The International Journal of

Multiphysics

Special Edition:

Multiphysics Simulations - Advanced Methods for Industrial Engineering

Selected Contributions from
1st Fraunhofer Multiphysics Conference

ISBN 978-1-907132-36-0

5 Wates Way, Brentwood, Essex CM 15 9TB, UK

Through-process simulation of aluminium casting A356 – simulation of solidification and stress analysis during heat treatment

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Abstract

A method is presented for a through-process simulation of the complete manufacturing chain of an aluminium casting (A356). The typical manufacturing chain for aluminium castings consists of different processes: casting, heat treatment and machining. Each of these processes is simulated with the corresponding software. The most influential parameters for the mechanical property, e.g. the chemical composition of the alloy, the secondary dendrite arm spacing, the formation of stresses and distortion, are taken into account. These parameters are passed through the manufacturing chain from one process to the next. Due to different data structures the quantities transferred between different software packages must be interpolated which is realized with the aid of the interface software MAGMAlink and Python Scripts. Here this through-process simulation method is verified experimentally with a laboratory scale casting (step plate). The influence of cooling rates on the subsequent microstructure is also considered. The simulation results are compared with experimental examinations such as microscopic metallography to estimate the secondary dendrite arm spacing. Future application of this through-process simulation to industry castings, e.g. cylinder head, is planned.

Introduction

These days internal combustion engine (IC Engine) development is driven by the demands for high engine out power and low fuel consumption. To archive these goals the engine developers have to work on reducing the weight of the engine by applying aluminium cylinder heads, blocks and pistons. Due to this concept the mechanical and thermal loads on the structural parts of the engine increase from each engine generation to the next, with the result of reaching material limits soon. However introducing new materials like ceramics would increase the costs of the product enormously.

In this research an A356 aluminium alloy is used. In general hypoeutectic aluminium silicon alloys have a good strength/weight ratio and are well castable [1]. The optimization process was and is still relying on experiments. Because of the high expenses only a rare number of process variations and design variations can be done. Hence it is a goal of this work to model and simulate the whole production process of an aluminium cylinder head.

Strategy and Methods

The production process consists of casting, machining and T6 heat treatment (solution annealing and ageing) (Figure 1). In the first approach a laboratory geometry (step plate) is used. A methodology had to be developed, to pass through the different simulation results to the individual simulation software. In order to predict the fatigue life of shape castings, it was necessary to track the microstructural development and residual stresses through all the manufacturing steps from casting via heat treatment to subsequent machining. The mould filling and adjacent solidification was simulated by the finite difference method based casting simulation software MAGMA, in order to predict the primary as-cast microstructure and residual stresses. By simulating the heat treatment, modifications of the primary structure and development of residual stresses due to the inhomogeneous temperature field were considered Therefore the software packages MatCalc, DEFORM and ABAQUS were used.

