ARCHIVES of FOUNDRY ENGINEERING

ISSN (1897-3310)
Volume 12
Issue 1/2012

37 – 42

7/1

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

The deformation of wax patterns and castings in investment casting technology

A. Herman*, M. Česal, P. Mikeš
Department of Manufacturing technology, Czech technical University in Prague, faculty of Mechanical engineering, Technicka 4, 16607 Prague 6, Czech republic
*Corresponding author. E-mail address: ales.herman@fs.cvut.cz

Received 01.02.2012; accepted in revised form 19.03.2012

Abstract

The dimensional accuracy of the final casting of Inconel alloy 738 LC is affected by many aspects. One of them is the choice of method and time of cooling wax model for precision investment casting. The main objective was to study the initial deformation of the complex shape of the casting of the rotor blades. Various approaches have been tested for cooling wax pattern. When wax models are cooling on the air, without clamping in jig for cooling, deviations from the ideal shape of the casting are very noticeable (up to 8 mm) and most are in extreme positions of the model. When blade is cooled in fixing jig in water environment, the resulting deviations compared with cooling in air are significantly larger, sometimes up to 10 mm. This itself does not mean that the final shape of the casting is dimensionally more accurate with usage of wax models, which have deviations from the ideal position smaller. Another deformation occurs when shell mould is produced around wax pattern and furthermore deformations emerge while casting of blade is cooling. This paper demonstrates first steps in describing complex process of deformations of Inconel alloy blades produced with investment casting technology by comparing results from thermal imagery, simulations in foundry simulation software ProCAST 2010 and measurements from CNC scanning system Carl Zeiss MC 850. Conclusions are so far not groundbreaking, but it seems deformations of wax pattern and deformations of castings do in some cases cancel each other by having opposite directions. Describing entirely whole process of deformations will help increase precision of blade castings so that models at the beginning and blades in the end are the same.

Keywords: Application of information technology to the foundry industry; Innovative foundry technologies and materials; Investment casting; Wax patterns

1. Introduction

The method of the investment casting allows producing complex shaped castings with small dimensional tolerances and excellent surface quality. The big advantage is the production of castings from materials difficult to machine. Using a different technology would result in high costs, or their production would be impossible. In comparison with machining the dimensional accuracy of castings produced by precision casting cannot be compared even though when compared with other methods of casting it is very accurate (IT 9 to 11). Of course, even with such a perfect and precise production arise dimensional inaccuracies that occur for various reasons. The actual dimensional inaccuracies are divided into:

- systematic - poor handling of castings, incorrect assembly of wax model, i.e. These defects can be eliminated by following the prescribed technology more carefully,
- random - difficult or almost impossible to remove defects.

Another factor that influences the size and characteristics of the wax model and casting is deformation. It occurs especially in parts that don't have a constant wall thickness.

The main factors affecting the dimensional accuracy of investment castings:

- volume expansion (contraction) - used materials have main influence - wax, shell material and casting material, considerable influence has as well precision of molds for wax models,
- deformation of wax models - major influence has wax model cooling and its further processing and storage,
- deformation of shell - the composition of layers, method of smelting wax model and firing and flushing of shells,
- deformation of the casting itself - the shape of the casting and gating system, the shell temperature, pouring temperature and if used forms of isolation.

2. Dimension changes

The most important influence in dimensional accuracy of the final casting is very wax model. The final size wax models can be changed by changing the injection parameters, at which wax is injected into the mother mold, which is practically the only possible way.

The achieved tolerance is determined by:

- mixture of wax - increasing injection temperature increases shrinkage of models. The structure and chemical composition of the wax mixture has an influence on the expansion and contraction. The course of contraction or expansion in the temperature interval is not linear,
- the shape and size of components - the value of shrinkage in different basic planes depends not only on the shape and size of component, but also on the placing of inlet part,
- method of production wax model - this includes both injection of wax into the mother mold and the injection parameters.

2.1. Changes in shell dimensions

Changes in shell during drying and annealing are defined primarily by used type of ceramic (granules and binders), the number of shell layers and method of shell heat treatment (drying, rinsing and annealing), furthermore the technology used in smelting wax mixture.

The fact that you cannot ignore is that during annealing the shell expands. Here, the size of the shell expansion depends directly on the ceramic filling, which is used, or to be more precise on the coefficient of expansion. The number of layers, in which is encased wax model has also effect on dimensional changes. In contrast, when drying the shell doesn't expand, but shrinks a little. Shrinkage is moderate (up to 0.4%). Biggest influence on this contraction has the binder which actually dries.

