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OPTIMIZATION OF THE INJECTION MOLDING PROCESS FOR COMPLEX-SHAPED CERAMIC ORIFICES USING COMPUTER SIMULATION

OPTYMALIZACJA PROCESU FORMOWANIA WTRYSKOWEGO DLA OTWORÓW CERAMICZNYCH O ZŁOŻONYCH KSZTAŁTACH Z ZASTOSOWANIEM SYMULACJI KOMPUTEROWEJ

The flow of the feedstock during its inject into a complex-shaped mould is studied. The model of nonlinear viscosity flow is used for the feedstock behavior analysis. The dependence of the shear viscosity effective coefficient on the powder concentration in the feedstock was determined by methods of computing micromechanics. The rheological equation of the feedstock contains the stuff (particles) concentration as a parameter. Using computer simulation, the optimization of the orifice for argon-arc welding as an example of a complex-shaped mold filling with feedstock (selection of the injection gate location) has been carried out. The results showed that the most uniform mold filling and the minimum number of defects were reached in case of the injection gate location at the narrow end of the orifice.

Zbadano przepływ surowca podczas wtryskiwania do formy o złożonym kształcie. Do analizy zachowania surowca wykorzystano model nieliniowego przepływu lepkości. Zależność efektywnego współczynnika lepkości ścinania na stężenie proszku w surowcu została ustalona metodą komputerowego obliczania mikromechaniki. Równanie reologiczne surowca zawiera stężenie materiału (cząsteczek) jako parametr. Za pomocą symulacji komputerowej przeprowadzona została optymalizacja otworu dla spawania w osłonie argonu jako przykład wypełniania surowcem formy o złożonym kształcie (wybór umiejscowienia otworu wtryskowego). Wyniki wskazały, iż najbardziej jednolite wypełnianie formy i minimalną ilość defektów uzyskuje się w przypadku umiejscowienia otworu wtryskowego przy węższym końcu formy.

1. Introduction

One of the most critical stages of designing articles by the injection molding is the mold filling process. Formation parameters, which are the injection pressure, both mold and melt (feedstock) temperatures, are very important for the production of articles with minimum porosity and without defects. On this stage any mistakes can lead to obtaining low-quality articles. The investigation results of mold filling with feedstock obtained by mathematical modeling methods were mentioned in works [1 - 4]. These results of mathematical modeling of the separate technological operations of injection molding process, as well as the modeling process in whole were obtained on some assumptions concerning these operations or the process in whole. As the obtained results are associated with the preform shape, in each case the optimization of that operation is carried out based on the design of the experiment methods, appropriate statistical methods and mathematical modeling methods for the injection process [3, 4]. For the validation of the obtained results it is necessary to conduct their comparative analysis with experimental data. Also we should mention that there is almost a lack of results in the scientific literature obtained by mathematical modeling methods, which concern the behavior of the feedstock flow during the injection molding depending on the character of this flow and both the volume fraction and the distribution of the solid particles in the feedstock.

The target of this work is the mathematical modeling and optimization of the complex-shaped mold filling by the feedstock that will allow one to ensure a minimum content of possible defects of the finished articles.

The feedstock flow is studied using the model of nonlinear viscous slow flow with the shear viscosity coefficient:

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the quasistatic equation $\sigma_{ij,j} = 0,$
the rheological equation $\sigma_{ij} = p\delta_{ij} + 2\frac{\tau}{\gamma}e_{ij},$
the incompressibility conditione $e_{ij}\delta_{ij} = 0,$
(1)

where $p = \frac{1}{3}\sigma_{ij}\delta_{ij}$ is the average pressure; $\frac{\tau}{\gamma} = \eta$ is the shear viscosity coefficient of the feedstock, γ is the intensity of the shear strain rate (or shear rate), τ is the intensity of the shear stress; σ_{ij} is the stress tensor components, a comma in the index mark implies the differentiation sign; e_{ij} is the strain rate tensor components; $\delta_{ij} = \begin{cases} 1, & i = j, \\ 0, & i \neq j. \end{cases}$

The shear viscosity coefficient of the feedstock is described by the nonlinear equation

$$\eta(\gamma) = \sigma_0 \frac{\sqrt{1 + n^2}}{\sqrt{\gamma^2 + n^2\gamma_0^2}}, \qquad (2)$$

where $\sigma_0 = \sigma_p c, \quad \gamma_0 = \frac{\sigma_0}{\eta_0}, \quad n = n_0 \sqrt{c_{crit}^2 - c^2}\frac{1}{c},$ $\sigma_0, \gamma_0, n, n_0$ are the auxiliary constants and the approximation parameters; σ_p is the shear yield stress of the powder; c is the powder volume fraction in the feedstock; c_{crit} is the critical (limit) powder volume fraction in the feedstock; η_0 is the effective shear viscosity coefficient of the feedstock. This equation has nonlinear dependence on the shear rate and it takes into account the powder volume fraction in the feedstock.

