different temperature levels, on different time scales and sometimes with different strain rates, which is governed by different deformation mechanisms. To have a reasonable compromise between the stability in the results when doing calculations in different process steps and agreement between simulations and performed creep and tensile tests, a unified creep formulation is used as the fundamental constitutive law, [2]. The model is based on Norton’s power law and includes by that, strain rate sensitivity and the possibility to describe creep at elevated temperature, see (1) below.

\[
\dot{\varepsilon}^m = A \exp\left(-\frac{Q}{RT}\right) \left(\frac{\sigma}{\sigma_{ref}}\right)^m
\]

The Arrhenius expression scales the response according to the temperature dependency and the model is therefore applicable in a wide temperature range. The reference stress \(\sigma_{ref}\) describes the isotropic strain hardening by a classical power law,

\[
\sigma_{ref} = \sigma_0 \left(1 + \frac{\varepsilon}{K}\right)^m
\]
\[
\sigma_{\text{ref}} = \sigma_{0,\text{ref}} \left( 1 + \frac{E h}{n \sigma_{0,\text{ref}}} \right)^n,
\]

where the hardening parameter \( h \) is based on the inelastic strain to capture the effect of hardening when e.g. dislocations are piling up and annealing when the temperature is elevated, allowing diffusion processes to be active. The model is governed by two temperature dependent properties, the initial reference stress \( \sigma_{0,\text{ref}} \) and the hardening parameter \( n \). The response of the creep equation and the hardening law can be illustrated by the classical creep curve and the stress-strain curve in figure 2 left and right, respectively. It should be noted that the stress response of the material is not directly given by the reference stress curve illustrated by the dashed line in figure 2 right, but a similar response where the level of the response depends on the strain rate, see the full line in the same graph.

![Creep and Hardening Response](image)

**Figure 2.** Left: The creep response of the material model. Right: The hardening response of the material model.

The following subsections will give a short summary of how the different process steps influence the mechanical fields and the mechanical properties due to changes in the microstructure. The proposed implementations are used on industrial examples in the simulation sections.

### 2.1. Cooling rate sensitivity during casting and quenching

The stresses mainly build up during the cooling and quenching steps, where thermal gradients promote different thermal contraction and corresponding internal constraints, which can lead to stresses in the material. For high cooling rates, not only the thermal gradients influence the level of the internal stresses but also the mechanical properties are reported to depend on the cooling rate. Kessler et.al. [3] have performed a series of measurements in a quenching deformation dilatometer to determine the properties at different temperature levels for different cooling rates for a wrought aluminum alloy. It was seen by the measurements that the examined alloy had a clear cooling rate dependency at the lower and intermediate temperature levels. The same dependency has been adapted for the considered alloy in this paper, A356, and two of the resulting curves are shown in figure 3.

![Cooling Rate Sensitivity](image)

**Figure 3.** Influence of the cooling rate on the mechanical properties for the considered alloy in this paper, A356, for two different temperatures.
In the simulations, the influence of the cooling rate has been included by using the locally calculated cooling rate to modify the input data for the hardening law according to the curves shown in figure 3. That is, the initial reference stress depends locally on the cooling rate. In this way the hardening response of the material will be cooling rate sensitive and by that follow the curves in figure 3 in the simulations. The effect from this modification is mainly expected to be seen in the quenching process but of course it also has an influence during cooling in the casting process.

2.2. Annealing during casting and solution treatment

During mechanical loading at lower temperatures, plastic deformation leads to strain hardening of the material, which can be measured by a classical tensile test. The response is typically described by a power law, which can be used to fit the tensile measurements for many alloys, see equation (2). At elevated temperatures the mechanical response is no longer making a contribution to additional strain hardening and it is observed that, depending on temperature and time, the already existing strain hardening vanishes. This type of softening is called annealing\(^1\), which is caused by dislocations starting to diffuse to e.g. the grain boundaries and by that removing the dislocation obstacles that caused the hardening effects at lower temperatures. In this work it is proposed to use the inelastic strain rate to both describe the strain hardening and the annealing of the material, by multiplying the contribution from the inelastic strain increment to the strain hardening parameter by a temperature dependent factor. The strain hardening variable used in the strain hardening law, equation (2), is updated according to the equation below

\[
\Delta h = f_h \Delta \varepsilon^{in},
\]  

where \(\Delta h\) is the increment in the strain hardening parameter \(h\).

