Numerical Simulation of Investment Casting of Gold Jewelry: Experiments and Validations

Marco Actis Grande, and Somlak Wannarumon

***Abstract*—**This paper proposes the numerical simulation of the investment casting of gold jewelry. It aims to study the behavior of fluid flow during mould filling and solidification and to optimize the process parameters, which lead to predict and control casting defects such as gas porosity and shrinkage porosity. A finite difference method, computer simulation software FLOW-3D was used to simulate the jewelry casting process. The simplified model was designed for both numerical simulation and real casting production. A set of sensor acquisitions were allocated on the different positions of the wax tree of the model to detect filling times, while a set of thermocouples were allocated to detect the temperature during casting and cooling. Those detected data were applied to validate the results of the numerical simulation to the results of the real casting. The resulting comparisons signify that the numerical simulation can be used as an effective tool in investment-casting-process optimization and casting-defect prediction.

***Keywords*—**Computer fluid dynamic, Investment casting, Jewelry, Mould filling, Simulation.

I. INTRODUCTION

JEWELRY casting is one of the most difficult and processes in handling the casting quality and defects. As well as the casting materials are precious alloy, which possibly cause high production cost in term of casting defects.

Computational Fluid Dynamics (CFD) and numerical simulation have applied to various applications in different industries, because they can help casters to comprehend behaviors of casting processes and to reduce production cost and time, which are caused by casting defects.

Within this decade, CFD and numerical simulation were applied to jewelry manufacturing process; they was proved that they have potential to work as a tool in preventing casting defects [1] – [4]. However many aspects need to be further studied: the study of the precious alloys' physical properties and of investment materials including the investigation of the dynamics of the investment casting process.

In this paper, CFD was applied to simulate the investment casting of jewelry products. The numerical simulation software used in this research is FLOW-3D. The basic concept of the software is to solve Navier-Stokes equations in a discrete fashion with a control-volume method.

The objective of the research is to extend the previous works [2] to model 'virtual casting laboratory'. To achieve this target, it needs to optimize and fine tune the process parameters, which are based on the thermal and chemical properties of mould material used and casting precious alloy used.

This paper is organized in five sections; starting by introducing the research area in this section. The next section provides the reviews of the related works. The research methodology and experiments are described in section III, while the results of the experiments are discussed in section IV. Finally, the contributions of the research are concluded in section V.

II. REVIEWS OF RELATED WORKS

A. Computational Fluid Dynamics

The most fundamental consideration in CFD is how one can treat a continuous fluid in a discretized fashion on a computer. One method is to discretize the spatial domain into small cells to form a volume mesh or grid, and then apply a suitable algorithm to solve the equations of motion. Additionally, such a mesh can be either irregular or regular. Finite Difference Method (FDM) is one of the efficient discretization methods. It is simple to program and currently only used in few specialized codes. Modern finite difference codes make use of an embedded boundary for handling complex geometries making these codes highly efficient and accurate. FLOW-3D is simulation software, which is based on FDM concept. It can solve Navier-Stokes equations in a discrete fashion with a control-volume method. It is successful and popular to use in modeling mould filling in the casting process.

B. Jewelry Casting Simulation

The researches in jewelry casting simulation have been done by only some researchers such as M. A. Grande, L. Porta, and D. Tiberto [1], M. A. Grande, A. Zambruno, M. Rosso, S. Bezzone, and A. Incognito [2] focused in mould filling, while J. Fischer-Bühner [3], [4] played attention in solidification of the jewelry casting process, and J. Wright [5] mainly discussed on the significance and roles of computer simulation in jewelry production, provided some key directions of the research developments in this area and explained the methods of sensitivity analysis and calibration

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of the simulation.

III. METHODS AND MATERIALS

A. Designing the Simplified Test Tree

The experiment was started by designing a simplified test tree, which consists of three objects as shown in Fig. 1. The reasons to design the three different objects were as follows:

- Stepped wedge has a variation of part thickness,
- Quad ring has corners, which challenge in casting,
- Ball or sphere ring is one of the most difficult casting shapes.

