Computer Simulation of the Investment Casting Process: Widening of the Filling Step

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Abstract

Computer simulation as it applies to jewelry manufacturing technology has, in the last years, proven to have tremendous potential as a tool in helping to prevent casting defects. Nevertheless, many aspects of its use need to be widened to further improve results, including investigations into the precious alloys' physical parameters, the properties of investment materials and the dynamics of the process itself. Regarding the latter, the need to understand and, most importantly, to be able to predict the "when," the "how fast" and "where" the molten metal travels is of crucial importance, particularly when the filling and the solidification times are of the same order of magnitude. The paper focuses on the study of the filling times (both in terms of simulation and experimental validation) of different types of objects, with particular care for the filigrees' process dynamics.

Introduction

The correct choice of the parameters to be used in the program software represents a crucial aspect in the research of a defined and effective modeling procedure. As specified by Jörg Fischer-Bühner at the 2006 Santa Fe Symposium,[1] the application of computer simulation requires reliable material data for a large number of different casting alloys and a set of different investment materials. The widening of the materials' database is, therefore, a crucial aspect in guaranteeing the spreading of the application of simulation in jewelry production, as well as a key for its success. The use of Computational Fluid Dynamics (CFD) in the product engineering can indeed reduce times in the design and production of a new pattern—the common "trial-and-error" approach is becoming less and less acceptable. The ability to use simulation programs in the first step of designing and modeling complex structures helps to reduce the number of different alternatives required for testing in the experimental phase, thus making the process before the "final" jewelry production faster and (most of all) less expensive. The idea at the basis of each CFD is, therefore, to use the software as a "virtual laboratory" for the following:

- Testing prototypes
- Identifying project errors
- Looping the cycle until a properly working model is identified

In this paper, the software used for simulating the process was FLOW–3D. Its main feature is the possibility to solve Navier-Stokes equations in a discrete manner with a "control-volume" approach. Moreover, FLOW–3D is able to structure the Finite Difference mesh grid in multiple blocks, which may be both linked and nested, allowing more localized refinements (where needed) using less computer resources.

This kind of flexibility suits the need for defining thin-complex shapes such as the filigrees, whose filling dynamics and related problems are examined in the experimental part of the paper dealing with the industrial application of simulation.

As already pointed out, an important aspect for the setting of a proper modeling procedure is the correct choice of the parameters that are set up in the software. A decisive step of the work is the definition of these values, since they have significant importance for the practical applications that follow. Attention was targeted on different parameters that related to different processing temperatures (alloy melting range, casting temperature) as well as to other different physical characteristics, such as density, alloy viscosity, pressure and de-pressure present during the casting steps and, at the end, the properties of the refractory materials. It is therefore evident that, even in the very first steps, it is necessary to have a set of information important for obtaining a result that is coherent to the reality. Quite often, since all the required data are not available, it is necessary to proceed with further analysis (mainly thermo-chemical) for their determination.

Set-Up of the Experiment—The Simplified Tree

The first part of the work is focused on the study and analysis of simplified components, with a shape like that shown in Figure 1, illustrating the tree set as starting point according to previous studies carried out at the Politecnico di Torino (at Alessandria).[2,3] The evaluation of such a simplified model is needed in order to verify the potential repeatability of the analysis and of the computational prevision. Nevertheless, it has to be remembered that (unfortunately, at least from the research point of view) real industrial production is far away from such "simple" components, therefore the agreement of the experimental results to the simulation has to always be verified again when dealing with the "real" production.

Figure 1 *Simplified tree used for calibration of the processing conditions*

Another important aspect is related to the alloy considered. It has been stressed elsewhere[1,4,5] how important all the materials acting in the process are, as well as how much work is needed to derive all the data required for a complete and exhaustive simulation. In particular, Jörg Fischer-Bühner, at the 2007 Santa Fe Symposium,[6] focused attention on how the properties of the alloys could be far different from one to another (for instance, in terms of thermal conductivity) and how this impacts both the simulations and the final results (for instance, in terms of shrinkage porosity).

In this work, the attention was focused on the evaluation of the properties (and the impacts on the results in terms of filling) of three different alloys: one 18K yellow (Legor A182N), one 18K red and one 14K red (Legor OR134).

The differential thermal analysis (DTA) of the 14K red gold alloy is reported in Figure 2 below.