2.2. Deformations of wax models

The main disadvantage of using wax models is that immediately after removal injected model from the mold its components begin to deform due to uneven temperature field. It is not possible to remove wax model from the form at low temperatures - wax gets very sticky at low temperatures, and the model would have to be crushed from mold, similarly model cannot be removed in non-solid state. Here is the main problem. If there are in the model very different wall thicknesses, e.g. blades - thin blade shape and a massive lock, which at the time of removal is not in the solid state. Among the ways of slowing the deformation is almost immediate consolidation of the extracted wax model in the jig, where the ideal shape is defined. This method is also known as "braked hardening".

The resulting deformation of the wax models is highly undesirable, since they affect the quality of the final casting and cause significant inaccuracies in it.

To avoid distortion of the wax model in investment casting method, cooling jigs are used after removing model from mold, or in the case of very large wax model several jigs (see Figure 1). If the final shape of the casting has non uniform wall thicknesses and shapes, different parts of the model doesn't cool down, nor shrink at the same time. Non-simultaneous cooling of different places in model causes different dimensions change in parts of the model and so-called stress or deformation appears.

Types of tension in the wax models:

- phase tension - when combined two elements of different thicknesses in one unit, the tension is balancing differences of deformation of structures. Two kinds of stress arise, in the thin wall tensile stress and vice versa in thicker wall compressive stress,
- shrinking tension - another distortion occurs when mold resists against shrinkage. The emergence of shrinkage depends on the shape of the model. The form is absolutely rigid (usually aluminum alloy or steel),
- heat stress in the wax models - this tension arises when the two bodies with various thicknesses of walls, but at the same temperature are connected .This type of stress causes a deformation. Profile with thin wall is cooled down before thick-walled profile. Thinner wall is stronger and resists shrinking at the other wall, which has a greater thickness. All this leads to shape deformation of the wax model. The greater the differences in thickness are, the higher the stress (deformation).

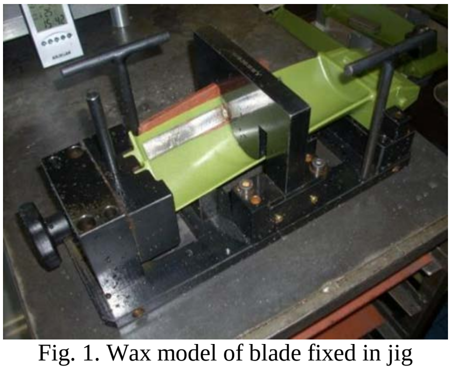

Fig. 1. Wax model of blade fixed in jig

3. Checking of the shape of the impeller blades

It is obvious from the previous paragraph that castings produced with investment casting technology are in the end influenced by particular deformations of wax pattern and ceramic mold. To evaluate magnitude of dimension inaccuracies on the blade wax pattern and on subsequent casting of blade, series of measurements had to be done. Analysis was carried out on the coordinate measuring machine Carl Zeiss MC 850. This machine is equipped with an active scanning system Vast XT 2.1 Scanning System.

It is a contact measurement with a fixed sensoring system. This means that the system does not allow positioning of the measuring sensor. In order to measure all the required elements it is required to build a special configuration of sensors - measuring probes. To measure the horizontal cut direction + Y and -Y ball touch probes with a diameter of 3 mm were selected, for measuring cylindrical risers (used for alignment) in direction + X and-X, ball touch probes with a diameter of 1.5 mm were chosen and for measuring the vertical cut in the direction -Z ball touch probe with a diameter of 3mm was selected. After the build of configuration sensors it is needed to classify this configuration, i.e. determine the location of measurement touch probes relatively to a reference sensor. This classification is carried out using calibration norm, in this case it was a sphere. When measuring it is necessary that the part is fixed with sufficient rigidity so it doesn't move or deflect during measurement. Fixing has to be done in that way, so that it can perform measurements in a single setup. The blade was fastened at the bottom lock part, where the fastening lock into the impeller will be machined. The components of this type are generally offset by RPS (Referenz Punkte System) where the principal coordinate system of the machine (in this case whole gas turbine) is transferred using RPS point to the individual part (i.e. blade) and thus can then be measured to evaluate the main part of the coordinate system of the whole machine.