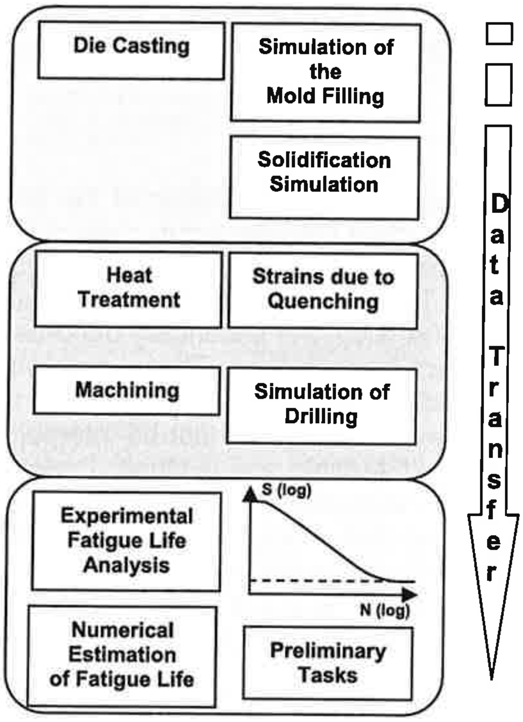

Fig 1: Through process modelling chain

MatCalc is a software package for computer simulation of the kinetics of microstructural processes. The metal forming process simulation software DEFORM offers an advanced system for simulating heat treatment processes. It calculates mechanical and metallurgical responses of parts during heat treatment. ABAQUS is a finite element software package which performs static and/or dynamic analyses of structures. The results of the casting simulation were transferred to ABAQUS, followed by one equilibrium step to get a result file (odb file). An output database file (odb) generated from the ABAQUS analysis contains model and result data. The ABAQUS odb-file can be accessed by Python scripts using the ABAQUS API, which makes it possible to read from and write to an output database and the accessed data can be written in a neutral text file. Because the file format which is used by DEFORM (key-file) is known, it is possible to generate this key file with mesh and stress data by Python scripts and use it for DEFORM. The material properties originate from the MAGMA material database and literature. One important aspect of the heat treatment simulation is distortion due to quenching. A rapid quenching creates a great amount of Mg and Si in solution, this is important for the adjacent ageing process. On the other side a high cooling rate leads to distortions and high residual stresses which are unfavourable for fatigue life. From this it follows that optimized cooling conditions have to be found.

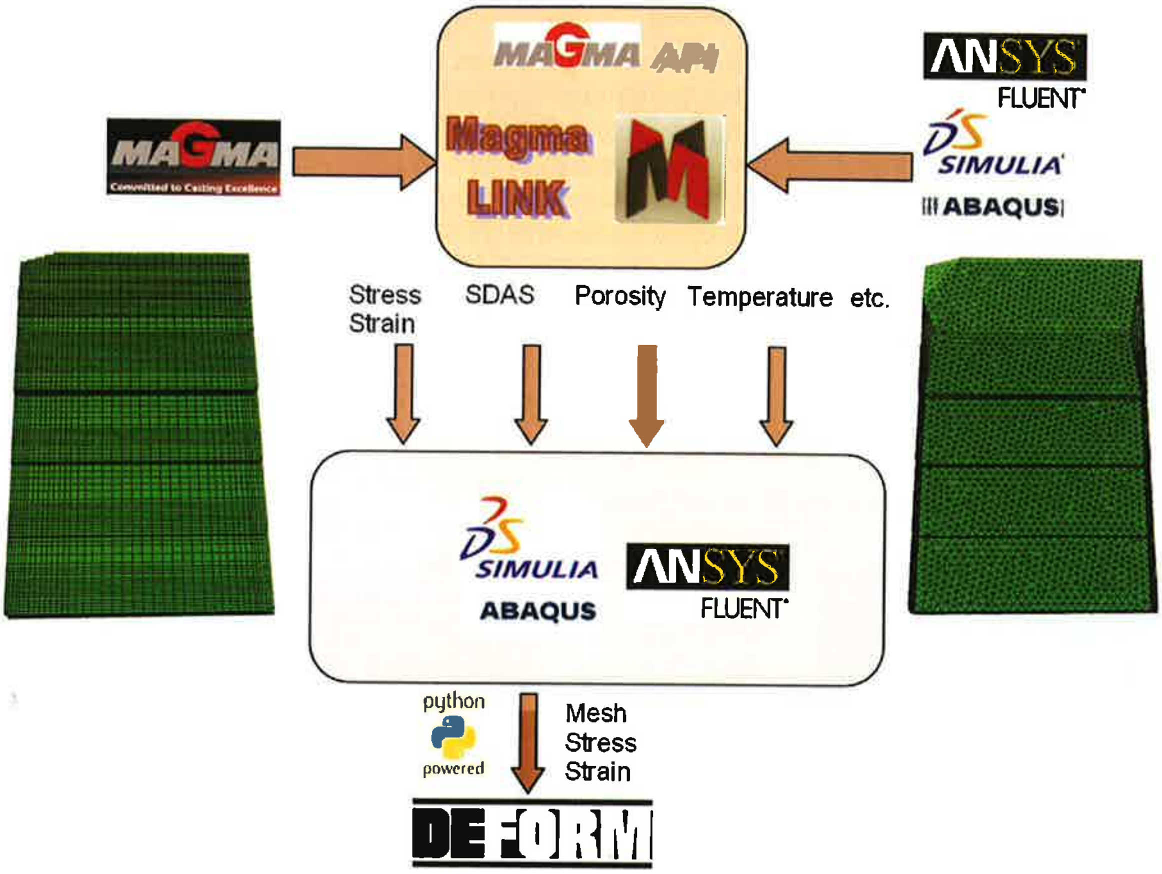

Fig 2: Scheme of the data transfer between the software packages MAGMA, ABAQUS, FLUENT and DEFORM.