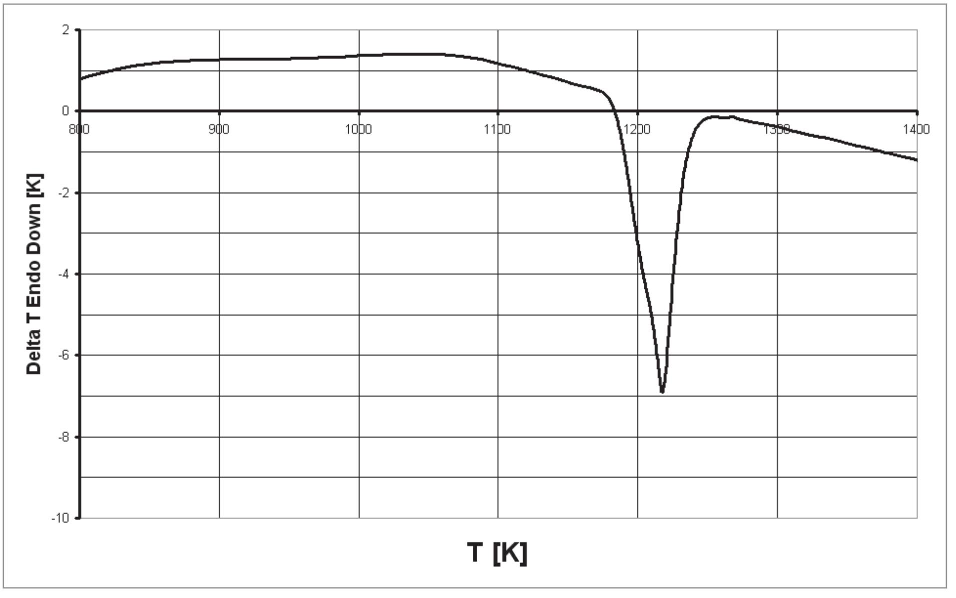

Figure 2 *DTA analysis of the studied alloy, carried out using a Perkin Elmer DTA7 testing machine*

The investment material used throughout all the study was Ultravest.

Experimental tests were aimed at verifying the computational model conditions. A set of trees with the properly mounted thermocouples was prepared, as shown in Figures 3a and 3b.

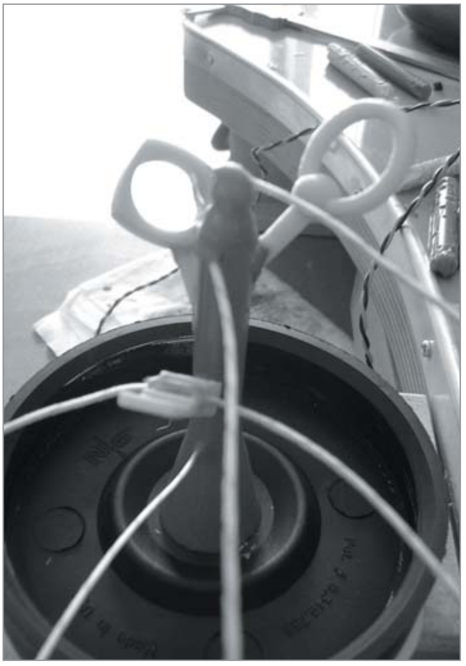

Figure 3a *Thermocouples inserted in the wax tree, side view*

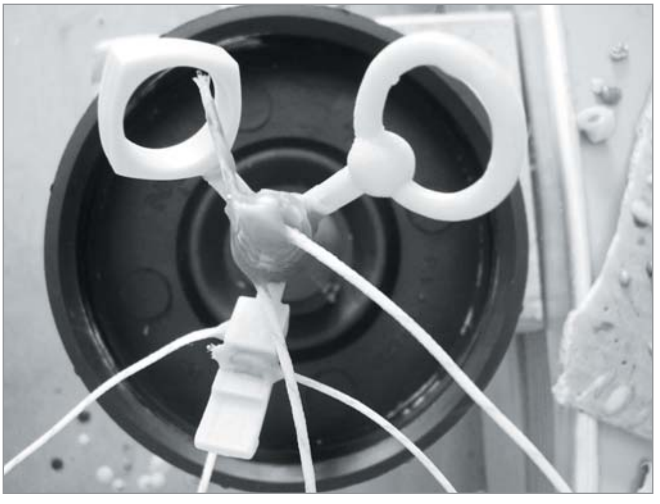

Figure 3b *Thermocouples inserted in the wax tree, top view*

Thermocouples were mounted in different positions on the feed sprues, directly on the components and in the investment material, in order to monitor the range of temperatures as a function of the location. A low-frequency acquisition (20Hz) was used for this purpose. Figure 4 shows the location of thermocouples in a stepped-wedge pattern after the casting. Type K thermocouples, covered with glass fiber, were used.