The first measured wax models of blades were 2.9% bigger, which was due to shrinkage of Inconel alloy. By making wax models larger, the RPS method can't be used. Measuring software is not able to compute alignment of the component at these conditions. For the alignment the classical method was used plane - line - point (3-2-1), shaped area located at the bottom of the blades were used.

In the second step, the Inconel castings of blades were measured. In this case it would be possible to use RPS alignment, but to have the same conditions as in the measurement of wax models, plane - line - point alignment was used again.

To measure the shape of blade 3D model of blade was used and 7 cuts were defined. 6 horizontal cuts in the Z = 8o, 120, 160, 200, 240, 265 mm and a vertical cut located in the center of the blade. Circa 190 to 250 points was placed at horizontal sections depending on the length and curvature of each specific cut. Measuring these cuts with a single sensor could not be done, so they were divided into two parts and sensors measured + Y and - Y. The points on the leading edges (the curves between these parts) were not measured because edges are rough and to evaluate these points is irrelevant. Vertical section includes 70 points and was measured by sensor -Z.

All sections (cuts) were measured in a scanning manner, i.e. the probe is pressed against the surface with a constant force and measures points continuously while moving. This method is much more productive than individual points measuring. All measurements were carried out in CNC mode. The obtained results were evaluated in two ways: graphical protocol and 3D model.

In order to get a detailed idea about the shape of blades, each slice was evaluated separately in the graphic log (Fig. 2). These protocols show variations in defined measuring points from the ideal shape represented by 3D model. Black curve shows the shape of cut obtained from 3D model. Green color shows positive deviations leading from the material and red negative leading towards the material. The blue curve is envelope of the measured deviations. Scale is 20:1.

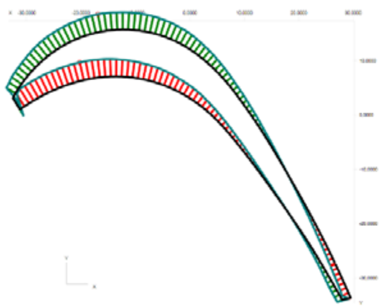

Fig. 2. Cut out from graphics protocol 3D visualization

For a better idea graphic evaluation was created directly to the CAD model in a measuring software (Fig. 2.4).The size and direction of deviation could then be seen in 3D view and creates a better idea of deformations of functional parts of blades. Scale of measured deviations is 7:1.

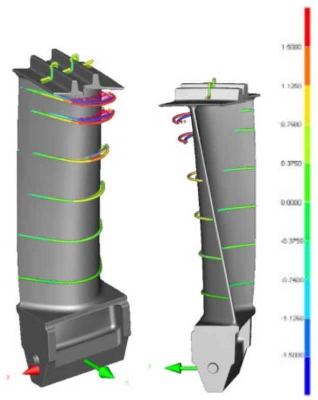

Fig. 3. Measured dimensions differences shown on 3D model

4. Simulations of cooling processes

To reduce the need for casting a series of verification castings whenever any technological process change is proposed, foundry simulation software ProCAST 2010 is used. Due to the enormous breadth of parameters that software ProCAST allows to change, it was possible to use simulation of solidification of wax models as well as for castings from alloy Inconel 738 LC.

ProCAST simulation software is based on FEM calculations, thus the first step is to create 3D models of all simulated components, the second step is to create the tetragonal mesh on models, and then the third step is to set all parameters of casting and solidification process exactly as in real process. Then we can start the calculation itself and remains only to evaluate the results.

For the purposes of our simulations it was necessary to create models of blade and its cooling jig. 3D model was based on blade original drawings and models used to create injection molds for wax. Model of the cooling jig was based on the measurement of currently used equipment. The model of blade when compared to the actual casting has several simplifications, such as removing labels, removal of minor bumps, etc. Model of the jig is completely faithful in bearing surfaces and all dimensions, which fixes the blade, but in all shape details that are not important for accurate simulation is simplified to the basic shapes. Bearing area was shared by blade and jig, thus presuming an idealized situation that the blade fits perfectly into the jig.

