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Application of computer simulation of thermoset resins casting in rapid prototyping techniques

RAPID COMMUNICATION

Summary — The article presents a methodology of the technological process to manufacture technical cast profile models based on the example of gear wheels in silicone molds produced with the vacuum casting (VC) method. In this process, designing of the model manufacturing begins with the preparation of the silicone mold structure. At this stage the properties of the material to be cast into the silicone mold should be taken into account. The properties, including the viscosity, density, reactivity and crosslinking thermal effect of the material should be build into designing of the prototype. They determine also the geometry of the runner system supplying mold cavity and its vents.
Key words: rapid prototyping, gear wheel, silicone mold, vacuum casting, Moldflow program.

ZASTOSOWANIE KOMPUTEROWEJ SYMULACJI ODLEWANIA ŻYWIC CHEMOUTWARDZALNYCH W TECHNIKACH SZYBKIEGO PROTOTYPOWANIA
Streszczenie — W artykule przedstawiono metodykę procesu technologicznego wytwarzania w matrycach silikonowych, wykonanych metodą odlewania próżniowego (VC), modeli kształtek technicznych (na przykładzie kół zębatych, rys. 2). W procesie tym planowanie wytwarzania modelu rozpoczyna się od opracowania konstrukcji matrycy silikonowej (rys. 5). Należy wziąć przy tym pod uwagę właściwości materiału, który będzie odlewany w matrycy silikonowej. Właściwości materiału, z którego wykonany będzie prototyp, w tym lepkość, gęstość, reaktywność i efekt cieplny sieciowania, determinują geometrię układu wlewowego doprowadzającego ciekłą żywicę do gniazda formującego i układu kanałów odpowietrzających (rys. 3).
Słowa kluczowe: szybkie prototypowanie, koło zębate, matryca silikonowa, odlewanie próżniowe, program Moldflow.

It is possible to manufacture gear wheel prototypes with the application of modern rapid prototyping (RP) methods [1—3]. RP techniques encompass direct manufacturing systems (incremental and decremental) and indirect technologies based on rapid tool manufacturing (*e.g.* casting mold) [4, 5]. Tools used for the construction of prototypes are produced in the rapid tooling (RT) process. RT process includes direct tool manufacturing with the use of incremental RP systems and indirect production of tools (*e.g.* silicone molds) applying the technology of casting at a reduced pressure *i.e. v*acuum casting (VC) [6, 7].

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The VC technique is one of RT methods used for the manufacturing of silicone molds and prototypes at a lowered pressure in suitable chambers. Silicone molds make possible to fabricate test and functional prototypes with the use of casting waxes, polyester, vinylester, epoxy and polyurethane resins as well as their composites [8]. Silicone molds can be used for the manufacturing of both individual prototypes and short batches of products ranging from several to several dozen pieces [9].

An essential element that supports the design of tools used for casting the resins (silicone molds) is the application of programs for the simulation of thermoset resin casting. One of such programs is Autodesk Moldflow Insight 2010 (Mflow). Apart from the main module used for the simulation of thermoplastics injection, the program contains modules which can be utilized for the simulation of the thermoset resin casting process.

Application of the program enables a faster design of the mold: geometry, the number of runners and the positioning of the venting system, which allows to avoid further corrections of the tool being designed, often performed by trial and error.

In our studies we wanted to join experimental investigations on the crosslinking process of thermoset resins (unsaturated polyester) and computer simulations of their casting process by Mflow to improve designing and eliminate errors in the structure of master model and molds produced using rapid prototyping and vacuum casting techniques.

EXPERIMENTAL

Materials

The material used for the manufacturing of the master model is SL 5170 photo-crosslinking resin (produced by 3D Systems, USA) designed for stereolithography.

Silicone molds were cast using silicone rubber of the MM240TV A+B type (produced by ACC Silicones, Great Britain), supplied by Milar (Poland).

Gear wheel prototypes were made of the following materials:

— preaccelerated polyester resin with trade name Polimal 109 (UP) [10] and Luperox K-1 used as a crosslinking agent, both supplied by „Organika-Sarzyna" SA (Poland);

— alkyl, benzyl, dimethylammonium chloride modified bentonite named Nanobent Z1 (Z1), manufactured by ZGM Zębiec (Poland) used as a filler of UP.