In contrast with the other investigations we have performed in the connection of the rate sensibility of the shear viscosity coefficient with the powder volume fraction.

For the calculation of the effective shear viscosity coefficient, the feedstock is considered as a micro-heterogeneous medium where the matrix is a linear or nonlinear viscous phase and the filler is a lot of solid incompressible particles. To take into account the real structure of the feedstock, we proposed the direct simulation method on the representative cell. Using both the stress and strain rate fields, which were obtained on the basis of the Finite Element Method, the average values were calculated over the representative cell. The effective shear viscosity obtained in that way takes into account the particle shape, the orientation and the volume fraction. The calculation results showed that the effective viscosity increases with the increasing powder volume fraction [5]. The critical concentration of the powder in the feedstock was observed when the viscosity increased sharply. As a rule, this situation occurs when the direct contacts (without binder) between some particles start forming.

The simulation of a complex-shaped mold filling with the feedstock was conducted for both the argon-arc welding and the abrasive spraying orifices. The information on the orifices was given by the Bakul' Institute of Superhard Materials NAS of Ukraine (Fig. 1, 2).

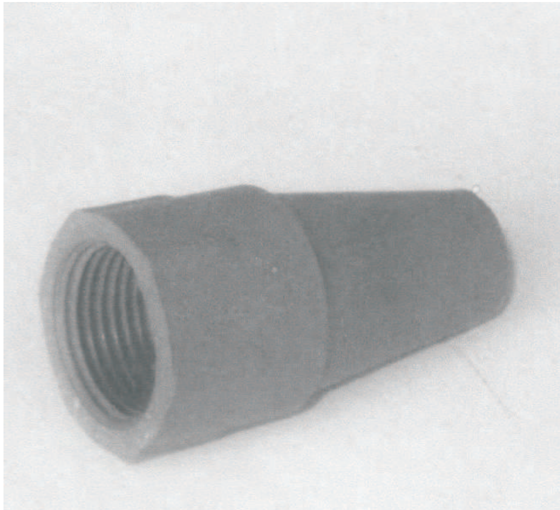

Fig. 1. Orifice for argon-arc welding

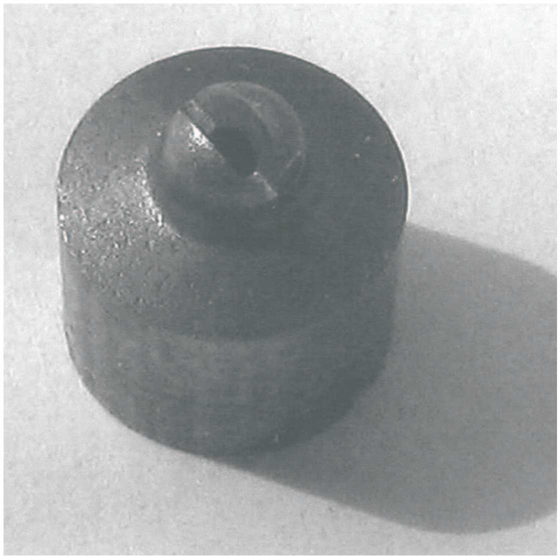

Fig. 2. Orifice for abrasive spraying

The simulation based on the Finite Element Method was conducted using the rheological model of the feedstock flow during the mold filling (1) with energy balance equation [1].

The important parameters for mold filling control and optimization are
– injection gate location;
– part geometry;
– material (feedstock ingredients: binder and powder);
– process conditions (both mold and feedstock temperatures and injection time)

By means of a variation of these factors, we can influence the quality of the mold filling that influences the finished article properties. In this work, the mold filling optimization has been conducted by a variation of the injection gate location and the part geometry.

