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SIMULATION AND EXPERIMENTAL RESEARCH ON THE VACUUM CASTING OF NON-METALLIC COMPLEX PARTS USING FLEXIBLE MOLDS

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Vacuum casting is a modern technique, one of the most interesting and spectacular applications of Rapid Prototyping models, which has proved its appropriateness and effectiveness especially in new product development stage, because it allows the fabrication of pieces in small- batches and individual production at low prices and in short time. It also facilitates to prototype complex parts with the faithful reproduction of form details and surface quality of the master model used. The purpose of the work reported in this paper is to simulated and evaluated, through a case study, the vacuum casting process of non-metallic parts in flexible molds. For this it was considered a wax piece with a complex geometry (having bores, horizontal, vertical and inclined surfaces), produced by vacuum casting in Essil 291silicone rubber molds. Results obtained from simulation process done by Autodesk Mold Flow software have been used in experimental research in order to set the proper process parameters, including casting point location and vents number and position. During the experimental investigations technological features of cast material were studied (by using four wax types: 863 Pink, 864 Red, 865 Green, and 866 Blue), volume of air traps, optimal working parameters and dimensional accuracy of parts manufactured. Based on these results were determined the corrective coefficients applicable to CAD dimensions in order to fabricate the master models by SLS, so wax parts produced by vacuum casting to result at the correct dimensions.

Key words: rapid Prototyping, rapid tooling, vacuum casting, non-metallic materials, flexible molds.

1. INTRODUCTION

The Rapid Tooling technology has evolved a lot in the last decades; today it is possible to fabricate a complex pattern and other tooling for casting in a few hours and provide a casting in a several a day.

In the last decades, many companies have made great investments to improve manufacturing technologies for the development of new products [4]. These technologies include CAD software to design complex geometries, and allowed the solution of problems and are being used to assist medical applications [5]. There have been made a lots of researches about Rapid Prototyping and Rapid Tooling technologies, while the casting of the wax parts in a silicone rubber molds was not studied as much as. Ribeiro et al studied in [12] the process to obtain wax patterns using room temperature vulcanizing silicone rubber molds and good accuracy was obtained for special conditions. Others like Horacek and Lubos [6] studied the influence of injection parameters on the dimensional stability of wax patterns produced by injection molding process. In their work, they found the relation between various injection parameters and their dependency on other parameters. In other studies [14] compared been accuracy of wax patterns created by polyurethane mold, and room temperature mold. From all the parameters studied by the authors above it was found that the injection temperature is relevant for the dimensional accuracy of the parts.

Nowadays, because of the request on the market qualitative speaking of the manufacturing parts and the complexity of these, Rapid Tooling is the perfect options to solve this problem. It is estimated that total profits on new products are often reduced by as much as 60% because of the company’s inability to get the product market quickly enough as demonstrated in [13].

In the last few years, Rapid Tooling technology has evolved toward building molds that provide up to 40% faster cycles than are possible with conventional technology. That emphasis on productivity accompanies a shift in Rapid Tooling applications from prototype to full production tooling.

The advantages of flexible molds are: efficiency, by reducing waste and energy consumption; agility for enabling customization and flexibility for the modification and implementation of design concepts [1, 2, 9, 12,].

The information and data used during this research have been achieved by research consisting of simulation and evaluation, through a case study, the vacuum casting process of non-metallic parts in flexible molds. In the case study proposed, it was considered a wax piece with a complex geometry (having bores, horizontal, vertical and inclined surfaces), produced by vacuum casting in Essil 291silicone rubber molds. Results obtained from simulation process done by Autodesk Mold Flow software have been used in experimental research in order to set the proper process parameters, including casting point location and vents number and position.

2. SIMULATION OF NON-METALLIC PARTS VACUUM CASTING PROCESS

The analysis of the thermo-plastic material flow used in the casting process has been done by MPI/Flow software (Fig. 1) and it goes through usual stages. At this step, the part material is chosen from software database, namely the wax produced by Argüeso, and the type of analysis – Flow/Filling only [12]. They are also selected MCP PLC 001 vacuum casting machine and casting parameters are set. The silicone rubber Essil 291 (produced by Axson Technologies) is chosen as mold material too. The study has been focused on the following aspects: temperatures analysis, filling time, determination of the optimal casting point positions, and vent positioning.