The methodology of transferring the results of the MAGMASOFT process simulation to the FEM software ABAQUS is shown in Figure 2. For that purpose two options are figured out. One possibility consists of using MAGMAlink, thereby in ABAQUS the casting geometry has to be meshed and material properties have to be allocated. Then the ABAQUS input file has to be generated, this input file is written in ASCII file format and easy to edit. Concerning the data transformation the most important information in the input file are the coordinates of the nodes and the element connectivity. MAGMA link uses this input file and an interpolation algorithm is used to transfer the MAGMA quantities to the ABAQUS mesh. The second option is to use the MAGMA API which enables the possibility to interact with an user programming interface (C). Thereby a C-subroutine is used to export the mesh data (node coordinates, element connectivity) in a text file. The mesh information of the second simulation software must also be available in a text file format. In the next step the C++ library MapLib developed by the Fraunhofer Institute for Algorithms and Scientific Computing (SCAI) is used to map simulation results between these two different meshes. If necessary it is also possible to include the computational fluid dynamics software FLUENT into this simulation chain.

Configuration of the benchmark casting

Figure 3 shows the step plate casting which was cast with dimensions of 150 x 200 mm, some sections of the casting were designed to have different thicknesses of 4, 6, 10 and 16 mm to investigate the effects of different cooling rates on the microstructure. Cooling rate plays an important role in the microstructure development. Higher cooling rate leads to a shorter solidification time and a smaller grain size, hence the grain density increases with cooling rate [1]. The chemical composition of the alloy is shown in Table. 1. For this material the liquidus temperature is at 616 °C, the solidus temperature at 556 °C. The permanent mold has cooling channels and is liquid cooled. It is assumed that the cooling liquid has a constant temperature of 260 °C. The filling time is seven seconds, an entire casting cycle take 240 s. After five casting cycles the maximum temperature of the mold is reached.

Tab. 1: Alloy composition of A356 in weight percent

Al	Si	Mg	Cu	Fe	Sr	Ti
91,7	7,00	0,42	0,49	0,12	0,024	0,11

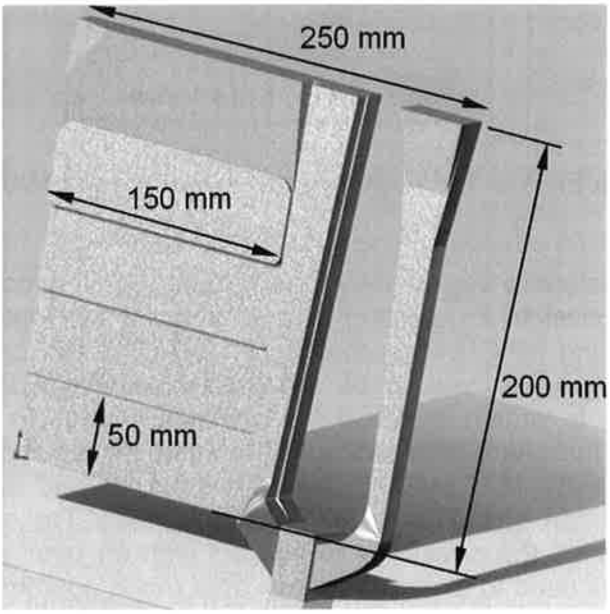

Fig 3: A356 laboratory casting (step plate)

In this initial step of the simulation chain the main focus was on the calculation and mapping of the features of the as-cast microstructure like secondary dendrite arm spacing (SDAS), residual stresses and deformations. Therefore these microstructural features are simulated with commercial casting software. This simulation results are verified by light optical microscopy. The cooling rate is an important processing parameter that affects the SDAS. Since each step of the plate has its different cooling characteristics different microstructures were expected for different steps. Furthermore a method is presented to map simulation results from the casting software to other software packages.

Simulation results

In Figure 4 the qualitative result of calculating the secondary dendrite arm spacing (SDAS) is shown. The SDAS is known to significantly effect the fatigue strength of cast aluminium alloys [2]. Due to the fact that the melt is filled from right hand side of the step casting, the cooling rate is much lower there; hence bigger dendrite arm spacing is expected in this region. As a result of this, the distribution of the SDAS is not symmetrical. In the hotter regions the dendrites have more time to grow and this tends to result in a coarser grain structure. The mapping result is qualitatively satisfying, the error caused by mapping is much lower than errors caused by other factors like incorrect heat transfer coefficients, material properties etc. In the structure mechanics software ABAQUS the transferred SDAS could be used further in a material model which incorporates the dendrite sizes. In a subsequent work a method will be presented to simulate and predict the fatigue behaviour based on the simulation results from the casting software.

