Influence of Mould Material on the Mechanical Properties of Wax Models

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Abstract

The article presents results of research on the influence of the mould material on selected mechanical properties of wax models used for production of casting in investment casting method. The main goal was to compare the strength and hardness of samples produced in various media in order to analyse the applicability of the 3D printing technology as an alternative method of producing wax injection dies. To make the wax injection dies, it was decided to use a milled steel and 3D printed inserts made using FDM (Fused Deposition Modeling) / FFF (Fused Filament Fabrication) technology from HIPS (High Impact Polystyrene) and ABS (Acrylonitrile Butadiene Styrene). A semi-automatic vertical reciprocating injection moulding machine was used to produce the wax samples made of Freeman Flakes Wax Mixture – Super Pink. During injection moulding process, the mould temperature was measured each time before and after moulding with a pyrometer. Then, the samples were subjected to a static tensile test and a hardness test. It was shown that the mould material influences the strength properties of the wax samples, but not their final hardness.

1. Introduction

The investment casting method is one of the key techniques used in the prototyping of castings. [1]. It enables production of high-quality castings with low roughness, high dimensional accuracy and complex shapes. In this casting method wax patterns which are obtained by injecting a wax mixture into a wax injection die are used [2]. A set of wax models are attached on sprue tree and depending on the variant of this method, are flooded with casting gypsum or a ceramic shell is created (classic approach). Ceramic suspension usually consisting of hydrolyzed ethyl silicate, quartz sand, ethyl alcohol and hydrochloric acid [3 – 4]. Further steps include melting/burning of entrapped models, annealing and pouring the mould with liquid alloy. A general diagram of this process is shown in Fig. 1.

One of the most important elements of the process is the proper preparation of accurate wax models. Consequently even the smallest loss or surface defect of such model results in a defect of the casting. The wax mixture at a temperature between 60°C and 75°C is injected into the die under pressure. The wax injection dies are mainly produced by the subtractive methods (machining) of metal alloys and also (in the case of unit/small-lot production) by vulcanization of rubber or cross-linking of silicones. The most important properties of the dies material are: easy removal of the model from the mould, no physico-chemical reactions between the wax mixture at the injection temperature and the rapid dissipation of the model's solidification heat. The properties of wax models depend on the chemical composition of the mixture and the cooling rate [5], which is significantly influenced by inter alia mould material, specific heat, thermal conductivity and density.
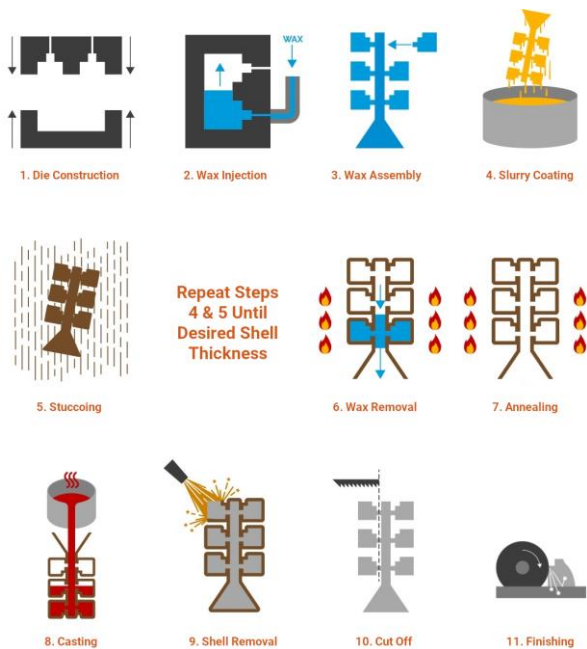
Fig. 1. Schema of investment casting process [based on 6]

Fig. 2. The 3D model of designed wax injection die

Fig. 2. Geometry of 1BA sample, explanations in Tab.1.

