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Integration of Virtual Engineering and Additive Manufacturing for Rapid Prototyping of Precision Castings

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Abstract

The present paper is concerned with the practical interconnection between virtual engineering tools and additive model manufacturing technologies and the subsequent production of a ceramic shell by rapid prototyping with the use of Cyclone technology to produce the aluminium casting prototype. Prototypes were developed as part of the student formula project, where several parts originally produced by machining were replaced by castings. The techniques of topological optimization and the combination with the tools of the numerical simulation were used to optimise the virtual prototype before a real production of the first prototype. 3D printing of wax pattern ensured direct and fast assembly of the cluster without any additional operations and troubles during dewaxing. The shell was manufactured in 6 hours thanks to a system of quick-drying of individual layers of ceramic shell. It has been verified that the right combination of individual virtual tools with the rapid prototyping can shorten the development time and delivery of the first prototypes from a few months to a few weeks.

Keywords: Product development, Innovative foundry technologies, Virtual engineering, Rapid prototyping

1. Introduction

Foundry industry faces new challenges caused by market pressure and the rapid development of additive technologies. While requiring speed and quality prototypes, these technologies necessitate a change in the approach to the design of the machine components themselves. The techniques of topological optimization and generative design have unleashed the designers' imagination to such an extent that, in many cases, the manufacture of a designed part's shape is hardly feasible using conventional technologies. We will have to get used to the concept of "hybrid technology", which requires the use of 3D printing and, for some shapes, it will be possible to use just full 3D printing of metals, not only for prototype production. To meet the increasing demand for castings, it will be necessary to work with all the virtual engineering tools available, which will be a red thread from the casting concept, through its optimization and virtual production, to the control of the required properties.

Virtual engineering (VE) is a term coined to describe the operationalization of virtualization in engineering processes. Starting in the late 1990's, this process has led to a targeted combination of engineering activities with a wide range of digital data processing [1]. VE is applied as an interdisciplinary approach that uses and combines identical approaches in several different engineering fields, in order to enhance cooperation, accelerate decision-making processes improving the quality of the offered solutions in an effort to cut down the costs and required investment. On the other hand, VE works with rather diverse technologies, methods, and tools in different engineering fields. According to [2], VE can be viewed at three basic levels. The first-level VE works in methodical and technological dimensions including comprehensive modelling, simulation of products and characteristics using development, and virtual product examination [3]. The second-level VE is concerned with the implementation of a product including its economic dimension, simulating the interaction and behaviour of products during their entire life cycles [4]. The third-level VE then works in terms of organisation and commerce, extending virtualization to the entire company operation, leading to a complete overhaul of the industrial product paradigm and its implementation. This level is close to the idea of Virtual factory as described in [5]. The VE used in casting at present is mostly of the first level including elements of Virtual Prototyping (VP) and Virtual Manufacturing (VM), which can be extended by the virtualization in the dimension of Virtual Reality (VR). The application workflow that can be used in VE is shown in Figure 1 with the computer-aided process phases from the system concept to the manufacture the physical prototype.

