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EXPERIMENTAL VALIDATION OF POLYMER COMPOSITE INJECTION MOULDING PROCESS SIMULATION

The paper presents the chosen results of investigations on polymer flow during the mould cavity filling phase of the injection moulding process. The process is characterized by high dynamics, which causes several technological difficulties, both during injection mould design and during product implementation to the production stage. Greater understanding of the phenomena which occur during filling of the injection mould may lead to more effective design of processing tools and shortening of the time for implementation and production time. The results of computer simulations of the injection process have been compared with the results of video recording of the plastic flow during the filling phase. A specialized injection mould which enables observation and registration of the plastic flow during processing has been employed. The mould enables direct monitoring of the course of the phenomena inside the mould cavity in two planes. Transparent sight-glasses have been used, made of a material called Zerodur® which is characterized by a coefficient of thermal expansion close to zero. To record the flow, a digital video camera has been employed. The camera enabled registration of the flows with the rate of 25 fps. This reduced the scope of the investigations, since at higher plastic flow speeds the registered image became less clear. The video sequences registered during the investigations were later digitally processed in order to ensure in-depth analysis. For the simulation investigations, professional computer software, Autodesk Moldflow Insight 2011, has been employed. The results of the investigations enabled the documentation of specific phenomena which occur during the plastics or their composites injection process. The registered video sequences have been compared to the results of numerical calculations and then it was estimated to what degree the computer simulation of the injection process may be useful in practice. The investigations were performed on a wide scale, however, only chosen results have been presented. As an example, the issue of flowing around a rectangular obstacle of the plastic stream has been described. The obtained results of the investigations are so encouraging that they made the authors continue such experiments.

Keywords: composites, injection molding process, computer simulations, flow registration

WERYFIKACJA DOŚWIADCZALNA SYMULACJI PROCESU WTRYSKIWANIA KOMPOZYTU POLIMEROWEGO

Przedstawiono wybrane wyniki badań przepływu polimeru podczas wypełniania gniazda formy w procesie wtryskiwania. Proces ten charakteryzuje się dużą dynamiką, przez co stwarza szereg trudności technologicznych zarówno podczas projektowania form wtryskowych, jak i na etapie wdrożenia wytworu do produkcji. Dogłębne poznanie zjawisk zachodzących podczas wypełniania formy wtryskowej może prowadzić do efektywniejszego projektowania narzędzi przetwórczych oraz skrócenia czasu wdrożenia i czasu produkcji. Porównano wyniki symulacji komputerowych procesu wtryskiwania z rezultatami rejestracji wideo przepływu tworzywa podczas trwania fazy wypełniania. Wykorzystano specjalistyczną formę wtryskową umożliwiającą obserwację i rejestrację przepływu tworzywa w procesie przetwórstwa. Forma ta umożliwia bezpośrednie monitorowanie przebiegu zjawisk wewnątrz gniazda formującego w dwóch płaszczyznach. Zastosowano transparentne wzierniki wykonane z materiału o nazwie Zerodur®, który charakteryzuje się współczynnikiem rozszerzalności cieplnej bliskim zeru. Do rejestracji przepływu zastosowano cyfrową kamerę wideo, która umożliwiła rejestrację przepływów z szybkością 25 fps. Ograniczyło to zakres badań, gdyż przy dużych prędkościach przepływu tworzywa obraz rejestrowany stawał się mało czytelny. Sekwencje wideo zarejestrowane podczas badań poddano obróbce cyfrowej w celu wnikliwej ich analizy. Do badań symulacyjnych zastosowano profesjonalny program komputerowy Autodesk Moldflow Insight 2011. Wyniki badań umożliwiły udokumentowanie specyficznych zjawisk zachodzących w procesie wtryskiwania tworzyw polimerowych i ich kompozytów. Porównano zarejestrowane sekwencje wideo z wynikami obliczeń numerycznych i oceniono, w jakim stopniu symulacje komputerowe procesu wtryskiwania mogą być użyteczne w praktyce. Badania przeprowadzono w bardzo szerokim zakresie, jednak z konieczności przedstawiono tylko wybrane wyniki badań. Jako przykład opisano zagadnienie opływania prostokątnej przeszkody przez strumień tworzywa. Otrzymane wyniki badań są na tyle zachęcające, iż skłoniły autorów do kontynuacji tego typu eksperymentów.