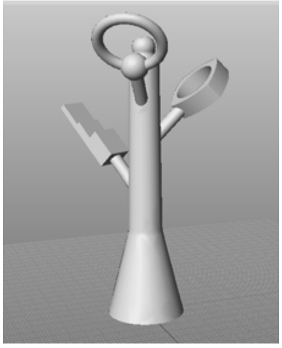

Fig. 1 The simplified test tree used in this study

The previous research indicated that it is necessary to start by using a simplified tree and its evaluation in order to verify the confident of the numerical simulation results in the further experiments, which were derived from the industrial cases.

B. Data Acquisition

A set of the wax tree models of the test tree mentioned in the previous section were prepared. In this section, they were divided into two types of data acquisition.

The first one is sensor acquisition, which a set of sensors with the system operating at 1000 Hz were designed based on the National Instruments equipment. The sensors were allocated on the different positions (P1, P2, S1, O2A, and SC3) of the wax-tree model as shown in Fig. 2, to detect the filling times in the different locations of the investment mould.

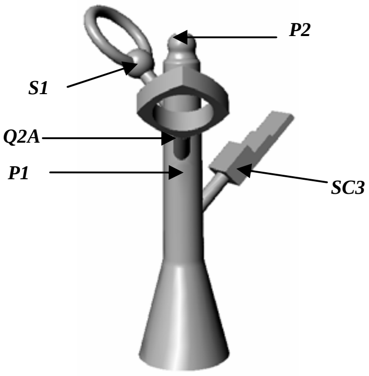

Fig. 2 The positions of a set of sensors were allocated on the wax tree

The second one is thermocouple acquisition. In order to monitor the range of temperature as a function of the positions on the tree and mould, the thermocouples were properly mounted on the wax tree models in the different positions; on the feed sprues, on the objects, and placed in the investment mould, illustrated in Fig. 3. Type K thermocouples coated with glass fiber and a set of low-frequency acquisition (20 Hz) were used in this case.

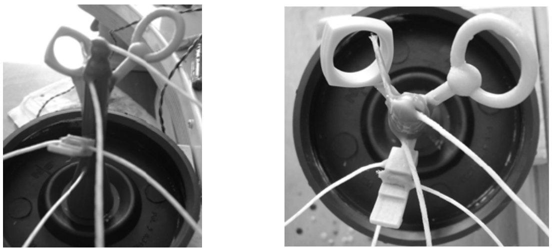

Fig. 3 The thermocouples were mounted on the wax tree

C. Casting Trials

In the casting trials, the precious alloy used was the 14K (carat) red gold alloy; while the investment material used was Ultravest.

The process conditions of the casting of the simplified test tree are:

- Casting temperature (T-casting) = 1273 K,
- Flask temperature (T-flask) = 823 K.

D. Case Study of Filigree Casting

The case study focused on the industrial case was organized to analyze the casting of ‘leaf-like’ filigree object shown in Fig. 4, which play important role in the industrial application, because of the difficulty in mould filling.

This section aims to optimize the process parameters and to improve the quality of the filigree casting. The study was organized by starting the numerical simulation to obtain the critical indications and to validate the simulation results with the real casting.

Fig. 4 The wax pattern of ‘leaf-like’ filigree object

The virtual tree consisted of a set of filigrees was modeled as shown in Fig. 5.

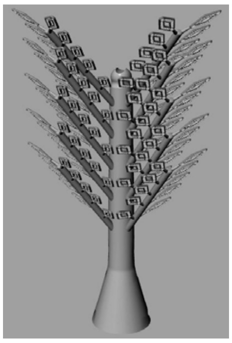

Fig. 5 The virtual tree consisted of a set of filigrees

The first assumption was performing the casting trial with the process parameter set as T-casting = 1293 K and T-flask = 933 K. The resulting simulation should indicate incomplete filling. If the results support the assumption, then the applied pressure during casting would be increased. The temperatures of casting and flask would be optimized as well. Furthermore the investment material properties would be taken into account to improve the quality of the casting.