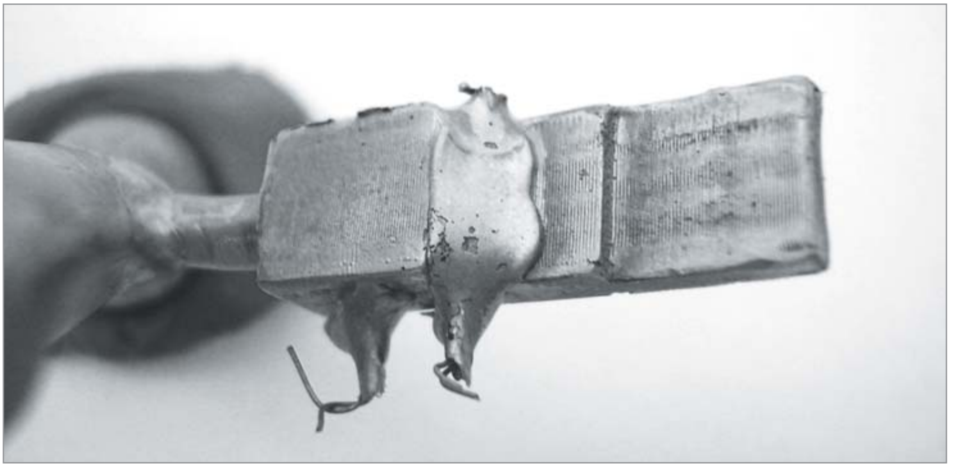

Figure 4 *Thermocouples used for recording the cooling step, located in different areas of the stepped-wedge model and in the surrounding investment*

The mapping of the temperature trends, as previously underlined, is tremendously important for the confirmation of the simulation. The trend of cooling may provide useful information on the shrinkage porosity, while the evaluation of the temperatures in the investment material gives precious data on the interrelation between it and the pattern, thus enabling us to foresee the gas porosity (or better, to confirm it through the evaluation of the temperatures). Figure 5 is an extract of the simulation referring to the evolution of the temperature as a function of time.

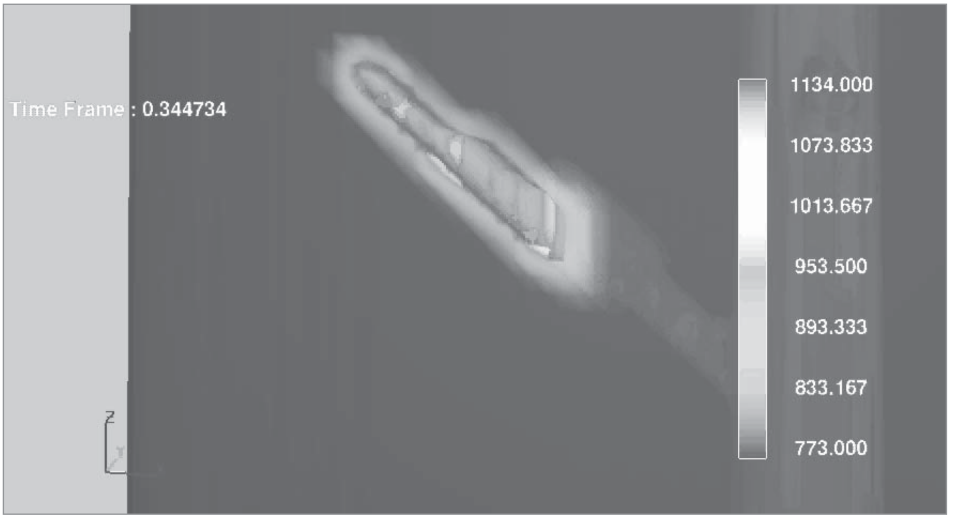

Figure 5 *Modeling of the cooling phase—detail of the stepped-wedge model. The temperature scale is in K (Kelvin)*

The low-frequency acquisition does not, however, allow us to check the behavior of the molten metal during the filling (i.e. where the metal goes and when) with the required precision. In order to experimentally verify this aspect, which plays a particularly important role in the filigree processing (better explained later on), a system operating at 1000 Hz was properly designed and manufactured in the Electrical Labs of Politecnico di Torino (at Alessandria), based on National Instruments components.

Figure 6 shows the location of the sensors on the tree for the simplified model, with their respective identifying codes.

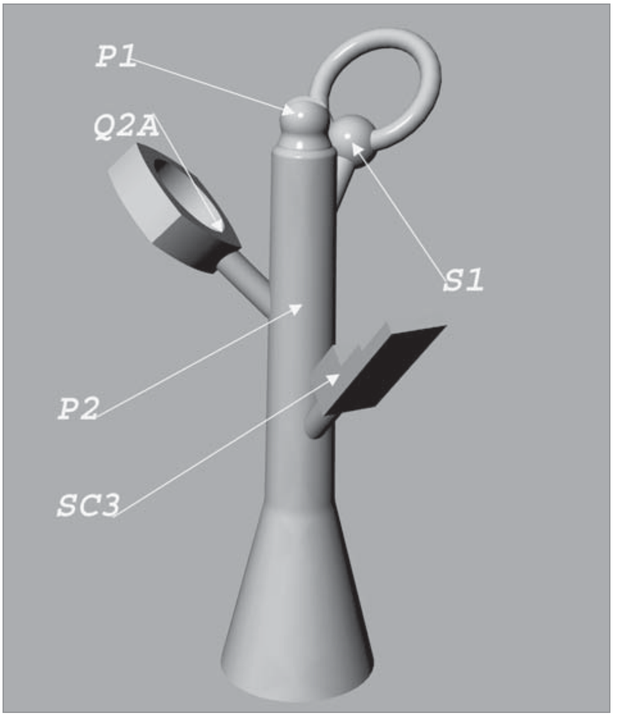

Figure 6 *Distribution of the sensor for determining the metal flow on the simplified test tree*

Different areas of the tree were monitored, both on the patterns (S1 top, Q2A middle and SC3 bottom) and on the main sprue (P1 top and P2 middle).