Słowa kluczowe: kompozyty, proces wtryskiwania, symulacje komputerowe, rejestracja przepływu

INTRODUCTION

The processing of plastics and their composites by means of the injection method is a widely used process in many branches of contemporary industry. The participation of filled plastics (composites) in products

designed for use not only in everyday life is still increasing. Due to this fact, it is fully justifiable to perform investigations in order to provide in-depth analysis of the phenomena which occur during widely understood plastics processing. The present paper is an attempt to present a chosen part of the results of investigations which consist in the registration of plastic flow in the mould cavity during the filling phase. Such investigations have been performed by several scientific research centres all around the world [1-5], however, the level of recognition of the phenomena occurring during filling the injection mould is still insufficient.

METHODOLOGY OF INVESTIGATIONS

Injection mould

For the investigations, a specialized injection mould with unique structure has been employed. The construction of such a mould was preceded by numerous attempts led by means of several prototypes. The final design of the injection mould was prepared by means of the professional software package I-DEAS NX. The final shape of the mould is shown in Figure 1. The mould enabled the authors to register the phenomena which occur during the flow of the plastic inside the mould cavity. The mould was equipped with two transparent sight-glasses (with surface area equal at least to the area of the mould). At the beginning, polycarbonate sight-glasses had been used. They ensured a high level of transparency but caused significant limitations in the value of the processing temperature. At an injection temperature over 240°C or at a high injection speed, sight-glasses deformation and degradation took place. Eventually, sight-glasses were prepared from a special ceramic material called Zerodur® [6]. The material presents an almost zero coefficient of thermal expansion, which makes it insensitive to high temperature gradients which prevail during filling the mould cavity (due to this fact glass sight-glasses were not possible). Then the sight-glasses were placed in the mould, so that the plastic flow recording would be possible in two planes per-pendicular to the polymer flow direction. The recording was done by means of a digital video camera. The camera enabled recording with a maximal speed of 25 images per second. This speed was in many cases insufficient. Additionally, it became necessary to assemble a special set of lighting based on LED diodes. The sets were assembled in such a way that additional lighting of the mould cavity where the recording took place would be possible. The recording was performed during full darkness in the lab (the tests were performed mainly at night). The mould cavity is in the shape of a rectangular prism with the dimensions of 100x40x4 mm. Within this space, the modification of the final shape of the mould piece is possible on a large scale. This effect was achieved due to the modular structure of the mould cavity.
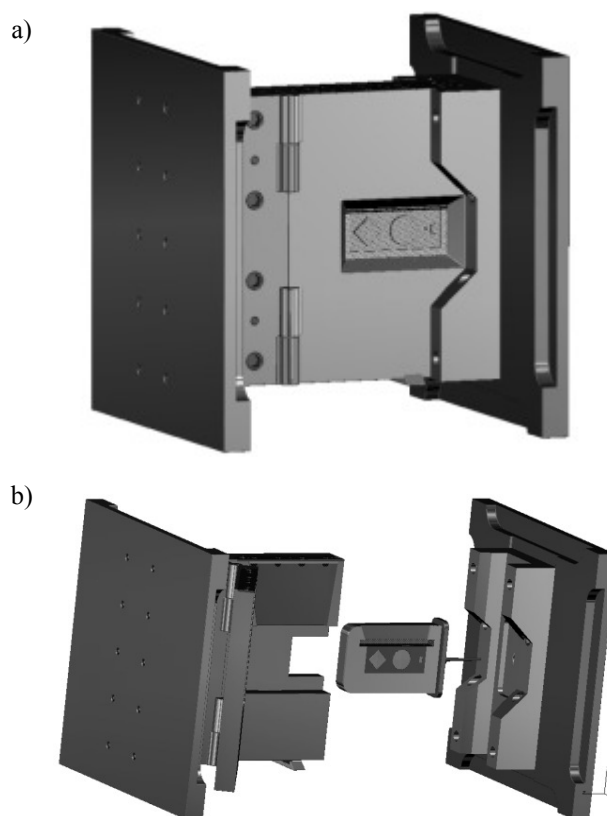
a)

b)

Fig. 1. Injection mould: a) closed, b) open
Rys. 1. Forma wtryskowa: a) zamknięta, b) otwarta

It is possible to use maximally ten modules with the dimensions of 20x20 mm at the same time. The details of the mould cavity structure are shown in Figure 2.
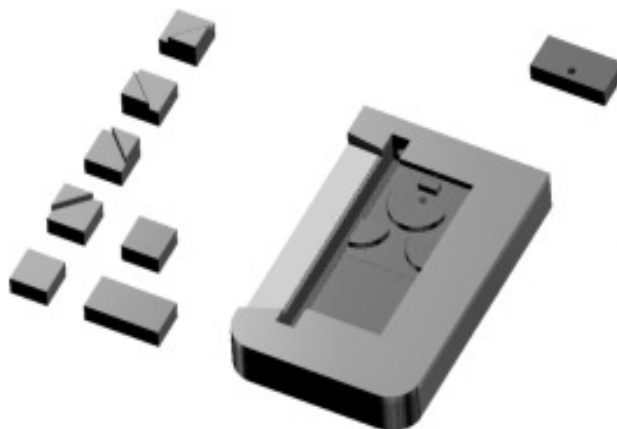

