Validation of stress prediction during solidification of cast components

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Abstract

The development of appropriate techniques for casting complex, thin walled, light weight structures and housings, to assist the aerospace sector in achieving the required reductions in component weight and concomitant increase in strength, has become a challenging area of research. Some of the difficulties experienced during cast-processing relate to the filling of complex thin sections, controlling solidification behaviour, as well as compensating for thermal distortions. During casting the metal starts to solidify and undergoes changes in phases where different material laws are valid. In the fluid state the metal is almost stress free but as the part starts to solidify and shrink, stresses are induced in the casting due to constraints from the mould. Some of the induced stresses are relieved through creep effects corresponding to the visco-plastic behaviour of the material.

Traditionally, companies have relied on the “trial-and-error” approach with the experience of certain individuals to design and compensate for distortion. They have also used expensive and time consuming bending and straightening techniques making corrections for distortions.

Many casting simulation packages have been developed which can assist with optimising the filling and solidification behaviour of the metal during casting. Modelling the thermal distortions during casting poses many difficulties due to the complexities associated with all the thermo-mechanical influences. In order to accurately simulate distortion one has to fully integrate all the processing phenomena such as fluid filling, thermal heat transfer, solidification and stress.

The current research project is aimed at predicting the distortion behaviour occurring during casting with the intention of using this capability as a tool to assist with process development of complex, thin walled, lightweight components.

The initial objective is to determine the reliability of a fully coupled finite element model using A356 alloy and the investment casting process. A carefully designed box shaped experimental casting was used to validate the commercial finite-element code ProCAST (casting simulation software), with respect to distortions as well as residual stresses.

Introduction

During casting the volume of the metal in the mould is constantly changing due to thermal contractions and phase transformations. This volume change can result in non-uniform distortion behaviour, or where there are constraints from the mould and the casting itself, stresses are introduced into the casting. Some of these stresses are relieved as a result of creep effects at higher temperatures and some are recovered through springback during mould and gate removal.

Residual stresses are captured stresses remaining in the casting and can only be recovered during heat treatments. The residual stresses which are in tension can significantly reduce the fatigue life and corrosion behaviour of the casting [5,11].

Thermal distortions occurring during casting affect the final shape of the component. The ability to predict the shape evolution during investment casting requires a significant degree of confidence in the mathematical model defining the process and the behaviour of the material. The model must accurately simulate all the physical phenomena influencing the shape of the component, thus fully coupling fluid filling, thermal heat transfer as well as all thermo-mechanical interactions [2,3,5,6,8,12].
Material properties, such as the enthalpy curve and the solidification path (i.e. the fraction of solid versus temperature curve), density, viscosity and thermal conductivity can be computed automatically from thermodynamic databases based on the chemical composition of the metal. ProCAST has an automatic link to

the thermodynamic database in CompuTherm LLC [1]. Beside the thermal properties, it is also possible to automatically calculate some thermo-mechanical properties such as the Young's modulus, the Poisson's ratio and the thermal expansion coefficient based upon the phases obtained from the thermodynamic database. In future other properties which are required for stress modelling, such as, yield stress, hardening, visco-plasticity, etc, will be available in these thermodynamic databases [8,10,12,14].

One of the important factors which strongly influence the cooling behaviour of the metal during casting is the formation of an air gap, or inversely, a contact pressure condition, which can be formed between the metal/mould interface. The casting simulation software accounts for these influences by employing a multi-body mechanical contact algorithm (an augmented Lagrangian treatment of contact problems) which automatically modifies the interface heat transfer coefficient to compensate for both conditions [1,3,4].

After the metal has solidified in the mould the shell must be removed from the casting and captured residual stresses in the metal should be relieved due to springback. The model can take this into account by changing the mould condition at a given point in time to a vacant material condition, thus removing all the mould constraints from the casting. The gates which are attached to the casting also contribute to the residual stresses in the component and therefore need to be removed [2,3,5].

Experimental Procedure

An experimental box shaped part, representing an electronic type housing casting, with wall thicknesses varying from 3 to 6mm was used with the intention of creating a non-symmetrical thermal cooling behaviour. The geometry of the complete casting including the pouring cup and gating system is shown in **Figure 1 & 2**. The aim being to induce stresses in the component, which would result in creating residual stresses and distortions in the final component.

The geometry was meshed with the commercial software MeshCAST using finite element tetragonal elements.

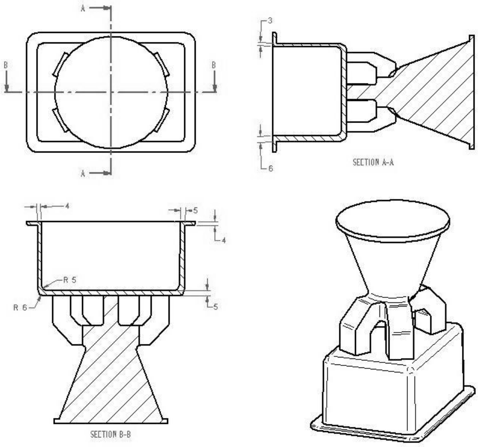

Figure 1: Drawing of casting geometry.