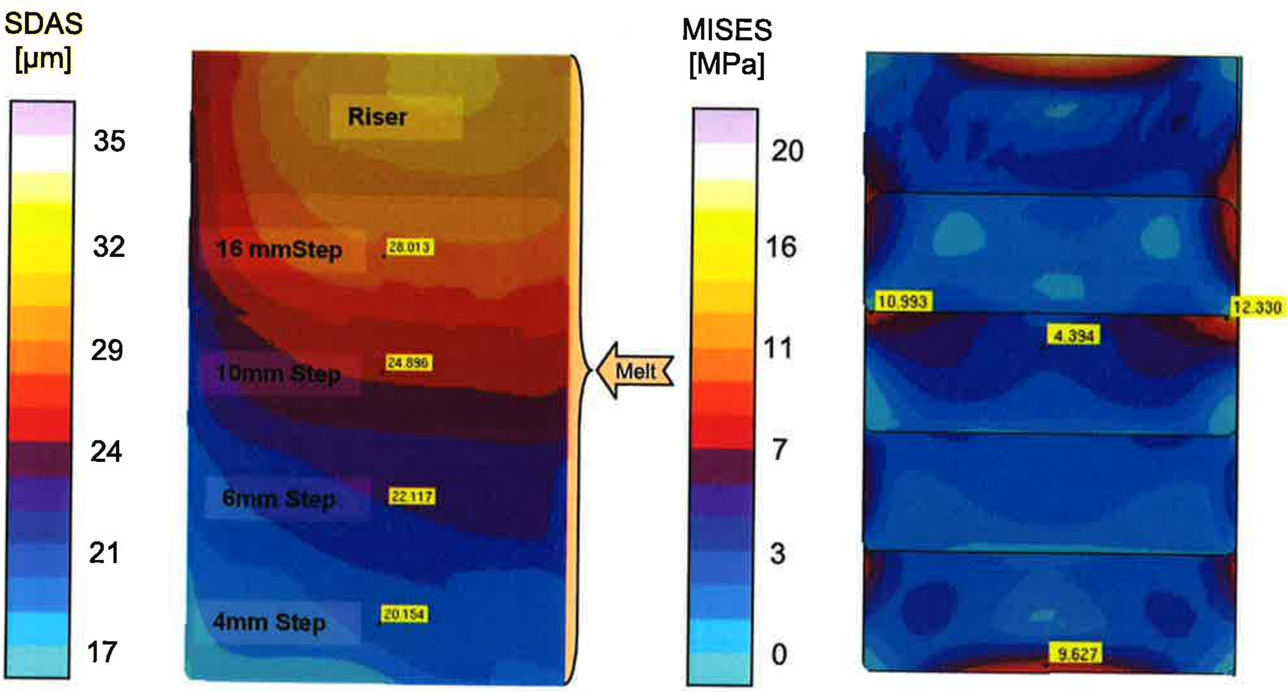

Fig 4: Secondary dendrite arm spacing and residual stresses in the as cast condition

Solidification starts from the left bottom corner. The distribution of the SDAS is correlated to the temperature field. The riser at the top of the casting acts also as a thermal reservoir which keeps the alloy liquid. Due to the high heat conductivity and the enhanced cooling in the mold, the solidification time for the hottest areas in the riser is approximately 60 seconds. This leads to an unbalanced solidification. Generally eutectic modifiers and grain refiners are added in small amounts to the molten aluminium silicon alloys to refine the eutectic phase and therefore to improve the mechanical properties. These modifiers are not taken into account in the casting simulation; hence the simulation results show a coarser structure than the experimentally determined values.

During the manufacturing route of parts made of A356 an essential step is the heat treatment which results in strengthening of the material due to precipitations. The common heat treatment is T6 which consists of solution annealing, quenching and ageing at elevated temperatures. The as-cast samples were solution heat treated at 530 °C for four hours followed by quenching in 80 °C tempered water. The artificial ageing was accomplished at 200 °C for different times (30 min, 3h and 4h).