In this way it is possible to add inelastic strain to the strain hardening parameter at low temperatures, resembling strain hardening, and subtract inelastic strain from the hardening parameter at higher temperatures, resembling annealing. This functionality plays an important role during solution treatment, where the material is more or less stress free with no strain hardening at the end of solution treatment. Of course, annealing also has an influence on the mechanical behavior during the casting process which is also seen in the simulations.

The temperature dependent factor \(f_h\) in the hardening evolution law, equation (3), is assumed to follow the curve given in figure 4. The curve has been adjusted to give a classical update at lower and intermediate temperature levels, where \(\Delta h = \Delta \varepsilon^{in}\), and to remove hardening at higher temperature levels to resemble annealing. The adjustments of the curve have been done with simulations, but of course the goal is to couple this adjustment to measurements.

\[\text{Figure 4. Temperature dependent factor for the hardening update.}\]

\(^1\) In literature annealing is used for cold worked metals and divided into the processes: recovery, recrystallization and grain growth, [4]. For cast alloys we use the term annealing to describe the combined effect of increasing ductility and reducing strength.
2.3. Precipitation hardening during artificial aging

The final step of the heat treatment process is used to strengthen the material due to precipitation hardening. However, the effect of this step is quite sensitive to the process temperature and the time the part is heated. According to measurements presented in [5], the considered A356 alloy has an increased yield strength and tensile strength when precipitation hardened at 150 °C and 205 °C for 3-5 hours. For a higher aging temperature, 260 °C, the material starts to overage already after approx. 1 hour, and after 5 hours the influence of precipitation hardening has vanished.

The influence of precipitation hardening is included in the simulations by modifying the mechanical data that describes the yielding behaviour. The aging temperature and aging time is used to evaluate the influence on the yield curves and hence used to scale the initial reference stress in the hardening function, equation (2). The curves presented in figure 5 illustrate the input to the simulations presented in the next section. It is assumed that the quench process was fast enough to maintain the supersaturated solid solution of alloying elements to make an optimal initial condition for the artificial aging process.

![Figure 5. Influence of precipitation hardening on the yield curves, left: different aging times at 205 °C and right: for different temperature levels after 5 hours.](image)

3. Modelling gravitational load during solution treatment

During solution treatment, structural parts can experience a considerable amount of deformation due to their own weight. To achieve a prediction of a components final distortion, it is necessary to consider all relevant steps of the manufacturing process. This imposes some challenges for the simulation of the integrated process. The importance of an appropriate simulation technique stems from a relatively new trend in the automotive industry to apply distortion engineering to structural parts, by designing support frames in a way that exploits the distortion capability during solution heat treatment in order to control the deformation so that subsequent straightening operations are minimized [6].

Typically the parts are placed in a support frame, which means that the deformed parts need to be positioned into the supports and at the same time the coordinate system changes compared to the casting process. The positioning must be done in a way that the system, including contact between the part and the supports under the influence of gravity, becomes statically determinate.

The gravitational load is extremely small compared to the thermal load in heating or cooling steps so that the solution of a linear sub-step in a Newton-Raphson scheme is close to a singular solution of the equation system and the detection of global convergence, i.e. the fulfillment of the force equilibrium after several Newton-Raphson iterations, is very sensitive to these conditions. The first Newton-Raphson iteration requires appropriate initial conditions for the contact algorithm, and if the system is statically indeterminate, subsequent iterations will either reveal a rigid body motion or will simply diverge. Furthermore, if one wants to account for the thermal influence of the supports and/or their deformation, a new enmeshment of the calculation domain and mapping of state and history variables from the end of casting to the beginning of heat treatment is needed. This will require additional equilibrium iterations at the start of the heat treatment simulation. Altogether, it is extremely import to
have sufficient and well described boundary conditions to get convergence and ‘high’ accuracy in the solution.

4. LPDC wheel example

Several simulations have been performed to examine the influence of different process settings and the influence of cooling rate sensitivity, strain hardening scale factor and finally precipitation hardening during artificial aging. The initial conditions for the heat treatment simulations are based on a casting simulation with the implemented modifications activated. The considered example in figure 6 to 8 is an aluminum rim with an approximate diameter of 420mm and width of 205mm. The wall thickness is in the interval of 10-30mm.

4.1. Influence of different solution treatment temperatures

Due to the relatively high temperature level during solution treatment, stresses are relaxed to zero during this step and hardening vanishes due to annealing. This is shown for 3 different solution treatment temperature levels, where the v. Mises stress level is shown in the right graphs and the hardening variable in the left side of figure 6. The 3 different temperatures are: $T_{\text{sol}} = 525 ^{\circ} \text{C}$, $T_{\text{sol}} = 500 ^{\circ} \text{C}$ and $T_{\text{sol}} = 475 ^{\circ} \text{C}$.