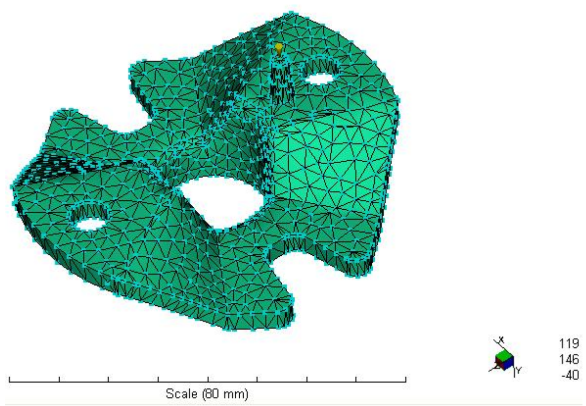

Fig. 1 – Finite elements network obtained from meshing and casting funnel placement.

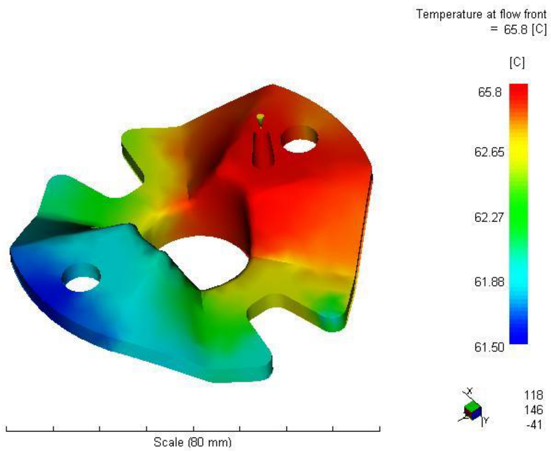

Fig. 2 – Temperature evolution in vacuum casting of wax.

Analyzing temperature with flow modeling software, the results are presented using color keys for maximum clarity, the colors indicates temperature in different zones of the part. As shown in finite elements analysis, using Mold Flow software, the casting temperature (Fig. 2) varies between 61.5°C (blue areas) and 65.8°C (red areas).

The marginal layer of mold is thicker (at the point of observation) and the heat share is lower. That also means the warmth incurred by shear is less. As the molten material lost some heat during its flow for distant points of casting gate, the heat intake per unit of time is smaller and the marginal layer becomes thicker than close to casting gate. For the solidification of molten material, it is not important the flow path, but the material running time during the casting process. Thus, increasing of marginal layer thickness, away from the casting funnel, the flow becomes slow. Such a flow casting speed causes a filling resistance of mold cavity.

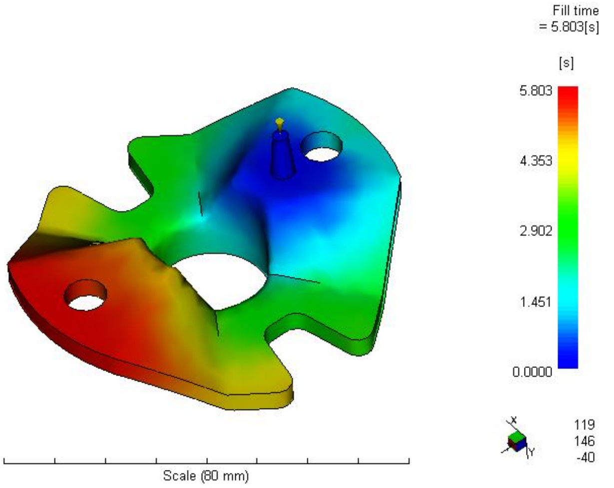

Fig. 3 – Mold filling diagram.

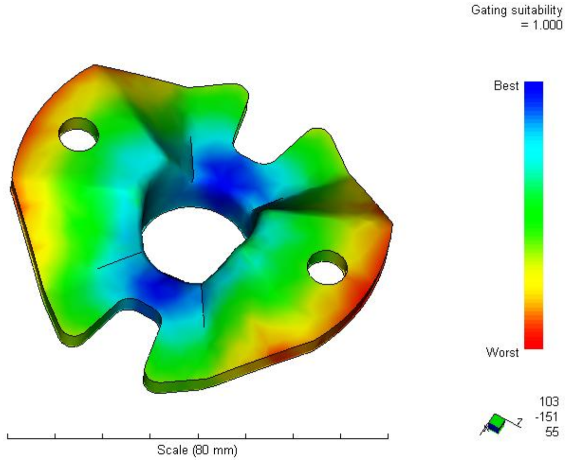

Fig. 4 – Optimal casting points.

