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NUMERICAL ANALYSIS OF RESIDUAL STRESSES AND DEFORMATION OF INJECTION MOULDED PARTS MANUFACTURED FROM POLYMERIC COMPOSITE WITH DIFFERENT PROCESSING CONDITIONS

Simulations of the injection moulding process of polypropylene with a glass fibre content were conducted using special software - MOLDFLOW PLASTICS INSIGHT ver. 4.1. A seven - parametric rheological Cross - WLF model was chosen for the research. For holding phase simulation as well as to determine the inner stresses and deformation of the parts, the pvT dependence should be known. The Tait equation was used in the numerical calculations. In the first step of the simulation a solid model of the part was created using the Master Modeller modulus of I-DEAS NX software. A sample for cracking resistance tests, of the SENB type, with runners was modelled. Then the cooling conditions were introduced to the program. The next step modelled the injection mould geometrical shape and mesh creation. The crucial moment in the simulation is the introduction of the data describing the processed polymer properties. They were the thermal properties as well as the rheological and mechanical properties of the injected composite: PP with a 25% glass fibre content. In the next step, the processing conditions were entered into the simulation program (Moldflow Plastisc Insight ver. 4.1). The simulation research was conducted on the basis of the design of an experiment that was prepared with the use of Statistica 6.0 software. The changes of four processing parameters were taken into account: holding pressure, injection temperature, injection velocity and mould temperature. The simulations were made for extreme values of these parameters. The results of the numerical simulations of the residual stresses and strains on the injection moulded parts are presented graphically and conclusions were drawn from them.

Keywords: **injection molding process, polypropylene composite, simulation calculations, injection molding parameters, pvT relation, residual stress, strain injection moulded parts**

ANALIZA NUMERYCZNA NAPRĘŻEŃ WŁASNYCH I ODKSZTAŁCEŃ WYPRASEK UZYSKIWANYCH Z KOMPOZYTU POLIMEROWEGO PRZY ZMIENNYCH WARUNKACH PROCESU WTRYSKIWANIA

Symulację procesu wtryskiwania kompozytu polipropylenu z włóknem szklanym przeprowadzono za pomocą specjalistycznego programu MOLDFLOW PLASTICS INSIGHT ver. 4.1. Do badań przyjęto siedmioparametrowy model reologiczny Crossa - WLF. Do symulacji fazy docisku oraz w celu określenia naprężeń własnych i odkształcenia wyprasek jest niezbędna znajomość zależności pvT. W obliczeniach numerycznych wykorzystano równanie Taita. W pierwszym etapie symulacji zbudowano model bryłowy wypraski, który przeprowadzono za pomocą modułu Master Modeler Pakietu I- DEAS NX. Model obejmuje próbkę pomiarową do badań odporności na pękanie typu SENB i układ wlewowy. Następnie wprowadzono do programu warunki chłodzenia wypraski. W kolejnym kroku zamodelowano kształt geometryczny formy wtryskowej i nałożono siatkę MES. Kluczowym momentem w badaniach symulacyjnych jest wprowadzenie do symulatora danych opisujących właściwości przetwarzanego tworzywa. Dane te obejmują właściwości cieplne, reologiczne i mechaniczne wtryskiwanego kompozytu PP z 25% zawartością włókna szklanego. W kolejnym kroku wprowadzono do programu symulacyjnego (Moldflow Plastisc Insight ver. 4.1) warunki procesu wtryskiwania. Badania symulacyjne przeprowadzono, opierając się na sporządzonym programie badań. Program ten został opracowany z wykorzystaniem pakietu Statistica 6.0. Uwzględniono w nim zmienność czterech parametrów procesu wtryskiwania: ciśnienia docisku, temperatury wtryskiwania, prędkości wtryskiwania oraz temperatury formy. Symulacje przeprowadzono dla skrajnych parametrów procesu wtryskiwania. Wyniki symulacji numerycznych naprężeń własnych i odkształceń wyprasek przedstawiono graficznie i sformułowano wnioski.

Słowa kluczowe: **proces wtryskiwania, kompozyt polipropylenu, obliczenia symulacyjne, parametry wtryskiwania, zależność pvT, naprężenia własne, odkształcenia przetwórcze wyprasek**

INTRODUCTION

Nowadays the programs for injection moulding process simulation are a commonly used tool used in the industry and are a subject of numerous research works. Increasingly more companies are convinced that it is necessary to use simulation for injection moulding process analysis because of economic and quality aspects. During recent years, many programs for the computer simulation of injection moulding processes arose. The most used programs are AUTODESK MOLDFLOW and CADMOULD. The users of these simulation programs should have knowledge about CAD systems, technology of the injection moulding process and the basics of polymer flow in injection moulds. Computer simulation programs enable the realization of reliable numerical calculations but only if enough information about the processed polymer properties or its composite is available [1-3].