The cooling rate has a direct impact on the crystallization process, which in the case of waxes should be understood as the process of crystalline phase formation from the liquid phase. Longer crystallization times result in more crystals, which ultimately affects the mechanical properties of the models. There are 3 stages of wax crystallization: nucleation (I), growth (II), and agglomeration (III) [7] as a result depending on the cooling rate, wax crystals are formed mainly in the form of needles, plates and malcrystalline forms [8-10, 14]. Moreover, it should be emphasized that the normal form of wax crystallization is a hexagonal plate, while the needle form is formed by the curling of the edges of a previously formed plate. Currently, an important aspect in the crystallization of waxes is also the use of pour point depressants (PPDs), which affect the manner and rate of crystal formation [7].

One of the key elements of the wax crystallization process is the Wax Appearance Temperature (WAT), which is the temperature limit at which crystals start to form. There are many different methods to determine the WAT temperature, including: Density and Viscosity variation (Rheometry), Differential Scanning Calorimetry (DSC), Laser Dispersion, Chromatography, Optical Microscopy and X-ray Diffraction [10-11].

2. Materials and methods

The main goal of the research was to compare the selected mechanical properties of wax models produced in various media. Using the Autodesk Inventor software, a three-dimensional model of the wax injection die representing the geometry of the 1BA sample was made (Fig. 2), in accordance with the standard used in the EN ISO 527-2: 2012 strength tests. The geometry of the 1BA sample and its dimensions are shown in Fig. 3 and Table 1, respectively.
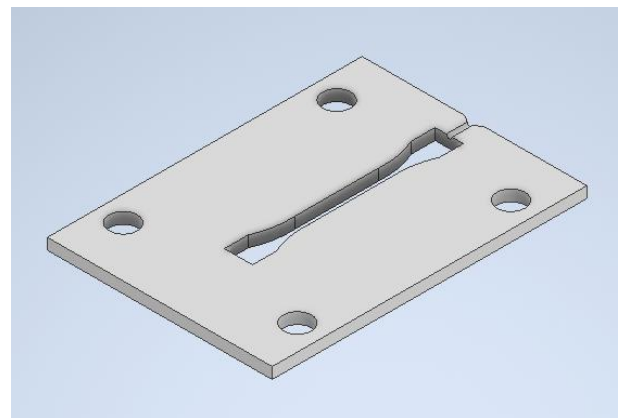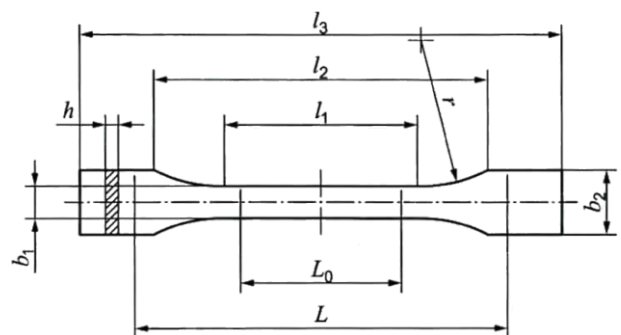
Table 1.
Dimensions of the 1BA sample (EN ISO 527-2:2012)

No	Name	Value [mm]
l_3	Total length	≥ 75
l_1	The length of the part delimited by parallel lines	$30,0 \pm 0,5$
r	Radius	≥ 30
l_2	The distance between wide parallel parts	58 ± 2
b_2	Width at the ends	$10 \pm 0,5$
b_1	Width of the narrow part	$5,0 \pm 0,5$
h	Thickness	≥ 2
l_0	Length of the measuring section	$10 \pm 0,2$
l	Initial distance between the handles	l_{2+0}^{+2}

For the purpose of test a wax mixture of 118174 Freeman Flakes Wax – Super Pink, characterized by the quickest solidification time in the Freeman Flake Wax line was used. Quick solidification is an important factor due to the low thermal conductivity of polymer injection die. The other properties of the wax mixture are: injection temperature 71-74ºC, congealing temperature 62ºC, hardness 46 Shore D, flash point (COC) 240°C [12].

Three different materials were used to produce the wax injection dies: steel, ABS and HIPS. The steel injection die was made by milling a slot in a 4 mm thick sheet. The polymer injection dies were made using a Zortrax M200 3D printer operating in the 3D printing technology – FDM/FFF [13]. It consists of plasticizing a thermoplastic material in the form of a line (filament) in the print head and applying it to the platform layer by layer, resulting in final 3D model. Commercially

available filaments from Devil Design HIPS Natural and ABS+ Black were used. The key criterion in their selection was the glass transition temperature, which should exceed the temperature of the injected wax. Otherwise, the wax injection die could be permanently deformed. The parameters of the model printing process are presented in Table 2. Table 3 presents selected material properties.