According to the indications provided by Legor[7] and the thermal analysis carried out, the processing conditions were settled for the simplified tree as follows: Tcasting 1273 K (1832°F), Tflask 823 K (1022°F). Figure 7 shows the results obtained in terms of the filling times for the 14K red gold alloy.

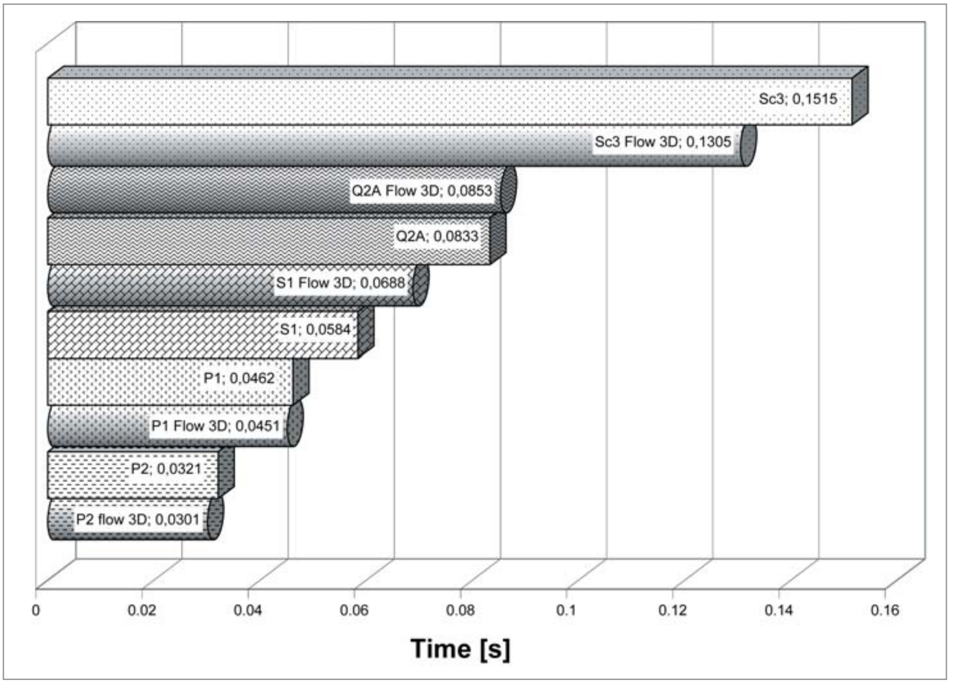

Figure 7 *Comparison between the predicted (Flow-3D) and measured filling times for the simplified tree*

It has to be noted that the measured filling time is lower than 0.2 seconds—the process conditions applied determine a relatively fast process. It is also remarkable to notice the low error between simulation and experimental which is, in the worst case, lower than 15% of the total time. Also, the reiteration of such tests on other alloys (18K yellow and 18K red) and the converging results show that the prevision of the software tends to be close to the reality, apart from an underestimation of the filling times of the areas close to the top end.

Nevertheless, the real production is far away from such simplified patterns!

Experimental—Industrial Case

The following step of the research was focused on the analysis of the problems related to the production of a "real" component. The chosen pattern is shown in Figure 8.

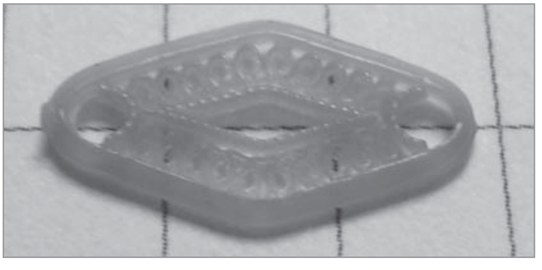

Figure 8 *Wax pattern of a "leaf" to be modelled and studied*

The aim of this part of the study was to look for the best-performing processing parameters for the optimization of the production, that is to say, to assist the industrial partner and try to improve their quality. CAD drawings of the patterns and of the tree, as mounted in production, were derived using Rhinoceros. The "virtual" model of the tree was therefore obtained, as shown in Figure 9.