Fig. 2. Structure of mould cavity
Rys. 2. Konstrukcja gniazda formującego

Injection moulding process

This paper presents the results achieved during the investigations on a polypropylene composite with chalk. The polypropylene produced by the Italian company Sirmax called Isofil H20 TC F Bianco was used. The chalk is 20% weight of the composite. A composite with such a composition of filler caused many technological problems. The white colour of the injected plastic made it much easier to precisely record

the flow. The machine used for the investigations was the German Krauss-Maffei injection moulding machine - KM 65/160. The machine was equipped with a high-quality control system - C4. Using such a precise and modern machine enabled us to solve the above-mentioned problems. The investigations were performed within a wide range of variability of injection conditions, however, in the present paper only the results for chosen cases have been presented.

Computer simulations

The computer simulation consisted in several numerical analyses in order to perform computer modelling of the injection process for the chosen composite. The purpose of the investigation was to obtain the results which concern the predicted character of flow for the chosen plastic, and then to compare them to the experimental results. The comparison was to e.g. evaluate the degree of credibility of numerical calculations performed by means of professional computer software. For the investigations, the pro-fessional software Autodesk Moldflow Insight 2011 has been used. In order to perform correct analysis, the input of a number of input data became necessary. First of all, the shape of the mould cavity and injection gating system had to be designed. The design was prepared by means of the I-DEAS NX software package. Then, the mesh of the finite element was plotted on the model. Afterwards, the data concerning the material properties of the processed plastic was entered into the simulation software. In order to do it, an in-built database with the plastics properties was has been used. This helped to reduce the time needed to perform arduous lab tests concerning the mechanical, thermal and rheologic properties of a composite. When the final phase of the data was input to the software, we were able to determine the conditions for the injection process. It should be observed that the correct performance of the above-mentioned activities significantly influences the correctness and adequacy of the obtained results of calculation. The human factor at this stage is the most important. Inputting the data which differ, even on a minimal scale from reality causes the occurrence of calculation errors which disqualify the results of the investigations. In Figure 3, the viscosity plot and the pvT chart for the composite used in the investigation are shown. In order to model the rheologic properties of the plastic, the seven-parameter model Cross-WLF, has been employed [7-15]. The chosen rheologic model is rather compli-cated, but ensures very good imaging of the composite properties.

The technical parameters of the injection moulding machine have also been input into the software (e.g. clamping force, perpetual screw diameter, maximal injection pressure etc.).
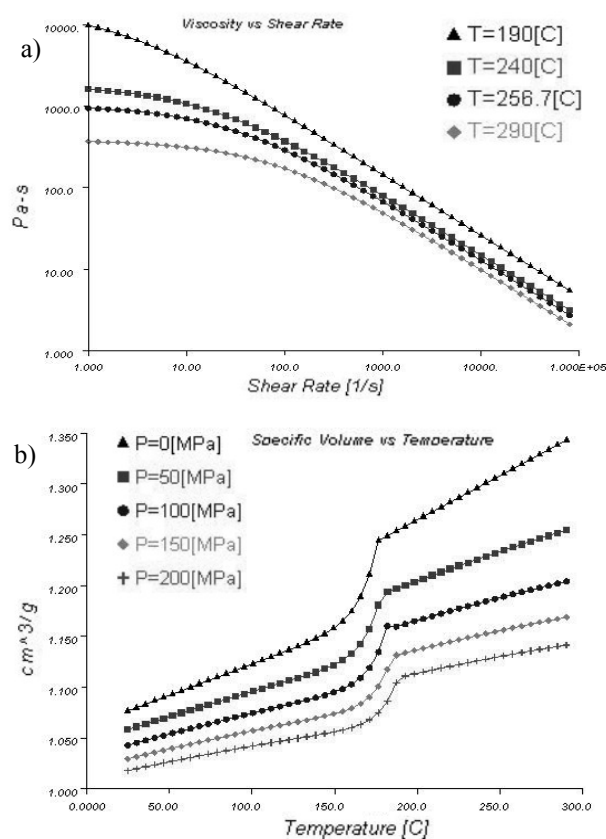

Fig. 3. Flow curves (a) and pvT chart (b) for polypropylene with chalk

Rys. 3. Krzywe płynięcia (a) oraz wykres pvT (b) dla kompozytu polipropylenu z kredą

Moldflow Plastics Insight enables the edition of solver parameters. It makes possible the manual definition of some values e.g. convergence tolerance, time steps or applied equation of state.

