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Incorporating predicted local mechanical behaviour of cast components into finite element simulations

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Abstract

A software which enables the incorporation of local variations in both elastic and plastic mechanical behaviour predicted by a casting process simulation into a Finite Element Method (FEM) simulation is presented. The software uses a piecewise linearization of the Hollomon or the Ludwigson equation to characterise plastic mechanical behaviour of the material on an element level throughout a component. The accuracy obtained in the linearization is investigated, and the performance of the software is studied using different input parameters. The applicability of the software is verified and demonstrated on a ductile iron component, and a simulation strategy for cast components denoted *a closed chain of simulations for cast components* is discussed.

Keywords: C. Casting E. Mechanical F. Plastic behaviour

1. Introduction

In the automotive and transportation areas the pursuit for vehicles with low fuel consumption and low amounts of emissions drives the demand for designing cast components with high performance and low weight. In this design process both materials with a low density, such as magnesium and aluminium, and materials with higher density and higher strength, e.g. cast irons, have to be considered, where the higher strength of the material may be utilized to reduce the volume of the component and thus decrease the total weight of the component. Simultaneously, the increasing safety and quality demands on vehicles increase the need to accurately predict the load response of cast components, and the importance of the correct use of Finite Element Method (FEM) analyses as well as geometry optimisation methods becomes critical. These analyses are typically based on assumptions of homogeneous mechanical behaviour throughout the cast component. The mechanical behaviour of cast alloys is however known to be determined by microstructural parameters which to different extents are affected by the actual design of the component as well as casting process related parameters. As an example the mechanical behaviour of cast aluminium alloys is highly dependent on the secondary dendrite arm spacing (SDAS) [1-3], determined by the local solidification time [4] which typically varies throughout the component. In cast irons the mechanical behaviour is similarly highly controlled by graphite morphology and pearlite content [5-8]. The casting process thus results in non-homogenous mechanical behaviour throughout a component, which needs to be considered to correctly predict the mechanical response and

performance of the component [9]. In addition residual stresses induced in the component by the casting process contribute to the behaviour of the component [10].

The mechanical behaviour of a material is commonly characterized by a curve obtained from a tensile test, showing the true stress σ (Pa) versus the true total strain ε_T (-). A linear elastic region and a non-linear plastic region is identified, where the true elastic strain ε_{el} (-) is determined by Hooke's law, $\varepsilon_{el} = \sigma/E$, in which E is Young's modulus (Pa). Several models have been proposed for the plastic region [11], e.g. the Hollomon equation [12] and the Ludwigson equation [13]. The Hollomon equation, Eq. (1), describes the relationship between stress and plastic strain ε_{pl} (-) using the strain hardening exponent n_H (-) and the strength coefficient K_H (Pa) as

$$\sigma_H = K_H \cdot \varepsilon_{pl}^{n_H} \quad (1)$$

The strain hardening exponent has a value between zero and unity, where $n_H = 0$ corresponds to a perfectly plastic material where $\sigma_H = K_H$, and $n_H = 1$ describes a linear deformation hardening material in which $\sigma_H = K_H \cdot \varepsilon_{pl}$. The effect of different values of the strain hardening exponent on the shape of the plastic deformation curve predicted by the Hollomon equation is shown in Fig. 1. The strength coefficient K_H gives an indication of the strength potential of the material but must be evaluated in combination with the strain hardening exponent.

The Ludwigson equation, Eq. (2), adds a correction term to the Hollomon equation at low plastic strains, using the parameters n_L (lnPa) and K_L (lnPa). This correction term leads to a more accurate description of the plastic behaviour found in ductile iron and compacted graphite iron [14].

$$\sigma_L = \sigma_H + \exp(K_L + n_L \cdot \varepsilon_{pl}) \quad (2)$$

The relationships between casting process parameters, microstructural parameters and mechanical behaviour of cast alloys have been intensively studied in the literature [1-8, 14, 15], and simulation methods to consider casting process related mechanical properties using experimentally determined alloy specific material parameters have been proposed [16-18]. Recent research has however enabled the possibility to use casting simulation software to predict not only elastic but also plastic mechanical behaviour of cast components, where relationships between microstructural parameters and the parameters of the Hollomon equation or the Ludwigson equation have been developed for cast aluminium alloys by Seifeddine et al. [19] and for cast irons by Larsson et al. [14]. The applicability of these predictions on a local level has however been limited due to the lack of tools to incorporate these results into FEM simulations. Instead the same behaviour in all elements has been assumed [20].

