Simulation of Mechanical Behaviour of Cast Aluminium Components: A Literature Review

Jakob Olofsson

Jönköping University, School of Engineering, Dept. Mechanical Engineering,
Materials and Manufacturing – Casting, P.O. Box 1026, SE-551 11 Jönköping, Sweden
Email: jakob.olofsson@jth.hj.se Phone: +46 (0)36-10 16 59

ABSTRACT

A literature review on methods to consider mechanical behaviour of cast aluminium alloys in finite element method (FEM) simulations of cast aluminium components has been performed. The mechanical behaviour is related to several microstructural parameters achieved during the casting process. Three different methods to consider these microstructural parameters are introduced. One method predicts the mechanical behaviour of the component using casting process simulation software. The other two methods implements numerical models for mechanical behaviour of cast aluminium into the FEM simulation. Applications of the methods are shown, including combinations with statistical methods and geometry optimisation methods. The methods are compared, and their different strengths and drawbacks are discussed.

Keywords:

Aluminium, FEM simulation, microstructure, mechanical behaviour

1. INTRODUCTION

The constantly increasing demands on environmental, safety and economical issues on vehicles drive the demand for lightweight components with high performance and low life-cycle cost. By designing lighter components, the weight and the emissions of the vehicle can be reduced. Simultaneously the mechanical loads, e.g. fatigue load or crash load, on the component must be considered in order to meet safety and quality demands. The correct usage of tools such as finite element method (FEM) analyses and geometry optimisation thus becomes more and more important in order to, in the design phase, correctly predict the behaviour of the component in service. These tools are highly dependent on correct input of the mechanical behaviour of the material in the component in order to accurately and correctly predict the performance of the component.

Cast aluminium components are manufactured by several different casting processes, e.g. high/low pressure die casting (HPDC/LPDC), gravity die casting and sand casting. During the casting process the microstructural characteristics, which determine the actual performance of the material in the component, are obtained. One important microstructural characteristic is the secondary dendrite arm spacing, SDAS (λ), which is as a function of the local solidification time where a short solidification time (i.e. a high cooling rate) gives a small SDAS.[1, 2] SDAS is widely used as a measure of microstructural refinement,[3] but changes in SDAS are also accompanied by several other microstructural

changes.[4-7] A decreasing SDAS generally increases the yield strength (YS),[4, 5, 7] the ultimate tensile strength (UTS)[1, 2, 5-9] and the ductility[1, 3, 5-7] of the material, but the trends may have variations due to concurrent changes in size and shape of eutectic Si-particles.[9-11] The plastic behaviour and fracture of cast aluminium alloys is furthermore highly affected by the characteristics[12-14] and damage[11, 15-18] of the Si-particles, where especially ductility[13] and strain hardening rate is increased with increased aspect ratio of the Si-particles.[15, 16, 19, 20]

Damage of the Si-particles consists of three stages: *cracking or debonding*, *microcrack formation and growth*, and *local linkage of microcracks,*[6, 21] and both cracked[6, 11, 17, 18] and debonded[18, 22] particles may initiate global fracture. Particle fracture is caused by incompatibility stresses between particle and matrix,[18, 22] and in general larger and longer particles are more likely to crack.[6, 17] The probability of particle-cracking, p_{pc}, can be described by Weibull statistics as[11]

$$p_{pc} = 1 - \exp\left[-\left(\frac{V}{V_0} \right) \left(\frac{\sigma_p}{\sigma_{p0}} \right)^m \right] \quad (1)$$

where V is the particle volume, V_0 is a reference volume, σ_p is the tensile stress in the particle, σ_{p0} is a reference stress and m is the Weibull modulus.

The mechanical properties are also reduced by the presence of iron-rich intermetallic phases, most importantly α-, β- and π-Fe phases,[7, 23, 24] and by the structural integrity[25-32] of the component, i.e. the presence of structural defects such as porosity, oxide films, macro- and micro-porosity. While yield strength is relatively unaffected by porosity,[25-27] both UTS and elongation to fracture decrease with increased amount of porosity.[25, 27] Defects generally affect fracture strength, elongation to fracture and fatigue life of cast aluminium alloys[28, 29] and cause variations in properties achieved during the casting process.[30] Elongation to fracture is reported to depend on defects as[31, 32]

$$e_f = e_{\max} \left(1 - f_d\right)^{n_G} \quad (2)$$

where f_d is the area fraction of defects, e_{max} is the tensile ductility of defect-free material, i.e. the highest achievable elongation to fracture, and n_G is an empirical constant interpreted as the index of defect susceptibility of the material. A low value of n_G implies that the alloy can tolerate a larger concentration of defects.[31]

The mechanical behaviour of the material within the component thus originates from the casting process and will vary throughout the component. Since the local and non-local mechanical response of structures are affected by non-uniformity in material behaviour it is important to consider these local variations of the material behaviour within the component when analysing the mechanical response of the component.[33] In addition, the manufacturing process leads to variations in material quality, which affects the performance of the actual component in service. Thus to correctly predict the behaviour of cast aluminium components, it is important to include the material behaviour within the specific component in simulations, and to study the variations in component performance due to the casting process. These parameters vary with the design of the component, and can to different extents be predicted using casting simulation software. The current contribution aims to study and discuss different methods to include material behaviour specific to cast aluminium alloys into finite element simulations of mechanical behaviour of components. This knowledge is of direct

importance to the process of designing cast components, since it combines knowledge of design, simulation and casting. All these different aspects need to be considered in order to be able to design robust and optimised cast aluminium components.