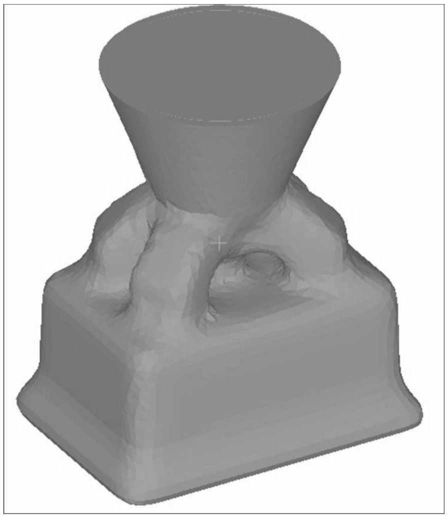

Figure 2: Mould geometry

The shell mould was created in the software by using an automatic mesh displacement and blending technique. Modelling the actual geometry of the mould is extremely difficult due to the fact that the shell thickness of the mould is non-uniform. The layered dipping process during mould manufacture causes this effect. Although, the automatically generated mould mesh shows reasonable matching with the actual shape of the mould, future models will be created using an optical digital image scanning technique together with a mesh smoothing algorithm. This will provide a more accurate representation of the geometry [1,13].

The wax injection process was not simulated in this project. In some cases this can have a significant influence on the final shape of the casting. By removing the wax pattern from the die at the optimal time after injection the non-uniform distortion behaviour can be reduced significantly. If the part is removed too early, it can distort under its own weight, causing sagging in some areas while, if the part is removed too late, constraints from the die can influence the wax shrinkage behaviour.

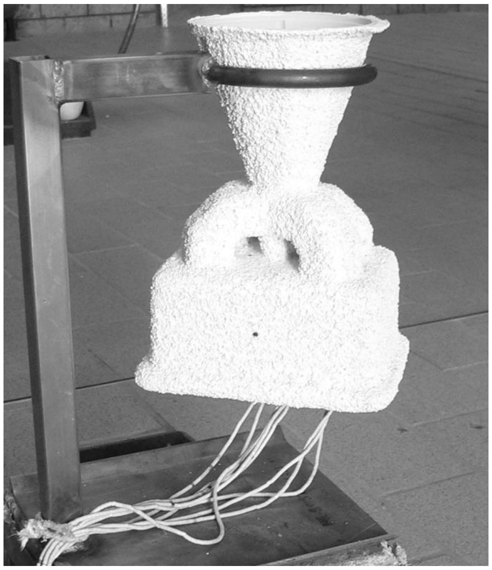

Figure 3: Instrumented casting

In order to ensure that the thermal model agrees with the actual casting, an instrumented experiment was completed where temperature comparisons were made, see **Figure 3**. The boundary conditions were then computed using an inverse method and then applied to the model [9].

Various geometric profiles of the die, wax and final component were measured using two different techniques, a touch probe from a co-ordinate measuring machine (CMM) and an optical scanning digitizing system, GOM ATOS. The latter method compared extremely well with the CMM measurement method [13].

An elesto-plastic material model was used for the casting simulation. After determining the chemical composition of the alloy (A356), some of the thermo-mechanical data was computed from the thermodynamic database.

The finite element software ProCAST is also capable of using various material models to define the thermo-mechanical behaviour of the metal during solidification such as vacant, rigid, elasto-plastic, and elasto-visco-plastic. Three visco-plastic material models are available in the software: Perzyna, Norton and Strain Hardening Creep. In the future creep tests will be completed in order to determine the elasto-visco-plastic behaviour of the metal [1,10].

The process was then modelled with a fully coupled fluid, thermal, solidification and stress analysis, simulating the casting process. Comparisons were made between cross-sectional profiles of the model and the casting. The next step in the project will be to measure the residual stresses in the casting and to then also compare this with the model's predicted residual stresses [7].

Results and Discussion

As shown in **Figures 4 & 5,** the casting simulation shows good agreement with the thermocouple data obtained from the instrumented casting.

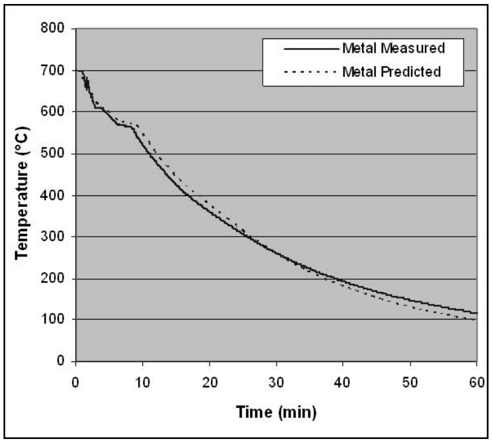

Figure 4: Mould temperature-time comparison between the model and the actual casting.