Table 2.
3D printing parameters

Material	HIPS	ABS
Filament weight (g)	41	46
Layer thickness (mm)	0,09	0,09
Print quality	High	High
Type of filling	Solid fill	Solid fill
Print time	7h 21min	7h 21min

Table 3.
3D printed moulds material characteristic

Material	HIPS	ABS	Tool steel
Density (g/cm^3)	1,03-1,08	1,06	$\approx 7,86$
Melting point (ºC)	180-270	204-238	1425-1540
Glass transition (ºC)	100	105	-
Thermal conductivity (W/mK)	0,16-0,22	0,25	≥ 36
Tensile strength (MPa)	22	45	470-850
Price (USD/Kg)	21	21	$\geq 3,5$

The next stage of the research was to carry out the injection process of the wax mixture into the injection dies using a semi-automatic reciprocating injection moulding machine (Fig. 4). The process parameters presented in Table 4 were determined experimentally. Two-stage cooling was applied. The first took place between the halves of the mould on the machine and the second one outside the machine, when the injection die filled with wax cooled in the air. This allowed to slightly shorten the total cooling time.

Table 4.
Injection process parameters

Property	Steel mould	ABS/HIPS mould
Pressure time (s)	10	10
Cooling in the mould (s)	50	110
Cooling out of the mould (s)	60	120
Summary (s)	120	240
Injection temperature (°C)	67-72	67-72
Injection pressure (bar)	2	2

The tensile strength test was carried out using an Instron 4481 universal testing machine with self-clinching jaws. The test was carried out in accordance with EN ISO 527-2: 2012, and the applied tensile speed was 10 mm/min.

The Shore D hardness test was carried out in accordance with the PN-EN ISO 868: 2005 standard. The Sauter HBD 100-0 durometer with load was placed on a stand. The result was read 30 s after the load was applied.

Fig. 4. Wax injection stand

3. Results and Discussions

The first noticeable difference between tested injection dies was cooling time needed for safe unmolding of the wax part. For steel, this time was a total of 110 s, where for polymeric die materials it was necessary to extend this time to 230 s. This is due to the difference in thermal properties of both materials.

Another obstacle in the use of polymer injection dies are their lower strength properties compared to injection dies made of metal alloys. In the injection machine, the nozzle is pressed directly against the edge of the injection die, which, if the pressure is too high, may result in mechanical damage (cracks, chipping, etc.).

The tensile test results for samples produced in injection dies made of various materials are shown in Figures 5-7. Averaged results are shown in Figures 8-10. The tensile strength and Young's modulus values for waxes injected into polymer injection dies are very similar and clearly greater than the values obtained for the samples made in a steel injection die. This is influenced by the thermal properties of the die material. For polymer injection dies, heat reception was less effective, therefore crystallization could take place more slowly, which results in greater mechanical strength and a greater value of Young's modulus. The size of the deformation at break, apart from the cooling rate, could also be influenced by the surface quality of the obtained models.
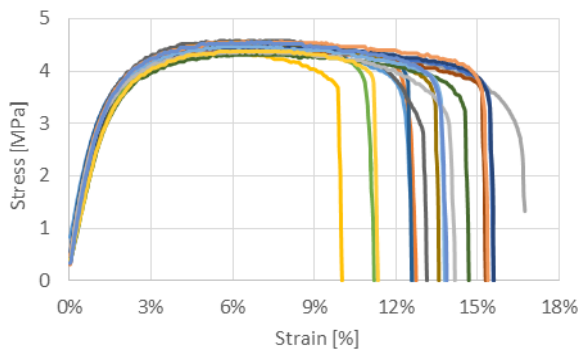
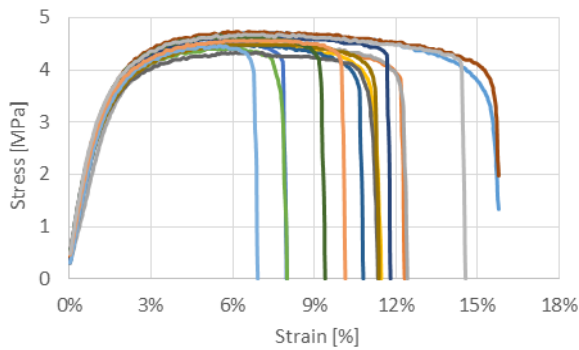Fig. 5. Tensile test results for samples from the HIPS mould