Gelation of UP

Gelation of UP was studied according to PN-C-89082/15:1987 using gel timer of type WB2 with a rotating cell, designed in our University [11]. The gel timer enabled to study gelling curves of thermoset resins *i.e.* gel time and temperature, setting time, maximal temperature and reaction time. Differentiation of these curves makes possible to study the kinetics of crosslinking reactions.

Mold design

The mold is constructed with an indirect RT method, because it is made by silicone rubber casting into the so-called base master model, received as a result of the application of incremental rapid prototyping systems, for example. In this case, the master model is manufactured on the basis of the 3D-CAD model [12], which can be additionally used to conduct a finite element method (FEM) analysis of the mold structure and an analysis of the process of filling it with a liquid material and its solidification as a result of cooling or crosslinking. The analysis of mold filling was made with Autodesk Moldflow Insight 2010 system (Mflow), designed primarily for simulation of polymer injection [8].

Silicone mold manufacturing

The manufacturing of the mold was typical of this technology and included six stages:

— preparation of the gear wheel master model with runner and venting channels using SL 5170 resin, by stereolithography (a SLA250/50 device produced by 3D Systems);

— preparation of the mold box and fixing the base model into it (a container for liquid silicone rubber);

— mixing the MM240TV silicone rubber (component A) with a crosslinking agent (component B) and preliminary degassing of the composition;

— filling the mold box with the degassed silicone composition and its re-degassing in a vacuum chamber — Vakuum UHG 400 Easy, produced by Schuechl (Germany), crosslinking and heat treatment of silicon rubber (additional crosslinking at high temperature);

— dismantling the mold box, cutting the silicone mold and removing the master model;

— flush cleaning burr off the mold, if necessary.

RESULTS AND DISCUSSION

Gelation process

Gelation was studied for unmodified UP and for UP modified with 0.5 or 1.0 wt. % of Z1. Obtained differentiated gelling curves are presented in Figure 1. They enabled to determine the crosslinking parameters of these samples, listed in Table 1. Addition of 0.5 or 1.0 wt. % of Z1 slightly influences decrease of UP crosslinking reactivity *i.e.* increases the gelling time (t_{gel}), curing time (t_{cur}) and maximal reaction temperature time (t_{max}). It is important for the casting process that maximal reaction temperatures (T_{max}) decrease from *ca*. 96 to *ca*. 90 °C and reaction temperature growth rates (dT/dt) drop from 0.9 to 0.7 K/s (Fig. 1). Specified parameters of UP modified with 1.0 wt. % of Z1 fulfill conditions required for the casting process.

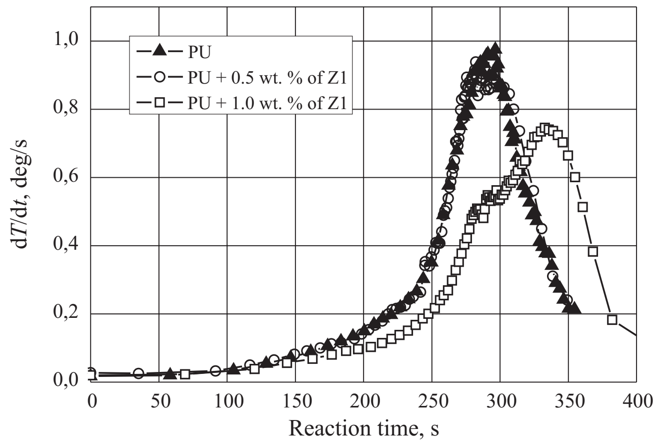

Fig. 1. Influence of Nanobent Z1 addition (0.5 or 1.0 wt. %) on differentiated gelation curves of UP composition

T a b l e 1. Crosslinking parameters of the studied UP compositions determined using gel timer

Composition type	Crosslinking parameters			
	t_{gel}, s	t_{cur}, s	t_{max}, s	T_{max}, °C
UP	736	906,0	1603	96,2
UP + 0.5 wt. % of Z1	992	1260	1898	91,7
UP + 1.0 wt. % of Z1	1103	1919	2201	90,5
Arotran Q6055*)	1200	—	2250	90,0

*) Resin with similar parameters available in Mflow data base.