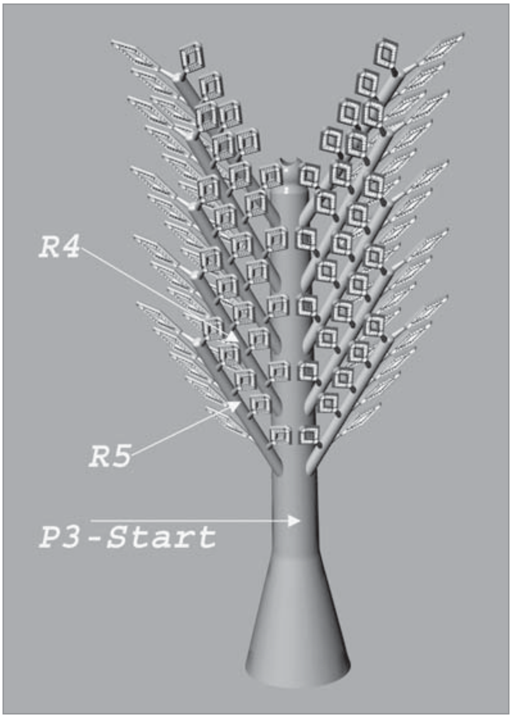

Figure 9 *Virtual drawing of the tree, representing the real casting tree*

The "filled leaves/total leaves" ratio (hereinafter referred to as FL/TL) obtained as a result of the production at the industrial site was rather far from 100%.

Taking into account the indications from the datasheet,[7] as well as the industrial processing, the simulation was carried out starting with the following parameters: Tcasting 1293 K (1868°F), Tflask 933 K (1220°F). The first indications derived from the simulation were confirming the expectations. Figure 10 shows a detail of a leaf after the filling process is completed.

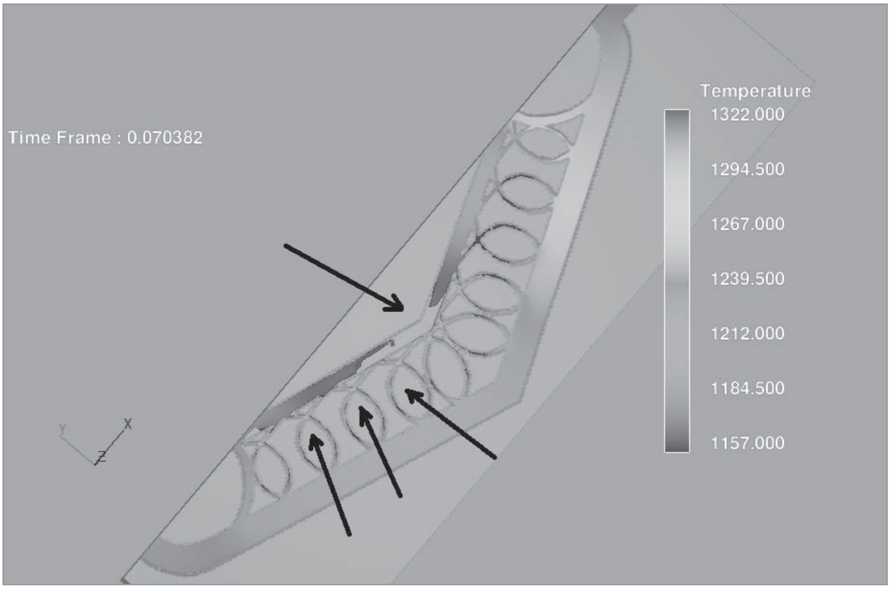

__Figure 10__ Detail of the leaf after filling. The arrows indicate the un-filled areas.

The image clearly shows some areas into which solidification occurs before the metal has correctly filled the surface. It has to be remarked that the time foreseen for filling each individual leaf is about 0.055 seconds (as suggested by the simulation applying the given parameters).

The experimental validation of the simulation was carried out to confirm the incomplete filling of the tree. Results are shown in Figure 11.

__Figure 11__ Un-filled tree: Tcasting 1293 K (1868°F), Tflask 933 K (1220°F)

The black arrows underline that the incomplete filling takes place all over the tree. The FL/TL ratio was, in this case, 15.2%.

The next step was to increase the applied pressure during casting (i.e. increase the different applied vacuum between the melting chamber and the flask chamber), while keeping the other values constant. But also in this case, the software already predicts a negative result, as shown in Figure 12.