**Figure 6.** Left: Vanishing hardening distribution after solution treatment at 525 °C. Right: v. Mises stress level as function of time at the selected point for 3 different solution temperatures.

4.2. Influence of different quench media – end of quenching

Quenching after solution treatment is a compromise between sufficiently fast cooling to get an optimal precipitation hardening afterwards and a low cooling rate to reduce the thermal gradients and by that the transient and residual stresses [7]. The residual stress distributions after quenching are shown for 3 different quench media in figure 7. As expected the residual stress level is highest for water quenching with $T_{\text{water}} = 40 ^{\circ} \text{C}$ compared to water quenching with $T_{\text{water}} = 95 ^{\circ} \text{C}$ and air quenching.

**Figure 7.** v.Mises stress level at the end of quenching. Left: Water quenching $T_{\text{quench}} = 40 ^{\circ} \text{C}$, Middle: Water quenching $T_{\text{quench}} = 95 ^{\circ} \text{C}$ and Right: Air cooling $T_{\text{quench}} = 25 ^{\circ} \text{C}$.
4.3. Influence of aging temperature and time

Finally, the aging process is considered for 3 different aging temperatures, $T_{\text{aging}} = 150 \, ^\circ\text{C}$, $T_{\text{aging}} = 205 \, ^\circ\text{C}$ and $T_{\text{aging}} = 260 \, ^\circ\text{C}$. The influence on the yield stress level is shown at the considered point for the different temperature levels in figure 8. The yield stress evolution is governed by the temperature level and aging time according to the graphs in figure 5. At the lowest aging temperature, the influence of precipitation hardening is delayed, while at 205 °C the precipitation hardening is quite early and stable during the rest of the process. It is clearly seen that at $T_{\text{aging}} = 260 \, ^\circ\text{C}$ the material overages very quickly.

![Figure 8.](image_url)

**Figure 8.** Left: Temperature profile of the considered heat treatment process. Right: Evolution of the yield stress at the considered point for the 3 different aging temperatures.

5. Deformation of structural parts during solution heat treatment

Figure 9 shows a rear spoiler with a fictitious arrangement of support pins from below. The part is approximately 900mm long, 50mm high and has a thickness of 2-5mm. Figure 10 shows the vertical displacement for different support scenarios, where the numbers indicate the active pins. The two selected results show the deformation after 30 minutes of solution annealing at 480 °C. It is clearly seen how the different number of supports affects the results.

![Figure 9.](image_url)

**Figure 9.** Rear spoiler with fictitious arrangement of support pins.

![Figure 10.](image_url)

**Figure 10.** Deformations during solution treatment for different support systems.

In the example, the pins are modeled as rigid and fixed in space using contact boundary conditions [8]. Also note that pins 2, 4 and 6 slightly surround the front edge in order to fix the part against sliding as can be seen in figure 9.
6. Conclusion and future work
The work presented in this paper shows the influence of including the evolution of local mechanical properties in the casting and heat treatment processes. Three modifications have been implemented and tested on industrial cast aluminum parts for the automotive industry, a wheel and a rear spoiler. The motivation has been to describe the influence of cooling rate sensitivity, annealing and precipitation hardening to get a consistent description of the mechanical material behavior. For the wheel example, the focus has been on different process conditions and for the rear spoiler the focus has been on the distortions during solution treatment due to the gravitational forces. The used material data are based on measurements and the applied modification due to cooling rate and precipitation hardening are based on information from literature. No coupling was done directly to the microstructure evolution. Future work will be focused on evaluating measurements of properties at different states. Typically, one has measurements of mechanical properties after fabrication, i.e. as-cast conditions, and after heat treatment. Ideally, the samples for determination of the as-cast properties should be remelted and cooled down to the testing temperature with an appropriate cooling rate corresponding to the casting process, which in the case of A356 can be sand casting, die casting or high pressure die casting. If the samples are just heated to the testing temperature, the measured mechanical properties actually refer to the heating phase of the solution treatment step. Data should be recorded with each sample going through the course of casting and heat treatment until reaching the testing temperature and time. Extending the knowledge of the material behavior with further measurements, hopefully also makes it possible to make a more direct relationship to microstructure calculations. Mapping of results between the process steps and handling of gravitational loads and supports to avoid a singular system are presented and discussed.

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