The current work addresses this problem, and aims to present and verify a newly developed software which enables incorporation of local elastic and plastic mechanical behaviour as well as residual stresses predicted by a casting simulation into a FEM simulation. The software enables the use of a simulation strategy where state-of-the-art casting simulation software and FEM simulation software are combined to accurately predict the mechanical behaviour and performance of cast components in service. This strategy is of direct importance for the work of design engineers, solid mechanics engineers and material engineers, whose skills need be combined in order to develop truly optimized and reliable light-weight cast components with high performance and quality. The strategy aims to

increase the accuracy of the virtual product development process, which decreases the need for physical prototypes and testing and thus reduces the development cost for cast components.

2. Software verification

2.1. Implementation

A software has been developed which, based on material parameters predicted by a casting simulation software, creates material definitions for a FEM simulation. The plastic behaviour is characterized using a piecewise linearization of the plastic material behaviour predicted by the Hollomon or the Ludwigson equations. In addition the residual stresses predicted by the casting simulation software may be included as initial conditions to the FEM simulation. The casting simulation is performed using a development version of the commercial casting simulation software MAGMAsoft [21], which is based on the Finite Difference Method (FDM) and able to include all steps of the casting process in the simulation. The formation and evolution of microstructural constituents during solidification is determined using physical models, e.g. those by Wessén et al. [22] and Wessén and Svensson [23]. The plastic mechanical behaviour of the component is predicted on a local element level using the previously mentioned relationships for aluminium alloys and cast irons [14, 19]. The MAGMALink module of MAGMAsoft is applied to adapt the results from the FDM model to the FEM model.

The new software is implemented using the Python programming language [24], and is controlled from a graphical user interface in Abaqus/CAE [25]. The software is able to create individual material definitions of the elastic and plastic behaviour for every element of the FEM mesh, which results in as many material definitions as there are FEM elements. For large components containing a large number of elements this approach will however yield a very large amount of material data and a large input file for the FEM solver. In order to reduce the amount of material data a number of intervals may in the software be specified for each parameter (E , n_H , K_H , n_L respectively K_L) in which the average value of the interval is used for the elements with values within the corresponding interval range.

2.2. Linearization evaluation

Many foundries act as sub-suppliers of cast components, and perform casting simulations e.g. to ensure castability and high quality of their products. The FEM simulations of the components may however be performed elsewhere, e.g. at the customer's product development department. To be able to provide the customer with predicted residual stresses and local mechanical behaviour of the component independent of the customer's choice of FEM solver it is of interest to base the simulation on a material model which is implemented in a large number of commercial FEM solvers. In the present work the piecewise linear plastic material model is chosen, which describes the plastic behaviour by a linearization between given points of the plastic part of the material's tensile curve. During the FEM simulation the stress-strain curve is interpolated between the specified points of the curve.

A linearization of the non-linear plastic stress-strain curve is a simplification which will introduce some degree of error, and the accuracy of the linearization will depend on the number and the distribution of the linearization points. In the current work a simple distribution method is adopted,

where a user-defined number of linearization points are distributed from $\varepsilon_{pl} = 0$ to a defined maximum plastic strain $\varepsilon_{pl,max}$. To improve the accuracy of the linearization in the region of low plastic strains, where the curvature of the stress-strain curve is high, the strain is divided into two intervals separated by an interval divider at $\varepsilon_{pl} = \varepsilon_{div}$. Half the number of linearization points are evenly distributed in the first interval, and the remaining points are evenly distributed in the second interval. This approach is schematically illustrated in Fig. 2, where a total number of 4 linearization points are divided into two intervals at $\varepsilon_{pl} = \varepsilon_{div}$, thus 2 equally spaced points are positioned within each interval.

In order to investigate the magnitude of the error introduced by the linearization and to locate an appropriate position of the interval divider a linearization evaluation has been performed. A given non-linear stress-strain curve predicted by the Hollomon equation was compared to a linearization of the same curve. Two different values of the strain hardening exponent were considered, in the first case $n_H = 0.1$ and in the second case $n_H = 0.2$, and the linearization parameters were selected as shown in Table 1. The comparison was performed in the plastic strain range $\varepsilon_{pl} = 0-0.1$, in which the accuracy of the linearization of the Hollomon curve, $\sigma_{H,LIN}$, was evaluated at $m = 10\,000$ evenly distributed points using the Mean Percentage Error (MPE, (%)) determined as

$$MPE = \frac{100}{m} \sum \frac{|\sigma_H - \sigma_{H,LIN}|}{\sigma_H} \quad (3)$$

The obtained variations of the MPE are shown in Fig. 3. It is seen that, as expected, an increasing number of linearization points has a positive effect on the accuracy and the MPE decreases. This effect decreases with increasing number of points, and after 40-50 points the effect is small. The effect of adding an interval divider is much more significant, and effectively reduces the MPE also for a small number of linearization points.