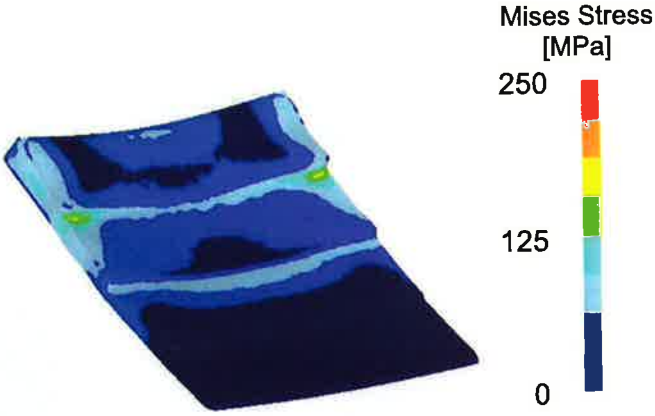

Fig 5: Von Mises stress distribution after quenching considering as-cast residual stresses from the casting simulation and distortion, amplified by a factor of 60

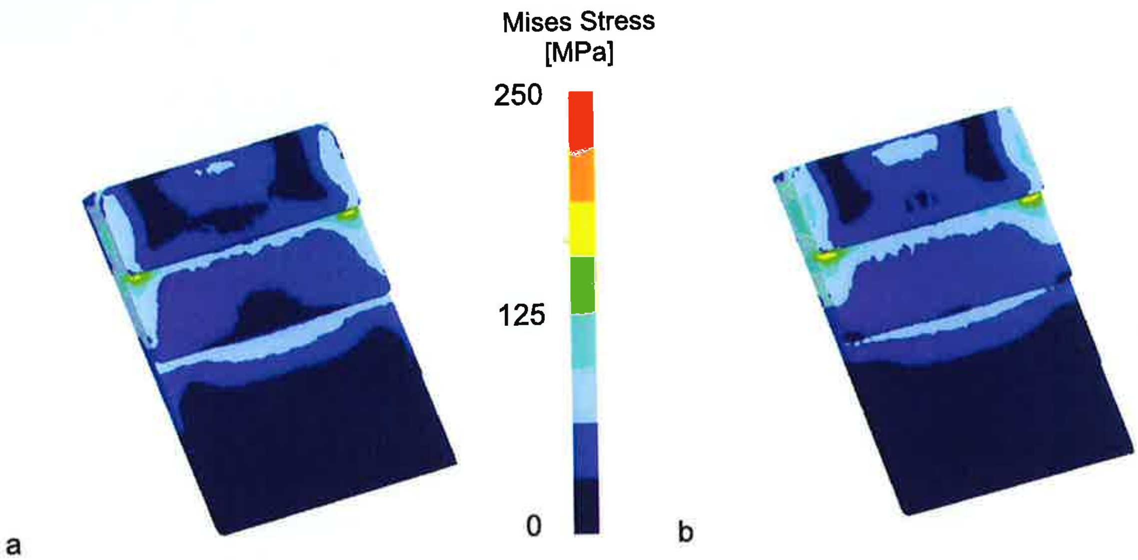

Fig 6: Von Mises stress distribution after quenching (a) with mapped as-cast residual stress and (b) without as-cast residual stress

The large thermal gradients that arise during the quenching operation induce large thermal stresses. These stresses, if sufficient, will cause inelastic yielding leading to strains in the component and they typically remain after the ageing treatment because the temperatures are insufficient to allow fully stress relaxation. If the magnitude of the distortion is above the acceptable standards, the casting is rejected [3]. The distortion shown in Figure 5 is scaled with the factor sixty. For the real production process the deformation and the residual stresses created by the heat treatment play an important role and the distortion should be minimised. To analyse the evolution of the stress-field, quenching in 80°C water was simulated with DEFORM. Then an additional step for cooling to 20 °C was appended. In Figure 6 the results of those operations can be seen. The von Misses stresses are nearly identical for both cases with and without as-cast residual stresses. This result was expected because most of the stresses were exhausted during the annealing process. The relaxations are different; hence the distortions and the developing of the stresses are also different. The areas of interest are these which are showing significantly increased stresses since these may be sources for cracks caused by interfering with stresses arising from the in-service-loads.

Experimental validation

For analysing the secondary dendrite arm spacing by light optical microscopy the step plate was cut along five cross sections every 25 mm shown in Figure. 7. From every cross section four metallographic samples (one each step) were taken and analysed by an Olympus BX51M light optical microscope. Thereby 20 individual readings were taken on each metallographic sample and the average value of the SDAS was determined which yielded the SDAS-distribution throughout the plate.