The mold filling simulation was conducted for the feedstock which was made of paraffin binder and silicium nitride powder with the volume fraction of 54 %. The mechanical and thermophysical properties of the binder and powder were used for the calculation. To describe the rheological behavior of the feedstock the equation (2) was applied. In addition, the technological parameters of the injection molding unit, as well as the process parameters (mold filling time, green part cooling time, holding under pressure time, both mold and feedstock initial temperatures) were taken into account.

2. The effect of the injection gate location on the filling of the mold with the feedstock

The injection gate location has an important effect on the green part quality and it is selected according to several factors. The most important ones are the entire filling pattern and the maximum pressure of the injection molding. The uniform mold filling allows one to minimize the most typical defects that are weld lines and sink marks. Weld lines are formed in the areas where two melt fronts meet together and merge irregularly, while sink marks appear due to the non-uniform preform shrinkage. Therefore, the simulation was directed towards the determination of the conditions that prevent the weld line and sink mark formation or allow a minimization of their number and size during the feedstock filling of complex-shaped molds.

The effect of the gate location was examined for argon-arc welding orifice (Fig. 1). The simulation was conducted for the gate locations from the wide and narrow ends and from both ends simultaneously.

The mold filling patterns, according to time and weld lines for every gate location, are represented in Fig. 3a – 3c (the left figure is the front view and the right figure is the back view of the orifice). Comparing the front and back views of the mold filling, we can observe a uniform filling from the narrow end gate location (Fig. 3b) and a non-uniform filling for other cases.

Weld lines are undesirable if strength and surface appearance are the main requests of the finished article. The location of such lines is especially critical in the stress concentration areas. As shown in Fig. 3b, the smallest weld lines are observed with the narrow end gate location when the mold filling is uniform. The maximum of such defects is formed with the gate location from the wide end and from both ends of the orifice. Generally, using several injection gates leads to the formation of different feedstock flows; hence the appearance of weld lines becomes more probable. Therefore, avoiding additional injection gates is recommended wherever possible, as they also cause overpacking of the mold with the feedstock.

The maximum injection pressure (that is, the pressure near the gate location) versus time during the mold filling with the feedstock is shown in Fig. 5. The pressure increases with time and reaches its maximum value at the end of the filling. In the mold filling from two injection gates the pressure is in the minimum, but it increases sharply at the end of the process. This phenomenon may cause the non-uniform mold filling. The maximum pressure is observed in the case of the injection gate location from the wide end of the orifice.