2. LITERATURE REVIEW

Finite element (FEM) simulations have been extensively used for understanding the plastic behaviour of cast aluminium alloys on the micro- and meso-scale levels. FEM based micromechanics approaches have been applied to study the effect of e.g. non-uniformly distributed voids of different shapes and sizes,[34, 35] stress distributions around Si particles,[36, 37] the effect of reinforcing particles[38] and particle decohesion.[39]

On the macroscale, i.e. simulations of entire structures, a complete modelling of the microstructure within the macrostructure is not realistic. *Concurrent multi-scale simulation methods* that combine meshes of the entire structure on a macroscopic level with meshes of a representative volume element describing the micromechanical behaviour of the material have been presented.[40, 41] These methods are highly advanced and not commonly used in development of industrial components. Instead the traditional method to use globally constant homogeneous material data acquired from measured data is still commonly used in the design process of cast aluminium components. The effects of the casting process on the mechanical behaviour of the component, such as local variations in SDAS, structural integrity etc., are then not considered. In the current work three different methods to consider the effect of the casting process and microstructural parameters on the mechanical behaviour of cast aluminium in macro-level FEM simulations have been studied. One method predicts the mechanical behaviour of the component, and two methods include microstructural behaviour in the FEM simulation based on the internal state variable (ISV) approach. The ISV approach is reviewed elsewhere,[42, 43] but in short aims to capture the *effects* of a representative volume element instead of capturing all the complex *causes* at the microstructural level. The behaviour of observable state variables (OSVs) e.g. deformation, are described by a sufficient number of internal state variables (ISVs) representing the internal structure of the material.[43] As long as the macroscale ISV representation is complete, the complete microstructural arrangement is not necessary.[44] An example of an ISV approach is to describe deformation with formation and growth of cracks using a constitutive model, i.e. a set of equations describing the behaviour of an element of the material when subjected to an external influence such as stress.[45]

2.1. The MMP-method

The development of casting simulation software has provided new possibilities to accurately predict microstructural parameters on a local level throughout a cast component. The predictions are performed by determining cooling curves and microstructure evolution during solidification.[46, 47] Recent research has been aimed at relating microstructural parameters that can be locally determined by casting simulation software to mechanical behaviour,[48-51] and to apply these relations to determine local mechanical behaviour.[52] For an A357 alloy with low defect content the UTS was found to mainly depend on SDAS, grain size, aspect ratio of eutectic Si-particles, and hardness of the material.[48] A microstructural index was defined to combine these parameters, and by plotting UTS as a function of this index a numerical correlation was

found, able to predict the UTS with an error less than 5%.[48] For an A356 alloy no significant influence of grain size was noted, and UTS respectively YS could be accurately predicted by combining SDAS, the cross section fraction eutectic Si-particles and the hardness of the material.[49]

An add-on module to a commercial casting simulation software has been developed by Seifeddine *et al.*[50] The module uses the casting simulation software to predict microstructural parameters and their local variations throughout a cast component based on solidification models by Wessén *et al*.[47] Chemical compositions of the alloy within the ranges of (wt-%) Si < 12%, Cu < 4%, Mg < 0.5% and Fe < 0.7%[50] may be used. Based on the predicted microstructural parameters, YS, UTS, elongation to fracture and their respective local variations throughout the component are determined. The effect of defects may be accounted for through a user defined dimensionless quality parameter q which determines the true plastic strain at failure, $\varepsilon_{pl,f}$, from a maximum plastic strain, $\varepsilon_{pl,f}$, through the relationship[51]

$$\varepsilon_{pl,f} = \varepsilon_{pl,\max} \cdot q \qquad (3)$$

The maximum plastic strain is determined through tensile testing of material re-melted with a gradient solidification technique that leads to a very low content of defects.[52] The predictions were compared with measured results for an as-cast A354 alloy cylinder head component, see Fig. 1. A good correlation was obtained for yield strength and ultimate tensile strength, while the elongation to fracture showed a larger scatter.[50]

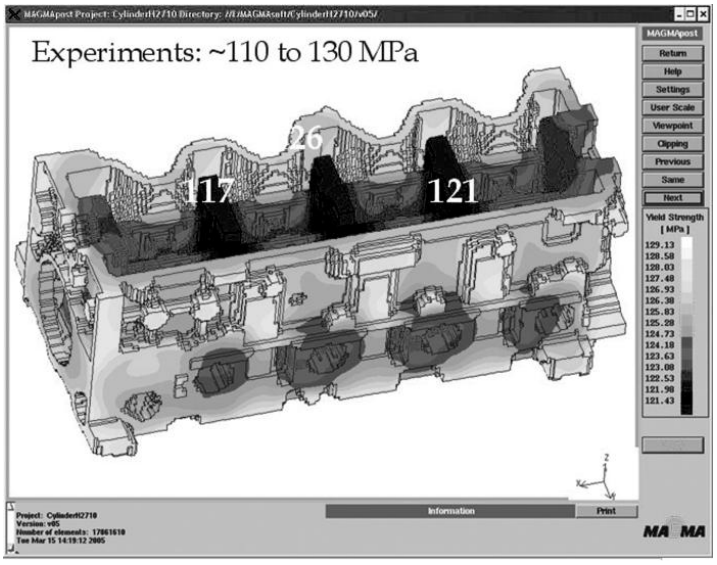

Figure 1: Comparison between yield stregth predicted using the add-on module developed by Seifeddine et al. and experimentally measured yield strength.[50] Figure reprinted with permission from Teksid Aluminum SrL.

The module was recently extended to determine the entire plastic behaviour of the material. The plastic behaviour is characterised using the Hollomon equation, which relates true plastic stress, σ_H, and true plastic strain, ε_{pl}, as[53]

$$\sigma_H = K_H \cdot \varepsilon_{pl}^{n_H} \qquad (4)$$

Here the material constants n_H and K_H are introduced. The strain hardening exponent n_H defines the work hardening capacity of the material, and ranges from zero to unity where $n_H=0$ corresponds to a perfectly plastic material and $n_H=1$ to a linearly deformation hardening material. Common values for metallic materials are in the range 0.1-0.5, corresponding to shapes of the plasticity curve as shown in Fig. 2. The constant K_H, commonly known as *the strength coefficient*, can be expressed as a function of YS and strain hardening exponent,[54] and thus indicates the strength of the material when evaluated in combination with the strain hardening exponent.