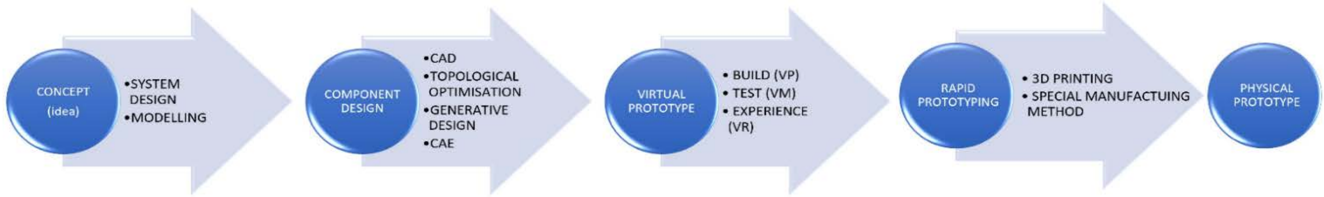

Fig. 1. VE using individual platforms

2. Virtual prototyping

Virtual Prototyping (VP) is a set of methodologies designed for the support of processes at the project-development stage. VP includes the combination of several tools including a Computer Aided Design (CAD), Computer Automated Design (CAutoD) and Computer Aided Engineering (CAE) used to verify a design before making a physical prototype. Casting-related VP is basically a design activity creating optimal shapes of castings. Until recently, the casting shapes have been designed to meet at least the basic requirements of the design technology. This means that the design of a part should take into account the way it is going to be manufactured and the properties of the materials used to ensure efficient and quality manufacture. The compliance with the technological requirements of design concentrated on the way a model is divided with respect to the manufacturing technology selected. This involved the elimination of hot spots through ideal joints and transitions
of walls, in many cases responding to the need of directional solidification in order to eliminate casting defects. For these reasons, the casting shapes were rather conservative to meet the requirements of functionality and the manufacturing technology chosen in the first place. The advances of new methods of optimizing 3D design (including cloud solutions) such as topological optimization and generative design as well as the new 3D printing methods, have promoted the design of part shapes to be on a par with artistic castings.

2.1. Topological optimization

Topological-optimization-based casting designs aim to find the optimal layout of the material in the design space. This replaces the traditional approach of manual design or parametric optimization. An advantage of topological optimization is that it is independent of the design size.

In the optimization process, material is removed from the total volume of a design part while observing the prescribed limitations such as:

– part external boundaries
– part strength limitations
– preserving interconnecting areas

The below example analyzes a machine part that, previously processed by the original machining workflow, was now manufactured as a casting with the use of topological optimization. The project was implemented as part of a competition of student formulas (Dragon 10 formula) where a major requirement for the castings was a reduction in weight and increased rigidity, given a development and manufacture time limitation to one month. Among others, the project focused on the casting of the left rocker of the rear axle, using the AlSi7Mg0.3 alloy. The force load is based on a simulation of the car dynamics using the Adams Car
software. Next the ANSYS Workbench 18.1 program was used to carry out a structural analysis for each load status used as input data for topological optimization.

Figure 2 shows the input model for topological optimization, called workspace, in which the part being optimized must be situated. From this pace, through several iterations, 82 % of the material was removed. Subsequently in CAD, the result of the topological optimization was finalized and validated by an FEM analysis. The topological optimization took 4 days for this case.

