Presented at the 71st World Foundry Congress, 19-21 May 2014, Palacio Euskalduna, Bilbao, Spain

Centrifugal Casting of Large Ti-6Al-4V Structural Components supported by Process Modelling

Ole Koeser[1], Badarinath Kalkunte[1], Dr. Rui Yang[2], Dr. Nan Hai[3]

[1]Calcom ESI, Lausanne, Switzerland
[2]Institute of Metal Research (IMR), Shenyang, China
[3]Beijing Institute of Aeronautic Materials (BIAM), China

ABSTRACT

The usage of large structural Ti components in airframe and spacecraft can lead to significant weight saving and thus reduce fuel consumption and emission. From a cost point of view such intrinsic components can be manufactured by a centrifugal investment casting process. The large size of the castings (order of size 1-2 m), its thin-walled geometrical features (lower limit 5 mm) and the limited superheat (40°C imposed by the clean-melting process) requires the application of centrifugal casting to obtain a complete mold filling. Casting modelling capabilities were developed to predict centrifugal mold filling, solidification, porosity formation, stress and deformation to support the casting process design. The article shows in detail the features of the casting modelling (material properties, interface heat coefficient, boundary conditions), how the modelling results compare with the real casting and what measures were actually taken to ensure and improve the quality of the casting parts. This work was achieved in the frame of the FP7project COLTS with European and Chinese partners (http://www.colts-project.eu/).

Keywords: Casting simulation, TiAl, centrifugal casting, Investment casting, porosity, process modelling, deformation, misrun

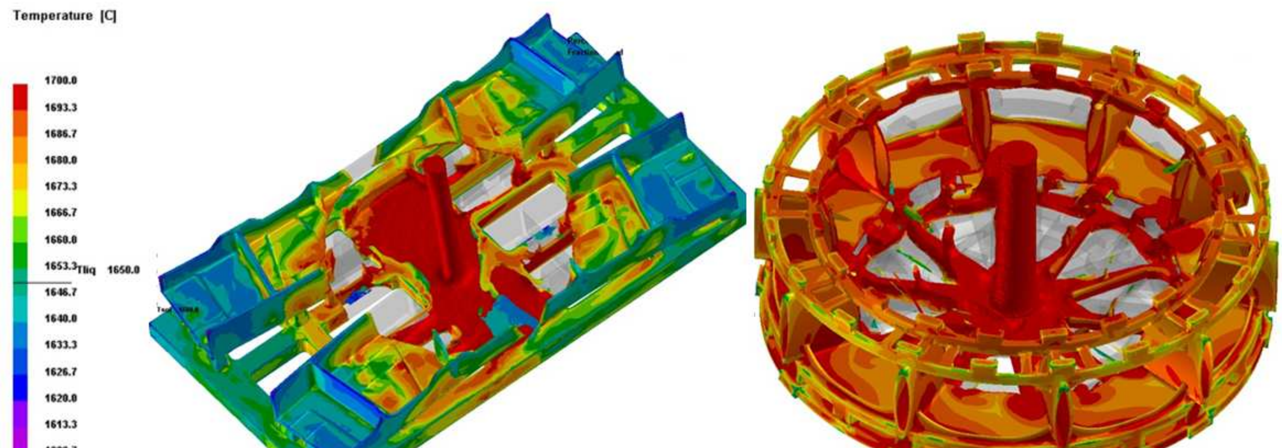

Figure 1: Casting modelling results of a doorframe component (left side) and an engine casing (right side) geometry

