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This is the published peer-reviewed version of a paper published in the conference series *IOP Conference Series: Materials Science and Engineering (MSE)*.

Citation for the published paper:

Olofsson, J., & Svensson, I. L. (2012). Casting and stress-strain simulations of a cast ductile iron component using microstructure based mechanical behavior. *IOP Conference Series: Materials Science and Engineering*, 33(1), 012051.

DOI: <http://dx.doi.org/10.1088/1757-899X/33/1/012051>

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Casting and stress-strain simulations of a cast ductile iron component using microstructure based mechanical behavior

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Abstract. The industrial demand for increased component performance with concurrent reductions in component weight, development times and verifications using physical prototypes drives the need to use the full potential of casting and Finite Element Method (FEM) simulations to correctly predict the mechanical behavior of cast components in service. The mechanical behavior of the component is determined by the casting process, and factors as component geometry and casting process parameters are known to affect solidification and microstructure formation throughout the component and cause local variations in mechanical behavior as well as residual stresses. Though residual stresses are known to be an important factor in the mechanical behavior of the component, the importance of local mechanical behavior is not well established and the material is typically considered homogeneous throughout the component. This paper deals with the influence of solidification and solid state transformation on microstructure formation and the effect of local microstructure variations on the mechanical behavior of the cast component in service. The current work aims to investigate the coupling between simulation of solidification, microstructure and local variations in mechanical behavior and stress-strain simulation. This is done by performing several simulations of a ductile iron component using a recently developed simulation strategy, *a closed chain of simulations for cast components*, able to predict and describe the local variations in not only elastic but also plastic behavior throughout the component by using microstructural parameters determined by simulations of microstructural evolution in the component during the casting process. In addition the residual stresses are considered. The results show that the FEM simulation results are significantly affected by including microstructure based mechanical behavior. When the applied load is low and the component is subjected to stress levels well below the yield strength of the material, the residual stresses highly affect the simulation results while the effect of local material behavior is low. As the applied load increases and the stress level in the component approaches and passes the yield strength, the effect of residual stresses diminishes while the effect of local mechanical behavior increases. In particular the predicted strain level is heavily affected by the use of local mechanical behavior. It is proposed that it is important to include both local mechanical behavior and residual stresses in stress-strain simulations to predict the true mechanical behavior of the component.

1. Introduction

The solidification process of cast iron is a complex interaction between physical, chemical and mechanical phenomena. Much research has been aimed at understanding the solidification of cast iron, and solidification models have been developed which are able to simulate the solidification process and predict microstructural features. By combining these solidification models with simulations of fluid flow it is possible to simulate the entire casting process of a specific component and predict the local variations in microstructure throughout the component.

The mechanical behavior of cast irons is commonly characterized by a tensile curve which shows true stress σ (Pa) versus total true strain ε_T (-). A linear elastic region described by Hooke's law ($\varepsilon_{el} = \sigma/E$, where E (Pa) is Young's modulus) and a non-linear plastic region are identified. In this work the plastic behavior is described using the Hollomon equation $\sigma = K \times \varepsilon_{pl}^n$ [1] where the strength coefficient K (Pa) and the strain hardening exponent n (-) relate true stress and true plastic strain ε_{pl} (-).

The mechanical behavior of cast irons is known to be controlled by microstructural parameters, where graphite fraction and morphology has been shown to be important contributors to the deformation behavior of the material [2-4]. In previous research models to predict Young's modulus [5, 6] and the parameters of the Hollomon equation [7, 8], i.e. the strength coefficient and the strain hardening exponent, have been developed. By combining these models with solidification models it is possible to predict both elastic and plastic mechanical behavior throughout cast iron components using casting simulation software [9].

During the solidification process of a cast iron component the solidification conditions vary throughout the component, which cause local variations in the final microstructure and mechanical behavior [6] as well as formation of residual stresses. Though the effect of residual stresses on the mechanical integrity of cast iron components has been studied [10], the effect of local variations in mechanical behavior on the stress-strain response has not been previously investigated.

The current work aims to investigate this effect by using casting process simulation and stress-strain simulations of a ductile iron heavy truck engine support. The simulations have been performed using a recently presented simulation strategy called a *closed chain of simulations for cast components* [9]. The simulation strategy combines different types of simulations, schematically illustrated in Figure 1. The results from each simulation step is the basis for the next simulation step, thus the denotation a *closed* chain of simulations. The strategy uses solidification and solid-state transformation models to predict microstructure formation and mechanical behavior on a local level throughout the component, and incorporates the variations in mechanical behavior into an FEM simulation of the mechanical behavior of the component. The effect of these variations on the behavior of the component needs to be established since it directly affects the process of designing cast iron components, which concerns the work of metallurgists as well as CAE and design engineers.

Figure 1. The closed chain of simulations for cast components [9]. The figure is reprinted with permission from Elsevier.

2. Simulation setup

2.1. Casting process simulation

The casting process simulation of the component has been performed in a development version of MAGMASoft [11] which uses solidification [12] and solid state transformation models developed by e.g. Wessén and Svensson [13] to predict microstructure evolution throughout the component, and the previously mentioned microstructural relationships [7, 8] to predict the local variations in the parameters of the Hollomon equation.