When models were done, they had to be converted into tetragonal mesh for further computations. After creating a surface mesh it was necessary to thoroughly check the entire surface mesh on models and any errors must have been corrected so that the mesh had the required parameters of triangles. This means to remove very small angles at the vertices and correct too small triangles emerging on the contacts of areas. After correcting the surface mesh several resulting tetragonal meshes for thermo-mechanical calculations in the simulation software ProCAST were created. A complicating factor was that it was necessary to maintain the numbering of nodes in each case setting, ie. the actual blade model from wax, wax blade in the jig and blade casting from alloy Inconel 738 LC. This was due to fact, that the results of mechanical stress and deformation of individual steps of simulation are then loaded as initial conditions for the next step.
To optimize computations different mesh density is used in different places of model so that important areas preserved details. The resulting tetragonal mesh had 5.3 million elements.
Obviously the simulation is trying to exactly copy the physical process of solidification, i.e. in each step were used ProCAST software options to load as the default state of deformation and stress in the casting results from previous simulations. Simulation steps that needed to be followed were the following:

- injected wax solidification in metal mold,
- free cooling of wax blade on the air during the fixing in jig,
- final cooling of wax blade fixed in jig in the water,
- free cooling of wax model stored in the warehouse,
- the solidification of blade casting from Inconel 738 LC.

In this early stage of research general model of foundry wax defined in software ProCAST was used for simulations of blade. This wax is clearly not entirely consistent with the wax used in production, therefore it is necessary for further research to fully define own material, which would have coincided with the thermomechanical properties of real wax material. Knowledge of these parameters for waxes, however, is generally very small and cannot be used of available tabulated values, as in metals and metal alloys. Necessary data is unable to provide neither the manufacturer of wax so at this stage of research is the measurement of physical parameters needed taken in the laboratories at the Faculty of Mechanical Engineering, CTU in Prague. So far about one half of all needed properties was measured and described. Input data are mostly temperature related function of property i.e. density related to temperature. Temperature range must cover all values needed for simulations, so from room temperature 20°C to 80°C which is enough above liquidus. Properties needed for complete simulation are:

- thermal conductivity λ (W/m/K),
- density ρ (g/cm^3),
- specific heat c (kJ/kg/K),
- Young's modulus E (MPa),
- Poisson's ratio ν,
- thermal expansion α (1/°C),
- shear modulus constant and relaxation (time dependent) (kPa).

So far thermomechanical properties were measured. Example of obtained data for density is on Fig. 4.

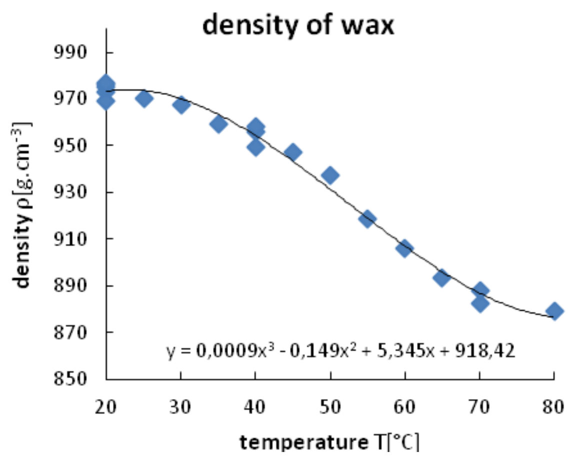

Fig. 4. Density of model wax related to temperature

The simulation itself is completely autonomous and the only requirement, which in this case arose, was considerable computing power. Calculations carried out on the computer workstation equipped with 6 core AMD 1100T (6 x 3.4GHz) and 16GB RAM. Because the models used had very fine mesh in order to achieve accurate results, the simulation took in tens of hours each.

After removing all the errors in the process of simulation, results were obtained for temperature field, the distribution of liquid and solid phase for both wax and alloy Inconel 738 LC, stress and strain fields on all parts and in all steps. Direct comparison of results from simulations and measured data showed that results are of the same order and in terms of strain amplitude, without exception, were deformed in the same direction in both simulation and real case. However, the simulations showed the absolute amplitude of deformation greater than real case, which so far can be blamed on the use of general wax as material in the simulation. After obtaining the necessary data on the thermomechanical wax used, the entire simulation will be repeated and again evaluated.

Cutout of overall deformation vector results at z=160mm is presented at fig. 5. This situation should be comparable to the one presented at fig. 2.

