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Optimization of 3D Printed Patterns for the Hybrid Investment Casting Technology

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Abstract

Currently, great emphasis is placed on the production of castings with complex shapes. The hybrid investment casting technology using 3D printed models offers new possibilities in the production of such complex and thin-walled castings. The motivation for this paper was to find a solution to the problem with ceramic shells cracking during the 3D model firing stage. The main factors affecting the shell cracking are the thermal expansion of the model and the shell material, and the newly considered pressure of the gas closed in the ceramic shell cavity. First, thermal analyses were performed of a commercial material used for 3D printing - Polymaker PolyCast™. The characteristics yielded by the measurements helped establish the glass transition temperature, the autoignition temperature and the behaviour of the gas produced by the model burning. Suitable experimental models in the shape of tetrahedrons were designed and used for a number of experiments. The tests confirmed that cracks only occur during shock firing in models printed by the FFF technology with 0% of infill. A solution suggested for further experiments is purposeful venting of the models. Practical testing of the optimization has also been performed. The last step was measurement of the heat transfer through the ceramic shell after being placed in the annealing furnace. There were temperature evolution profiles in the system model-ceramic shell obtained.

Key words: Ceramic shell cracking, Hybrid investment casting technology, 3D printed model, FFF technology

1. Introduction

Currently, great emphasis is placed on the ecology of all production processes. This also relates to mechanical engineering, where there is an increasing tendency towards decreasing the weight of components in automobiles, aircraft or various appliances. Designers must design the components with the lowest weight possible while ensuring sufficient structural parameters. Each component designed is then optimized. This is a new challenge for foundry engineers resulting in the search for new ways to produce light castings with complex shapes.

A dynamic increase in the needs of designers leads to fast developing prototypes and thus also greater demands on production. There is an increased demand for the production of Rapid Prototype shells for the purpose of producing several pieces of test castings and their subsequent optimization. Hybrid investment casting (HIC) is based on the conventional investment casting method, where we use wax sprue with assembled 3D printed patterns. Instead of wax patterns injected into moulds, it uses models printed on 3D printers using various thermoplastics and resins. Many companies producing thermoplastics and resins have seized the opportunity and produce materials suitable for 3D model printing. The hybrid technology is not limited by the mould parameters for wax injection but by the parameters and capabilities of the 3D printer. 3D printers can be used for printing models with almost any complex shape. As with the wax models, there are also certain requirements imposed on the material used for producing models for burnout process. The firing of the models from the shells must be performed by shock in order to prevent the ceramic shells from cracking due to the different expansions of the model material and the ceramic shell. Ideally, the model should collapse in on itself or the expansion joint must be melted to allow the model to expand when being fired [1,2].

The motivation for this paper was the optimization of 3D models printed with commercial material Polymaker PolyCast™ for the hybrid investment casting technology. The material was chosen for its unique parameters suitable for the HIC technology. Another motivating factor was making an analysis of the possible factors affecting the cracking of the shells during firing with regard to the different thermal expansion of the materials, the parameters of the printed models and an analysis of the model materials. The intention was also to increase the awareness of the issue explored and prove or disprove it using experimental models in the university foundry [3, 4].

In professional literature, Fedorov et al. [5] analysed the surface quality of castings made by the HIC method using models printed with polyvinyl butyral (PVB) and acrylonitrile butadiene styrene (ABS). They verified that the surface structure of the PVB castings is better than that of the ABS. The thermal expansion of the models from PVB is lower, and thus, the shell layers are less strained than with ABS. A higher melting point of ABS leads to worse and incomplete combustion of the residual ash in the ceramic mould cavity.

Kumar et al. [6] studied how to improve the surface properties of castings made by the HIC method. They suggested applying a thin surface layer of wax over the printed models, which results in a better quality of the casting surface. This also significantly decreases the risk of the shell cracking during firing. They verified that the lower the density of the model infill the lower the risk of the shells cracking during firing. The best option was using hollow models. The QuickCast concept was based on the principle that the hollow model becomes softer at a lower temperature and the model walls collapse into the model. The critical level of strain on the shell walls is not reached. They verified the fact that with a smaller number of shell layers the risk of its disruption increases.

Like the previous authors, Chen et al. [7] describe the issue of shell cracking with respect to different material expansions. By increasing the strength of the ceramic shell, we decrease the risk of its cracking. By adding polymer and organic fibres in the suspension, the strength of the shells at temperatures ranging from 200 to 500 °C increased. In addition, they proved in their research the initiation of cracks at the place with a notch – the tip of the resin turbine blade. The shell cracking was prevented by adding fibres. By producing a stronger shell, its permeability decreases.