2.2. Incorporation of predicted mechanical behavior

An in-house developed software [9] has been applied to create material definitions for the FEM simulation based on the results from the casting process simulation. The materials are defined by a linear elastic region and a piecewise linear plastic region, in which a number of points along the plastic part of the stress-strain curve are specified. In this work the stress-strain curve was defined from $\varepsilon_{pl}=0\%$ to $\varepsilon_{pl}=10\%$. This range is divided into two intervals, from 0% to 1% respectively from 1% to 10%. Each interval is described by 10 linearization points, thus in total 20 linearization points are used. These settings have in previous work been shown to be an efficient way to describe the non-linear stress-strain curve, see reference [9] where the settings are further explained.

Four different material descriptions are considered with parameters as shown in Table 1. The descriptions correspond to different ways of using data from the casting process simulation in the FEM simulation:

- LOCAL uses individual material definitions for every element of the FEM mesh, i.e. about 132 000 material definitions, to capture the local variations in mechanical behavior. This is a *closed connection* between casting process simulation and FEM simulation which uses *component specific microstructure-based mechanical behavior*, enabled by the *closed chain of simulations for cast components* [9].
- AVERAGE uses *weighted averages* of the predicted mechanical behavior parameters throughout the component to create a *very accurate homogenous description* of the material in the component. Since all parameter values throughout the FEM mesh are included in the weighted average values the variations in the parameter values are taken into account.
- MAXMIN uses the *mean of the maximum and minimum values* of the mechanical behavior parameters to create a *simple homogeneous material description*. Since only the maximum and minimum values are used to determine these mean values the variations in parameter values throughout the FEM mesh are *not* taken into account.
- TABLE uses tabulated homogeneous material data for the standard material EN-GJS-600-3, which is similar to the material used in the casting process simulation. The use of tabulated material data is a common way of performing FEM simulations of cast iron components in the industry, but do not consider any component specific effect of the casting process on the mechanical behavior of the material in the component. To characterize the plastic behavior of the material the strain hardening exponent and the strength coefficient in this work have been derived from tabulated values of yield stress σ_Y , ultimate tensile stress σ_U and ultimate elongation ε_U as $n=\ln(\sigma_U/\sigma_Y)/\ln(\varepsilon_{pl,Y}/\varepsilon_{pl,U})$ respectively $K=\sigma_Y/(\varepsilon_{pl,Y})^n$.

Table 1. Parameter values used in the different material descriptions.

Material name	E [GPa]	n [-]	K [MPa]	No. material definitions
LOCAL	168.1-175.5	0.108-0.175	707.1-1668.1	132 000
AVERAGE	170.7	0.13	1046.2	1
MAXMIN	171.8	0.14	1187.6	1
TABLE	170.0	0.25	1733.0	1

2.3. FEM simulation

A FEM mesh of the component consisting of about 132 000 second order tetrahedral elements was created in Abaqus [14] format. Four surfaces were fixed and a load was applied as shown in Figure 2. The load is linearly increased from 0 to 150 kN with a 15 kN load increase in every timestep of the simulation. This load level was chosen to achieve a maximum stress level around the estimated ultimate tensile stress for the material (600 MPa). The 0.2% offset yield stress of the material is first exceeded at an applied load of 60 kN.

Figure 2. FEM simulation loadcase setup.

FEM simulations were performed using all four material variants, with and without including the residual stresses predicted by the casting process simulation. The simulations *without* residual stresses will be referred to using the name of the material description used in the simulation (TABLE, MAXMIN etc.) and the simulations *with* residual stresses included are referred to with the additional suffix -RS (e.g. TABLE-RS etc.). For every simulation the predicted maximum von Mises stress and maximum von Mises strain in the component at every timestep were extracted. To evaluate the accuracy of the simulations one simulation is selected as a reference, and the relative error in maximum value (*MVE*) is determined as the difference in maximum values predicted by the simulation under consideration (*C*) and the reference simulation (*R*) divided by the value predicted by the reference simulation, i.e. $MVE = (C - R) / R$. A negative value of relative error thus corresponds to an underrated maximum stress or strain value, and a positive value corresponds to an overrated value.

3. Results and discussion

3.1. Casting process simulation results

The casting process simulation shows that local variations in solidification conditions leads to different microstructures in different regions of the component. This leads to variations in Young's modulus and the parameters of the Hollomon equation throughout the component, shown in Figure 3.

3.2. Effect of local variations in mechanical behavior.

To evaluate the isolated effect of local variations in mechanical behavior the simulations without residual stresses are first considered. Comparing the results from the LOCAL simulation and the AVERAGE simulation it is found that not only does the maximum stress value change when the local variations in mechanical behavior are neglected, the location of the maximum stress may also be found in another location, see Figure 4. The variations in material behavior thus affects the stress distribution throughout the component, and the incorrect location of maximum stress or strain may be predicted when homogeneous material behavior is assumed. This effect is most significant in geometrical stress concentrations, and may lead to incorrect conclusions about the severity of stress concentrations and the mechanical performance of the component.