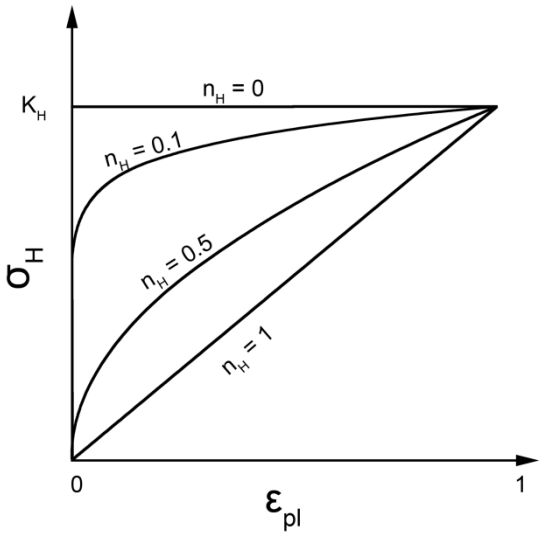

Figure 2: Effect of different values of the strain hardening exponent n_H on the shape of the plastic stress-strain curve predicted by the Hollomon equation.

In the add-on module the parameters in the Hollomon equation have been related to the local values of Fe-content and SDAS (λ) in the form[52]

$$n_H = (a_1 \cdot \mathrm{Fe} + a_2) \cdot \ln(\lambda) + (a_3 \cdot \mathrm{Fe} + a_4) \quad (5)$$

$$K_H = (b_1 \cdot \mathrm{Fe} + b_2) \cdot \ln(\lambda) + (b_3 \cdot \mathrm{Fe} + b_4) \quad (6)$$

where the constants $a_{1\text{-}4}$ and $b_{1\text{-}4}$ are derived from tensile test data. A strong correlation between SDAS and both strain hardening exponent and strength coefficient was reported, and the strain hardening exponent was found to decrease with increasing Fe-content.[52]

The predicted tensile behaviour of the material can be used as input for subsequent FEM simulations of a component.[55] This method to predict microstructure-based mechanical properties is further discussed in following sections and will be referred to as *the MMP method*.

2.2. The FC-method

A method for FEM simulation of thin-walled cast aluminium components has been developed by Dørum et.al.[56] The plastic material behaviour is described in a parametric form as

$$\sigma = \sigma_0 + \sum_{i=1}^{2} A_i \cdot \left(1 - \exp\left[-c_i \cdot \varepsilon_{pl,eq}\right]\right) \quad (7)$$

where σ is the flow stress, σ_0 is the yield stress, and $\varepsilon_{pl,eq}$ is the equivalent plastic strain. The hardening parameters A_i and c_i are determined for the specific alloy using a least-square fitting method to tensile data obtained from uniaxial tensile tests. A material model implemented in a commercial FEM software in combination with a fracture criterion is applied to determine when fracture occurs within an element. The fracture criterion used is the Cockcroft-Latham ductile fracture criterion[56]

$$W = \int \max(\sigma_1,\ 0)\mathrm{d}\varepsilon_{pl,eq} \leq W_c \tag{8}$$

in which the value of the Cockcroft-Latham integral W is compared to a critical value at fracture, W_c, known as the fracture parameter. Fracture is defined to occur when the value of the Cockcroft-Latham integral reaches the value of the fracture parameter.[56] Only tensile stresses are assumed to contribute to damage, thus in the Cockcroft-Latham integral the maximum principal stress, σ_1, is compared to zero. The Cockcroft-Latham fracture criterion is convenient to use since it is based on only one parameter, W_c, that can be determined from a single test.[57] The fracture criterion is rewritten as an ISV damage evolution law for the damage variable D according to[58]

$$\dot{D} = \begin{cases} \dfrac{\sigma_1}{W_c} \cdot \dot{\varepsilon}_{pl,eq} & \text{for } \sigma_1 > 0 \\ 0 & \text{for } \sigma_1 \leq 0 \end{cases} \tag{9}$$

which has been implemented in an explicit commercial FEM code and calibrated using simulations and measurements from notched specimen tests and plate bending tests.

Thin-walled components are commonly modelled using shell elements, and in the FC method layered shell elements with five integration points through the thickness of an element are used. It is noted by the authors that the stress distribution in the thickness direction of the shell elements is assumed to be zero, which is not a correct representation of all stress states.[56] HPDC aluminium components experience varying material properties through their thickness, known as skin effect, where the interior material generally is less ductile than the surface material. This is accounted for by assigning different values of the fracture parameter in different layers, thus different degrees of ductility are allowed before fracture is reached in the specific layer. During the FEM simulation the layer in which the fracture parameter is reached is inactivated. When a defined number of layers have been inactivated, the entire element is removed from the simulation. By studying the removal of elements it is then possible to follow the evolution of the fracture in the structure.[57] Fig. 3 shows the predicted fracture deformation of a U-profile subjected to a three point bending test, where removed elements on the front wall indicate fracture. This Fracture Criteria based method will in the following sections be referred to as *the FC method*.

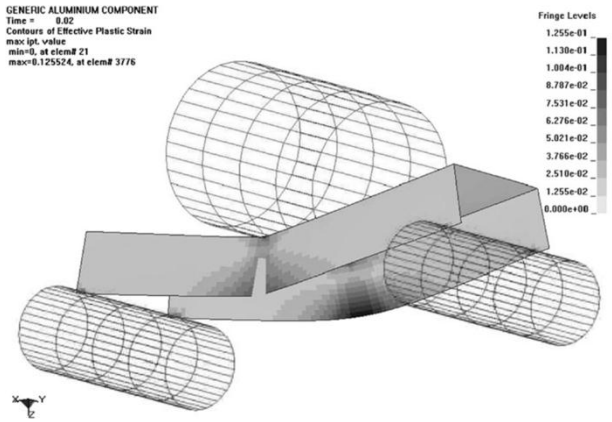

Figure 3: Simulated deformation mode for an U-profile (AlSi4Mg alloy) subjected to three-point bending test using the FC method.[56]
Figure reprinted with permission from Elsevier.