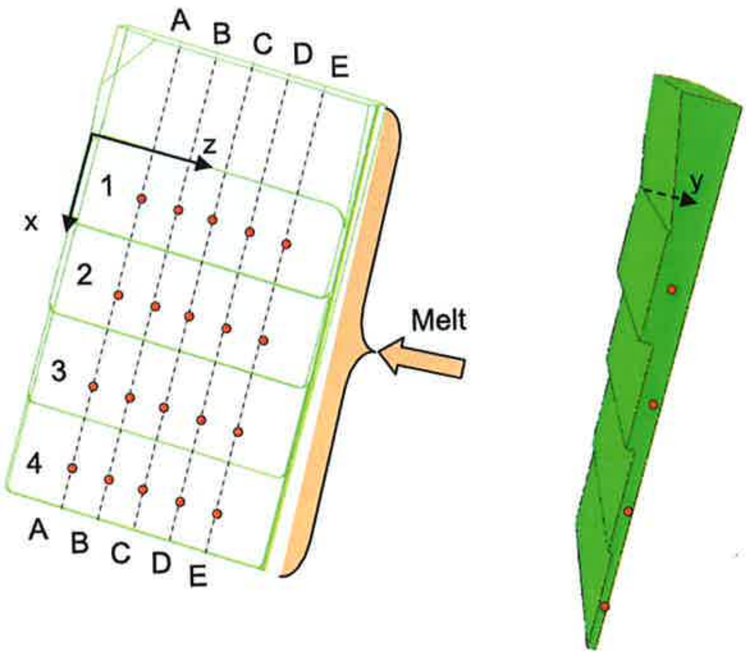

Fig 7: Cutting planes and locations of the samples for measuring the SDAS

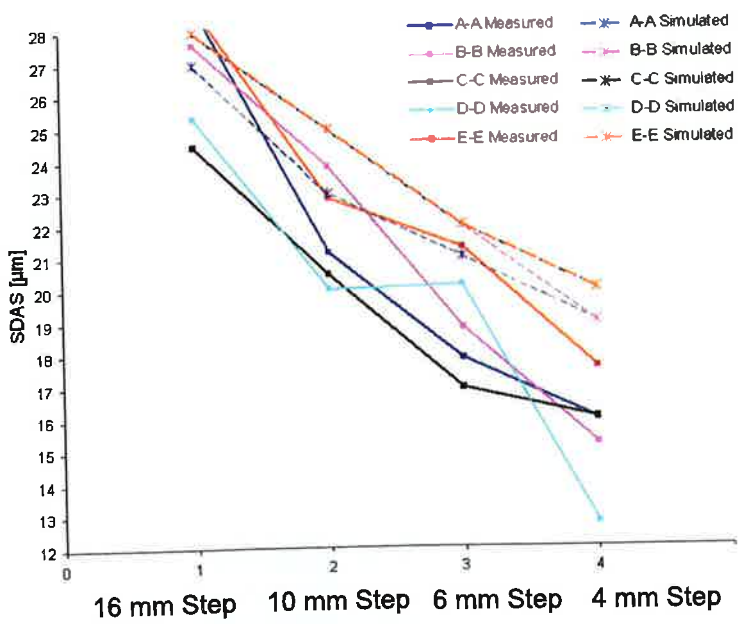

Fig 8: Comparison of measured and simulated SDAS. Only 3 simulated curves are visible, because the curves C-C and D-D are covered by E-E

A general good agreement behaviour regarding to the SDAS was obtained (Figure 8). On the left bottom corner the step-plate is in contact with three faces of the mold thus here is the steepest temperature gradient. The riser on the right hand side and the ingate at the top act as thermal reservoirs, hence the temperature gradient from plane C-C to plane E-E is relative flat. The results for SDAS in the cutting-planes C-C, D-D and E-E are almost equal because of the analogue cooling-rates in these points. A clear tendency of increasing SDAS with increasing height of the steps can be seen in Figure 8. There is some deflection of the linear behaviour in the measured results especially for the cutting planes D-D.

Summary and future works

A through-process simulation strategy for manufacturing of aluminium components, by bridging different simulation tools has been presented and examined exemplarily for a laboratory casting (step plate). It was demonstrated that the transfer of the important simulation results between different software packages can be done with the available tools like MAGMAlink and scripting. In the first step the focus was on the evolution of microstructure in the cast component because the SDAS is known to significantly affect the fatigue strength of cast aluminium alloys. The simulation results for predicting this important feature of the microstructure show a reasonable agreement with reality.

In a next step the verification of the calculated stresses will be accomplished by different experimental methods. The used flow stress data from MAGMASOFT will be compared to measured values from Gleeble experiments. Following material modes will be developed considering SDAS in order to predict fatigue. The prediction of stresses is strongly dependent on material parameter like flow curves which have to be determined by experiments. The verification of the calculated stress results is another important topic.

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