The position of the interval divider is seen to affect the MPE, and the effect is different in the two different cases. In the first case where $n_H = 0.1$, Fig. 3a, the accuracy is generally improved with decreasing value of ε_{div} but increases if the lowest value of $\varepsilon_{div} = 0.002$ is selected. In the second case where $n_H = 0.2$, Fig. 3b, the highest accuracy is however obtained with the highest value of the interval divider, $\varepsilon_{div} = 0.02$, and the linearization error increases with decreasing ε_{div} . This difference is explained by the different curvatures in the two cases. As seen in Fig. 1 the first case, $n_H = 0.1$, corresponds to a high transition curvature in a narrow strain region compared to the second case, $n_H = 0.2$, in which the curvature is lower in a wider strain region. A higher value of ε_{div} is thus needed to accurately linearize the second case compared to the first. In addition the MPE is generally lower in the second case, which is more easily described by a linearization. It is found that for both cases an interval divider of $\varepsilon_{div} = 0.01$ gives a very high accuracy using only 10-20 linearization points.

2.3. Performance evaluation

To investigate the stability and the performance of the developed software a test matrix was set up. In order to cover a wide range of applications, the amount of input data was varied as well as different parameters of the software. Table 2 shows the evaluated number of elements, material definitions, linearization points and types of material characterization (elastic behaviour only (E), or both elastic and plastic behaviour using the Hollomon (H) respectively the Ludwigson (L) equation). The input for each evaluation was generated using a Python script. For every combination of input data three evaluations were performed, leading to a total of 270 evaluations. The evaluations were

performed using a standard laptop computer with a dual core 2.53 GHz processor and 4 GB of RAM. The calculation times were determined by implementing timestamps into the output file. The reported calculation times are the averages of the three evaluations, but in general very small variations were obtained when the same input data and set of parameters were used. The size of the output files in megabyte (MB) was also noted, which only depends on the amount of output data created and is thus independent of equation used for the plastic characterization.

Fig. 4 shows the calculation times and output file sizes obtained when all the available material data is used, i.e. the number of material definitions corresponds to the number of elements. It is seen in Fig. 4a that the calculation time increases linearly with the number of elements, and is slightly increased by using the Ludwigson equation instead of the Hollomon equation. The output file size, Fig. 4b, rapidly becomes very large, which motivates a reduction in the number of material definitions. Fig. 5 shows the calculation times and file sizes obtained when the number of material definitions is reduced. Comparing Fig. 4 and Fig. 5 it is clearly seen that both the evaluation time and the output file size is greatly reduced by reducing the number of material definitions. Fig. 4b and Fig. 5b also shows that the decrease in output file size when the number of linearization points is decreased from 40 to 20 is significant. By decreasing the number of linearization points the amount of output data can thus be significantly reduced. This motivates the use of an interval divider which, as previously shown, enables the possibility to decrease the number of linearization points without decreasing the accuracy of the linearization.

2.4. Verification

To verify the applicability of the software a simulation of a ductile iron engine support component was performed using a work flow illustrated in Fig. 6. The CAD-geometry was imported into a development version of MAGMAsoft, where a simulation of the casting process, including filling, solidification and a prediction of mechanical behaviour and residual stresses was performed. The predicted variations in strain hardening exponent throughout the component are seen in Fig. 7, and the minimum and maximum values of the material characterization parameters are shown in Table 3.

Similarly a FEM-model was created using the CAD-geometry of the component. The developed software was used to create the material definitions and initial conditions for the FEM simulation. The FEM simulation was defined by specifying boundary conditions and loads, and the simulation was performed using Abaqus. The resulting stress distribution in the component at a certain load is shown in Fig. 8. Details about the simulations as well as simulation results will be presented in future work. In the scope of the current work it is concluded that the local mechanical behaviour and residual stresses from the casting simulation were successfully incorporated into the FEM simulation by the developed software, and the applicability of the software for an industrial component has thus been verified.

3. Discussion

The software developed creates a link between casting simulation and FEM simulation and enables a design strategy for cast components entirely based on simulations. This strategy is denoted *a closed*

chain of simulations for cast components, and is illustrated in Fig. 9. The strategy uses casting simulation software to predict both elastic and plastic mechanical behaviour of the material locally throughout the component based on the chemical composition of the alloy, and is thus not dependent on experimentally determined alloy specific parameters. To the authors knowledge this has not been previously reported in the literature. Though other FEM simulation methods to consider mechanical behaviour of cast alloys have been presented [16-18] they are to different extent dependent on experimentally determined parameters. In addition local variations of mechanical behaviour throughout the component are not considered, but local variations in amount of defects are used to simulate local variations in mechanical performance.