INTRODUCTION

The development of casting process technology for very large thin-walled structural TiAl components follows a general trend in the product development. By imposing the requirements of the products (in this case for aeronautic and aerospace applications) to its limits, in term of material properties, light weight design and complexity, the capabilities on the manufacturing process (in this case its centrifugal investment casting) also need to be extended. The enabler for this process

improvement is the synthesis of concrete process design approach with modelling capabilities. On the modelling side it is required to provide predictive (validated) simulation capabilities. The simulation software needs to cover the principle physics of the manufacturing process. Potential problems (filling related defects like inclusions, misruns & blowholes, porosity, deformation) need to be identified in a way that its sensitive to the change of process parameters (like filling time, filling temperature, mold pre-heating temperature, mold rotation speed, ..).
In this context the following article will show how the current software capabilities were extended to address the specific demands on the centrifugal casting of large TiAl structural components inside the scope of the COLTS project. Once these capabilities were established the casting simulation software was applied in the process development, which is demonstrated by one application example.

IMPLEMENTATION AND VALIDATION OF MODELLING CAPABILITIES

For the purpose of implementation of the modelling capabilities, 4 different industrial components were chosen. Two components are typical applications from the aeronautical sector (compare ***Figure 1 left side airframe component, right side engine casing***), while two others are structural components (a cube like and a cylinder like structure) from the aerospace sector provided by the European Space Agency (ESA). All components are big in size (order of size 1 m) and at the same time thin-walled (4-5 mm wall thickness). Such complex geometries ensured that the casting simulation software could be verified in detail and the enhancement of the modelling capabilities could be laid to match the requested performance to enable finally to produce such complex geometries. ESI Group's casting simulation software ProCAST was used for this purpose.

The scope of the modelling approach were flow aspects (filling simulation), thermal aspects (solidification, cooling down of the part inside the ceramic shell), porosity prediction and stress evolution and deformation prediction. While ProCAST has already industrialized solvers for thermal, flow and stress aspects available, its capabilities were validated and respectively extended concerning the influence of the centrifugal forces. On one hand the flow solver performance was optimized to tackle the complex turbulence flow pattern (as visible in Figure 1) on a FEM model of several Million elements, on the other hand the influence of the centrifugal force direction to the porosity formation was implemented in the thermal solver.

Figure 2 shows the influence of the centrifugal force to the porosity formation. In the top part of ***Figure 2 (gravity)*** the porosity can be observed at the top of the part (using artificial demonstrator geometry). Due to the centrifugal forces (***Figure 2 bottom part***) the porosity is moved to the center of the casting as expected. A further validation of the porosity prediction can be found in the following sections.

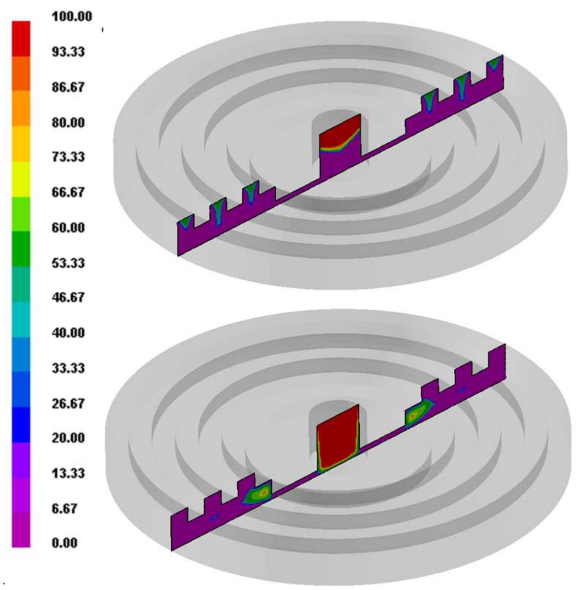

Figure 2: Porosity formation under gravity influence (top) and centrifugal force (bottom). The scale is corresponding to the porosity level in percent

Filling related defects such as inclusions are often observed in the last filling regions. The molten metal free surface transports the possible inclusions during the course of filling. The last region to be filled in the cube geometry also has metal streams meeting together, which could lead to potential misruns when these are at lower temperatures (closer to the alloy Liquidus). ***Figure 3*** shows the last filling results of a large cubic space frame (1m x 1m x 1m) together with x-ray observations at these regions. The comparison shows, that modelling results are in good agreement with the experimental observations.