The FC method has been used to study the effect of statistical variations of mechanical behaviour in a component.[58] The probability of particle fracture, $p_{pf}(W)$, was assumed to follow a Weibull distribution as[58, 59]

$$p_{pf}(W) = 1 - \exp\left[-\left(\frac{V}{V_0}\right)\left(\frac{W}{W_{c0}}\right)^m\right] \qquad (10)$$

where m is the Weibull modulus. Size effects are taken into consideration by using two scaling ratios, the ratio between the volume of the element (V) and a scaling volume (V_0) respectively the ratio of the Cockcroft-Latham integral W and a scaling fracture parameter W_{c0}. FEM simulations of a modified Arcan test with different loading angles and the fracture parameter as a stochastic variable were performed, together with actual testing using a high-resolution camera and image analysis software to determine the effective strain field in the specimen. It was concluded that force-deformation curves, fracture modes and the effective strain fields were accurately predicted, see Fig. 4. Both simulations and measurements showed differences in crack path between replicate tests.[58]

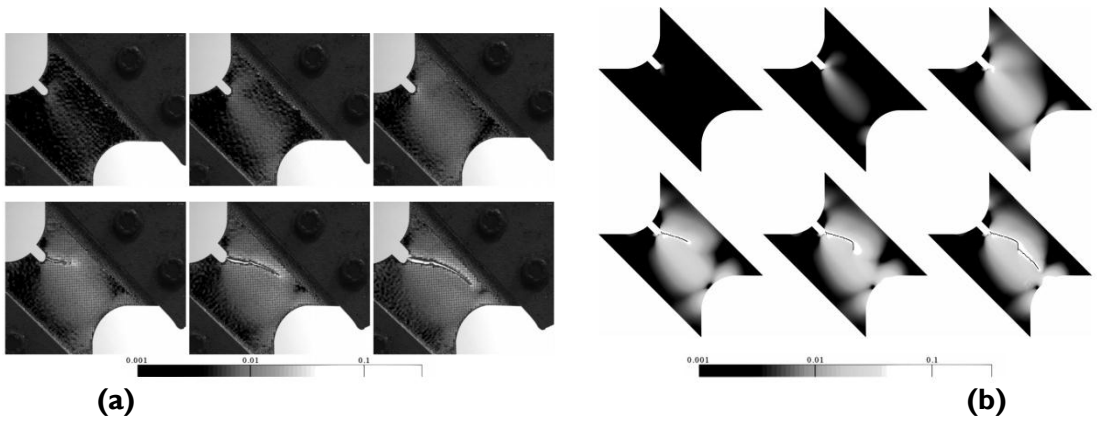

Figure 4: Comparison between (a) measured strain fields and (b) simulated strain fields using the FC method, of an Arcan test.[58]
Figure reprinted with permission from Elsevier.

Reduced ductility because of defect formation has been considered using stochastic fracture parameters on predicted locations in a U-shaped cast component, and the method was denoted a *through-process methodology*.[59] The HPDC process of the component profile was simulated in a commercial casting simulation software, using the simulated average contact time between melt and air as a measure of defect formation. The upper and lower boundaries of the fracture parameter with varying material quality were determined by tensile testing. The fracture parameter in the Weibull distribution in the FEM simulation was for each element assumed to vary linearly with the simulated average contact time. A number of FEM simulations on three-point bending tests of the U-shaped profile were performed, with the stochastic fracture parameters resulting in a scatter in FEM simulation results, see Fig. 5.[59]

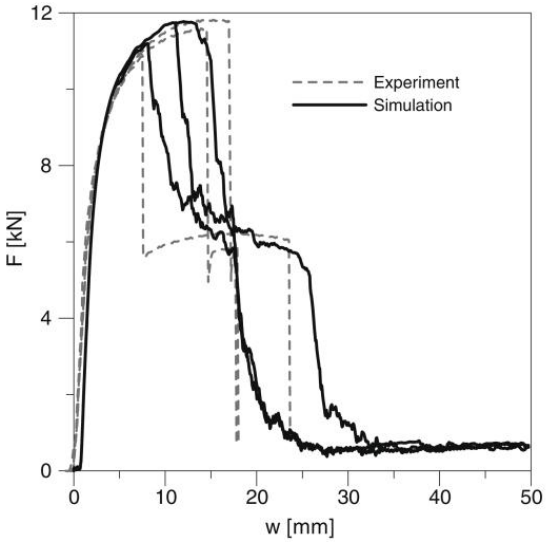

Figure 5: Comparison of predicted behaviour by three stochastic FEM simulations using the FC-method and three experimental measurements by three point-bending tests.[59] Figure reprinted with permission from Elsevier.

2.3. The CTG-method

Damage of Si-particles has previously been discussed as an important contribution to the plastic behaviour and fracture of cast aluminium alloys. Generally voids or cracks in metals nucleate on macroscale stress raisers such as inclusions, precipitates, porosities, oxide films or other secondary phases. Irrespective of nucleation site, damage evolution is typically divided into three components: *void nucleation*, *void growth* and *void coalescence*. A damage evolution model has been developed, where void nucleation is modelled using a time dependent model based on fracture mechanics.[60]

$$\eta(t) = C_{coeff} \cdot \exp\left(\frac{\varepsilon(t) \cdot d^{1/2}}{K_{IC} \cdot f^{1/3}} \left\{ C_1 \cdot \left[\frac{4}{27} - \frac{J_3^2}{J_2^3} \right] + C_2 \cdot \frac{J_3}{J_2^{3/2}} + C_3 \cdot \left\| \frac{I_1}{\sqrt{J_2}} \right\| \right\} \right) \quad (11)$$

Here $\eta(t)$ is the void nucleation density, $\varepsilon(t)$ the strain at time t, C_{coeff} is a dimensionless material constant related to initial void nucleation, K_{IC} is fracture toughness and C_1, C_2 and C_3 are alloy specific material parameters determined from mechanical testing with different stress states. Stress state dependence is included through the stress invariants, where I_1 is the first invariant of stress, and J_2 and J_3 is the second respectively the third invariant of deviatoric stress. In the case of Si particles in an Al alloy the length scale d is the average Si particle size and f the volume fraction of Si particles.

