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ON MODELLING OF MICROSTRUCTURE FORMATION, LOCAL MECHANICAL PROPERTIES AND STRESS – STRAIN DEVELOPMENT IN ALUMINIUM CASTINGS.

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ABSTRACT

Today, the industrial demands are to reduce product development time as well as costs of producing prototypes. In this context, virtual prototyping by numerical simulation offers an efficient way of lowering costs and shorten lead time.

Castings are produced by a manufacturing method which inherently affects the component’s properties depending on design, metallurgy and casting method. The wall thickness influences the coarseness of the microstructure and the material will have properties depending on the local metallurgical and thermal histories. This is independent on the material, i.e. whether the casting is based on cast iron- or aluminium-alloys. The distribution of local properties in a casting might vary substantially which makes it difficult to optimize the casting with good accuracy. Often, mechanical simulations of the load situation are based on the assumption that the cast product has constant material properties throughout the entire casting. Thus, if the microstructure is determined or predicted at a given point, it gives the possibility to calculate the local material behaviour more realistically.

The paper shows modelling and simulation of microstructure formation, related to mechanical properties as elastic modulus, yield stress, ultimate strength and elongation.

In the present work, a test case of a complex casting in an aluminium alloy is considered including simulation of the entire casting process with focus on of microstructure formation, related to mechanical properties as elastic modulus, yield stress, ultimate strength and elongation as well as residual stresses. Subsequently, the casting is subject to service loads and the results of this analysis are discussed in relation to the predicted local properties as well as the residual stresses originating from the casting simulation.

INTRODUCTION

There is today a big need to produce complex and compound components to lower cost and with shorter lead times. A big cost for production of cast components is production of physical prototypes and the execution of physical testing. It is not only the production cost that is large, but also the production time is long too. Only to (take forward) produce/prepare/one cast prototype can take from 2-10 weeks. Since the properties depend to a larger extent on the casting process, the prototypes must imitate the” true” component in an attractive way; which in turn makes the cost high and production time long.
If one instead could establish a methodology for development of cast components where parameters from the casting and production process are taken into account to predict for example properties and residual stresses, reliability will be increased and the precision of simulations and the number of physical prototypes will be drastically decreased.

The automotive, telecom and manufacturing industries are moreover strongly depending on sophisticated and complex geometries of cast components in continuation of improvement of their products. In order to become more efficient in product and production development, the time for the experimental testing must decrease or nearly entirely be eliminated. Therefore new and improved simulation methods and more reliable mathematical models are needed. Furthermore, improved simulation tools become the strongest competition means for producing complex cast components with high knowledge- and technology contents. Through combining a traditional production method with a sophisticated technology an old method can get a world-leading position within the component production technology area by Virtual product production (VPF).

To optimize a cast component, all main parameters and variations in the process must be taken into account in the further analyses, calculations and simulations. Examples on parameters are metallurgy treatment, chemical analysis, cooling conditions and resulting properties and residual stresses. Geometry and process relations exist, and lead to components containing a wide variety of properties over the entire geometry. Moreover, it can be built up residual stresses during cooling which is geometry dependent. These effects and new boundary conditions are necessary to be concerned (take with) in the continued work.

Nowadays, the designers consider that the cast material has similar properties in all parts and in most cases take the properties from a standardized test bar, which probably leads to incorrect results and conclusions in most cases.

In the present work a test case of a console for a front bumper on a truck is analyzed, see Figure 1. First the casting process is simulated in MAGMSOFT ref[1] taking the entire cycle of mould filling, solidification using microstructure formation and solid state cooling into account. Focus is on microstructure formation related to mechanical properties such as elastic modulus, yield stress, ultimate strength and elongation as well as residual stresses. Subsequently, the casting is subject to service loads and the results of this analysis are discussed in relation to the predicted local properties as well as the residual stresses originating from the casting simulation. It should be mentioned that both the casting simulation as well as the load analysis is carried out in MAGMASOFT.

![Figure 1 Left: Detailed view of the console with prescribed constant compressive stress corresponding to an equivalent crash force of 160 kN (worst case according to Swedish standards). Right: Positioning of a similar console on the front bumper.](image-url)
However, since as earlier mentioned, the microstructural and mechanical analyses are in focus in the present work, they will be briefly explained in the following.

MICROMODELLING OF SOLIDIFICATION AND MECHANICAL PROPERTIES

Today’s generation of computer simulation programs for cast components has mainly focused on fluid flow/mould filling, solidification and prediction of shrinkage and residual stresses. The development goes toward that simulation can predict microstructures, porosities and shrinkage and mechanical properties of the material that along with the design gives the component its mechanical properties. Here, one can see several development trends with the common aim that the resulting mechanical properties can to be imported into simulation programs to predict stresses and deformations.