IV. RESULTS AND DISCUSSIONS

A. Filling Study

The experiments of the filling study were done in both FLOW-3D simulation software and performing the real castings. The simulation in FLOW-3D is shown in Fig. 6.

We detected the filling times from the different location as explained in Section III *B* and illustrated in Fig. 2, and then compared the filling times of simulated casting with of the real one. The results are provided in Fig. 7.

The studied filling process spans a very short time interval less than 0.2 second. The comparison of the results indicates that the difference between the filling times of the simulated casting and of the real casting is approximately 15.63%, which could be considered as relatively low regarding the numbers of parameters involved. Furthermore, the repetitions of the tests with other precious alloys (18 K yellow and 18K red) prove that the results of simulations or simulated castings tend to be close to the reality or real casting.

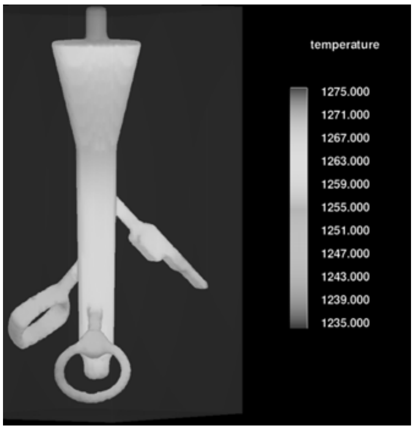

Fig. 6 The filling time of the simplified tree simulated by FLOW-3D

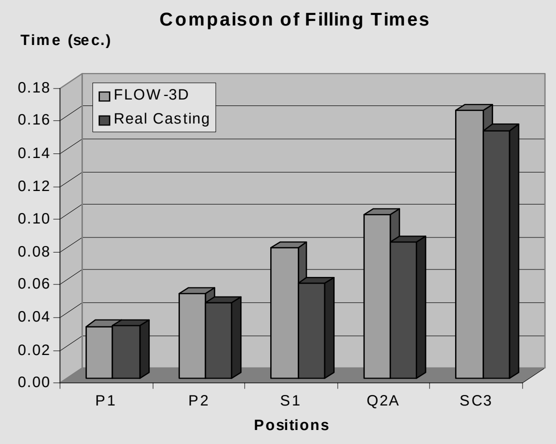

Fig. 7 Comparison of the filling times of the simulated casting and of the real casting in the various location on the test tree

B. Cooling Study

The experiments of the cooling phase were set up as explained in Section III *B* and illustrated in Fig. 3. In the study of cooling phase, the mapping of detected temperature is needed to validate the results of the simulation. The trend of cooling could provide the rationale of the shrinkage porosity. The temperature detection on the investment material indicates the interrelation between the investment material and the wax patterns, which leads to the prediction of gas porosity. Some of the results were shown in Fig. 8 and Fig. 9.

Fig. 8 The thermocouples were mounted in a stepped wedge to detect temperature during casting and cooling

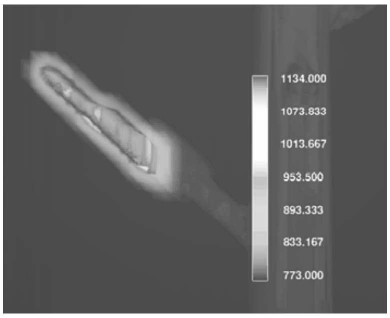

Fig. 9 Modeling of the cooling phase of the stepped wedge model

C. *Filigree Casting*

Based on the experiment assumption as mentioned in Section III *D*, in this case, the filigree was simulated in one-half, due to availability of mirror symmetry on the filigree itself, to optimize the resolution of the simulation results and processing time.

The first set of results from the simulation proved that the assumption is correct. The resulting simulation and real casting were shown in Fig. 10 and Fig. 11, respectively.