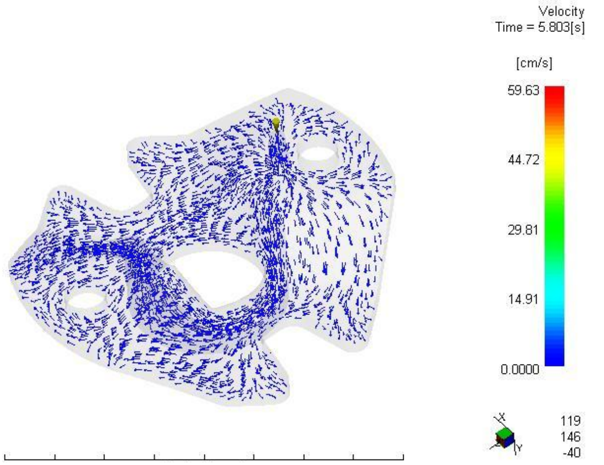

Fig. 5 – Movement of the wax molecules in mold cavity.

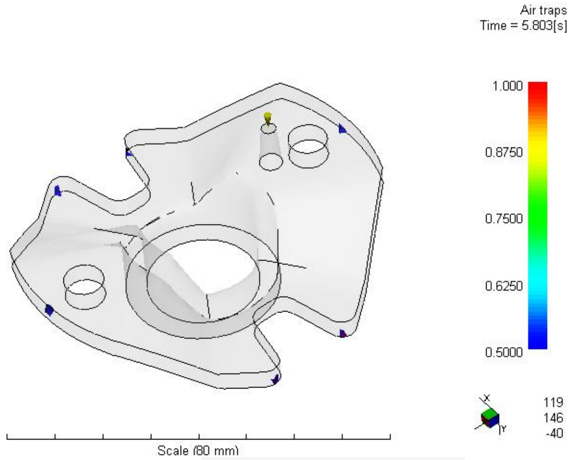

Fig. 6 – View of air traps positions.

Due to problems of mold filling, the molded part is characterized by the ratio of flow path and wall thickness. The mold filling occurred in a shorter time, the higher is the ratio of flow path and wall thickness. As defined in the analysis, the filling time of the mold is 5.803 seconds. Obviously, the material filling of the furthest points from the surface of the casting lasts the longest. The filling time diagram (Fig. 3) indicates the flow front position at regular intervals during the mold cavity filling process. The contours represented with the same color indicates the mold zones which were filled at the simultaneously.

Mold Flow software enables us the opportunity to determine the optimal casting point (Fig. 4). The figure caption explains that in the colors code obtained, the optimal point is located in the dark blue area, while the less desirable area for casting the red zone. The speed and flowing mode of wax in silicone rubber mold is shown in Fig. 5. Physical and mechanical properties of the part are largely determined by the orientation of macromolecules of material during the vacuum casting process.

During the casting process air inclusions may occur, due to the fact that bubbles accumulated through melting and mixing of molten material cannot be removed before casting them [15]. Air traps are caught inside the mold cavity. It becomes trapped by converging polymer melt fronts or because it failed to escape from the mold vents, or mold inserts, which also act as vents. Another common cause is race-tracking (the tendency of polymer melt to flow preferentially in thicker sections), caused by a large thickness ratio. Entrapped air will result in voids and bubbles inside the molded part, a short shot (incomplete fill), or surface defects. Lack of vents or undersized vents in these last-to-fill areas may also cause air traps and the resulting defects. It requires a proper positioning of vents in order to avoid this phenomenon. In the case study considered, the zones suitable for the vents positioning are shown in Fig. 6. Air-trap locations are in areas that fill last.

3. EXPERIMENTAL RESEARCHES

3.1. Master model fabrication

The manufacture of master model used in the vacuum casting proves was realized by selective laser sintering process (SLS) [7, 8, 10] using Sinterstation 2000 equipment. STL model and the master of the part obtained can be observed in Fig. 7. The model is positioned and oriented in the machine work area given the overall size of the part: length 80 mm, width 72 mm and height 22 mm. The appropriate scaling factors and working parameters were chosen depending on the master model material. Master model material used was Duraform PA.