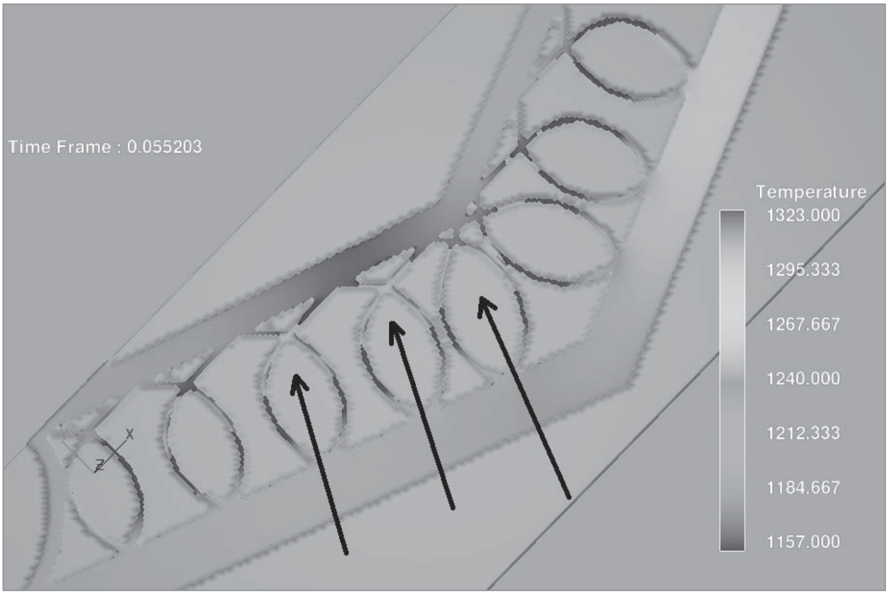

Figure 12 *Detail of the leaf after filling. The arrows indicate the unfilled areas, predominantly located in the spirals. The time frame is settled right at the beginning of solidification.*

In this case, the interesting aspect is related to the result obtained with the experimental, as shown in Figure 13.

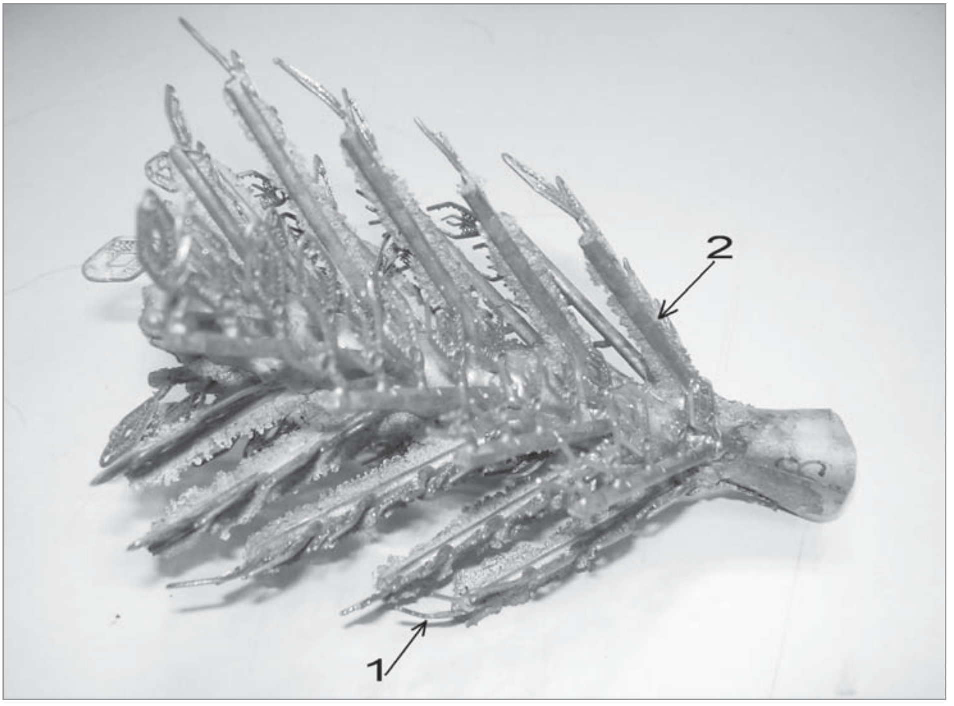

Figure 13 *Un-filled tree*

While the problems related to the low FL/TL ratio (higher than before, but lower than 20%) were still remaining, another problem also occurs. Some evidences of penetration of molten metal into the investment appear (as indicated by arrow 2), possibly due to exceeding the mechanical strength of the investment material.

This brings us to the following questions. Is it possible to evaluate the mechanical resistance and the wear resistance of the investment in a way that makes sense? If so, how do we evaluate them? Some interesting works have already been published on the analysis of investment materials.[8,9,10] Nevertheless, other aspects could be investigated, also taking into account the need by simulation of having access to different material data.

The optimization of processing parameters went through the variation of individual conditions, respectively related to the molten metal casting temperature, the flask temperature and the applied vacuum. A set of simulations was carried out keeping two of the previous parameters as a constant, and varying the third, in order to investigate the relative weight of each variable onto the final product quality. As the logical consequence of the chosen modus operandi, the first step was to simulate the process and then to verify its accordance to the experimental.

The result of the continuous backfilling between simulation and validation ended up in the final refining of the simulation, resulting in the definition of a process guaranteeing a 100% FL/TL ratio, being characterized by the following conditions: Tcasting 1303 K (1886°F), Tflask 973 K (1292°F).

As illustrated in Figure 14, the predicted time for the filling of the individual leaf is 0.035 seconds.