RESULTS OF INVESTIGATIONS

In Figure 4, the model FEM of the part used for investigations has been presented. It was a rectangular prism-shaped part with an obstacle of a narrowing type. Additionally, the gating system for the mould was modelled. After inputting the material data and processing conditions, the numerical calculations were performed. At the same time, the recording of the flow in the injection mould was done. The comparison of the experimental and simulation investigation results is shown in Figure 5. The comparison contains the frame-by-frame recordings obtained from the digital video camera with the corresponding computer simulation results.

The presented comparison concerns the process which was performed in the following conditions:
- volumetric flow rate 10 cm^3/s,
- maximum injection pressure 70 MPa,
- cooling time 20 s,
- injection temperature 240ºC,
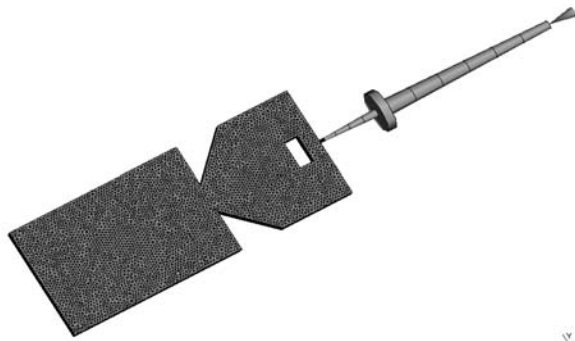- mould temperature ca. 20ºC.

Fig.4. Part model with FEM mesh

Rys. 4. Wypraska z nałożoną siatką MES

The process was performed in a way that does not lead to total fill-in of the mould cavity and does not skip the clamping phase. The reason for such a procedure was safety and to avoid damaging the sight-windows. Despite such an extensive limitation, it was possible to record the course of the mould cavity filling in the area of interest.
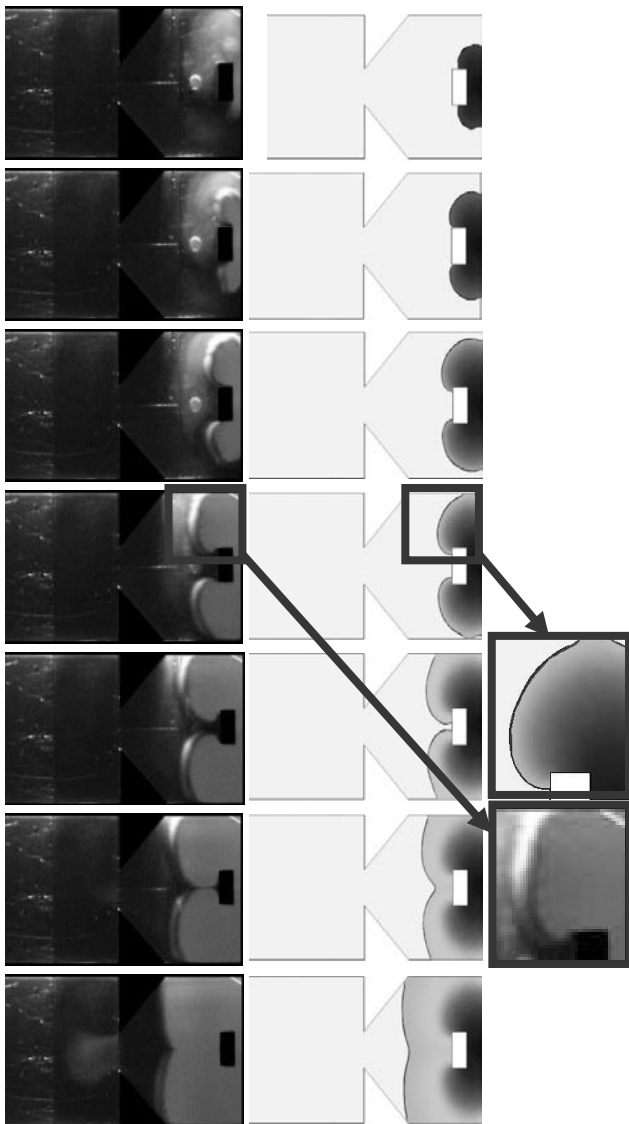

Fig. 5. Comparison of experimental and simulation investigation results

Rys. 5. Porównanie wyników badań eksperymentalnych i symulacyjnych

Several phenomena described so far have only theoretically been observed. The method of liquid plastic flowing around different obstacles, the propagation of gas bubbles and other inclusions have been documented; the stream flow, as well as meld and weld lines were also registered.