One other major problem in the investment casting of such large thin-walled components are their tendency to form un-desired deformation there-by making the part geometries go outside the required tolerances. ***Figure 4*** shows deformation comparison between simulation (top) & experiment (bottom) on the large cubic shaped frame. The reason for the deformation is the difference in wall thickness of the outer frame and the inner crossbars, leading to non-uniform temperatures during solidification & cooling. The thinner inner crossbars solidify quickly, drawing the inner corners of the outer frame due to the induced shrinkage, which is leading to an elasto-plastic deformation in these corner regions (not shown). As the thicker outer frame starts to solidify /shrink at a later stage, the inner cross bars (being relatively larger because of the plastic deformation) is bowed outwards by some millimeters (with respect to the plane built by the quadratic frame) as shown in ***Figure 4 bottom***. This behavior was very well reproduced in the modelling results (***Figure 4 top***).

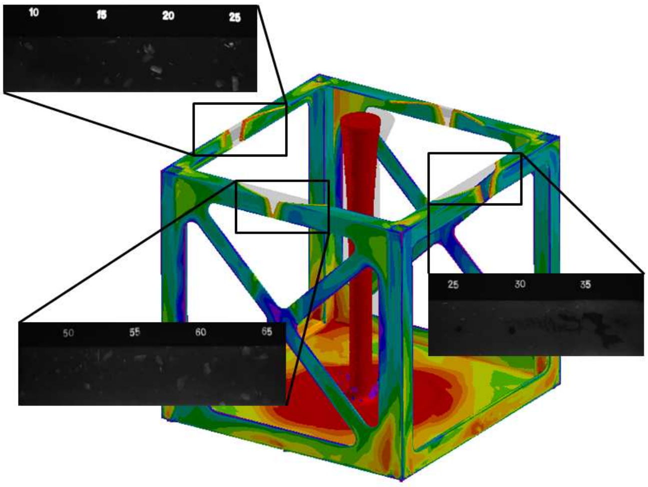

Figure 3: Inclusions and misruns in the last filling regions (Courtesy of University of Birmingham)

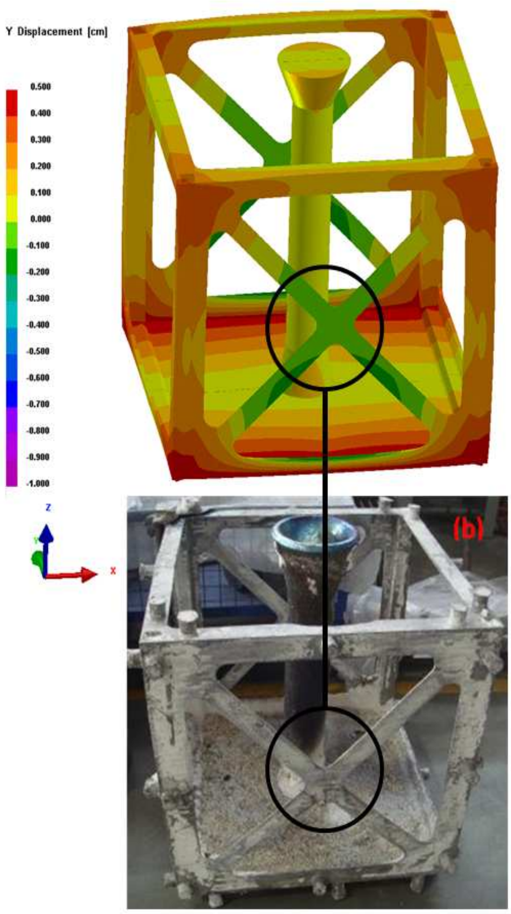

Figure 4: Predicted and experimentally observed deformation of a cubic shaped frame.