Similarly a void growth model has been developed, formulated as[61]

$$v_V(t) = \frac{4}{3} \cdot \left(R_0 \cdot \exp\left[\varepsilon(t) \cdot \frac{\sqrt{3}}{2 \cdot (1 - n_{HVG})} \cdot \sinh\left(\sqrt{3} \cdot (1 - n_{HVG}) \cdot \frac{\sqrt{2} \cdot I_1}{3 \cdot \sqrt{J_2}} \right) \right] \right)^3 \quad (12)$$

where $v_V(t)$ is the average void volume at time t, the material constant n_{HVG} is related to the strain hardening exponent of the Hollomon equation, and R_0 is the initial radius of the voids. The contribution of coalescence is accounted for through a coalescence term. The models for these three damage components have been implemented in FEM code using an ISV plasticity approach.[61] The material parameters (over 20 alloy specific material parameters determined through several material tests and regression analyses) have been determined for a T6 heat-treated A356 alloy. Failure of an element, modelled as a 50% decrease of the elastic modulus, occurs when the total amount of damage reaches unity. FEM simulations using the damage evolution model have been performed on notched tensile test specimens. The results are reported to correspond well with experimental data, and the stress state dependence of the model is shown to predict different results for torsion, compression and tension, as shown in Fig. 6.[61]

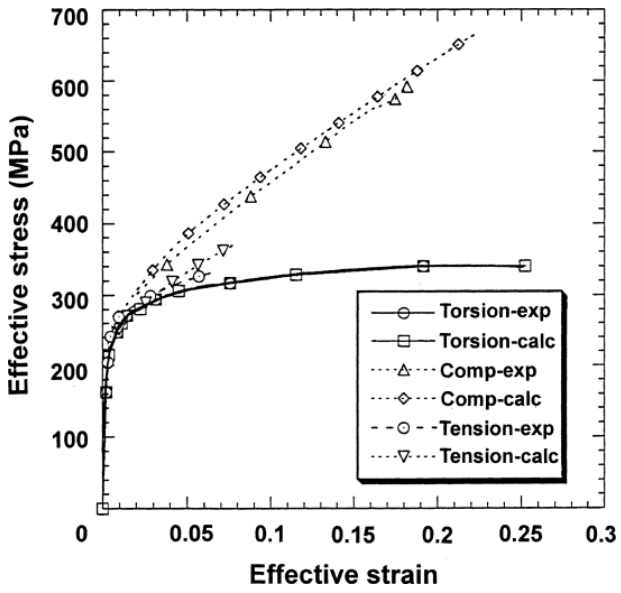

Figure 6: Comparison of experimentally measured and numerically predicted behaviour by the CTG-method for an Al-Si-Mg alloy in torsion, compression and tension.[61] Figure reprinted with permission from Elsevier.

The damage evolution model has been used in several studies in combination with design of experiment (DOE) methodology to investigate the effect and relative importance of several microstructural parameters on damage evolution.[61-67] By using the method to study the influence of damage on a component subjected to load it was shown that the weight of the component could be significantly reduced without increasing the amount of damage obtained in the component.[68] Recent work shows the process of calibrating the ISV model for a specific alloy,[69] and the model is proposed as the basis for a new design paradigm called *"Cradle-to-Grave Simulation-Based Design with Multiscale Microstructure-Property Modelling"*,[44] able to capture the entire life cycle of a component from casting through heat-treatment etc. to in-service performance

(load response, fatigue life prediction, crash analyses etc.). This cradle-to-grave method will in the following sections be referred to as *the CTG method*.

The CTG method has been applied to account for variations in microstructure, formulated as an integrated framework for design under uncertainty with multiscale modelling.[70] The CTG method in combination with material uncertainties has also been used for shape-optimisation of an automotive component.[71] The results from optimisation using the ISV material damage model were compared with the results from optimisation using the standard plasticity model available in the commercial FEM software by performing deterministic optimisations for minimum weight. It was shown that though the two deterministic optimisations resulted in similar weight reductions, the damage value obtained with the ISV model optimisation was only half the damage value obtained with the standard plasticity optimisation.[71]

3. DISCUSSION

The three different simulation methods deal with material specific behaviour in significantly different ways.

- The *MMP method* predicts component specific mechanical behaviour with local variations for a wide range of alloys and transfers the information to the FEM simulation software.

- The *FC method* uses the functionality of FEM software to include consideration of alloy specific material behaviour and a fracture parameter, information obtained from material testing.

- The *CTG method* extends the functionality of the FEM software by incorporating a micro-level damage evolution model that uses alloy specific material data obtained from extensive material testing.

The different methods correspond to different ways of transferring information in the process of predicting the mechanical behaviour of a cast component. Their application are thus significantly different, which is schematically illustrated in Fig. 7. This is a result of the different purposes for which the methods have been developed, and the different approaches leads to different strengths and drawbacks for the different methods.

The MMP method is a development of the functionalities in casting simulation software to predict local tensile material behaviour for general components in a wide range of alloys. The behaviour prediction is based on simulations of the manufacturing process, and does not need any additional data from material testing. The method has some limitations, e.g. the effect of structural integrity is limited to the possibility to define a quality parameter which determines the fracture strain. The approach in equation (3) can be seen as a simplification of the approach in equation (2), where a susceptibility index is used to characterise the material's sensitivity to defects. The predictions of the plastic behaviour, equations (5) and (6), are based on the Hollomon equation, which is not able to accurately predict the plastic behaviour of all types of heat treated aluminium alloys.[72] The predictions are based only on Fe-content and SDAS, while other microstructural parameters such as the characteristics of the Si-particles, are also known to affect the plastic behaviour, and it is not taken into account that different Fe-rich phases affect the mechanical behaviour differently. The constants in the relationships for the parameters of the Hollomon equation have been determined for as-cast alloys, and the effect of heat treatment on these parameters have not been

numerically established. Since the method only provides data to the FEM simulation, no consideration of different stress states is included in the FEM simulation, and no specific consideration of skin effect has been reported. In general, the MMP method is thus suitable to predict the mechanical behaviour of the material within as-cast components of general geometries in a wide range of alloys.