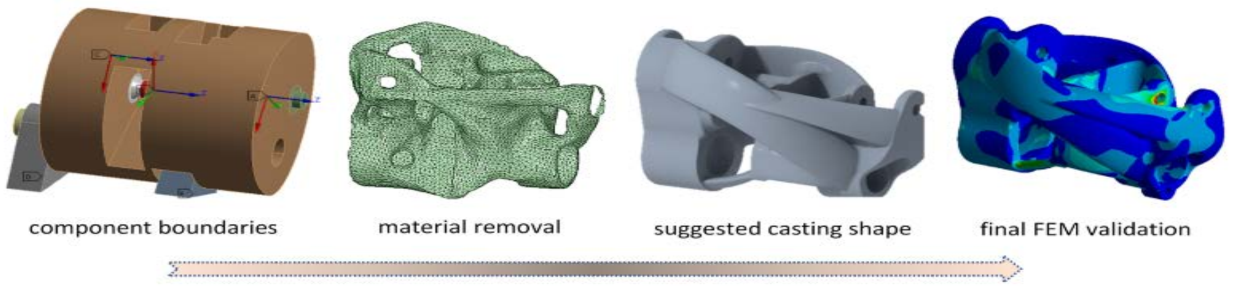

Fig. 2. Stages of topological optimization

3. Virtual Manufacturing

Virtual Manufacturing is a system in which the abstract prototypes of manufacturing objects, processes, activities, and principles evolve in a computer-based environment to enhance one or more attributes of the manufacturing process. The numerical simulation used in this phase is regarded as design-centred VM, which provides manufacture-related information to the designer during the design phase. In this case, VM means the use of manufacture-based simulations to optimize the design of product and processes for a specific manufacturing goal (DFA, quality, flexibility, etc.) or the use of simulations of processes to evaluate many production scenarios at many levels of fidelity and scope to provide information for design and production decisions [6]. The numerical analyses of the casting were done by a ProCAST program optimizing process parameters (casting temperature, shell pre-heating temperature), functions of the gating system (Figure 3), the actual solidification of the casting and the shell temperature distribution during cooling of the casting. A prediction was also made of the potential occurrence of shrinkage porosity in the casting – see Figure 4. The analyses conducted confirmed the necessity to change the shell temperature with respect to the fluidity of the thin parts of the casting and to isolate the lower part of the gating system and of the in-gates to ensure correct and longer feeding of the separately solidifying hot spots. The thermo-mechanical calculation was not performed for this case but is strongly recommended in the case of more complex casting shapes. The best prediction of the final dimensional accuracy can be achieved when a scanned pattern from 3D printing is used.

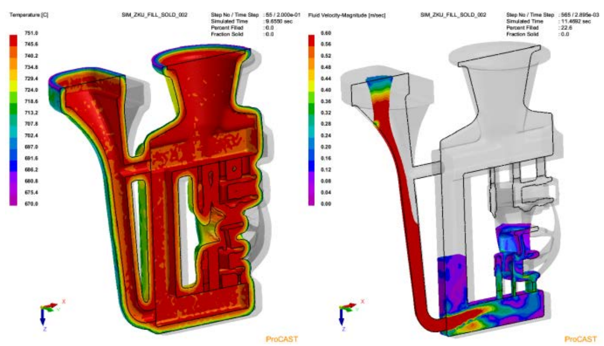

Fig. 3. Simulated filling and casting solidification

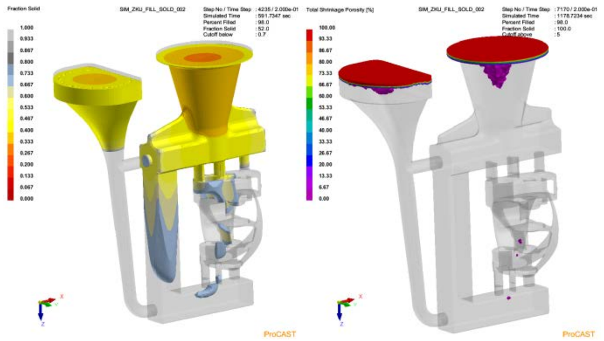

Fig. 4. Casting solidification (FS) and defect prediction

4. Additive manufacturing

Investment casting in combination with additive technologies has become a leader in the manufacture of smaller prototypes and small series of castings. The technology used is referred to as hybrid [7], with a printed model replacing the costly and time-demanding manufacture of a metal matrix. The CAD geometries of a casting were modified to take into account the shrinking of the model and metal. The model was manufactured using a 3D printing technology called material jetting printing (MJP), which has the capability of directly printing wax models. The ProJet MJP 2500 IC printer and VisiJet® M2 ICast RealWax™ were used. Figure 5 shows a printer manufactured by 3D Systems, which uses special wash-off of the supporting material so that the subsequent finishing is easier in terms of mechanics taking less time. The figure on the right shows the wax model with supports removed, which does not require any further finishing and can be used to prepare the pattern assembly (tree).