As shown in Fig. 9 the closed chain of simulations starts with the simulation of the casting process of the component. The specified chemical composition of the alloy determines the phase diagram for the material, and the microstructure evolution during solidification and heat treatment processes is modelled taking into account the effect of casting process related parameters. The final microstructure and its variations throughout the component determines the material behaviour on a local level, e.g. by relationships between microstructure and mechanical behaviour. The predicted local material behaviour is incorporated into a simulation of the component behaviour, typically performed using a FEM solver. Note that though in the current work the simulations have been performed using MAGMAsoft and Abaqus the simulation strategy in general is not software dependent but allows the use of area-specific state-of-the-art software as long as the results can be transferred between the software. The denotation *chain of simulations* suggests that additional links can be incorporated, e.g. machining simulation, geometry optimisation, reliability methods etc.

Though only the Abaqus format is currently supported by the software developed, the use of a standard piecewise linear plastic material model enables the use of a large number of FEM solvers. The linearization evaluation shows that a low degree of error is introduced by the linearization if the linearization parameters are chosen correctly, and that the interval divider approach is an efficient way to increase the accuracy while minimising the number of linearization points. The amount of material data can thus be kept at a moderate level without losing accuracy. By reducing the number of linearization points the number of material definitions may also be increased without increasing the file size, thus increasing the accuracy of the description of the plastic behaviour throughout the component. Though other approaches to select the linearization points may be considered, the interval divider approach is easy to use and is applicable to other models of plastic behaviour.

The convergence of the FEM results are not only determined by the linearization accuracy in each material definition, but also the number of material definitions and the size of the elements used in the FEM model. Both a high number of material definitions and a small size of the elements will lead to more accurate descriptions of the local variations of mechanical behaviour, but the different contributions to the FEM results needs to be further investigated in order to determine appropriate levels of linearization accuracy, number of material definitions and element size.

The closed chain of simulations strategy has been successfully applied to an industrial component by using the developed software and the workflow shown in Fig. 6. The workflow is not limited to this specific component but can be applied to a large variety of industrial components. In this first demonstration the same CAD-geometry was used for both the casting simulation and the FEM simulation, while in many cases the geometry of the final component differs from the geometry of

the casting due to intermediate machining operations. As long as the machined geometry is enclosed by the geometry of the casting this is however included by the adaption of results from the casting simulation.

The simulation strategy enables new possibilities to study the effect of casting process related parameters on the component, not only on the microstructural level but also on the mechanical behaviour of the component in service. Further investigations on the simulation results are however needed to study the importance of different contributions to the total mechanical behaviour of a component and to determine how the simulation strategy can be applied to the virtual product development process of cast components.

4. Conclusions

The software developed has successfully enabled the incorporation of predicted local elastic and plastic mechanical behaviour of a cast component into a FEM simulation. By using an interval divider the piecewise linearization approach used in the software gives an accurate description of the plastic behaviour of the material using a minimum number of linearization points. The software is able to handle large FEM models, and by specifying intervals for the material parameters the number of material definitions can be selected. The software enables a simulation strategy denoted *a closed chain of simulations for cast components*. The strategy has been demonstrated on a ductile iron industrial component.

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Fig. 1. Effect of different values of the strain hardening exponent n_H on the plastic deformation curve predicted by the Hollomon equation.

Fig. 2. Schematic illustration of the interval divider approach.

Fig. 3. Variation of MPE with different linearization parameters for (a) $n_H = 0.1$ and (b) $n_H = 0.2$.

Fig. 4. Results of (a) calculation time and (b) file size using all available material data.

Fig. 5. Results of (a) calculation time using 40 linearization points and (b) file size when the number of materials is reduced.

Fig. 6. Illustration of the simulation workflow.

Fig. 7. Variations of the strain hardening exponent n_H in the component predicted by the casting simulation.

Fig. 8. Stress distribution in the component predicted by the FEM simulation. Both local mechanical behaviour and residual stresses are included in the simulation.

Fig. 9. The closed chain of simulations for cast components.

Table 1: Linearization parameters used for the linearization evaluation.

ϵ_{div} [-]	Number of linearization points	n_H [-]	K_H [MPa]
No divider, 0.002, 0.005, 0.01, 0.02	10, 20, 30, 40, 50, 100	0.1, 0.2	1 500

Table 2. Test matrix for performance evaluation.

Number of elements	Approx. number of material definitions	Type of material characterization	Number of linearization points
15 000	100, 15 000	E	-
	100, 1 000, 10 000, 15 000	H, L	20, 40
50 000	100, 50 000	E	-
	100, 1 000, 10 000, 50 000	H, L	20, 40
100 000	100, 100 000	E	-
	100, 1 000, 10 000, 100 000	H, L	20, 40
200 000	100, 200 000	E	-
	100, 1 000, 10 000, 200 000	H, L	20, 40
500 000	100, 500 000	E	-
	100, 1 000, 10 000, 500 000	H, L	20, 40

Table 3. Values of mechanical behaviour in the component predicted by the MAGMAsoft simulation.

Parameter	Min	Max
E [GPa]	168.1	175.5
n_H [-]	0.108	0.175
K_H [MPa]	707.1	1668.1