The investment casting process is extremely complex as it contains many factors which influence the validity of a mathematical model. Each stage of the process, from wax injection, through mould manufacturing and firing, casting, shell removal, gate removal and heat

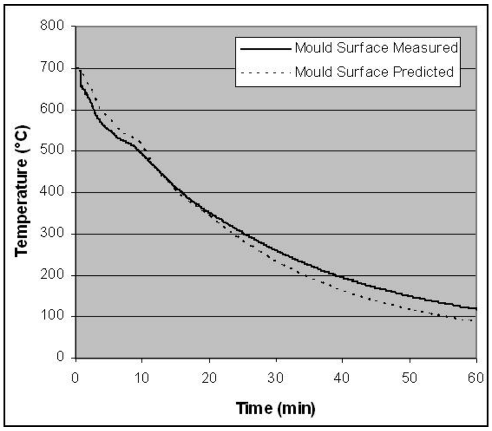

Figure 5: Metal temperature-time comparison between the model and the actual casting.

treatment to final component, all contribute to the final shape of the component. Ultimately one would like to simulate all these processes however; realistically a good compromise should be obtained.

In these trials, the distortion results of the model do not accurately represent the shape profile of the casting tested due to over simplification of the model. Extreme conditions were used to define the shell mould material behaviour in the model, one using a vacant model (**Figure 6**), and the other using a rigid model (**Figure 7**), each showed completely different stress behaviour. The actual conditions are a combination of these extreme conditions.

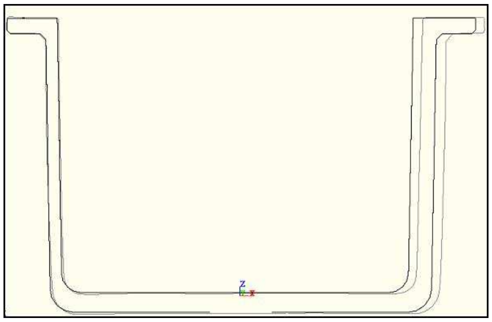

Figure 6: Geometric profile comparison of the actual casting (dark line) and simulation (light line) using a vacant mould material behaviour.

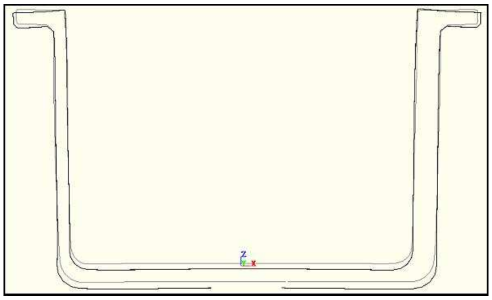

Figure 7: Geometric profile comparison of the actual casting (dark line) and simulation (light line) using a rigid mould material behaviour.

Depending on the shell mould manufacturing process, slight variations can effectively represent both these conditions. For example, extremely weak shell moulds can be created in various ways, introducing shell defects into the mould at required locations, selecting a weaker moulding material combination, changing the binder content in the dipping process, reducing the number of shell layers used, lowering the firing temperature etc. **Figure 8** shows mould cracking during solidification. The opposite can also be achieved. Obtaining accurate material properties for each of these conditions can be extremely difficult.

Figure 8: Shell mould after casting showing cracking along the edges.

The location of high stress regions in the casting are strongly influenced by the material mould defining the shell, as shown in stress contour plots in Fi**gures 9 & 10**. A weaker shell system will result in a much lower residual stress state. Inversely, a stronger shell will cause a higher level of residual stresses as well as result in a more heterogeneous distortion behaviour. Issues relating to hot tearing also become a problem.

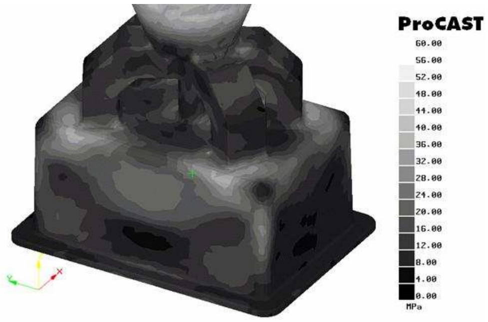

Figure 9: Effective stress profile after casting and simulation using a vacant mould condition.

Figure 10: Effective stress profile after casting and simulation using a rigid mould condition.

Conclusions

These initial trials have helped in gaining a greater understanding of the complexities involved in modelling the coupling of thermal-mechanical materials behaviour. The simplified material model used for the mould is not adequate enough for simulating the distortions in castings. A more complex model with multi-deformable bodies is required. In order to achieve this accurate material data for both the shell mould and metal should be determined.

The elasto-visco-plastic material properties of the metal can be obtained through a series of creep tests at various temperatures. Determining the thermo-mechanical properties of the shell model is more complex as it involves a multi-layered combination of materials which all in essence behave differently.

Other issues which need to be addressed are wax shrinkage behaviour during injection, in-homogeneity of the shell mould thickness, better meshes to represent the mould geometry and variable mould surface boundary conditions.

Validating the geometry is one area to compare the accuracy of the model, however the residual stresses of the casting remaining after shell removal and gate removal will ultimately be required. Methods such as shearography, stress photonics and X-ray diffraction will need to be investigated.

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