PROCESS DEVELOPMENT BY MODELLING

After the initial validation of the ProCAST software package for centrifugal casting applications (as described in the previous section) were achieved, this modelling framework was applied to develop the casting design & process parameters of these different casting components. The process design optimization of one of the 4 geometries, a cylindrical structure coming from ESA will be described in this article. While the first section will describe the modelling setup, the second section will explain the different process design steps.

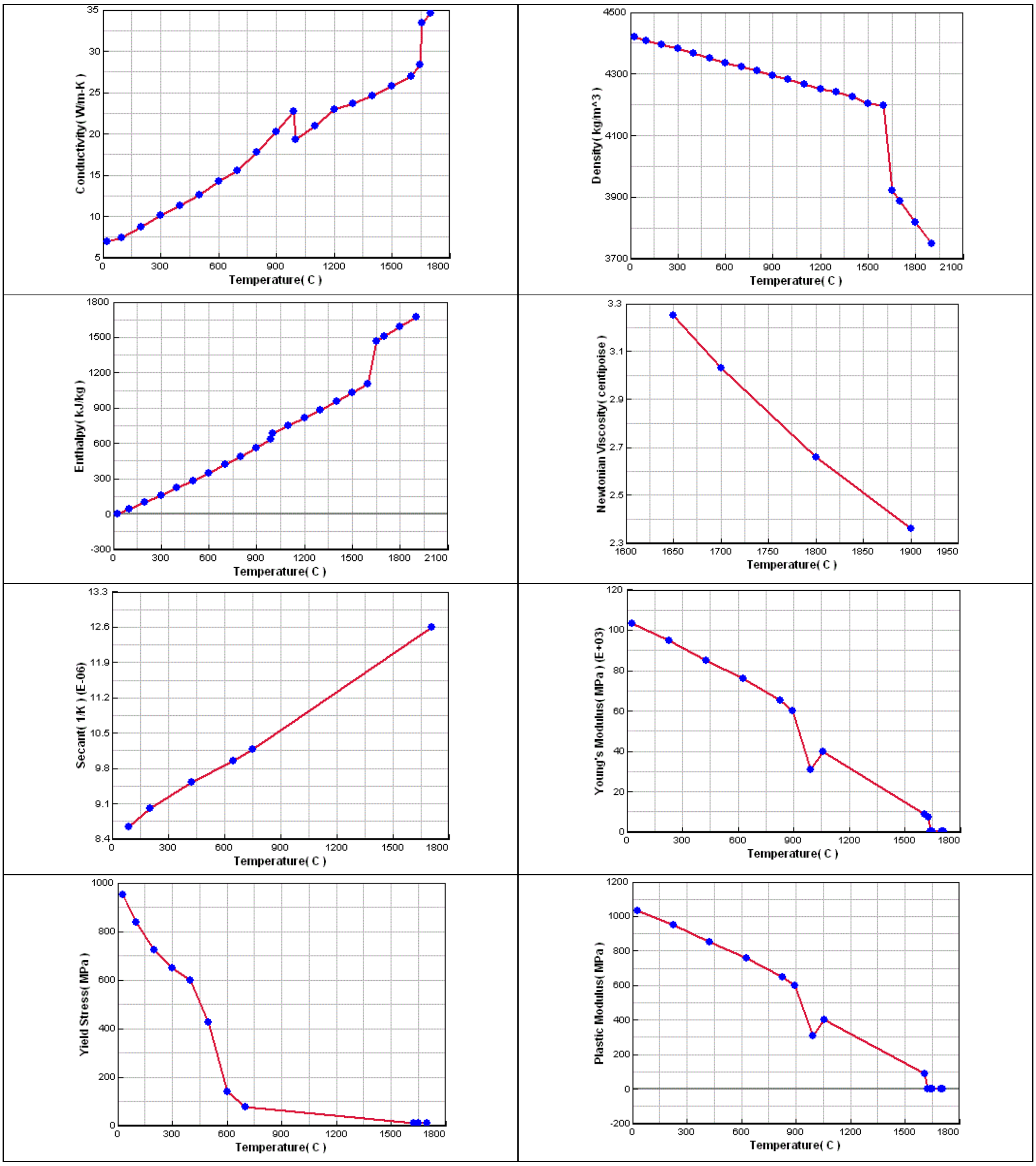

Figure 5: Material properties Ti6Al4V

The poisson's ratio of Ti6Al4V was set to 0.36.