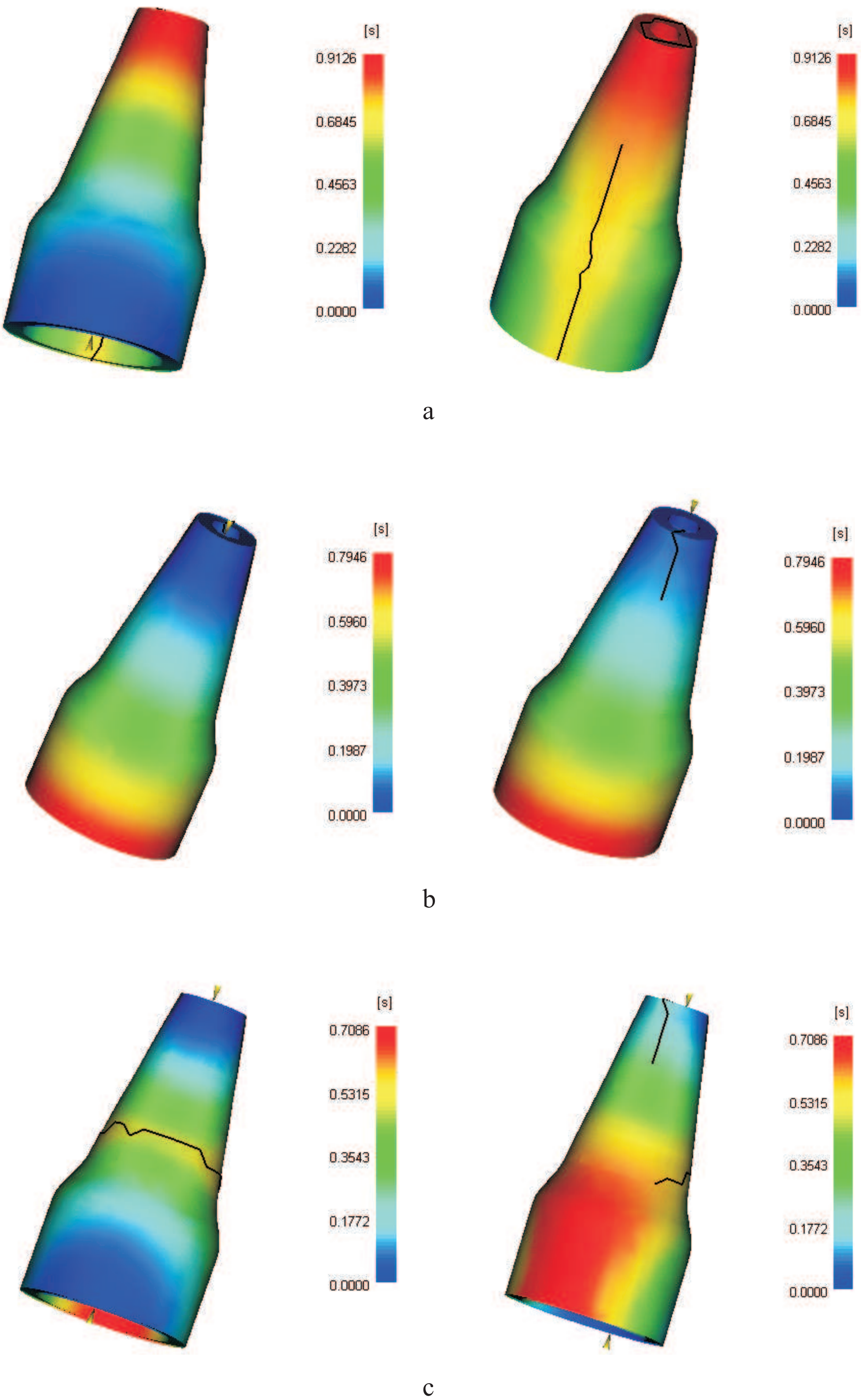

Fig. 3. Mold filling patterns according to time and weld lines for argon-arc welding orifice for gate locations: (a) from wide end of orifice; (b) from narrow end; (c) from both ends simultaneously. On the left is the front view of orifice and on the right is the back view

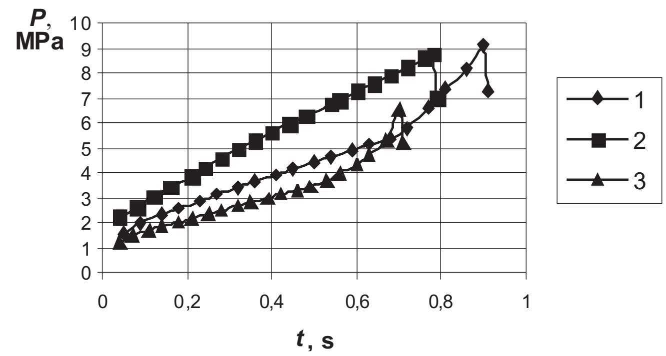

Fig. 4. The maximum injection pressure versus time for the cases of gate locations: from wide end of the orifice (1); from narrow end of the orifice (2); two injection gates from both ends of the orifice (3)

The presence of sink marks is also significant for the quality estimation of a green part. Such formations are considered as quality defects of article. Sink marks are caused by the localization of the material shrinkage near hte thick walls during the cooling of the green part. The simulation results showed the maximum sink mark index for the mold filling from the wide end (0.1027 %), the minimum – from the narrow end (0.0999 %) and from both ends the value was (0,1007 %).

The comparative characteristics of the mold filling with the feedstock from different gate locations are represented in Table.

It can be noticed that the uniform mold filling and the smallest weld lines are observed for the gate location from the narrow end of the orifice and other characteristics (filling time and maximum pressure) are average in comparison with other cases. The uniform mold filling results in a uniform shrinkage of the green part. And finally, the sink mark index is the smallest with the mold filling from the narrow end.

3. The effect of the part geometry on the stress concentrations for the mold filling with the feedstock

The effect of the sharp internal angles and the angles with fillet on the stress concentration for the mold filling with the feedstock was examined for both the argon-arc welding and the abrasive spraying orifices (Fig. 1, 2).

The maximum stresses are known to concentrate near the injection gate. Therefore, Fig. 6a and 6b represents the shear stress near the injection gates versus time for both the orifices with sharp angles and angles with fillet. For the mold filling with sharp corners, the values of the shear stress are larger than for the mold filling with fillets, in the first and the second case.