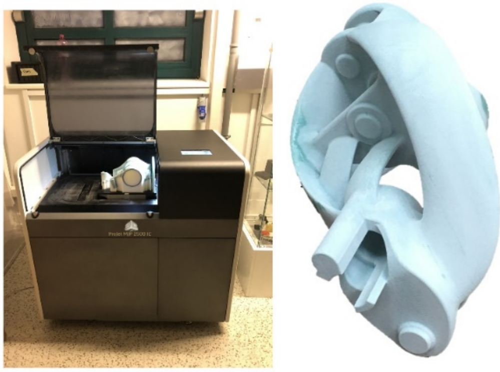

Fig. 5. ProJet MJP 2500 IC printer and 3D printed holder models

5. Ceramic shell and prototype production

The investment casting is itself a technology for rapid prototyping. The most time-demanding phase is the drying of layers, which, with water-based ceramic slurry, will take several days. This drying phase can be accelerated using Cyclone, a special device manufactured by MK Technology. This device can cut the manufacture of shells down to several hours. The drying system uses a fast and turbulent air flow to remove humidity. The infrared light outbalances the cooling down keeping the shell temperature stable at ± 1°C. The mirror inside the chamber reflects the infrared light to distribute it evenly across all parts of the shell. The continual rotation of the cluster ensures very fine and even drying, facilitated by the pre-dried air, which also accelerates the whole process [8]. To manufacture the shell in our project, ceramic suspension was used based on water, the PrimeCoat binder, and fused SiO_2 (-200mesh) with Zircon primary shell coat (80-100 size grade) and molochite (16-30 size grade) used for backup stucco coating. The Cyclon-based manufacture of the shell consisting of eight layers took a mere five hours. Once the shell was manufactured, the dewaxing was done, and the printed models burnt out. After the first spell in an autoclave, it was baked in an annealing furnace at 800°C. With the shell cooled down, the model was washed to remove all traces of the model used, particularly the residual ash.

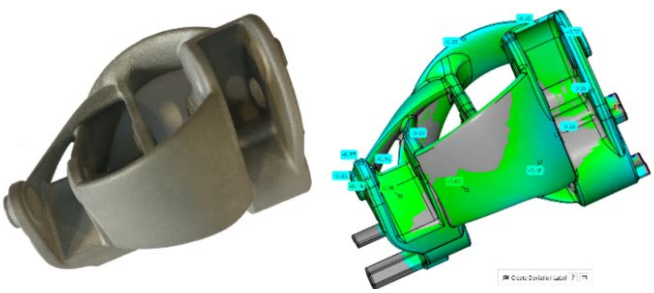

Fig. 6. Final casting after blasting and comparison of its size deviations from a CAD model

The shells were cast at AluCAST s.r.o. from a pouring temperature of 720°C. Before casting, the shell was pre-heated to 700°C. This temperature was higher than in the case of Al castings to ensure that the metal filled in all the profiles considering that only one part was to be produced "right on the first try." The pouring time was 5 sec. The T6 heat treatment was applied to the casting. As it had to meet especially the mechanical requirements, tensile tests were made for additionally cast samples. After verifying the dimension accuracy, the casting (Figure 6) was scanned to be matched with the CAD data. An ATOS Q scanner was used for this using a GOM Inspect software for subsequent analysis. The “Best Fit” algorithm was used for the alignment between CAD model and the casting. The maximum deviations detected of the casting shape were up to ±0.32 mm which was in accordance with the conditions of the prototype that accepted ±0.5 mm.

6. Conclusions

The development and production of the specified prototype using described workflow was solved within one month. The use of hybrid technology, i.e. 3D printing and subsequent production of the ceramic shell in the Cyclone device, shortened the usual prototyping from weeks to 3 days. It has been verified that the use of the printed wax material meets all the stuccoing and dewaxing requirements including the requirement for minimum ash content. The suggested workflow has been verified on the development of another nine castings prototypes. Further work will focus on the use of generative design in the design phase of the casting. We assume that this approach will speed up the initial casting design stage, as the manual CAD operations that are now necessary when using topological optimization are eliminated. Conditions during storage and transport of 3D printed wax models will also be optimized to minimize the effect of temperature on model expansion.

Acknowledgements

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