The computer programs used for injection moulding process simulation, despite their complex mathematical model, cannot take into account all the factors and interference that occur in the real process. Thus some simplifications are used and the mathematical model, from which a calculation model is devised, is not too complicated. Each simplification introduces an error to the calculations. The error value depends on the degree of simplifications used. Investigation of the injection moulding process based on computer simulations can be treated as preliminary and supportive [1-3].

BASICS AND ASSUMPTIONS

Simulations of the injection moulding process of polypropylene with a glass fibre content were conducted using special software - MOLDFLOW PLASTICS INSIGHT ver. 4.1. The spatial model of the injection moulded part was prepared in the Master Modeller modulus of the I-DEAS NX software. The continuum, mass and energy equations in the general form are not possible to solve for such a complex process like injection moulding, therefore it is necessary to make some simplifications. The simplification assumptions refer to the polymer as well as the geometrical shape of the region where the above-mentioned equations are applied [4-9]. An important simplification is the introduction of *no-flow temperature* - a temperature value in which the polymer stops flowing. At this temperature the polymer can be treated as a solid. By the assumption of no-flow temperature, the velocity of the components of the polymer solidified at the cavity mould wall are assumed as equal to zero. Moreover, it is assumed that the polymer flow is symmetrical to the midplane of the cavity. Besides basic equations, for injection moulding computer simulation, the proper rheological state equation of the polymer that determines the dependence between the polymer viscosity and the shear rate is also needed. There are many mathematical rheological models like Bird-Carreau-Yashuda, Cross-WLF model and others. The seven-parametric rheological Cross-WLF model was chosen for the research. It is described by the equation [4-9]:

$$\eta\left(\gamma,\dot{T},p\right)=\frac{\eta_0(T,p)}{1+\left(\frac{\eta_0\dot{\gamma}}{\tau^*}\right)^{1-n}} \tag{1}$$

and the dependence of viscosity η_0 on the temperature T and pressure p is described by the WLF equation

$$\eta_0(T,p)=D_1\cdot\exp\left[-\frac{A_1(T-T^*)}{A_2+(T-T^*)}\right] \tag{2}$$

where:

$$T^*(p)=D_2+D_3\cdot p \tag{3}$$

$$A_2=\widetilde{A}_2+D_3\cdot p \tag{4}$$

where: T - temperature, p - pressure, n, τ^* - constant parameters in the model (τ^* is the shear stress value for which molten polymer exhibits properties of a shear-thinned liquid), η_0 - viscosity at shear rate approaching zero.

D_1, D_2, D_3, A_1, $\widetilde{A}_2$ are constant parameters of WLF equation.

TABLE 1. **Values of Cross-WLF equation for PP with 25% glass fibre content**

TABELA 1. **Wartość parametrów modelu Crossa-WLF dla PP z 25% zawartością włókna szklanego**

Parameters	N	τ^*, Pa	D_1, Pa·s	D_2, K	D_3, K/Pa	A_1	$\widetilde{A}_2$, K
Value	0.3133	21131.1	$1.0946\cdot10^{15}$	263.15	0	34.189	51.6

For holding phase simulation as well as to determine the residual stresses and deformation of the parts, the pvT dependence should be known. The Tait equation was used in the numerical calculations. It describes the change of specific volume $v(p,T)$ along the isotherm dependent on two variable parameters: C and B that are a function of temperature. The Tait equation is usually presented in the form of [4-9]:

$$v(p,T)=v_0(T)\cdot\left\{1-C\cdot\ln\left[1+\frac{p}{B(T)}\right]\right\}+v_t(p,T) \tag{5}$$

when $T > T_{trans}$

$$v_0(T)=b_{1m}+b_{2m}(T-b_5) \tag{6}$$

$$B(T)=b_{3m}\cdot\exp[-b_{4m}\cdot(T-b_5)] \tag{7}$$

when $T < T_{trans}$

$$v_0(T)=b_{1s}+b_{2s}(T-b_5) \tag{8}$$

$$B(T)=b_{3s}\cdot\exp[-b_{4s}\cdot(T-b_5)] \tag{9}$$

where: $v_0(T)$ - specific volume at atmospheric pressure, T - temperature, P - pressure, C - universal constant equal 0.0894.