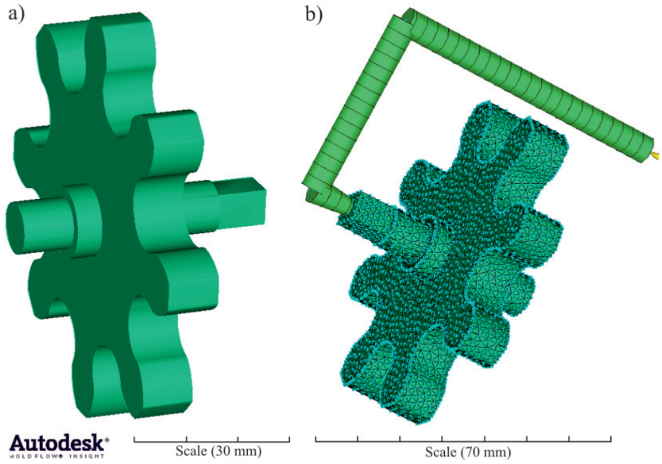

Fig. 2. Gear wheel model imported to Mflow system: a) STL model, b) FEM model with runner system

Mold design and simulation of casting

The Mflow system enables to conduct an analysis and simulation of the processes of casting and injecting a wide range of polymeric materials available in its material base. As the set did not contain the investigated resins destined for manufacturing of the prototype, a polyester resin of the Arotran Q6055 type, available in the base, was selected for the simulation of mold filling. Crosslinking parameters of this resin were similar to previously described properties of UP modified with 1 wt. % of Z1 (Table 1). The calculations and analysis of results were performed for a 3D gear wheel model designed in AutoCAD 2009 and then imported into Mflow in the STL format. As process simulation in this program is based on the finite element method (FEM), the model was covered with a grid of triangle finite elements of the dual domain type. The gear model used in the STL format and its FEM format are presented in Fig. 2.

The result of the analysis, presented in Figure 3, was the design and optimization of the geometry of the runner system, which ensures accurate filling of the mold. Because liquid resin was poured into the mold gravitationally, it was important to find the air traps. Low pressure during casting process may be not sufficient to remove air bubbles from the still liquid composition, which will weaken the part. The received results of the emergence of air traps (Fig. 3a) and optimization of runner dimensions and gate place were used for the distribution

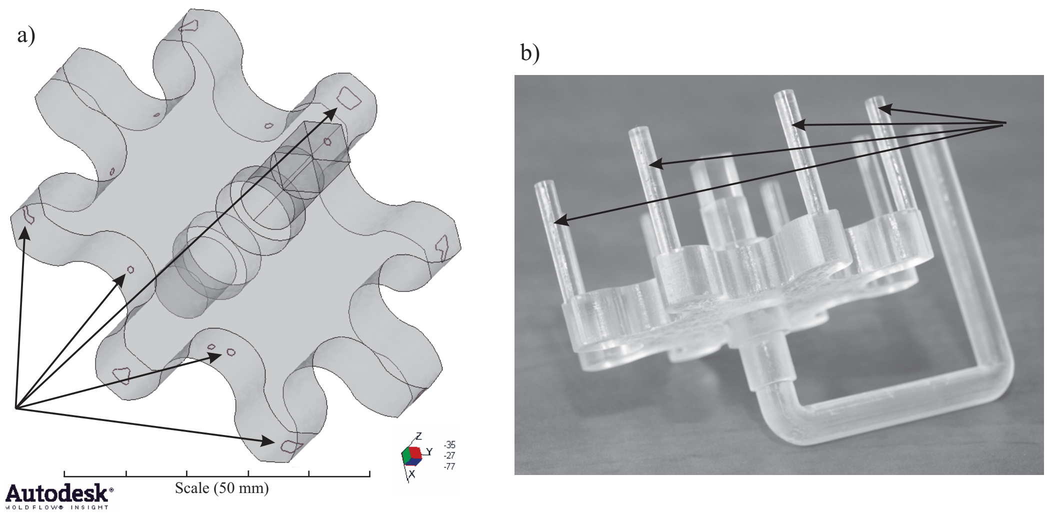

Fig. 3. Results of the mold filling simulation with air traps marked by arrows (a) and view of the master model made with stereolithographic method of adjusted shape, taking into account the results of the simulation with visible venting channels (arrows) and the runner (b)