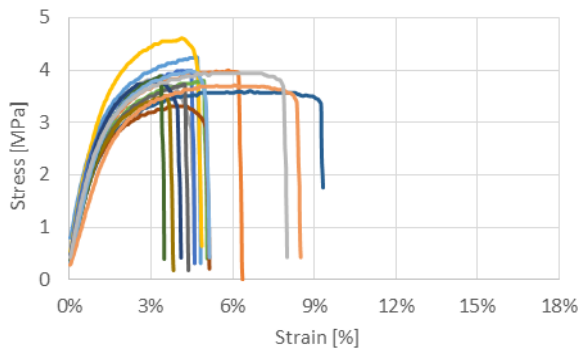Fig. 6. Tensile test results for samples from the ABS mould

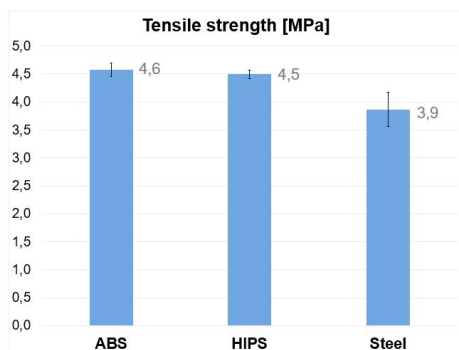Fig. 7. Tensile test results for samples from the steel mould

Fig. 8. Graph showing the tensile strength of the tested samples
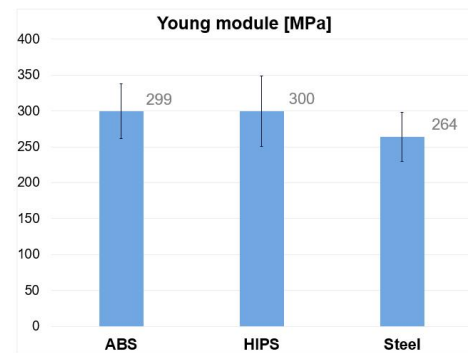

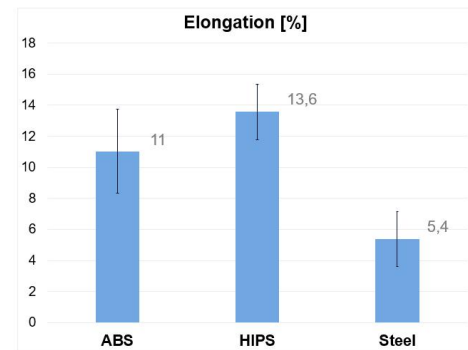Fig. 9 Graph showing Young module of the tested samples

Fig. 10 Graph showing elongation of the tested samples

The Shore D hardness test was also carried out for 5 random samples from each series, however, no differences or fluctuations in the obtained values were observed, which amounted to 30 Shore D.

4. Conclusions

The study confirmed the legitimacy of using the 3D printing technology as an alternative method of producing wax injection dies. It has been shown that wax patterns produced in 3D printed injection dies can have greater stiffness and strength than those obtained in steel dies. Unfortunately, due to the poorer heat reception by the polymer, it is necessary to extend the cooling time which directly extends the time of the entire process. When using polymer wax injection dies in reciprocating injection moulding machines, particular attention should be paid to their minimal loading by parts of the injection moulding machine. The biggest threat is the pressure of nozzle on the edge of the die which may result in cracking and final damage of the polymer tooling.

The application of 3D printed polymer injection dies does not adversely affect the properties of wax models, therefore the authors suggest an analysis of the possibility of using such a solution in specific cases when the economic calculation makes it impossible to start production in the classical terms and forces the use of cheaper equipment to start prototyping or unit and small production.

Acknowledgements

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