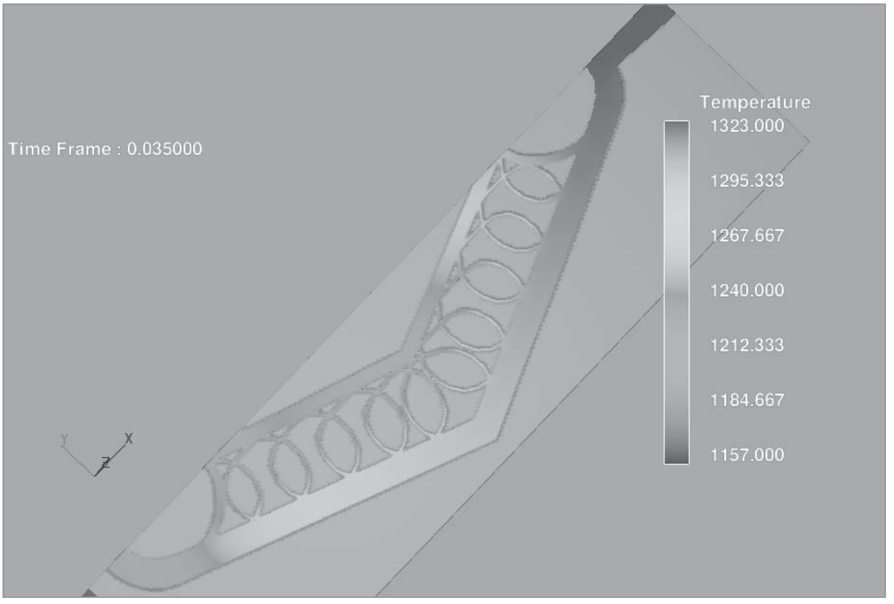

Figure 14 *Detail of the leaf after filling—complete filling was predicted*

It now became interesting to make a deepening on the total filling time required for the process. The situation was, however, a bit trickier than the one with the simplified model, since the introduction of sensors in the tree could determine a sensible variation of the local shape (i.e. the diameter of the thermocouple is much bigger than the spiral in the filigree), thus making the acquisition invalid. In order to solve the problem, a particular positioning of the sensors was studied and tested, as shown in Figure 15.

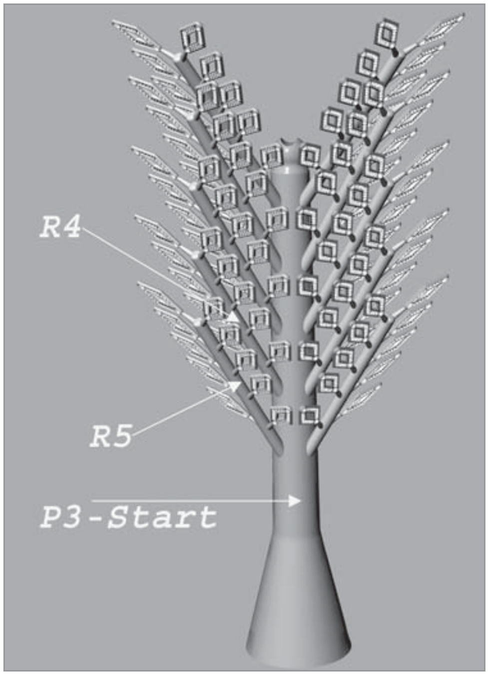

Figure 15 *Distribution of the sensors on the tree. In order to not interfere with the molten metal flow, the location of the sensor was in the middle of the feed sprue.*

The following plot (Figure 16) shows the comparison between the simulation and the experimental.

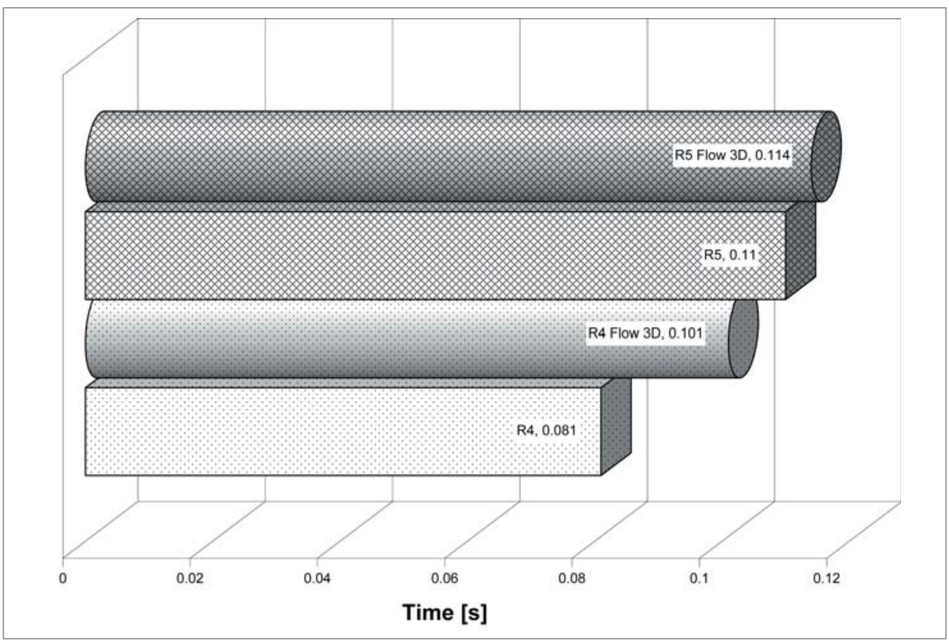

Figure 16 *Predicted (Flow-3D) and measured filling times*

The simulation is rather close to the tested condition, as illustrated for the simplified tree. The measured time for the completion of the process is 0.25 seconds. The maximum error between simulation and experimental is, therefore, in the range of 10%.