The mathematical models used ref [2, 3], describes the microstructure formation during solidification, including nucleation and growth kinetics for the phases and algorithms that describe the relation between the microstructure and mechanical properties. Note that this investigation aims to develop a relationship based on the isolated effect of microstructure on the mechanical properties, therefore, the influence of defects are not considered here.

The microstructure of aluminium cast alloys are widely defined as the distance of the spacing between the dendrite arms in terms of secondary dendrite arm spacing, SDAS. In this paper the SDAS is described as a function of local solidification time \( t_s \), equation [1], depicting the fineness of the microstructure constituents; \( C \) and \( n \) are constants which are related to the material’s chemical composition.

\[
SDAS = C \cdot t_s^n
\]  

(1)

The commercial cast aluminium alloy A354, that is commonly used when casting automotive component, is used in this study. As appeared in Figure 2, the finer the microstructure, graph a, the stronger the material and vice versa, graph b and c. A comparison of three identical tensile test samples at each SDAS has been performed and the material characteristics as Young’s modulus, strength coefficients and deformation hardening have been evaluated from the experimental curves. The scatter in data which mainly is due to a lower degree of inhomogenities between the samples and different levels of defects. The filled circles on the curves indicate the fracture points. The material has been gradient solidified to get low spread in material properties.

![Figure 2. Tensile test curves illustrating the tensile behavior of an Al-9%Si-1%Cu-0.4%Mg cast alloy where SDAS in a) is ~ 10 \( \mu \text{m} \), b) is ~ 25 \( \mu \text{m} \), and c) is ~ 50 \( \mu \text{m} \). The dashed curves are the corresponding simulated tensile curves and the filled squares imply that the quality of the material i.e. defect content, will determine where the fracture occurs. The filled circles denote the fracture of the particular tensile test sample.](image)
The influence of defects such as porosities and/or harmful intermetallic phases are incorporated in the modelling of the tensile test curve and assumed as affecting the mechanical performance, as seen from the simulated curves. The filled squares are to be considered as indicators, emphasizing that the inherent potential of the alloys might have not been reached due to the factors mentioned above.

**MECHANICAL ANALYSIS**

A mechanical analysis is carried out during the casting process as well as the subsequent loading situation of the cast part. In both cases, a standard mechanical model based on the solution of the three static force equilibrium equations is used, i.e.

\[
\sigma_{ij,j} + p_j = 0
\]  

(1)

where \(p_j\) is the body force at any point within the volume and \(\sigma_{ij}\) is the stress tensor.

The well-known Hooke’s law, linear decomposition of the strain tensor into an elastic, a plastic and a thermal part as well as small strain theory are applied

\[
\sigma_{ij} = \frac{E}{1+\nu} \left\{ \frac{1}{2} (\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) + \frac{\nu}{1-2\nu} \delta_{ij}\delta_{kl} \right\} \varepsilon_{ij}^{el} = E_{ijkl}^e \varepsilon_{ij}^{el} \\
\varepsilon_{ij} = \varepsilon_{ij}^{el} + \varepsilon_{ij}^{pl} + \varepsilon_{ij}^{th} \\
\varepsilon_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i})
\]

(2)

where the thermal strain is given by \(\varepsilon_{ij}^{th}(T_1 \rightarrow T_2) = \delta_{ij} \int_{T_1}^{T_2} \alpha(T) dT\).

In both cases the plastic strain is based on standard J2-flow theory with a temperature dependent yield surface. During the load analysis, isothermal conditions at room temperature are assumed and hence the thermal strain is set to zero in this case. The conditions during yielding are described by the associated flow rule, the von Mises yield surface and the consistency condition, i.e.

\[
\dot{\varepsilon}_{ij}^{pl} = \dot{\lambda} s_{ij} \\
f(\sigma, \varepsilon^p_e, T) = |\sigma| - \sigma_y(\varepsilon^p_e, T) \leq 0 \\
\dot{f} = \dot{f}(s, \varepsilon^p_e, T) = \frac{\partial f}{\partial s_{ij}} \dot{s}_{ij} + \frac{\partial f}{\partial \varepsilon^p_e} \dot{\varepsilon}^p_e + \frac{\partial f}{\partial T} \dot{T} \bigg|_{\varepsilon^p_e} \dot{T} = 0
\]

(3)

This material description is considered to be adequate for the casting simulation where the first order effect is the yield strength of the material as a function of temperature. In general, the temperature fields obtained during the casting simulation will be the driver for the thermally induced strains and stresses via the thermal strain. During the subsequent load situation, it is the mechanical load emulating a crash situation, which in general is the driver for the strains and stresses. The temperature dependent Young’s modulus and virgin yield stress used during the casting simulation are depicted in Figure 3 left, whereas the hardening curve at room temperature is depicted in Figure 3 right.
Figure 3 Left: Temperature dependent Young’s modulus and virgin yield stress used for the casting simulation. Right: Hardening curve at 20 ºC used in the load simulation.