TABLE

Comparative characteristics of the feedstock mold filling from different gate locations

Injection gate location	Characteristics of the feedstock mold filling			
	Filling time, s	Uniform of filling, weld lines	Maximum pressure near injection gate location, MPa	Sink mark index, %
From wide end of the orifice	0,91	Nonuniform, large weld lines	9,13	0,1027
From narrow end of the orifice	0,79	Uniform, small weld lines	8,78	0,0999
From both ends of the orifice	0,71	Nonuniform, large weld lines	6,58	0,1007

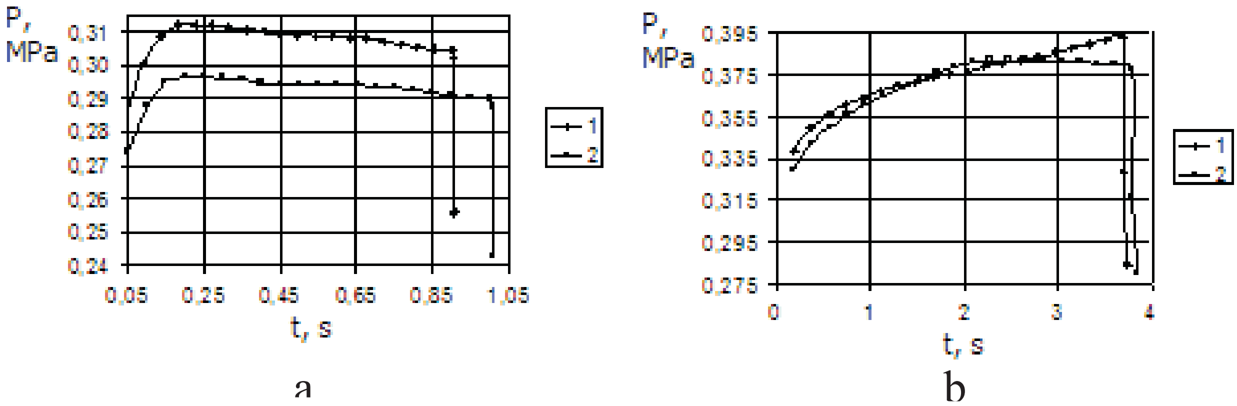

Fig. 5. Shear stress at wall near gate versus time for mold filling with feedstock: (a) for argon-brc welding orifice with sharp angles (1) and angles with fillet (2), radius 3 mm; for abrasive spraying orifice with sharp angles (1) and angles with fillet (2), radius 5 mm

4. Conclusions

1. A new rheological model of the feedstock flow during the injection molding is developed, which connects the nonlinear-viscosity feedstock behavior with the powder volume fraction.
2. The prevention of the defect formation such as weld lines and sink marks or their minimization during the feedstock filling of complex-shaped molds can be provided due to an optimal choice of the injection gate location – the one that takes into account the possibility of uniform mold filling.
3. The stress concentration reduction during the mold filling can be reached using internal corners with fillets.

REFERENCES

[1] V. V. Bilovol, L. Kowalski, J. Duszczyk, Numerical simulation of the powder injection moulding process for optimisation of mould design and process parameters, Adv. Eng. Mat. **2**, 127-131 (2000).

[2] C. M. Wang, R. L. Leonard, T. J. McCabe, Computational analysis of fluid flow and heat fransfer in the powder injection molding process, Adv. Powder Met. and Particul. Mater.: Proc. Int. Conf. and Exhib. Powder Met. and Particul. Mater., Nashiville, Tenn. May 16-19, 1993, 5, Princeton (N. J.), 31-34 (1993).

[3] V. V. Bilovol, L. Kowalski, J. Duszczyk, Modelling of transient temperature fields during filling stage of powder injection moulding, Powder Met. **43** [3], 228-232 (2000).

[4] Y. Maeda, H. Nomura, D. Sugiama, Optimisation of green compact forming conditions in metals injection moulding, J. Jpn. Inst. Met. **60** [11], 1108-1115 (1996).

[5] O. Frolova (Kirkova), L. Tkachenko, A. Maximenko, M. Shtern, Mold filling investigation using simulation of injection molding technology, Mathematical models and numerical experiment in material science **9**, 31-34 (2007) (in Russian).

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