The aim of the authors of this paper is to eliminate ceramic shell cracing during phase of firing by the optimization of 3D printed patterns and process parameters.

2. Analysis of pattern material Polymaker PolyCast™

The Polymaker company developed the PolyCast™ material (PVB) for the HIC technology. The producer gives the following parameters – PolyCast™ was developed using the technology, which significantly decreases the amount of residual ash, the technology, which allows the material to be perfectly smoothed when being etched in alcohol mist, and the and technologies, which facilitate the 3D printing. The parameters are well designed, and therefore, the material is widely used [8].

Thermal analyses of the material were performed at Masaryk University in Brno and the dilatometry at the Faculty of Mechanical Engineering of Brno University of Technology (BUT). The analyses provided significant information about the behaviour of the material during temperature changes.

2.1. Dilatometry

Dilatometry describes the behaviour of the material when the ambient temperature changes, see Fig. 1. A sample was tested using Setaram Setsys Evolution TGA-DTA/DSC for the temperature ranging from 25 °C to 107 °C, when both materials ceased to be measurable. The behaviour of the model wax Blayson (A7-FR/1100) at temperatures from 25 °C to 60 °C was predictable and its coefficient of thermal expansion was 149.5 [10^{-6}/°C]. At temperatures over 60 °C, the wax softened and melted. The behaviour of the PolyCast™ material at temperatures from 25 °C to 73 °C was based on the coefficient of thermal expansion of 124.4 [10^{-6}/°C]; from 75 °C to 91 °C it was based on a coefficient of 4052 [10^{-6}/°C], and the last change occurred between 93 °C and 107 °C, when the coefficient was 11000 [10^{-6}/°C]. The obtained data shows that the coefficient of thermal expansion of the material is lower than casting wax used in this experiment. The glass transition temperature of the PolyCast™ material was established to be 74 °C [3].

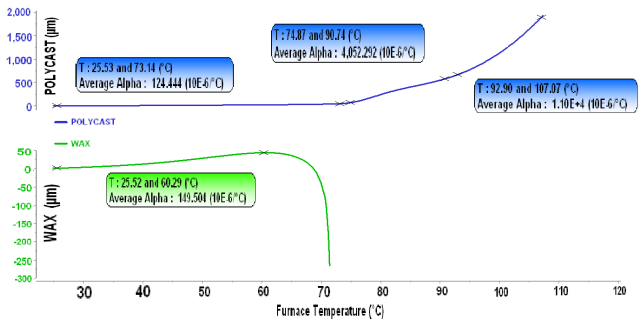


Fig. 1. Dilatometry of the Blayson (A7-FR/1100) foundry wax and the PolyCast™ material [3]

2.2. DSC – differential scanning calorimetry

Differential scanning calorimetry is used for studying the thermal properties of materials. A material sample with a weight of 11.22 mg was tested using Netzsch 449 Jupiter at temperatures ranging from 30 to 700 °C with the rate of heating of 10 K/min. The temperature range was chosen according to the temperature during burnout. The measurement, see Fig. 2, showed that the glass transition temperature was 70 °C and thermal instability occurred at temperatures from 300 to 480 °C. The autoignition temperature of the sample was 350 °C and the maximum combustion temperature was 505 °C [3, 9].

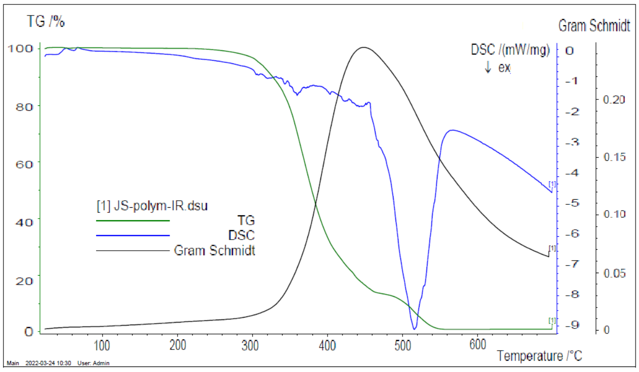


Fig. 2. Thermal analysis of the PolyCast™ material [3]