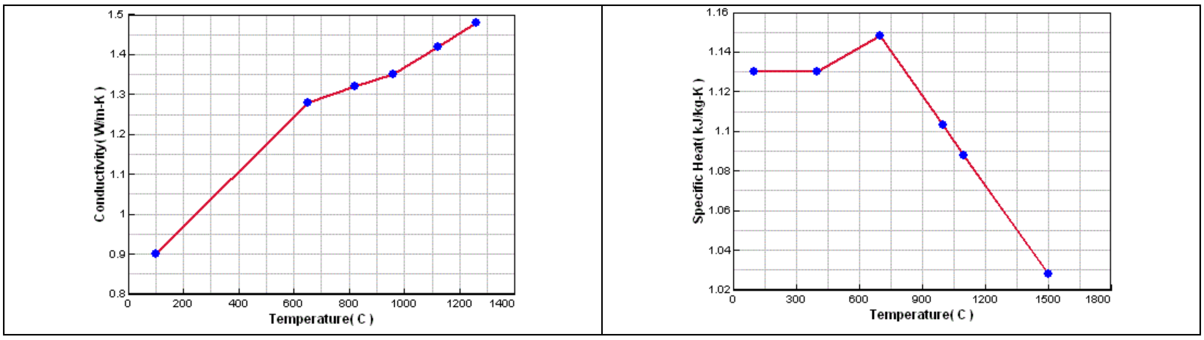

Figure 6: Material Properties Ceramic Shell

PROCESS PARAMETERS AND MODELLING SETUP

The current section would describe the process parameters and the modelling setup in detail for the selected cylindrical geometry.
Process parameters of the casting process: casting temperature = 1700°C; mass flow rate from the ladle = 37.5 Kg/s; rotational frequency = 200 rot/min. The material properties of the Ti6Al4V are as follows: TL= 1650°C; TS=1600°C. Further temperature dependent material properties are given in the ***Figures 5 and 6.***

Further, the properties of the ceramic shell (elastic properties) were set as follows: Young’s Modulus = 20’000 MPA; poisson ration = 0.3; thermal expansion coefficient 6e-6 1/K.
The interface heat coefficient between casting and shell was set to 400 $W/(m^2 \cdot K)$As the external boundary conditions an emissivity of 0.7 was used together with an external temperature of 30 0C.

MODELLING APPLIED FOR CASTING PROCESS DEVELOPMENT (APPLICATION/RESULTS)

The principle features of the cylindrical geometry can be described as follows: The basic shape of this geometry is a hollow cylinder of 4 millimeter thickness. At the bottom and at the top region thicker profile sections can be found. An initial gating system was designed to fill this structure. The filling is performed through the central axis of the cylinder which delivers the melt to four runners and later into the cylindrical cavity (***Figure 7***).