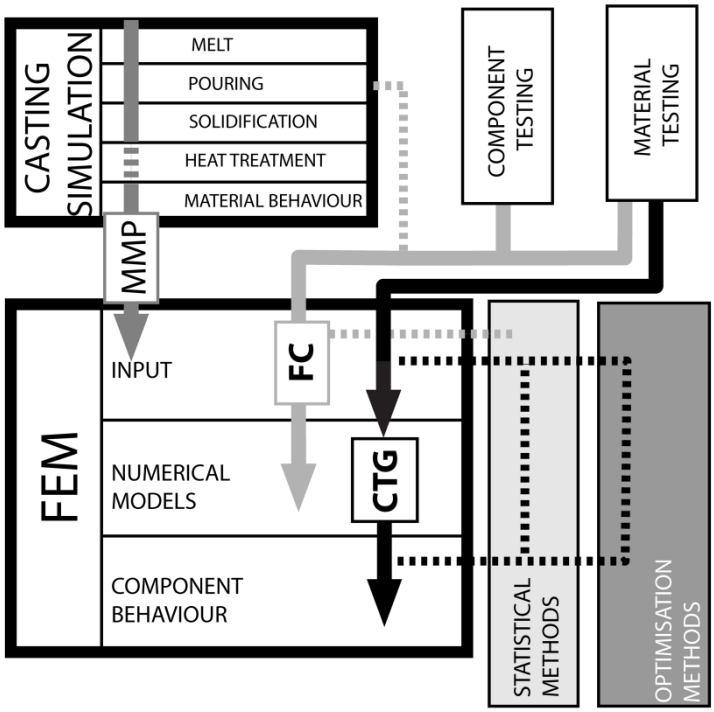

Figure 7: A schematic illustration of the application of the reviewed simulation methods.

The FC method is aimed at predicting the behaviour of thin-walled components of a specific alloy subjected to crash-load. The material behaviour is described using alloy specific hardening parameters, which need to be determined from material testing. No direct relationship between variations in microstructure and mechanical behaviour is included, but the fracture parameter may vary through-thickness to consider the skin effect of die castings, and local variations of the fracture parameter can be used. Structural integrity may be considered by defining different values of the fracture parameter, or scaling the fracture parameter with melt-air contact time predicted by casting simulation software. The melt-air parameter, determined in the pouring stage of the casting process, is indirectly related to the formation and growth of oxide films. The parameter is however not a direct measure of the total amount of defects, and its power to predict the true location of defects is limited. Variations in structural integrity can in the FC-method be considered through a statistical approach, equation (10), which is similar to the particle fracture approach shown in equation (1). By using data from different kinds of tests consideration of stress state dependence may be included in the FEM simulation. Since the Cockcroft-Latham integral uses the current maximum principle stress to determine damage evolution it is however not clear how damage accumulation, e.g. in the case of repeated loading, is treated. The general use of the FC method is limited by being based on shell elements, which is not appropriate for all types of load and only suitable for thin-walled components. The FC method is thus

suitable for thin walled components of a specific alloy subjected to crash-loads of general stress states.

The CTG method is developed for components of general geometry in a specific alloy subjected to repeated loading. The method is highly involved in the FEM simulation by determining total microstructural damage evolution as an ISV during the simulation, an approach that makes the method also useful for cyclic loading. Si particle characteristics and the size of the Si particles are accounted for in the damage evolution model in the CTG method. The CTG method uses an initial volume fraction of defects, and may be used in combination with statistical approaches to study the effect of various initial amounts of defects. No connection to casting simulation software or specific consideration of skin effect is however reported in the reviewed literature. Instead, global material parameters, optionally with statistical variations in areas where experimental measurements indicate large amount of defects, have been used. The possibilities of casting simulation software to predict local variations in mechanical behaviour or areas with a high risk for defects, as in the MMP method respectively the FC method, is thus not taken into account. This is a drawback since damage evolution should be considered in the design phase of the product development process, when no actual cast components are available to enable experimental measurements of the location of defects. The CTG-method can be used in combination with statistical approaches and different optimisation approaches. The CTG-method is suitable for components of a specific alloy of general geometry subjected to general loads.

To select a suitable approach for a specific simulation, the type of simulation to be performed as well as the purpose of the simulation thus needs to be considered. In order to perform a FEM simulation using the MMP method, a casting process simulation first needs to be performed for the specific component. Several casting process related parameters then need to be known in order to obtain a correct description of the microstructure within the component, from which the mechanical behaviour is determined. Both the FC method and the CTG method are highly dependent on experimentally determined material parameters, but once these parameters have been obtained the methods can be applied to other components of the same material. The mechanical behaviour is thus not as component specific as in the MMP method, but is on the other hand not dependent on a preceding casting process simulation. The FC method is limited to thin-walled components subjected to crash load, while the CTG method is applicable to general geometries subjected to a wider range of load types.

4. CONCLUSIONS

In order to perform accurate simulations of the mechanical performance of cast aluminium components it is important to understand the mechanical behaviour of the alloy. Three different approaches to consider mechanical behaviour of cast aluminium alloys in FEM simulations have been studied.

- The MMP method predicts component specific local mechanical behaviour from microstructural parameters obtained from a casting process simulation.
- The FC method uses layered shell elements and a fracture criterion to simulate mechanical behaviour of and fracture evolution in thin-walled components.
- The CTG method uses a micro-mechanics based damage evolution model implemented into the FEM simulation to predict damage and fracture evolution.