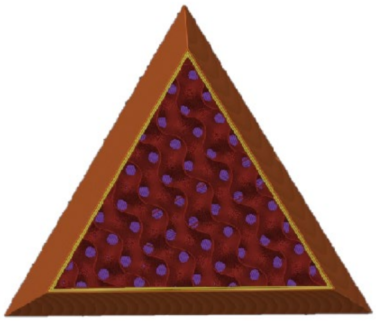
2.3. TG - thermogravimetry

Thermogravimetry describes how the weight of the sample changes depending on the ambient temperature. The parameters and the extent of the measurement are the same as for the DSC curve. The data obtained, see Fig. 2, clearly show that the beginning of the material weight loss corresponds with the beginning of the thermal instability 300-400 °C. When the autoignition temperature is reached (350 °C), a rapid decrease in the weight occurs accompanied by stagnation between the temperatures of 450-480 °C and the final burnout. The „Gram Schmidt“ signal represents the amount of gaseous substances released during the heating of the sample. The maximum amount of the substances released was measured at 420 °C [3, 9].

3. Selecting the experimental models

A suitable design of the shape of the experimental models was essential for the subsequent optimization. The requirement for the model was to display the greatest possible tendency to cracking during the firing of the model from the ceramic shell. On sharp edges with a small or no radius the shells usually crack.

A tetrahedron-shaped model was designed with a side of 100 mm. The models were printed on the Prusa i3 MK3S+ printer with the temperature of the extrusion 210 °C and that of the heated bed 70 °C. The amount of the infill recommended by the manufacturer is 20%. The first tests were performed on models with the infill of 0, 10, 20 and 30% and with the infill shape of a Gyroid, shown in Fig. 3a. During the 20-minute long shock firing at 650 °C it was the model with 0% of infill that cracked. For the next measurements, models with 0, 5, and 8% of infill were printed. Model tree is shown in Fig. 3b. Many more experiments on these models confirmed the tendency to crack in the ceramic shells with 0, 5% of infill. By decreasing the amount of infill in the models, the production cost decreases as well as the 3D printing time and the amount of the residual ash after the firing from the ceramic shell [3, 8].



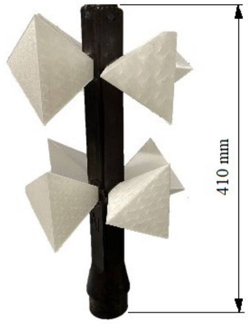


Fig. 3a. Tetrahedron with Gyroid infill Fig. 3b. Models tree with tetrahedron models [3]

After further decision-making, another option was to vent the cavities of the 0 and 5% infill models. A theoretical assumption for the cracking of the shells was the absence of the model infill and expansion of the air inside the model cavity. The infill of the printed models would serve as reinforcement and the model would not expand after being placed in the furnace; therefore, it would not create the strain on the shell layer. More experiments were conducted with vented models confirming the assumption. A list of selected experiments is shown in Tab. 1. In total, 13 shells with 36 models were made.

Table 1.
Overview of selected experiments with the models of Tetrahedrons [3]

Model	Infill [%]	Sprue	Firing [°C, 20 min]	Results
Tetrahedron	0, 10, 20, 30	Wax	650	x, ✓, ✓, ✓
Tetrahedron	0, 5, 8	Wax	650	x, x, ✓
Tetrahedron	0, 0, 0, 0	Wax	650	x, x, x, x
Tetrahedron	0*	Ceramic tube	650	✓
Tetrahedron	0*, 0*, 5*	PolyCast™	650	✓, ✓, ✓

* vented model, ✓ ceramic shell OK after firing,
x ceramic shell broken after firing

4. Experimental measuring of temperatures during the firing of the model from the ceramic shell

Materials used for the production of ceramic shells are ceramic slurries (binder + filling powder) and refractory material. The ceramic slurry binders were used on water basis. For the first layers, the suspension consisted of the Primcote® binder and the Ranco-Sil™ 4 – fused silica – 200 mesh, the Zirkon – 50/150 refractory material. For the back-up layers, the suspension consisted of the Wexcoat® 24 binder, the Ranco-Sil™ 4 – fused silica – 200 mesh and WEXPERM® FIBRES, and the Molochite 16/30 refractory material.