Fig. 7 – STL model and master model of part.

3.2. Manufacture stages of silicone rubber mold

Manufacture of silicone rubber mold used for vacuum casting of complex pieces of wax, was done in several stages. It begins with examination, cleaning and protecting master model surfaces. The next steps are materialization of the separation plan, suspension master model in the casting box, setting of casting funnel and vents. For this, it was performed an application, using the Visual C++ software, which automatically generates casting box size for the silicone rubber mold, depending on the master model size, in order to save both silicone rubber and hardener. Essil 291 silicone molding system is used in the prototyping, vacuum casting. Its formulation enhances the life expectancy of the moulds produced.

The experiments show remarkable performance results when used with PX Polyurethane system. Due to the low viscosity it discourages air entrapment when mixed, resulting in a quicker degas and release of air bubbles. Thus, the mold manufacturing process continues with the primary degassing of silicone rubber, its casting process, followed by secondary degassing.

Essil 291 demolds in 12 hours at 23°C but is usually cured at 40°C for this period. This is to cater for the expansion of the mould at 70°C during the cure of PX products thereby allowing for the resulting shrinkage of the PX products to give a correct dimension of the resulting part. To obtain good dimensional part accuracy, the rubber curing process has been done in the oven at a temperature of 40ºC for 20 hours. Finally, the two mold active elements have been separated by cutting and the master model has been extract.

3.3. Vacuum casting of wax parts

Experimental investigations are realized for 4 types of wax produced by Argüeso. They are easy to remove, have good flow and excellent memory. In each case it pursues the technological characteristics of the materials (Table 1), the degassing level, optimal working regimes and dimensional accuracy of parts produced [3]. Also, should be considered the results of vacuum casting process simulation (previously presented in this paper) in terms of casting funnel positioning, number and locations of vents.

Each type of wax has been processed by vacuum casting using following conditions: temperature of heated mold of 20ºC, 35ºC, 50ºC, 55ºC, and 4, 6, 8 vents respectively. An example of wax piece (Pink 863) obtained by vacuum casting is shown in Fig. 8.

Table 1

Technical specifications of waxes

Wax Type	**Behaviour**	
863 Pink	• Good general purpose wax with high flexibility and low shrinkage • Gives an extremely smooth surface	
864 Red	• Very low shrink wax for large flat pieces • Does not sink on flat surfaces • It can be carved and it is ideal for metal molds	
865 Green	• A good general purpose wax with high flexibility • A similar wax to 863 Pink but slightly less fluid	
866 Blue	• Very flexible wax for fragile pieces • Gives an extremely smooth, shiny surface • Low shrinkage and medium flow behavior	
Composition/ Information on ingredients	A mixture of refined hydrocarbon waxes, resins, polymers, ester waxes and coloring agent. There are no hazardous ingredients	
Casting temperature	72-74ºC	
Flash point	>190º	
Property	**Method**	
Dropping point	ASTM D 3954	70-78^{0}C
Curing point	(ASTM D 938)	64-68^{0}C
Hardness at 25^{0}C	(ASTM D 1321)	5-10±0.1mm
Viscosity at 100ºC	(ASTM D 3236)	80-110 mPa.s
Density		1.05 g/cm^3

Fig. 8 – Example of 863 Pink molded part (6 vents, mold temperature –50ºC, filling time of mold cavity –5.8 s).

3.4. Experimental determination of the air traps volume in wax parts

Determination of the air inclusions volume in wax parts is made by Shimadzu electronic balance. This allows experimental determination of body density based on its weight, weighed in air and in a liquid whose density is known (e.g. water). Relationship to calculate the density of wax molded part is [16]:

$$\rho_p = \frac{m_{p\_\text{air}}}{m_{p\_\text{air}} - m_{p\_\text{water}}} \cdot \rho_{\text{water}}, \tag{1}$$

where: ρ_p – density of part analyzed [g/cm^3]; m_{p_air} – piece mass, weighed in air [g]; m_{p_water} – piece mass, weighed in water [g]; ρ_{water} – water density [g/cm^3].

Obviously the air traps volume is influenced by number of vents and their placement. The results of experimental research in this regard are presented in Table 2. Lack of vents or undersized vents in the last-to-fill areas are a common cause of air traps and the resulting defects, but a large number of vents does not obligatory reduce the air inclusions in cast parts. In the case study considered, the optimal number of vents is 6 for all types of wax used.