The MMP method is able to predict mechanical behaviour for a wide range of as-cast alloys, while the FC method and the CTG method both require data obtained from mechanical testing of the specific alloy to be used. Both the FC and the CTG methods have been used in combination with statistical methods, and the CTG in combination with optimisation methods. The three methods reviewed have been developed for different purposes. To determine the appropriate approach and method for a specific simulation and component the geometry of the component, the type of simulation to be performed, the objective of the simulation as well as the availability of material data must be considered.

ACKNOWLEDGEMENT

The School of Engineering at Jönköping University is gratefully acknowledged for financing the work.

REFERENCES

1. P. Kumar and J. L. Gaindhar: *AFS Trans.*, 1997, **104**, 635-638.
2. P. R. Goulart, J. E. Spinelli, W. R. Osório, and A. Garcia: *Mater. Sci. Eng. A*, 2006, **421**(1-2), 245-253.
3. K. J. Oswalt and M. S. Misra: *AFS Trans.*, 1980, **88**, 845-862.
4. S. Seifeddine and I. L. Svensson: *Metall. Sci. Technol.*, 2009, **27**(1), 11-20.
5. S. Seifeddine, S. Johansson, and I. L. Svensson: *Mater. Sci. Eng. A*, 2008, **490**, 385-390.
6. Q. G. Wang: *Metall. Mater. Trans. A*, 2003, **34**(12), 2887-2899.
7. L. Ceschini, I. Boromei, A. Morri, S. Seifeddine, and I. L. Svensson: *J. Mater. Process. Technol.*, 2009, **209**, 669-679.
8. M. Ravi, U. T. S. Pillai, B. C. Pai, A. D. Damodaran, and E. S. Dwarakadasa: *Int. J. Cast Met. Res.*, 1998, **11**, 113-125.
9. C. H. Cáceres, C. J. Davidson, J. R. Griffiths, and Q. G. Wang: *Metall. Mater. Trans. A*, 1999, **30A**, 2611-2618.
10. C. H. Cáceres, C. J. Davidson, and J. R. Griffiths: *Mater. Sci. Eng. A*, 1995, **197**, 171-179.
11. Q. G. Wang, C. H. Cáceres, and J. R. Griffiths: *Metall. Mater. Trans. A*, 2003, **34**(12), 2901-2912.
12. C. H. Caceres, J. R. Griffiths, and P. Reiner: *Acta Mater.*, 1996, **44**(1), 15-23.
13. J. E. Gruzleski and B. M. Closset: 'The Treatment of Liquid Aluminium-Silicon Alloys'; 1990, Des Plaines, Illinois, American Foundrymens's Society , Inc.
14. E. Ogris, A. Wahlen, H. Lüchinger, and P. J. Uggowitzer: *J. Light Met.*, 2002, **2**(4), 263-269.
15. M. Tiryakioglu: *Mater. Sci. Eng. A*, 2006, **427**(1-2), 154-159.
16. G. Guiglionda and W. J. Poole: *Mater. Sci. Eng. A*, 2002, **336**(1-2), 159-169.
17. C. H. Caceres and J. R. Griffiths: *Acta Mater.*, 1996, **44**(1), 25-33.
18. M. Lebyodkin, A. Deschamps, and Y. Bréchet: *Mater. Sci. Eng. A*, 1997, **234-236**, 481-484.
19. Q. G. Wang and C. H. Cáceres: *Mater. Sci. Eng. A*, 1997, **234-236**, 106-109.
20. L. M. Cheng, W. J. Poole, J. D. Embury, and D. J. Lloyd: *Metall. Mater. Trans. A*, 2003, **34**(11), 2473-2481.