During all the thermal processes in the production of the ceramic shell and the subsequent casting, the ceramic shell is affected by the flow, radiation and conduction of heat. In order to determine how the shells conduct heat, a simple experiment was designed. The models used were again the tetrahedrons, into which type-K thermocouples were installed. Each thermocouple was located in a precise defined place, see Fig. 4. The first thermocouple was placed in the centre of the 3D model, the second one into the model wall and the third one has been assembled to the model surface with a hot melt glue gun. Such model was manually coated with 3 layers. Then, a fourth thermocouple was attached to the shell in order to represent the temperature between the third and the fourth layer of the ceramic shell. Then, the coating of the shell was finished; 8 layers in total. A fifth thermocouple was attached to the last layer, which represented the temperature near the surface shell. The furnace for firing is always set to 650 °C but the temperature fluctuates due to the furnace being opened when inserting the shells, switching on the afterburning chamber and removing the shells from the furnace. The temperature of burnout is 650 °C with respect to construction limits of afterburn chamber. The finished shell had to be placed appropriately into the furnace so that the wax being melted could flow down into a container and, at the same time, the thermocouple lines could be easily closed in the furnace door.

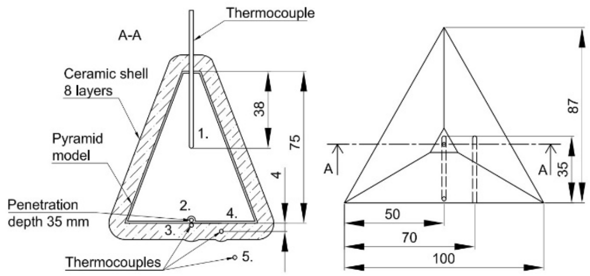


Fig. 4. Diagram showing the location of the thermocouples in the model

The thermocouples were connected to an AD transmitter with a measuring frequency of 20 Hz and data recording was started in the programme. The measurement was performed at 650 °C and lasted 30 minutes to allow all the signals to stabilize at the same temperature. After the measurement the shell was removed from the furnace and left to cool down in the air. The data from measurement are shown in figure 5.

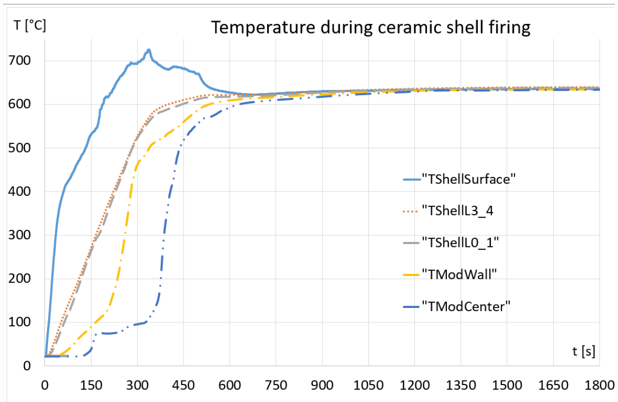


Fig. 5. Temperature at specific points during the ceramic shell firing

In the Figure 5, the following parameters can be seen.

- T = 70 °C temperature of the glass transition
- T = 200 ÷ 400 °C the most progressive increase in the temperature; the ceramic shell conducts less heat; the model conducts better
- The furnace temperature was set to 650 °C; fluctuation of the reference thermocouple temperature caused the afterburning chamber to switch on.
- The development of gases caused by the firing of the model material and the wax significantly heats the reference thermocouple on the surface of the shell to a temperature above 700 °C; there is correspondence with the DSC curves at 450 °C, when the most massive development of combustion products occurred due to the model material firing.

5. Practical optimization of a sword cross-guard model

In the school foundry at BUT, a problem occurred with shells cracking during the production of sword cross-guard castings in the stage when the 3D printed models are being fired from the ceramic shell. Therefore, the models had to be optimized and the risk of cracking minimised. The cracked shells were repaired with a refractory sealant but the repair was not optimal. The crack could reoccur at the place of repair and the metal could leak out. The finished steel castings showed flash defects at the place where the shell was repaired. An interesting fact is that the shells only cracked in the spherical part of the sword cross-guard. The defects of the ceramic shell are shown in Figure 6. The critical area of the sword cross-guard is shown in Figure 7.