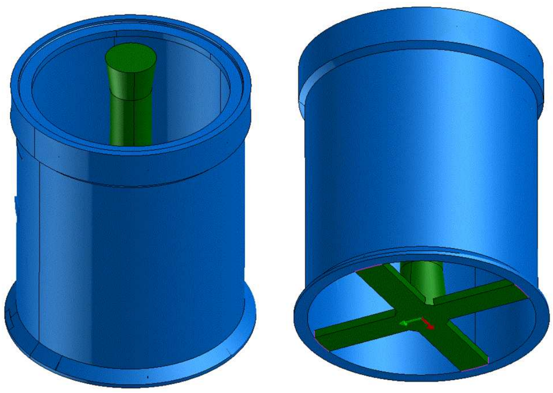

Figure 7: Initial version of the process design

The thicker section at the top of the cylinder needs more metal & higher temperatures to enable a sound filling. The long flow lengths coupled with the passage of the melt through thin cylinder sections meant a high risk of interrupted filling (misrun) towards the end (metal temperatures already the mushy zones during filling). ***Figure 8 top*** shows the filling problems that were identified in context with this initial version using the simulation software. ***Figure 8 (bottom)*** shows the validation of this prediction in the real casting experiment indicating partially unfilled regions (see x-ray right top section).

To overcome these filling problems two measures were taken (***see Figure 9***). The number of runners was increased from 4 to 6 and the cylinder was turned by 180 degrees in order to fill the more massive profile first. The down sprue & the pouring cup were adapted to suit these modifications. These measures eliminated any risk of interrupted filling in the casting cavity, and the same was observed in the real casting experiments (simulation results / actual validation not shown in this article).