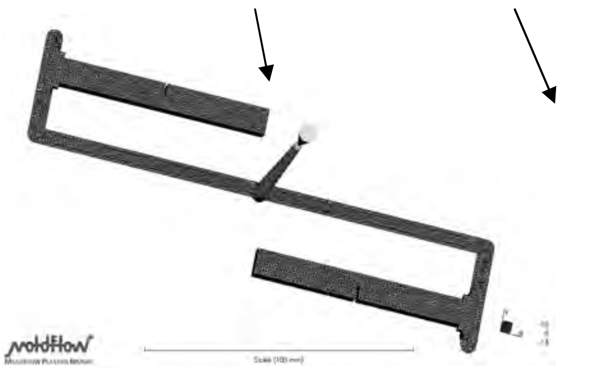
For semicrystalline materials $v(p,T) = = b_7 \cdot \exp[b_8 \cdot (T - b_5) - b_9 \cdot p]$, *p-v-T* curves were obtained from the tests made in the Department of Polymer Processing at the Lublin University of Technology.

TABLE 2. **Values of Tait equation parameters for PP with 25% glass fibre content**

TABELA 2. **Wartość parametrów równania Taita dla PP z 25% zawartością włókna szklanego**

Para-meters	b_{1m}, m^3/kg	b_{2m}, m^3/kg·K	b_{3m}, Pa	b_{4m}, 1/K	
Value	0.0009169	$6.103 \cdot 10^{-7}$	$9.17363 \cdot 10^{7}$	0.004313	
Para-meters	b_{1s}, m^3/kg	b_{2s}, m^3/kg·K	b_{3s}, Pa	b_{4s}, 1/K	
Value	0.0008523	$2.315 \cdot 10^{-7}$	$1.86593 \cdot 10^{8}$	0.001339	
Para-meters	b_5, K	b_6, K/Pa	b_7, m^3/kg	b_8, 1/K	b_9, 1/Pa
Value	413.15	$2.685 \cdot 10^{-7}$	$6.458 \cdot 10^{-5}$	0.1693	$4.891 \cdot 10^{-8}$

a)



b)

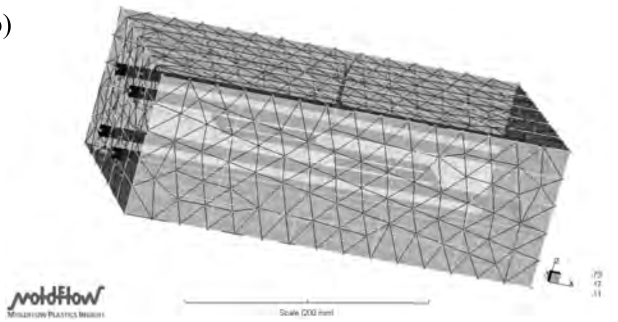


Fig. 1. FEM model of injection moulded part (a) and mould with runners (b)

Rys. 1. Model MES wypraski (a) i formy wtryskowej wraz z kanałami chłodzącymi (b)

At the beginning of the injection moulding process simulation, it is required to enter into the calculation program such data like: geometrical shape of the injection moulded part, properties of the processed polymer, processing conditions and data of the machine. In the first step of the simulation, a solid model of the part was created using the Master Modeller modulus of I-DEAS NX software. A sample for cracking resistance tests, of a SENB type, with runners was modelled. Then the cooling conditions were introduced to the program. The next step was the modelling of the injection mould geometrical shape and mesh creation (Fig 1). A double-cavity mould was modelled. The crucial moment in the simulation was the introduction of the data describing the processed polymer properties. They were the thermal properties as well as the rheological and mechanical properties of the injected composite: PP with 25% glass fibre content.

In the next phase, the processing conditions were introduced to the simulation program (Moldflow Plastics Insight ver. 4.1). The simulation research was conducted on the basis of the design of an experiment that was prepared with the use of Statistica 6.0 software. The changes of four processing parameters were taken into account: holding pressure, injection temperature, injection velocity and mould temperature. The simulations were made for extreme values of these parameters.

SIMULATION RESULTS AND DISCUSSION

The residual stress distribution for the composite of PP with a 25% glass fibre content is presented in Figure 2. The parts made from this composite were obtained with different mould temperature values. A higher mould temperature causes easier cavity filling and a decrease in the temperature gradient between the polymer and mould wall causes a decrease in residual stresses in the part. For lower mould temperature values, an increase in residual stresses of about 5% was observed.

a)

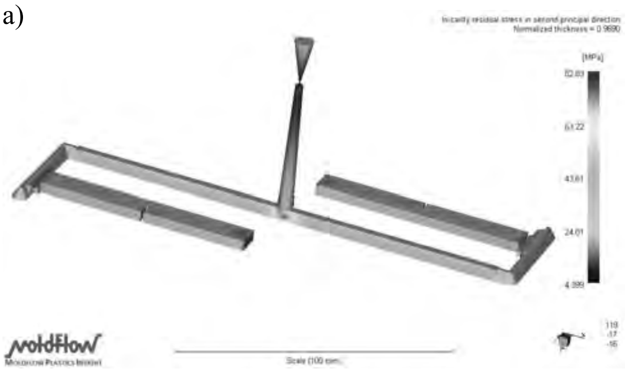
b)