Table 2

Air traps volume

Wax type / No of vents	Air traps volume in cast part [%]			
	866 Blue	863 Pink	865 Green	864 Red
4	2.6977	1.9208	0.5948	0.9887
6	0.3690	0.1670	0.3096	0.2305
8	0.9372	0.6648	0.9519	0.6415

4. RESULTS AND DISSCUSIONS ON DIMENSIONAL ACCURACY ANALYSIS OF WAX CASTINGS

The measurements of wax molded parts were done using Navigator Prismo equipment, according to the sketch shown in Fig. 9. Additionally, has been analyzed the circularity deviations of diameters ϕ24, ϕ8.4 (denoted in the following by Dim. 1.1, Dim. 2.1, and Dim. 3.1) and the flatness deviation relative to dimension 7 in measurement sketch (denoted in the following by Dim. 7.1). Dimensions measured were compared with CAD model and master model dimensions. Dimensions 1, 2, 3 are measured on the *Y* axis, 4, 5, 6 are the dimensions measured in the *X* axis and 7 is the only dimension measured on *Z*. It can be seen that on the axis *X* the average deviation is below the 1.5%, on the *Y* axis it has a value less than 0.65%, while the *Z* axis deviations occur up to 4%. Then the percentage contractions of each dimension have been measured by comparing the required dimensions of wax parts and the CAD model, but also in relation to the dimensions of SLS master model [11]. Deviations recorded (mean of 5 values measured) are shown in Fig. 10 and Fig. 11.

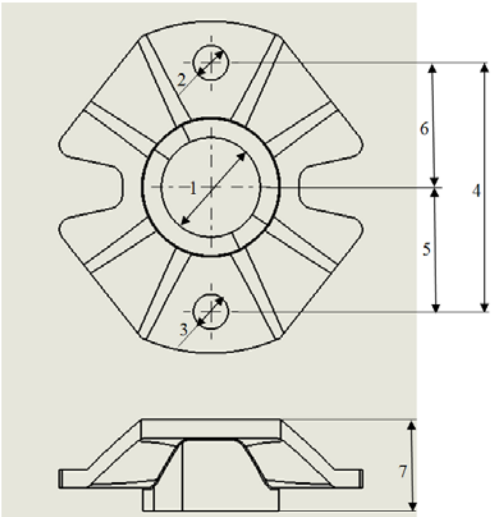

Fig. 9 –Part measurement sketch.

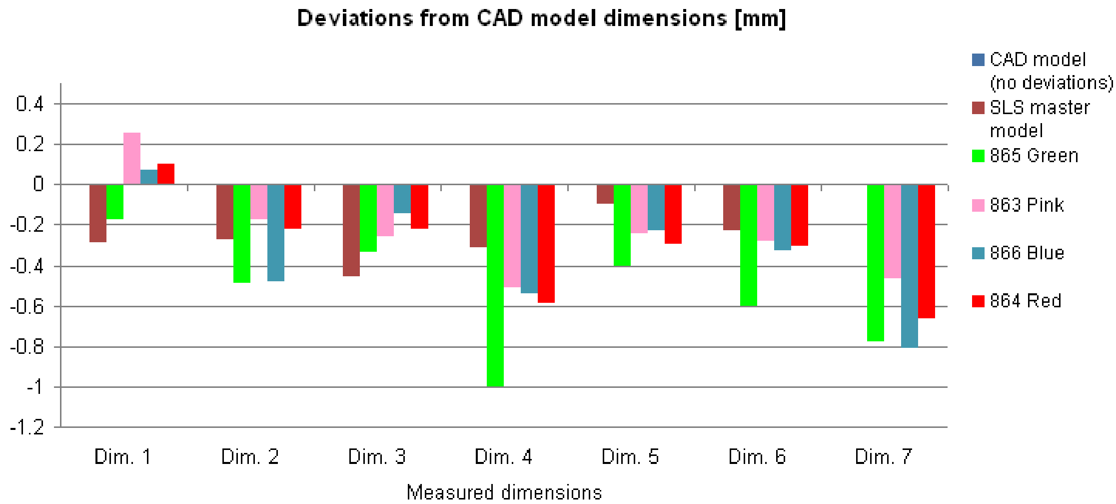

Fig. 10 – Deviations of wax part dimensions related to CAD model and SLS master model.