Figure 6 shows the weld lines of the injected composite (simulations results).

Fig. 6. Weld lines of injected composite (simulation)

Rys. 6. Linie łączenia strug wtryskiwanego kompozytu (symulacja)

The results of the investigation presented in this paper enable us to state that the streams of plasticized composite show the properties characteristic for viscoelastic material. Flowing round the rectangular obstacle occurs in the way which could astonish any layman. The plastic which flows around the obstacle (frequently with huge impetus) does not form a stream in a downstream direction but changes direction as if "gluing" onto the walls of the obstacle. It proves the theoretical considerations and the results of numerical analyses related to viscoelastic materials (liquids) flow.

The investigations brought satisfactory results. The authors realized though, that several technical details should be changed in the future. Such notions include the fact that the digital camera did not allow us to register the flow of plastic at a high injection speed (due to the limitation of only 25 frames per second) It is recommended for the future to use faster cameras.

The applied injection mould is a prototype and is still developing. The authors are testing different versions of sight-glasses, other systems of lightning for the mould cavity and plan to use pressure and temperature sensors in order to register these values during the flow of the plastic.

CONCLUSIONS

After performing the investigations and analysis of their results, the following conclusions were drawn:
1. Looking for new test methods is done in order to investigate thoroughly unexplained or disputable phenomena occurring during chosen manufacturing processes. Such investigations are performed in

order to find out about these phenomena, to analyse them and to use them for optimisation and cost reduction during manufacturing.

2. Comparison of the results of composite flow during the injection process with the results of simulation investigations enables us to state that specialized computer software enable one to predict the existence of specific phenomena for a given process. This means that already in the product design phase, it is possible to predict and optimise the manufacturing process.

3. Construction of specialized test stations enables the in-depth testing of so far unconfirmed theoretical predictions concerning the phenomena occurring during complicated manufacturing processes.

REFERENCES

[1] Yokoi H., Takematsu S., Visualization of Burning Phenomena during Cavity Filling Process, PPS 18.

[2] Yang S.Y., Nian S.C., Sun I.C., Flow Visualization of Filling Process during Micro-Injection Molding, International Polymer Processing, Hanser Verlag, XVII 2002.

[3] Banasiak A., Sterzynski T., The assessment of flow in the injection's mould of polymer with plate filler as marker, Polimery 2004, 49, 6, 442-448 (in Polish).

[4] Banasiak A., Bledzki A., Sterzynski T., Flow lines visualization by injection molding of a model system PE + talc, Proceedings, PPS Athens 2003, 93.

[5] Hasegawa S., Yokoi H., Murata Y., Dynamic Visualization of Cavity Filling Process in Ultra-high Speed and Thin Wall Injection Molding, PPS 2003.

[6] http://www.schott.com/lithotec.

[7] Nabialek J., Koszkul J., The influence of input data on the results of injection molding process simulation, 13-th International Scientific Conference AMME 2005, Gliwice 2005, 455-458.

[8] Koszkul J., Nabiałek J., The influence of viscosity model on the results of injection molding process simulation, 9-th international scientific conference AMME 2000, Gliwice-Sopot-Gdańsk 2000, 311-314.

[9] Lee K., Mackley M.R., The significance of slip in matching polyethylene processing data with numerical simulation, Journal of Non-Newtonian Fluid Mechanics 2000, 94, 2-3, 159-177.

[10] Shen Y.K., Huang S.T., Chen C.J., Yu S., Study on flow visualization of flip chip encapsulation process for numerical simulation, International Communications in Heat and Mass Transfer 2006, 33, 2, 151-157.

[11] Özdemir A., Uluer O., Güldas A., Flow front advancement of molten thermoplastic materials during filling stage of a mold cavity, Polymer Testing 2004, 23, 8, 957-966.

[12] Pantani R., Validation of a model to predict birefringence in injection molding, European Polymer Journal 2005, 41, 7, 1484-1492.

[13] Wilczyński K., CADMOULD-3D - computer modeling of polymers injection process - simulation of filling stage, Polymers 1999, 44, 6, 407-412 (in Polish).

[14] Kennedy P., Flow Analysis of Injection Molds, Hanser-Gardner 1995.

[15] Gordon G.V., Shaw M.T., Computer Programs for Reologist, Hanser Publishers, Munich - Vienna - New York 1994.