Once having obtained the complete filling of the tree and having significantly validated the simulations through experimental, the attention was focused on the evaluation of porosity in order to implement Computational Fluid Dynamics (CFD) parameters and procedures having significant interests and applications. FLOW–3D® provides some indications of the shrinkage porosity that can be derived from the given processing conditions. Figure 17 shows the predicted porosity in the aforementioned, optimized processing conditions.

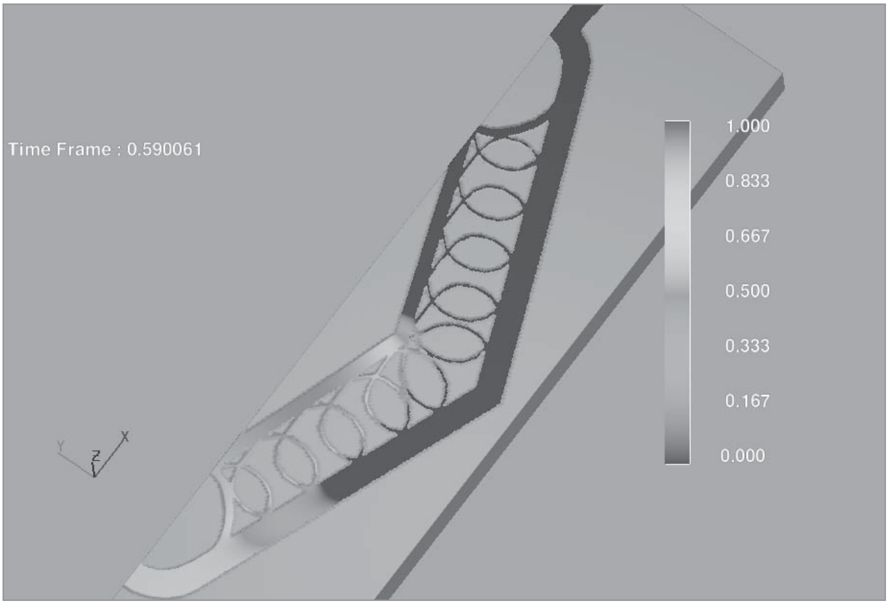

Figure 17 *Predicted shrinkage porosity. The scale on the right is the predicted percentage of porosity on the total surface.*

A relatively low percentage of shrinkage porosity is predicted by the simulation and are located in the areas opposite to the feed sprue.

The analysis carried out using Light Optical Microscopy on components located in different parts of the tree (top to mid to bottom) does not evidence sensible differences in the structures. This can be easily explained by taking into account the quickness of the process, not determining substantial differences neither in terms of filling nor in terms of solidification. Figures 18 and 19 shows some different areas of the "leaves."

Figure 18 *Detail of the leaf, area opposite the feed sprue*

Figure 19 *Detail of the leaf, feed sprue area*

Some relatively minor gas porosities are detected, possibly deriving from the high temperatures used in the process. Trials are under way to further improve the quality of the cross-sections.

Conclusion and Outlook

A good and repeatable agreement between simulation and experimental of the casting process could be obtained for different gold alloys. As for the production of 14K red gold alloy filigrees, a remarkable improvement of the castings' quality could be obtained through the combination of simulation and experimental validation. It has to be noted that the validation of the simulation requires, at least in the first steps, the possibility of operating with machines devoted to the research in order to verify the outputs deriving from Computational Fluid Dynamics (CFD). The amount of tests (and the time for their execution) required for the optimization of the processing cycle can indeed be drastically reduced. Nevertheless, a huge amount of work is required to further widen the application of the casting simulation tools, as a consequence of the large numbers of casting alloys and investments available on the market, whose characteristics are terribly important to get a reliable result. A natural development of the research could be the targeted evaluation of the characteristics of the refractory material, and the combination between the results and the simulation. The chance of combining this latter with the experimental data of the decomposition of the investment material could further widen its applicability and performance. Considering the aforementioned limits related to the missing material database, the results presented here, and in the Jörg Fischer-Bühner presentations of 2006[1] and 2007[6] clearly show that CFD has enormous and concrete possibilities to be a powerful tool for the current industrial production, and not simply an "interesting," possibility for future application.

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