In MAGMASOFT the mechanical field problem outlined above is solved in an FE-framework using 8-node brick elements. A more thorough description of the mechanical models implemented in MAGMASOFT can be found in [4,5].

RESULTS

Casting simulation

Figure 4 Left: Residual Mises stresses after the casting process. Right: Residual effective plastic strain after the casting process.
In Figure 4 the residual Mises stress and effective plastic strain after the casting process are shown. It is seen that the Mises stresses are in the range up to 96 MPa (Figure 4 left) assuming the highest values in the areas where noticeable effective plastic straining of up to around 6.0% has taken place (Figure 4 right).

Figure 5 left depicts the predicted dendrite arm spacing (SDAS), whereas Figure 5 right shows the corresponding elongation of the final casting. It is quite obvious to see that the finer the structure, the higher the elongation. This is in full correspondence with the expected outcome of the presented microstructural model.

Finally, in Figure 6 the ultimate tensile strength (UTS) and the yield stress at 0.2% effective plastic straining after the casting process are depicted. It is interesting to notice the substantial difference in levels, i.e. the UTS varies between 270 and 350 MPa, whereas the 0.2 yield strength is more or less constant at a level of 150 MPa. For the part under consideration this is an important result in the sense that for effective plastic strains lower than 0.2% the different sections of the casting will yield almost equally whereas for substantially higher strains there will be a noticeable difference in the corresponding stress levels for the same effective plastic strain depending on the location in the cast part. Moreover, since the part is supposed to obtain crash loads during service, it is of vital importance that the elongation is sufficiently high and the UTS is substantially higher than the virgin yield stress.

Load simulation

The above predicted mechanical properties were used in the subsequent load simulation. As a preliminary approach, no spatial distribution of these properties was applied, i.e. the same behaviour in all elements was assumed. As discussed above, the yield stress at 0.2% could be taken as constantly equal to 150 MPa. Combining this with an average UTS of 300 MPa and an elongation of 4%, the stress strain curve shown in Figure 2 right was generated.

Note that the values of the Young’s modulus and virgin yield stress correspond to the values at room temperature shown in Figure 3 left.
The results of subjecting the as-cast part to the crash load are presented in Figures 7 and 8. The normal stress in vertical direction in Figure 7 shows the expected tensile stress in the most upper left corner and the corresponding compressive stresses in the uppermost right corner. This corresponds to the reactive force moment making equilibrium with the crash load. Note the localized compressive zone in the uppermost part of the outer stiffening flanges in the left part of the casting. These stresses are a result of the load attacking the structure a little eccentric to the right as seen from the load (seen from the left of the casting in the figure). This results in an out-of-plane bending force moment.

Figure 7 right shows the horizontal normal stress component. First of all, the boundary condition of a prescribed normal stress of -11 MPa is recognized at the left part of the casting. Moreover, the mission of the crisscross-wise inclined stiffeners in the middle of the casting acting by and large as bars in alternating tension and compression is noticed.

In Figure 8 left the Mises stress field from the load situation is depicted. Both the distribution and the level of the Mises stress is coherent with the two normal stress components shown in Figure 7. It is interesting to compare the load induced Mises stress with the casting induced Mises stress field shown in Figure 4 left. First of all, it is obvious that the casting Mises stresses are lower, however, not negligible. Secondly the distribution is somewhat different which is no surprise since the two fields are originating from substantially different “loads”, i.e. i) a thermal contraction at high temperature in a mould presenting constraints and ii) a prescribed compressive stress at room temperature with the part constrained at the upper plane surface where it is mounted. Moreover, in Figure 8 right it is noticed that the effective plastic strain due to the loading is very low in most of the part and reaches its maximum in localized areas which coincide with the values of the high Mises stress. This is of course to be expected.
DISCUSSION

As is mentioned earlier, development of casted components without taking considerations of the parameters that the component gets caused by the production process. The first stage is aimed to improve the simulations of the final state by taking into account the microstructure development and resulting mechanical properties. These local mechanical properties are the base for the stress and strain calculations, however, in the present work, as a preliminary procedure no distribution of these properties has been considered in the load calculation.

CONCLUSION

In the present work a preliminary attempt to do an integrated analysis of the casting process and the subsequent loading situation for a complex aluminium casting is carried out. This comprises simulation of the entire casting process with focus on microstructure formation related to mechanical properties as elastic modulus, yield stress, ultimate strength and elongation as well as residual stresses. Subsequently, the casting is subject to service loads and the results of this analysis are discussed in relation to the predicted local properties as well as the residual stresses originating from the casting simulation.

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