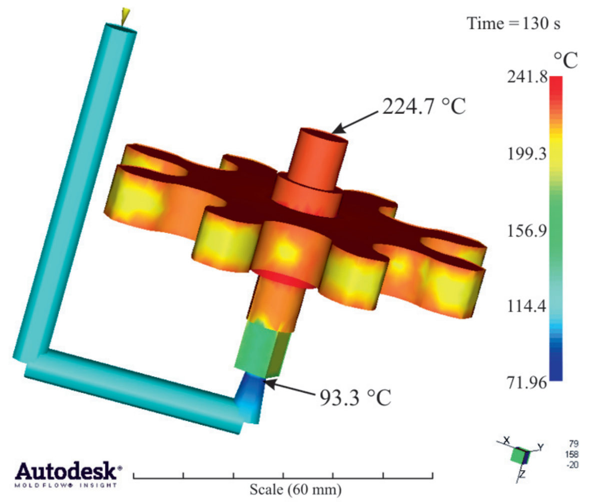

Fig. 4. Mflow simulation result presents the temperature distribution in the cast part at the moment of achieving the reaction exothermic peak (curing time 130 s) for the used resin

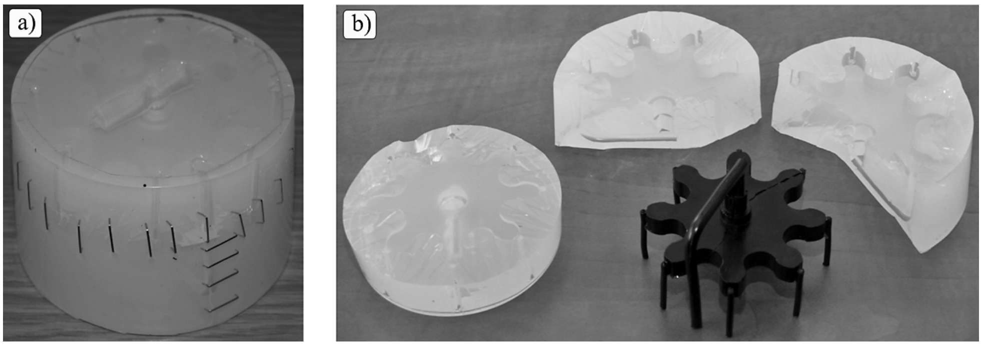

Fig. 5. Gear wheel prototype manufacturing: a) closed silicone mold, b) cast prototype made of UP composition removed from the mold and open silicone mold visible beside

of venting channels and runner designing in the stereolithographic model (Fig. 3b).

Another significant issue was to make sure that there was no local overheating during the crosslinking of the resin, which might cause excessive stresses in the cast part. The simulation results, shown in Figure 4, indicate that for the resin used, the difference between the lowest (*ca.* 93 °C) and highest temperature (*ca.* 225 °C) is approximately 130 °C (Fig. 4). Local overheating is not discernible, the temperature distribution is quite even, and the temperature *ca.* 224 °C is evenly distributed across the wheel body.

Gear wheel casting in the silicone mold

According to Mflow simulation results we have prepared sterelitograhic model of gear wheel and than silicon rubber mold (Fig. 5a). Gear wheels made of UP modified with 1.0 wt. % of Z1 composition have been casting by using VC method. Cast gear wheel removed from silicon mold is showed in Figure 5b. Mechanical properties of the UP composition used were similar to thermoplastics, which could finally be used for batch production of these parts. It allowed testing gear wheel prototype made of this resin in a real gear box application and conditions and whether it was necessary to correct its shape.

CONCLUSIONS

— The manufacturing process of silicone molds and prototypes produced in them does not usually include the application of FEM analysis. Described in the paper Mflow analysis aids eliminate errors in the structure of the molds and prototypes, and speed up the achievement of good parts.

— Nanobent Z1 addition influenced decreasing exothermal peak of UP crosslinking and minimizing temperature differences in cast part.

— The materials used for manufacturing of the prototypes (polyester resins) required special approach towards the casting process because of short lifetime of prototype, which is additionally shortened considerably as a result of temperature increase caused by high crosslinking thermal effect.

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