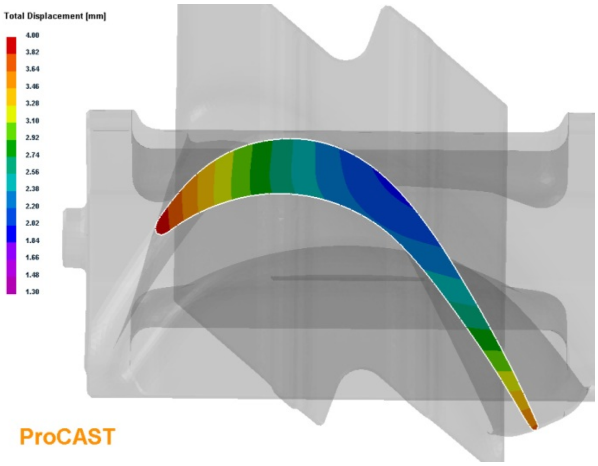

Fig. 5. Total deformation vector of wax pattern at z=160mm

To verify how accurate simulations were so far it was decided to capture whole process of making wax pattern of blade with thermo camera and compare results. Processed picture of wax blade just removed from mould is on fig. 6. Same situation, but results from simulation are shown on fig. 7. As it is clear, results differ only about 2°C in both min a max value.

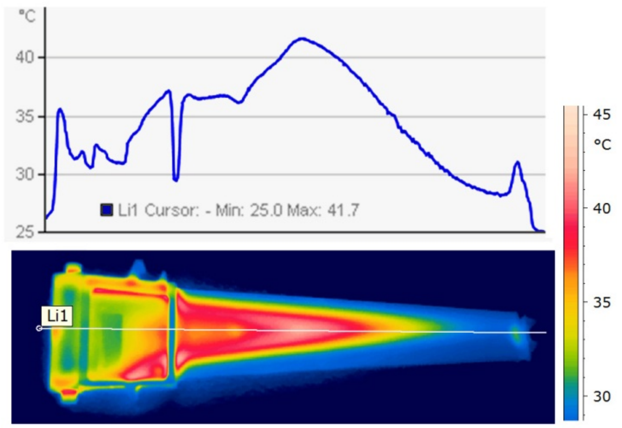

Fig. 6. Wax blade just removed from mould, thermal image

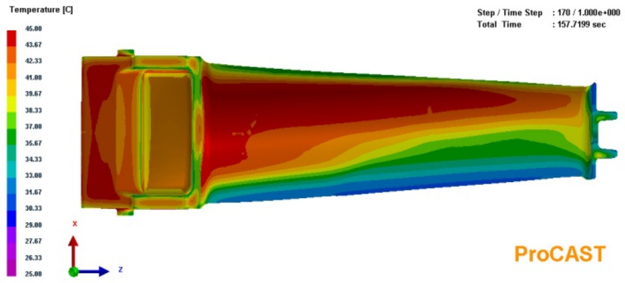

Fig. 7. Wax blade just removed from mould, simulation

5. Discussion of results

Experimental work so far consisted of three main parts, producing wax patterns, ceramic mould and casting of blade itself, then measuring dimensions of blade and simulating whole process virtually.

Making of wax patterns and casting Inconel blade was documented all the way with thermo camera. Resulting thermograms revealed huge differences in temperatures of different parts of blade wax pattern.

So far used production process is as follows:

- injecting wax into mould, 150 sec delay for cooling,
- removed and fixed in jig, placed in 18°C water for 420 sec,
- then stored in thermal stable storage at 22°C,

deformations after this processed exceeded almost 10mm in z=160mm measured from side of blade lock (Fig. 8).

Casting produced from this wax pattern was also measured and maximal deformation occurred in z=265mm which is last possible cut just before upper blade lock (Fig. 9) and exceeded 6mm. From detailed study of deformations of all measured cross-sections on both wax pattern and succeeding castings it is evident, that both deform mostly in the same manner (i.e. direction), but since deformations of castings have lower amplitude it seems, casting deformation has opposite direction than deformation of wax pattern. Same conclusions but with much bigger amplitude differences were obtained by simulations in software ProCAST 2010.