The results are summarized in Table 3. Dimensional deviations reported to the CAD model (for dimension 1–ϕ24 mm) do not exceed the value of 0.07 mm in absolute, meaning a relative error of 0.29%, while in relation to the master model the dimensional deviation was –0.28 mm, whose value relative error is

1.49%. On the *Z* axis for the dimensions 17.25 mm (CAD) and 17.2502 mm (SLS master model), the deviation has the value –0.7 mm and 0.7 mm respectively, which corresponds to a relative error of 4.05%.

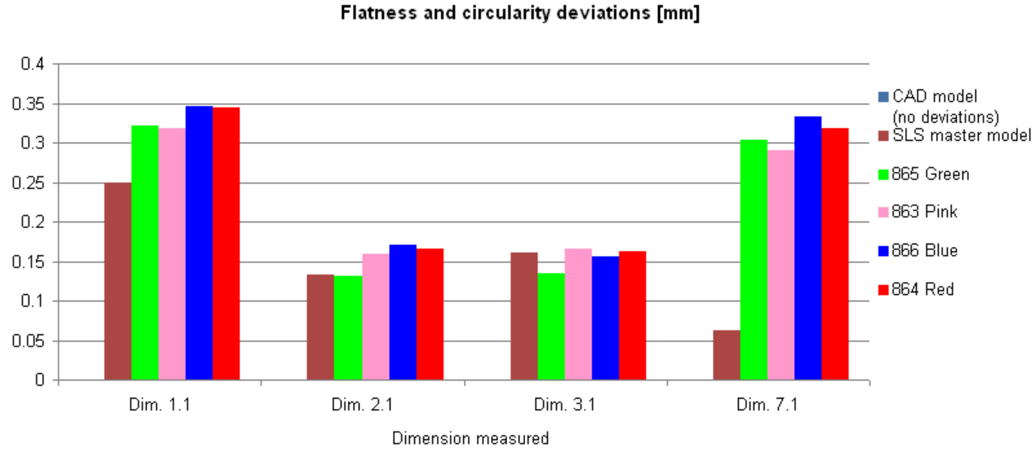

Fig. 11 – Flatness and circularity deviations.

The negative deviations in Fig. 4 are causes by wax contractions during the curing process. Based on these results were determined the correction factors, applicable to CAD dimensions, in order to achieve the right SLS master model, and forward the wax pieces obtained by vacuum casting to result at dimensions required in the work drawing. Thus, to correct the *X*-axis sizes, the correction factor imposed is 1.0224, on *Y*-axis it is 1.01097, and *Z*-axis corrective factor is 1.0423.

Table 3

Relative error of wax part related to CAD model and SLS master model

Dimension in the measuring scheme	CAD dimension [mm]	Measured dimension (mean value) [mm] on		Error			
		Was parts (mean)	SLS model	Wax parts		SLS	
				[mm]	[%]	[mm]	[%]
Dim. 1	ϕ24	24.0699	ϕ23.7158	+0.0699	0.29	-0.2842	1.49
Dim. 2	ϕ8.4	8.0620	ϕ8.1326	-0.388	4.02	-0.2674	0.86
Dim. 3	ϕ8.4	8.1696	ϕ7.5519	-0.2304	2.74	-0.8481	8.17
Dim. 4	60	59.3503	59.6925	-0.6497	1.08	-0.3075	0.57
Dim. 5	30	29.7196	29.9099	-0.2804	0.93	-0.0901	0.63
Dim. 6	30	29.6287	29.782	-0.3713	1.23	-0.218	0.51
Dim. 7	17.25	16.5496	17.2502	-0.7004	4.05	+0.7006	4.06

5. CONCLUSIONS

Simulation of the vacuum process is important because it provides valuable information in such a way as to eliminate possible errors of mold design and its execution. Simulation results have shown that the analysis has improved the quality of the parts by indicating exactly how the material flows, areas where the risk is, air traps forming in parts (recommended for vents' placement) and ideal location for casting funnel. Conclusions from simulation results have proved to be extremely useful being used in experimental research on vacuum casting of complex wax parts. In this paper, experimentally it was realized the vacuum casting process in the flexible molds. It was used 4 tips of wax for obtaining the complex nonmetallic parts.

The position of the vents and the optimal number and also finding the proper place of the casting gate, there were determined in the last researches considering a few simulations using the Autodesk Mold Flow.