21. G. Ran, J. E. Zhou, and Q. G. Wang: *J. Mater. Process. Technol.*, 2008, **207**(1-3), 46-52.
22. M. Dighe, A. Gokhale, and M. Horstemeyer: *Metall. Mater. Trans. A*, 2002, **33**(3), 555-565.
23. Q. G. Wang, D. Apelian, and D. A. Lados: *J. Light Met.*, 2001, **1**(1), 85-97.
24. J. Z. Yi, Y. X. Gao, P. D. Lee, and T. C. Lindley: *Mater. Sci. Eng. A*, 2004, **386**(1-2), 396-407.
25. J. Campbell: 'Castings'; 2003, Oxford, Elsevier Butterwort-Heinemann.
26. H. Zahedi, M. Emamy, A. Razaghian, M. Mahta, J. Campbell, and M. Tiryakioğlu: *Metall. Mater. Trans. A*, 2007, **38**(3), 659-670.
27. C. D. Lee: *Mater. Sci. Eng. A*, 2007, **464**(1-2), 249-254.
28. Q. G. Wang, D. Apelian, and D. A. Lados: *J. Light Met.*, 2001, **1**(1), 73-84.
29. C. Nyahumwa, N. Green, and J. Campbell: *Metall. Mater. Trans. A*, 2001, **32**(2), 349-358.
30. N. R. Green and J. Campbell: *Mater. Sci. Eng. A*, 1993, **173**(1-2), 261-266.
31. A. M. Gokhale and G. R. Patel: *Mater. Sci. Eng. A*, 2005, **392**(1-2), 184-190.
32. A. M. Gokhale and G. R. Patel: *Scripta Mater.*, 2005, **52**(3), 237-241.
33. F. Reusch and Y. Estrin: *Comput. Mater. Sci.*, 1998, **11**(4), 294-308.
34. P. Cannmo, S. Seifeddine, L. Svensson, and I. L. Svensson: 'Stress-Strain Modelling Influenced by Porosities in Cast Aluminium Allloys', Conference on Modelling of Casting and Welding Processes, Opio, France, 2006.
35. Z. Shan and A. M. Gokhale: *Acta Mater.*, 2001, **49**(11), 2001-2015.
36. A. Saigal and E. R. Fuller: *Comput. Mater. Sci.*, 2001, **21**(1), 149-158.
37. A. Tewari, S. Tiwari, P. Biswas, S. Vijayalakshmi, and R. K. Mishra: *Mater. Charact.*, 2010, **61**(11), 1211-1220.
38. H. Shen and C. J. Lissenden: *Mater. Sci. Eng. A*, 2002, **338**(1-2), 271-281.
39. J. Segurado and J. Llorca: *Acta Mater.*, 2005, **53**(18), 4931-4942.
40. R. J. M. Smit, W. A. M. Brekelmans, and H. E. H. Meijer: *Comput. Meth. Appl. Mech. Eng.*, 1998, **155**(1-2), 181-192.
41. S. Ghosh, D. M. Valiveti, S. J. Harris, and J. Boileau: *Modell. Simul. Mater. Sci. Eng.*, 2006, **14**(8), 1363-1396.
42. Ø. Grong and H. R. Shercliff: *Prog. Mater Sci.*, 2002, **47**(2), 163-282.
43. M. F. Horstemeyer and D. J. Bammann: *Int. J. Plast.*, 2010, **26**(9), 1310-1334.
44. M. F. Horstemeyer and P. Wang: *J. Comput. Aided Mater. Des.*, 2003, **10**(1), 13-34.
45. M. F. Ashby: *Mater. Sci. Technol.*, 1992, **8**, 102-111.
46. R. Vijayaraghavan, N. Palle, J. Boileau, J. Zindel, R. Beals, and F. Bradley: *Scripta Mater.*, 1996, **35**(7), 861-867.
47. M. Wessén, I. L. Svensson, S. Seifeddine, J. Olsson, and W. Schäfer: 'Simulation of cooling curves, microstructures and mechanical properties in cast Al-Si based alloys', Conference on Modelling of Casting and Welding Processes, Opio, France, 2006.
48. L. Ceschini, A. Morri, A. Morri, A. Gamberini, and S. Messieri: *Mater. Des.*, 2009, **30**, 4525-4531.
49. L. Ceschini, A. Morri, A. Morri, and G. Pivetti: *Mater. Des.*, 2011, **32**(3), 1367-1375.
50. S. Seifeddine, M. Wessén, and I. L. Svensson: *Metall. Sci. Technol.*, 2006, **24**(2), 26-32.
51. S. Seifeddine, T. Sjögren, and I. L. Svensson: *Metall. Sci. Technol.*, 2007, **25**(1), 12-22.
52. S. Seifeddine and I. L. Svensson: *Mater. Des.*, 2010, **31**, 6-12.

53. J. H. Hollomon: *Trans. AIME*, 1945, **162**, 268-290.
54. G. E. Dieter: 'Mechanical Metallurgy'; 1986, McGraw-Hill.
55. I. L. Svensson, S. Seifeddine, J. Hattel, P. Kotas, and J. Thorborg: 'On modelling of microstructure formation, local mechanical properties and stress-strain development in aluminium castings', Modeling of Casting, Welding and Advanced Solidification Processes, Vancouver, British Columbia, 2009.
56. C. Dørum, H. I. Laukli, O. S. Hopperstad, and M. Langseth: *Eur. J. Mech. Solid*, 2009, **28**(1), 1-13.
57. A. Reyes, M. Eriksson, O. G. Lademo, O. S. Hopperstad, and M. Langseth: *Mater. Des.*, 2009, **30**(3), 596-608.
58. E. Fagerholt, C. Dørum, T. Børvik, H. I. Laukli, and O. S. Hopperstad: *Int. J. Solids Struct.*, 2010, **47**(24), 3352-3365.
59. C. Dørum, H. I. Laukli, and O. S. Hopperstad: *Comput. Mater. Sci.*, 2009, **46**(1), 100-111.
60. M. F. Horstemeyer and A. M. Gokhale: *Int. J. Solids Struct.*, 1999, **36**(33), 5029-5055.
61. M. F. Horstemeyer, J. Lathrop, A. M. Gokhale, and M. Dighe: *Theor. Appl. Fract. Mech.*, 2000, **33**(1), 31-47.
62. M. F. Horstemeyer and S. Ramaswamy: *Int. J. Damage Mech.*, 2000, **9**(1), 5-28.
63. M. F. Horstemeyer, S. Ramaswamy, and M. Negrete: *Mech. Mater.*, 2003, **35**(7), 675-687.
64. K. Gall, M. Horstemeyer, D. L. McDowell, and J. Fan: *Mech. Mater.*, 2000, **32**(5), 277-301.
65. M. F. Horstemeyer, K. Gall, K. W. Dolan, A. Waters, J. J. Haskins, D. E. Perkins, A. M. Gokhale, and M. D. Dighe: *Theor. Appl. Fract. Mech.*, 2003, **39**(1), 23-45.
66. J. B. Jordon, M. F. Horstemeyer, K. Solanki, and Y. Xue: *Mech. Mater.*, 2007, **39**(10), 920-931.
67. M. T. Tucker, M. F. Horstemeyer, W. R. Whittington, K. N. Solanki, and P. M. Gullett: *Mech. Mater.*, 2010, **42**(10), 895-907.
68. M. F. Horstemeyer, R. J. Osborne, and D. E. Penrod: *AFS Trans.*, 2002, **110**, 297-314.
69. K. N. Solanki, M. F. Horstemeyer, W. G. Steele, Y. Hammi, and J. B. Jordon: *Int. J. Solids Struct.*, 2010, **47**(2), 186-203.
70. X. Yin, S. Lee, W. Chen, W. K. Liu, and M. F. Horstemeyer: *J. Mech. Des.*, 2009, **131**(2), 021006-021010.
71. K. N. Solanki, E. Acar, M. Rais-Rohani, M. F. Horstemeyer, and W. G. Steele: *Int. J. Des. Eng.*, 2009, **2**(1), 47-79.
72. M. Tiryakioglu, J. T. Staley, and J. Campbell: *J. Mater. Sci. Lett.*, 2000, **19**, 2179-2181.