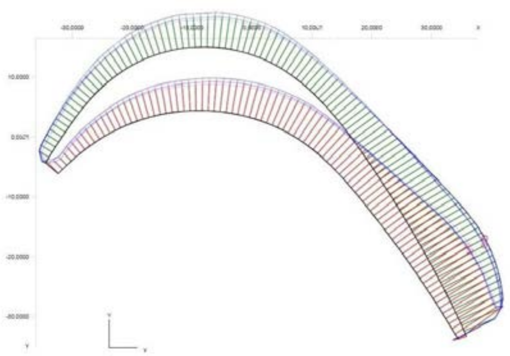

Fig. 8. Measured deformations of wax pattern at z=160mm

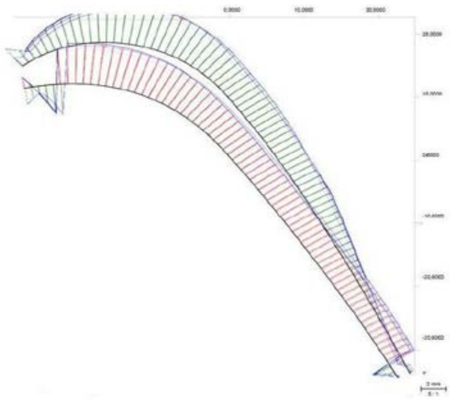

Fig. 9. Measured deformations of casting at z=265mm

6. Conclusion

The dimensional accuracy of the final casting from nickel alloy Inconel 738 LC is affected by many aspects. One of them is the choice of method and time of cooling wax model for precision investment casting.

When wax models are cooling on the air, without clamping in jig for cooling, deviations from the ideal shape of the casting are very noticeable (up to 8 mm) and most noticeable are in extreme positions of the model. For cooling models of blades in the cooling medium water at 18 ° C was used. The actual model was still clamped in the fixing jig which was to define its position and shape. Cooling ran for 7 minutes. The resulting deviations compared with cooling in air are significantly larger, sometimes up to 10 mm. This itself does not mean that the final shape of the casting is dimensionally more accurate with using wax models, which have deviations from the ideal position smaller. It is possible that these deformations on models are required and while smelting casting molds cause, that the resulting cooling of the casting gets to its ideal shape by shape changes during its cooling.
The relatively large deviations from the ideal position can be caused by inaccurate temperature of water used for cooling of models, respectively, higher air temperature at cooling place. Other factor influencing the inaccuracy of these dimensions is the careless handling of still not completely solid wax models. We need to include human factor, since poor handling could also end up in inaccurate clamping model in the jig for cooling under water. The temperature at cooling storage was 22 ° C and the temperature of a car that was used to transport wax models of blades to measuring was to 35 ° C, so it is possible that this adverse change in temperature has influence on the final deformation.

By comparing the simulation results obtained using ProCAST and measured values of the coordinate measuring machine MC 850 it is concluded that the deviation of wax models of blades from the ideal shape in these intervals are in tolerable range, since the simulation of cooling wax models was considering ideal conditions and so deviations that the simulation showed are up to a few small inaccuracies (0.1-1 mm) almost the same.

For the final casting of blades from Inconel alloy 738 LC was also performed simulations using software ProCAST. The remeasurement of castings, where wax model cooled down in water in jig was used, showed the smallest deviations from the ideal shape in the section closest to the beginning of the Z axis, and vice versa largest deviations in the cut, which is farthest from the beginning of the Z axis.

The analysis of results of measured blades, which were cast using wax model cooled down only in air, at 22 ° C, can be concluded that in this case deviations are the smallest in the cut, which is near the beginning of the Z axis, and vice versa the largest in the cut, which is located furthest from the beginning of coordinates.

To summarize the knowledge that we gained by measuring the blade, we can specify that in some sections the blade deforms almost same like wax models. It is also evident, that the whole profile of blade is shifted. This could mean that the blade casting does not deform at cooling, but is deflected in the Z axis without unwanted twisting.
However, if the setting of coordinate system worked correctly, it means that the deformations of the blade casting are undesirable and should be avoided. This can be achieved by spreading the pressure acting on the wax model surface in the cooling jig on more cross sections. This means that instead of defining the current position in the three sections is preferable to fix blade in jig e.g. at five locations.

Another task in further research is obtaining more accurate thermo-physical and stress-strain data of used wax mixtures for obtaining truly accurate results from simulations.

Acknowledgement

This paper was created with the generous support of the project TA01011425 "Research of improving the dimensional accuracy of wax models for the technology of investment casting." called by the Technology Agency of the CR under the ALFA program.

References

[1] V. Kosour, M. Horáček, T. Vaščák, Wax injection simulation. In Proceedings 51. International Foundry Conference Porotorž 2011. Ljubljana: Fleks, d.o. o, 2011. p. 1-9. ISBN: 978-961-90130-6- 9.

[2] J.C. Gebelin, M.R. Jolly, A.M. Cendrowicz, Simulation of Die Filling for the Wax Injection Process: Part I. Models for Material Behavior. Metallurgical and materials transactions B. August 2004, Volume 35B.

[3] W. Bonilla, S.H. Masood, P. Iovenitti, An Investigation of Wax Patterns for Accuracy Improvement in Investment Cast Parts. Int J Adv Manuf Technology. 2001, č. 18, p. 348-356.