Figure 3. Local variations in a) Young's modulus b) strain hardening coefficient and c) strength coefficient throughout the component predicted by the casting process simulation.

Figure 4. Predicted maximum stress at an applied load of 75 kN by a) the LOCAL simulation and b) the AVERAGE simulation.

To numerically evaluate the influence of local material behavior the LOCAL simulation is chosen as reference simulation, and the simulations *without* residual stresses are evaluated. Figure 5 shows the obtained development of the relative error in maximum stress, Figure 5a, and maximum strain, Figure 5b, during the simulation. In the elastic region the differences in load response are only determined by the variations in Young's modulus, an effect which is small at low loads. As the load increases and approaches the yield stress the effect however increases, and it is seen that, independent of material description, the assumption of homogeneous material behavior may lead to an error of about 5% in stress level and 5-10% in strain level in the elastic region. If tabulated material data is used, an error in stress level of more than 10% is obtained. As the load level further increases and enters the plastic region the differences between the material descriptions are significant. AVERAGE gives a rather constant error in stress level of only about 2% while the error in strain level increases from 10 to 17% with increasing load. The MAXMIN gives an error of about 7% in stress level and 10-35% in strain level. In the plastic region the effect of local variations in material behavior thus become significant and must be considered to capture the stress-strain response of the component. The use of tabulated data may underrate or overrate the stress level significantly ($\pm 10-15\%$), and the error in strain level may vary widely (5-25%). This shows that none of the homogeneous material descriptions are able to

describe the effect of local material behavior on the mechanical behavior of the component. The assumption of homogeneous material behavior leads to errors especially in predicted strain level. In order to obtain accurate FEM simulation results of a ductile iron component the local variations in mechanical behavior thus needs to be captured using solidification models and be incorporated into the FEM simulation. This motivates the use of component specific microstructure-based mechanical behavior in structural analyses of ductile iron components.

Figure 5. Relative error in a) maximum stress and b) maximum strain using different material definitions. Vertical line at 60 kN indicates the beginning of plasticity, i.e. the 0.2% offset yield stress is exceeded.

3.3. Effect of residual stresses.

A similar evaluation is performed of the simulation results *with* consideration of residual stresses. In this case the simulation with both local mechanical behavior and residual stresses, LOCAL-RS, is selected as reference simulation, and the results from the remaining simulations *with* residual stresses are evaluated. Figure 6 shows the obtained development of relative error in maximum stress and maximum strain. Comparing Figure 5 and Figure 6 it is seen that the trends and amounts of error are very similar. The conclusions about the importance of including local variations in mechanical behavior are thus still valid when residual stresses are included.

To evaluate the relative importance of including local material behavior versus including residual stresses the results from the simulations *without* residual stresses included are re-evaluated using the LOCAL-RS simulation as reference. The obtained development of relative error in maximum stress and maximum strain is shown in Figure 7, in which the results from the simulations *without* residual stresses are shown with black curves and the results *with* residual stresses are shown with grey curves. The results show that local material behavior and residual stresses affect the mechanical behavior of the ductile iron component in different ways. When the applied load is low the contribution from the residual stresses is dominating while the effect of local material behavior is low. As the applied load increases and the stress level in the component approaches the yield stress the relative importance of residual stresses however diminishes and the selected type of material description instead determines the accuracy of the simulation results. AVERAGE leads to a low error in stress level (about 2%) but a large error in strain level (about 10-15%). MAXMIN and TABLE gives a larger error in both stress (5-10%) and strain levels (about 10-30%). LOCAL has almost no relative error in stress or strain in the plastic region, thus to correctly determine the stress and strain levels in the component subjected to plastic loads it is more important to consider local variations in material behavior than to consider residual stresses. At low loads (less than 60 kN), the residual stresses must however be included to predict the correct stress level.

Figure 6. Relative error in a) maximum stress and b) maximum strain using different material descriptions and including residual stresses.

Figure 7. Combined effect of using different material definitions and not including residual stresses on relative error in a) maximum stress and b) maximum strain. Results *without* residual stresses are shown with black curves and results *with* residual stresses are shown with grey curves.

4. Conclusions

- The predicted mechanical behavior of the component is significantly affected by the local variations in mechanical behavior and residual stresses caused by the local variations in solidification conditions.
- Local variations in mechanical behavior cause a stress/strain distribution throughout the component that homogeneous material descriptions are not able to describe. This effect becomes noticeable already in the elastic region.
- Residual stresses gives an important contribution to the predicted stress level when the applied load is low.
- Local variations in mechanical behavior gives a larger contribution to the predicted stress level than residual stresses when the applied load is high.
- Both local variations in mechanical behavior and residual stresses must be included to correctly determine the stress and strain level at all loads.

Acknowledgements

The Swedish Knowledge Foundation is greatly acknowledged for financing the research profile COMPCast and its subproject CCSIM in which the current work has been performed. The authors would also like to thank Scania CV AB for supplying the component geometry.

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