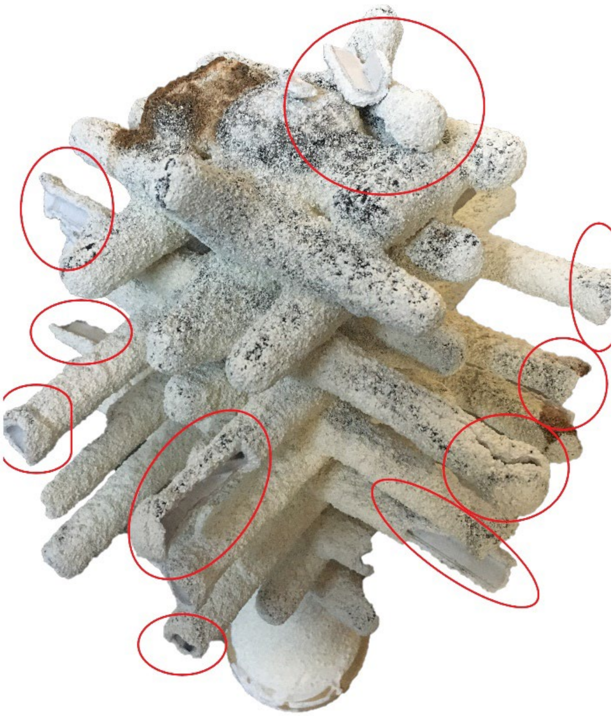


Fig. 6. Defects of the ceramic shell after the firing stage [3, 10]

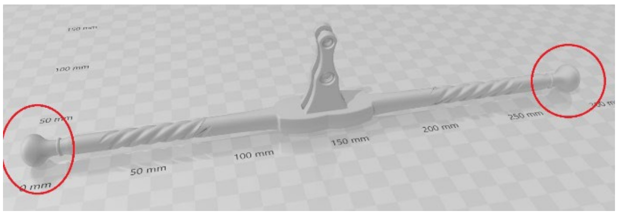


Fig. 7. Critical area of the sword cross-guard [10]

The optimization process consisted of for the first step, a model with 8% of infill was printed. Models were assembled to the wax sprue and coated in a standard way. Before the firing stage, it was left to dry for 24 hours. Shock firing was performed at 650 °C for 20 minutes. After the shell was removed from the furnace, it was disrupted in the spherical part of the sword cross-guard. For the second step were designed other experiments, 6 more models of a sword cross-guard were printed with 8% of infill and of hollow tubes with a diameter of 18 mm and length of 100 mm. The cross-guard models were assembled to the tubes with wax and, at the point of contact, a hole was punched with a red-hot wire to enable venting the model cavity. Coating was again performed in a standard way. In the firing phase, it was proposed to try firing at 300 °C for 20 minutes and then increase the temperature to 650 °C. Three shells were fired with a rise from 300 °C to 650 °C and the remaining three were placed in the melting furnace after the temperature had stabilized at 650 °C. The temperature rises can be seen in Figure 8. After the shells were removed from the furnace and cooled down, no cracks were found. The models were suitably optimized by venting, and standard firing at 650 °C for 20 minutes was recommended. [3]

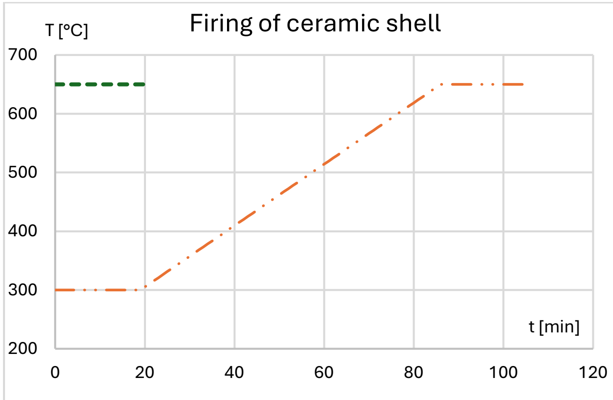


Fig. 8. Three temperature rises during the firing of a sword cross-guard ceramic shell [3]

6. Discussion

In experiments conducted outside the framework of this paper in our laboratory it was verified that the ABS material is not suitable for investment casting technology patterns. The amount of residual ash was too large and the shells cracked during firing. Therefore, the more suitable PVB PolyCast™ started to be used. Owing to its Layer-Free™ technology, PolyCast™ has better final surfaces due to etching in isopropyl alcohol mist. Nevertheless, there are still noticeable layers caused by the FFF print technology on the surface of the casting. In their article, Fedorov et al. [5] compared ABS and PVB with regard to firing and to the surface of the final casting and also recommended the use of PVB material.

Our experiments showed the necessity of venting the 3D printed hollow PVB model. Although Kumar et al. [6] in their work suggested the application of a thin layer of wax on the surface of the 3D printed model in terms of reducing the stress on the shell wall during firing and improving the surface of the casting. The models were printed from ABS material using FFF technology. The assumption was that the weak wax layer would melt first during the melting phase, thus creating an expansion joint for the expanding model. In their work, they verified that the lower the amount of model filler material, the lower the chance of shell rupture. Thus, it is best to use a hollow model, which is contrary to our practice with unvented models.