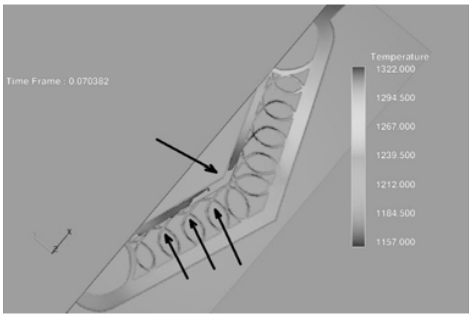

Fig. 10 The simulated filling of the filigree; the arrows indicate the incomplete filling

The filling time of filigree obtained in the simulation was 0.055 second. The simulation result clearly proves that the solidification occurred before the filling is completed. The results of the real casting also confirmed that the results of simulation are correct, as shown in Fig. 11.

Fig. 11 The incomplete filling filigrees were cast at the T-casting 1293 K and T-flask 933 K

To analyze the complete filling of filigree, the simple index was derived: the ratio of Number of Complete Filling Leaf (FL) by Total Number of Leaf (TL) or FL/TL.

From the real casting, the complete filling ratio (FL/TL ratio) of the first experiment was 15.2%.

Therefore, in the successive experiment, the applied pressure during casting process was increased, while other process parameters were constant.

The simulated casting indicated the incomplete filling as shown in Fig. 12. It is clear that the incomplete areas predominantly located in the spiral parts.

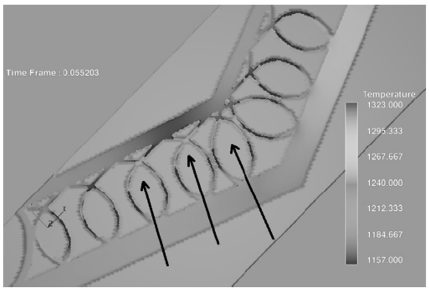

Fig. 12 The simulated filling of the filigree; the arrows indicate the incomplete areas

The real casting indicated the FL/TL ratio was 20%, which is higher than the previous one, but another defect appeared in this case. The molten metal penetrated into the investment, due to the exceeding of the mechanical strength of the investment material, illustrated in Fig. 13. Number 1 indicates the incomplete filling; while Number 2 indicates the molten metal penetrated into the investment.

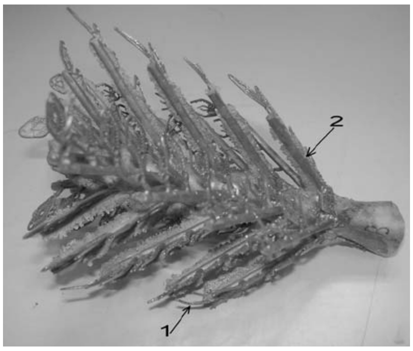

Fig. 13 The incomplete filling from the second experiment

The next successive experiments were run by optimizing the significant process parameters: casting temperature, flask temperature, and applied vacuum. A set of filling simulations were carried out by varying one-by-one the parameters; while others were constant, until the determined quality of casting was achieved.

The final refining of the simulation was ended by 100% of FL/TL ratio with the following conditions:
T-casting ~ 1303 K and T-flask ~ 973 K.

The results are illustrated in Fig. 14, the simulated filling time of individual leaf was about 0.0035 second.

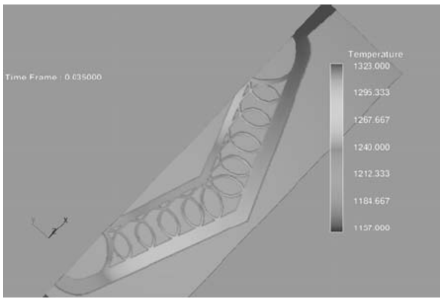

Fig. 14 The simulated complete filling of the filigree

After the complete filling of one leaf can be achieved, we moved on to simulate the whole tree. The whole tree composed of leaves was modeled for simulation as shown in Fig. 15 and also prepared the wax model for real casting. Mounting the sensors on the wax tree was sensitive to the original shape of the filigree, because the diameter of the thermocouple is much bigger than of the spiral parts of the filigree. Therefore the sensors were located on the thicker part such as main sprue and feed sprues, as shown in Fig. 15, to avoid interfering with the flow of molten metal.