Fig. 2. Residual stress distribution for PP with 25% glass fibre content: a) for mould temperature of 20°C, b) for mould temperature of 80°C

Rys. 2. Rozkład naprężeń własnych dla PP z 25% zawartością włókna szklanego: a) dla temperatury formy 20°C, b) dla temperatury formy 80°C

The residual stresses distribution results of the numerical simulation for parts manufactured with extreme holding pressure values are presented in Figure 3. When a higher holding pressure is used, the melt pressure during the cooling phase of the process increases and, at the same time, the packing of polymer macromolecules is higher, which results in higher values of residual stresses.

a)



b)

Fig. 3. Residual stress distribution for PA6 with 25% glass fibre content: a) for holding pressure of 30 MPa, b) for holding pressure of 50 MPa

Rys. 3. Rozkład naprężeń własnych dla PA6 z 25% zawartością włókna szklanego: a) dla ciśnienia docisku 30 MPa, b) dla ciśnienia docisku 50 MPa

One of the most important factors influencing injection moulded part deformation is the structure of the polymer used for the matrix of a composite. The other factor influencing the deformation size and kind is the kind and percentage content of the filler. The part shrinkage is an image of its deformation. The highest deformation values for PP were observed along the X axis and the lowest along the Z axis (Fig. 4a). Another situation was observed for PP composites with a fibrous filler in the form of a cut glass fibre (Fig. 4b). The highest deformation values were observed along the Y axis and the lowest along the Z and X axes. The main reason for the deformation in these parts is the difference in fibre orientation: parallel and transversal to the polymer flow direction. Shrinkage measured parallel to the flow direction is about 50% higher than in the transversal direction.

An important factor causing the deformation of parts made of PP with glass fibre is the symmetry of the part. The reason for the deformation of these parts is the asymmetrical location of the rectangular notch that is located in the middle-length of the SENB sample. Such a location of the notch disturbs the polymer flow and the orientation of fibres, causing part deformation. The changes in the Young modulus in the part made of the composite of PP with a 25% weight content of E-type glass fibre is presented in Figure 5.

a)

b)

Fig. 4. Deformation of injection moulded parts: a) for PP, b) for PP with 25% glass fibre content

Rys. 4. Deformacja wyprasek: a) dla PP, b) dla PP z 25% zawartością włókna szklanego

Fig. 5. Changes in Young modulus for part from composite of PA6 with 25% glass fibre content

Rys. 5. Przebieg zmian wartości modułu Younga dla wypraski z kompozytu PA6 z 25% zawartością włókna szklanego

CONCLUSIONS

Inner stresses occur in the parts without any external forces. When the part is in the forming cavity, the inner stresses are not balanced. After ejection of the part these stresses become balanced. Higher values of inner stresses obtained from numerical simulations of the injection moulding process were observed for parts manufactured with a lower mould temperature or higher holding pressure values. In both cases a noticeable increase in inner stresses was observed. A higher mould temperature results in easier filling of the cavity and a decrease in the temperature gradient between the part and cavity wall causes a decrease in the inner stresses in the part. When higher values of holding pressure are used, the packing of polymer macromolecules is better, which results in higher values of inner stresses.

REFERENCES

[1] Koszkul J., Nabiałek J., Koszkul M., Symulacja wypełnienia gniazda formy wtryskowej z wykorzystaniem programu Moldflow Plastic Insight, praca zbiorowa pod red. J. Koszkula, Materiały polimerowe i ich przetwórstwo, Wyd. Politechniki Częstochowskiej, Częstochowa 2000.

[2] Parlevliet P.P., Bersee H.E.N., Beukers A., Residual stresses in thermoplastic composites - A study of the literature - Part II: Experimental techniques, Composites: Part A 2007, 38, 651-665.

[3] Parlevliet P.P., Bersee H.E.N., Beukers A., Residual stresses in thermoplastic composites - A study of the literature - Part I: Formation of residual stresses, Composites: Part A 2006, 37, 1847-1857.

[4] Osswald T.A., Turng L-S., Gramann P.J., Injection Molding Handbook, Carl Hanser Verlag, Munich 2008.

[5] Rosato D.V., Rosato D.V., Rosato M.G., Injection Molding Handbook, Kluwer Academic Publishers 2000.

[6] Pötsch G., Michaeli W., Injection Molding, An Introduction, Carl Hanser Verlag, Munich 2008.

[7] Tucker L.Ch., Fundamentals of computer modeling for polymer processing, Carl Hanser Verlag, Munich-Vienna--New York 1989.

[8] Wilczyński K., Reologia w przetwórstwie tworzyw sztucznych, WNT, Warszawa 2001.

[9] Kowalska B., Skurcz wtryskowy a zależność pvT, Polimery 2007, 52, 4, 280-285.