Using the researches from this paper it was established, that the air bubbles volume accumulated in the parts, depends on the number of the vents and also the position of these on the parts. Using the measurements it was established dimensional errors for the plane surfaces and also cylindrical relating the CAD model and the master model manufactured by Selective Laser Sintering. In conclusion the dimensional errors are determined by the material contraction of the wax parts. To compensate the measurement errors it was determined the correctional factors considering the 3 axes X, Y and Z.

Theoretical research will be further focused on mathematical modeling and optimization of vacuum casting process. Experimental research done by the authors in the National Center for Rapid Prototyping on vacuum casting using silicone rubber molds, are expanding to the complex parts made of different types of resins (epoxy, polyester, polyurethane).

REFERENCES

1. BARETA, D.R. POUZADA, A.S. and COSTA, C.A., *The effect of rapid tooling materials on mechanical properties of tubular mouldings,* PMI International Conference on Polymer and Moulds Innovations, Gent, Belgium, 2007.
2. BEAL, V.E., AHRENS, C.H. and SABINO-NETTO, A.C., *Evaluating the use of aluminum inserts on stereolithography puzzle molds for injection molding of complex parts: a case study,* Proceedings ANTEC Conference, Nashville, USA, 2003.
3. BERCE, P., and RADU, S.A., *Precision analysis of wax parts processed by vacuum casting in silicone rubber mold,* XXIII Micro CAD, International Scientific Conference, Miskolc, Hungary, 2009, pp. 15–19.
4. FOLKESTAD, J.E. and JOHNSTON, R.L., *Resolving the conflict between design and manufacturing: integrated rapid prototyping and rapid tooling,* Journal of Industrial Technology, **17**, *4*, pp. 1–7, 2001.
5. GIBSON, I., CHEUNG, L.K., CHOW, S.P., SHEUNG, W.L., BEH, S.L., SAVALANI, W. and LEE, S.H., *The use of rapid prototyping to assist medical applications,* Rapid Prototyping Journal, **12**, *1*, pp 53–58, 2006.
6. HORACEK, M. and LUBOS, S., *Influence of injection parameters to the dimensional stability of wax patterns,* 9th World Conference on Investment Casting, San Francisco, 1996, pp. 1–20.
7. ILYAS, I.P., TAYLOR, C.M. AND DALGARNO, K.W., *Production of plastic injection mould tools using selective laser sintering and high speed machining*, Proceedings of the 6th National Conference of Rapid Design, Prototyping and Manufacturing, High Wycombe, 10 June, 2005, pp. 109–116.
8. KING, D., TANSEY, T., *Rapid Tooling: selective laser sintering injection tooling*. Journal of Materials Processing Technology, **132**, pp. 42–48, 2003.
9. MARTINHO, P., BARTOLO, P.J., QUEIROS, M.P., PONTES, A.J. and POUZADA A.S., *Hybrid moulds: the use of combined techniques for the rapid manufacturing of injection moulds,* Rapid Prototyping Journal, **15**, *1*, pp. 71–82, 2009.
10. O'DONNCHADHA, B., TANSEY, A., *A note on rapid metal composite tooling by selective laser sintering*, Journal of Materials Processing Technology, **153–154**, *1*, pp. 28–34, 2004.
11. RAHMATI, S., AKBARI,F. and BARATI, E., *Dimensional accuracy analysis of wax patterns created by RTV silicone rubber moulding using the Taguchi approach,* Rapid Prototyping Journal, **13**, *2*, pp. 115–122, 2007.
12. RIBEIRO, A.R. Jr., HOPKINSON, N. and AHRENS, C.H., *Thermal effects on stereolithography tools during injection moulding,* Rapid Prototyping Journal, **10**, *3*, pp. 176–180, 2004.
13. YANG, Y. and HANNULA S.P., *Development of precision spray forming for rapid tooling,* Materials Science and Engineering, **477**, *1–2*, pp. 63–68, 2008.
14. YARLAGADDA, P. and HOCK, T.S., *Statistical analysis on accuracy of wax patterns used in investment casting,* Journal of Materials Technology, **138**, pp. 75–81, 2003.
15. SHIMADZU CORPORATION KYOTO, *Instruction Manual for Simple Specific Gravity Measurement*, Kit AW/AX/AY Series, Japan, 2010.

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