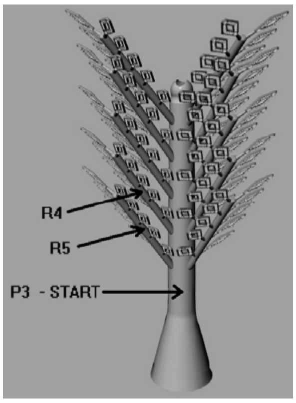

Fig. 15 The positions of sensor mounted on the test tree

Comparing the results of simulation and the results of casting, the filling times of both are illustrated in Fig. 16. The results of the simulation are close to the test condition. The measure time for the complete filling is 0.25 second. The average difference between the simulation and the real casting is about 11.7 %.

Further, we analyzed the shrinkage porosity, which could be derived from FLOW-3D. The result was illustrated in Fig. 17, the scale on the right-hand side indicates the predicted percentage of porosity on the total surface of the studying object. The low percentage of shrinkage porosity is located in the areas opposite to the feed sprue.

The porosity analysis was carried out using Light Optical Microscopy. The porosity was analyzed throughout the different parts of the filigree tree; that does not appear much difference in the results. The possible reason is a very fast process; therefore, there is not much difference in terms of filling and solidification.

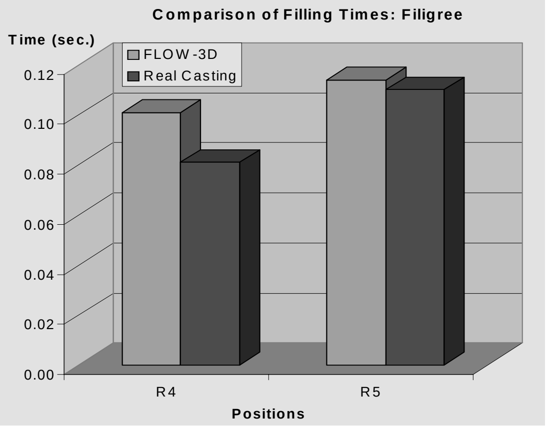

Fig. 16 Comparison of the filling times of the simulated casting and of the real casting in two locations on the filigree tree

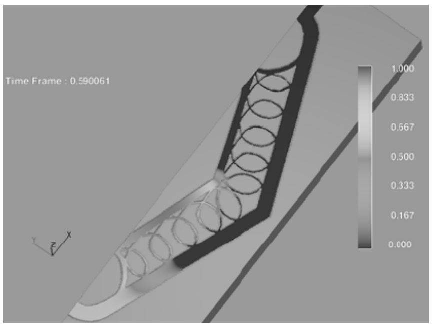

Fig. 17 The prediction of shrinkage porosity using FLOW-3D

However, some minor gas porosities were detected. They are possibly caused by the high temperature used during the process.

FLOW-3D is able to structure the finite difference mesh in multiple blocks, which allow more localized refinements. This flexibility suits the need for defining thin and complex shape like as filigree.

V. CONCLUSION AND FUTURE RESEARCHES

The experimental results imply that the virtual casting using numerical simulation has a potential to work as a prediction tool in filling, cooling and solidification. Therefore the numerical simulation could be used in the early stage of the design process, to reduce the number of iterative trials and testing, which finally lead to reduction of production cost.

To set up a virtual casting laboratory, the numerical simulation software requires the data and information, which refer to the properties of the significant casting materials and of investment materials, including the process parameters. Therefore, the construction of material databases of both casting-alloy and investment will be continued in the further works.

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