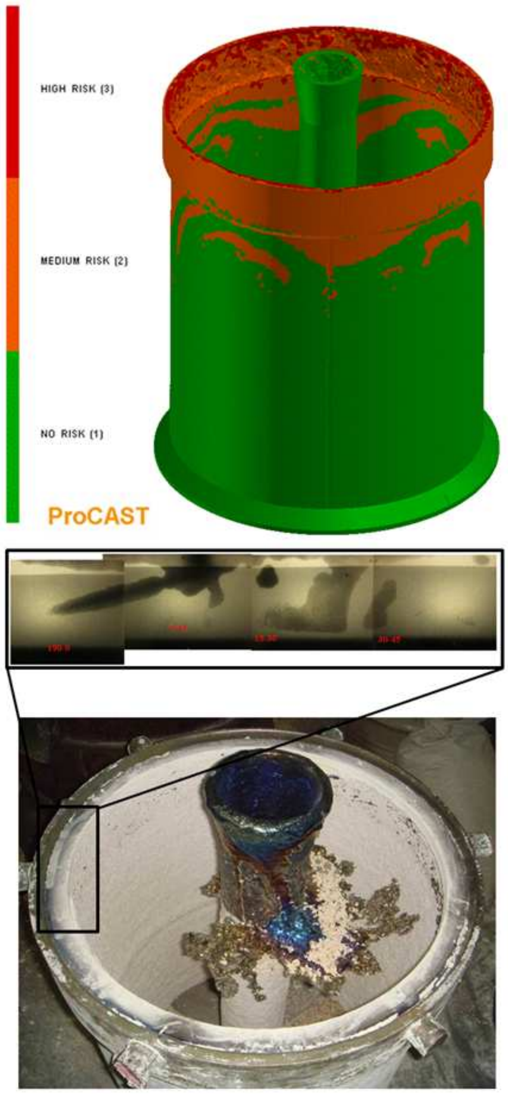

Figure 8: Filling and experimental result of the initial process design

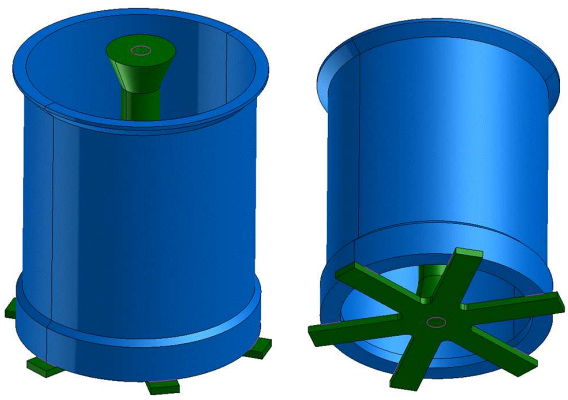

Figure 9: First process design change

While the first process design has largely improved the filling behavior a problem zone for porosity was identified by the casting simulation. The thin wall of the cylinder also with constant thickness is solidifying all through within a short time leading to shallow temperature gradients & hence establishing high risks for the formation of porosity. ***Figure 10*** shows the dispersed micro porosity that can be observed in the modelling results and in the x-ray of the real casting.
This problem was solved with a second design change. Three rows of horizontal rings were added onto the internal side of the casting to create local temperature gradients, and pull the porosity from the long (thin) cylindrical sections onto these thicker sections (***Figure 11***). These rings were later removed by machining in an additional process step to achieve a sound casting.

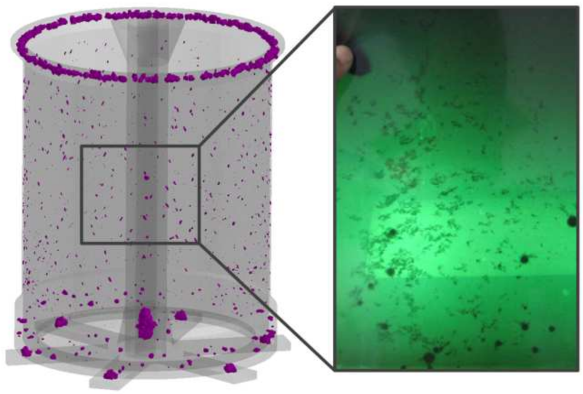

Figure 10: Simulated and measured porosity distribution on the thin cylindrical section – first process design change

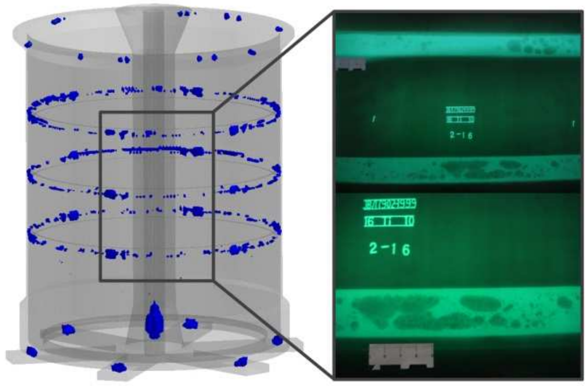

Figure 11: Simulated and measured porosity distribution on the thin cylindrical section - second process design change with internal rings

CONCLUSION

The article showed the implementation of casting simulation capabilities for centrifugal casting of large thin-walled structural components made of TiAl. The modelling approach was validated with different industrial cases and a good agreement was shown between the shop floor trials and the simulation results in terms of filling, porosity and deformation predictions. The developments now enables use of a simulation software in the early stages of casting process development of large thin walled titanium structures using centrifugal process, helping designers identify potential problems, and hence act accordingly to develop sound casting parts.

REFERENCES

[1] Recommended values of Thermophysical properties for selected commercial alloys by Kenneth C Mills, Woodhead Publishing Limited

[2] Technical Data Sheet, 21Mar08, ATI Allvac, www.allvac.com

[3] Z. Guo, N. Saunders, J.P. Schillé, A.P. Miodownik, Modelling high temperature flow stress curves of Titanium alloys, MRS International Materials Research Conference, 9-12 June 2008, Chongqing, China

[4] M. Vanderhasten, L. Rabet, B. Verlinden, Temperature deformation of Ti6Al4V at low strain rate, Association of Metallurgical Engineers Serbia and Montenegro, Scientific paper UDC:669.280’5’11’292-152.5=20

[5] M.Fukuhara, A.Sanpei, Elastic moduli and internal frictions of Inconel 718 and ti-6Al-4V as a function of temperature, Journal of Materials Science Letters 12 (1993) 1122-1124

[6] ProCAST 2013 User’s manual, ESI Group