Experiments with tetrahedron models verified that cracks always extended along the sharp edge where the ceramic shell is weakest. At the edge of the shell, the shell dries out more quickly during coating and therefore has a reduced ability to coat with refractory, thus weakening the shell locally. Chen et al. [7] proposed increasing the strength of the ceramic shell by using additive polymers and organic fibers. They also presented a theoretical assumption of collapsing the model into the inner cavity of the model, which would reduce the stress on the shell. They further confirmed that crack initiation occurs exclusively at the edges of the models. This is consistent with our conducted experiments.

7. Conclusion

The paper studies the possible factors affecting the cracking of ceramic shells and focuses on a detailed analysis of the Polymaker PolyCast™ material, which was specifically designed for the HIC technology. Thermal analyses showed how PolyCast™ behaves during the firing stage. The analyses determined the glass transition temperature to be 70 °C, the auto-ignition temperature 350 °C and the maximum amounts of the gaseous substances released at 420 °C. Several experiments were then conducted leading to the conclusion that the ceramic shells of hollow models tend to crack. After venting the cavities of the hollow 3D printed models, the problem with mould cracking was solved and our assumption about the expansion of the air closed in the model cavity was confirmed. Therefore, it is suitable to continue using 8% of the Gyroid infill in the 3D models printed with PolyCast™ and to vent the models before sticking them to the sprue. Subsequently, measurements were performed of heat transfer through the shell layers to the centre of the model during the firing stage. These data were used to check the time of the temperatures rising to the required levels. Then, optimization was proposed for the production of the ceramic shell for a sword cross-guard casting, again verifying the optimization by venting the model.

Further research will study the pressure of the air expanding inside the model cavity during the firing of the model from the shell. There is an assumption that with the temperature increasing in the shell, the pressure of the closed air increases and decreases with the permeability of the coated ceramics. This pressure also increases with the development of gases produced by the 3D printed models firing until burnout completely. Simple experiments will be designed for these three terms of the equation to measure the pressures and compare them with the pressures calculated theoretically.

Acknowledgements

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References

[1] Pacific Kiln. (2020). *Flash Fire Dewax System*. Retrieved February 27, 2024, from https://www.pacifickiln.com/investment-casting-products/flash-fire-dewax-system/

[2] Horáček, M. (2009). *Dimensional accuracy of castings produced by the fusible model method.* Brno: Brno University of Technology, Czech Republic. (in Czech).

[3] Štěpán, R. (2022). *Optimizing the properties of 3D printed models for ceramic shell casting technology.* Brno: Diploma thesis, Brno University of Technology, Czech Republic. (in Czech).

[4] Krutiš, V., Novosad, P., Záděra, A. & Kaňa, V. (2022). Requirements for hybrid technology enabling the production of high-precision thin-wall castings. *Materials.* 15(11), 3805, 1-13. https://doi.org/10.3390/ma15113805.

[5] Fedorov, K., Fayazbakhsh, K. & Ravindran, C. Surface roughness and dimensional tolerances in A319 alloy samples produced by rapid investment casting process based on fused filament fabrication. *International Journal of Advanced Manufacturing Technology.* 119, 4423-4437. https://doi.org/10.1007/s00170-021-08644-5.

[6] Kumar, P., Ahuja, I. S. & Singh, R. (2016). Effect of process parameters on surface roughness of hybrid investment casting. *Progress in Additive Manufacturing.* 1, 45-53. https://doi.org/10.1007/s40964-016-0004-9.

[7] Chen, X., Li, D., Wu, H., Tang, Y. & Zhao, L. (2011). Analysis of ceramic shell cracking in stereolithography-based rapid casting of turbine blade. *International Journal of Advanced Manufacturing Technology.* 55, 447-455. https://doi.org/10.1007/s00170-010-3064-x.

[8] Polymaker. (2024). *Polymaker PolyCast Product Information Sheet*. Retrieved February 27, 2024, from https://polymaker.com/product/polycast/

[9] Polymer Science Learning Center. (2024). *Differential Scanning Calorimetry*. Retrieved February 27, 2024, from https://pslc.ws/macrog/level5.html

[10] Bednárik, M. (2021). *Proposal to change the production of molded parts to the technology of casting into ceramic shells.* Brno: Diploma thesis, Brno University of Technology, Brno University of Technology, Czech Republic. (in Czech).