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Finite Element Method application for determining feedstock distribution during powder injection moulding

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Analysis and modelling

ABSTRACT

Purpose: The general topic of this paper is problem of model ling of a polymer-powder mix flow during filling, in which the high-speed steel was used along with paraffin and polypropylene as a binding agent.
Design/methodology/approach: Modelling of the polymer-powder mix flow process during filling was performed using the finite element method in Cadmould environment; polymer-powder mix was injection moulded using Arburg injection moulder. Computer simulation results were compared with experimental results.
Findings: The presented model meets the initial criteria, which gives ground to the assumption about its usability for injection moulding of polymer-powder slurry process, employing the finite element method using the Cadmould software. The computer simulation results correlate with the experimental results.
Research limitations/implications: It was confirmed that using of finite element method in powder injection moulding process can be a way for reducing the investigation costs Results reached in this way are satisfying and in slight degree differ from results reached by experimental method. However for achieving better calculation accuracy in further researches it should be developed given model which was presented in this paper.
Originality/value: Nowadays the computer simulation is very popular and it is based on the finite element method, which allows to better understand the interdependence between parameters of process and choosing optimal solution. The possibility of application faster and faster calculation machines and coming into being many software make possible the creation of more precise models and more adequate ones to reality
Keywords: Computational materials science; Finite Element Method, Powder Injection Moulding

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1. Introduction

The need to use the new engineering materials and contemporary fabrication technologies arises from the continuous development of civilisation and demand for the new, better products. Product price, apart from the high properties of the manufactured elements, is also of the significant importance to the customer. Manufacturing cost may often be reduced by employing the mass- or big-lot production. Forming of the polymer-powder mixes may be an example, required for the

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widely known injection or extrusion of plastics [1-12]. Powder injection moulding is a branch of the widely known powder metallurgy. Powder metallurgy is not only fabrication of powders from metals and their alloys, and designing their properties, but – first of all – consolidation of the powders into a compact solid, which is, as a rule, the completed product, and only in few cases it may be the material as a green [4]. Moreover, despite its name, the non-metallic powders and metallic Or non-metallic fibers are used in powder metallurgy, which are merged with metals powders[6]. Development of injection moulding technology is connected with the more and more intensive use of programs for simulation of this process, making it possible to analyse filling of the mould cavity, packing and cooling phases, as well as analysis of the green deformation during cooling both in the mould and after its removal. There are many economic and qualitative considerations for which the injection simulation analysis should be carried out [13-17]. This work presents results of investigation consisting in modeling of the polymer-powder mix during filling, in which the high-speed steel powder was used along with paraffin and polypropylene as the binding agents.

2. Investigation methodology

The M2 (HS6-5-2) high-speed steel powder with high wettability was used for injection moulding due to its spherical shape. This powder is sprayed with the inert gas and has the average grain size of about 20µm. Output data from the control panel generated by Arburg injection moulding machine (Fig.1) are used in this work during forming process of the polymer-powder slurry with the following composition:

- HS6-5-2 high-speed steel powder – 70% volume fraction
- polipropylen i parafina – 30% polypropylene and paraffin – 30% volume fraction

The slurry filling temperature was 170°C. Moreover, data obtained during the rheological tests of the polymer-powder slurry was used. These tests were made on the ThermoHaake capillary rheometer. The data obtained during the tests represent the viscosity curve versus shear rate and test temperature, i.e., 170, 180, and 190°C, results of these investigations are presented in Table 4.

Simulations of the polymer-powder mix flow during filling, in which the high-speed steel powder, and paraffin and polypropylene as the binding agents were used, were carried out in the Cadmould program; this software was developed for filling process simulation of the thermoplastic plastics and rubber using FEM (Finite Elements Method), which makes it possible to eliminate flaws caused by, among others: short filling, air cavities, burns, contraction cavities, uneven distribution of material, traces of streams merging, overfill of the mould cavity, underfill, contraction/warping, skewing, non-uniform cooling [18-22].

For simulation requirements mould, process, and material data were used as presented in tables 1-3, and the following assumptions were made:

- mould filling time: 0.4 sec,
- mould filling up to 99% (compaction phase follows),
- filling temperature 180°C,
- temperature on the forming surface: 30°C,

temperature of green removal from the mould cavity: 70°C.

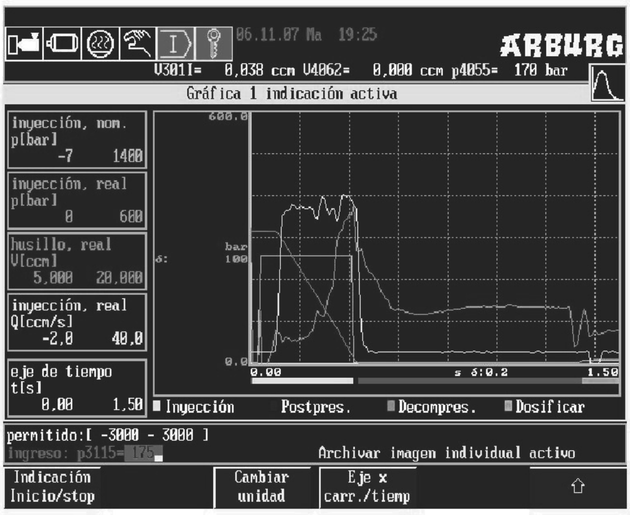

Fig. 1. Arburg injection moulding machine control panel display presenting the injection forming conditions

In Figs. 2 and 3 the dimensioned geometry of a plate with constriction and feed channel is presented, whereas in Fig. 4 there is the real model of the injection moulding machine cavity developed in Cadmould program. Thickness of the particular elements of the formed green is an important issue in designing the injection moulds, because of the cooling rate of the filled cavity. Thickness of the formed plate in the discussed case is 3 mm; therefore, the biggest thickness is characteristic of the feed channel, which is presented in Figure 6.

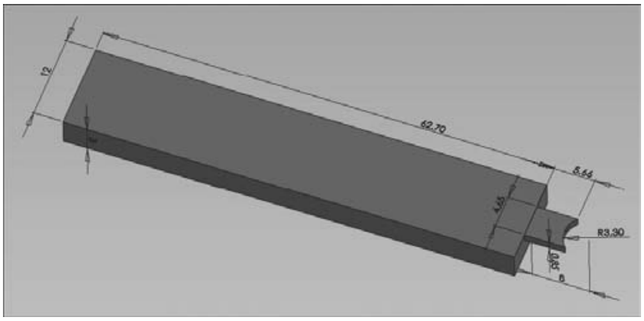

Fig. 2. Drawing of the formed green with constriction

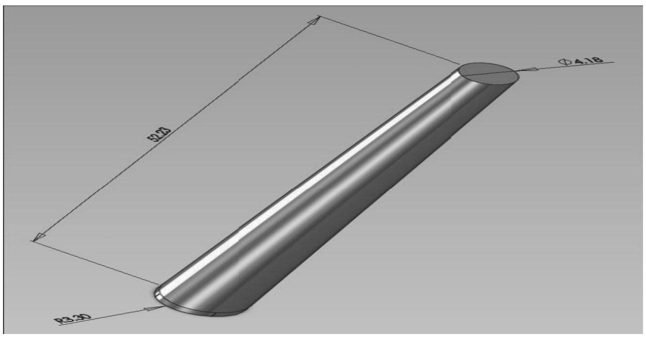

Fig. 3. Feed channel

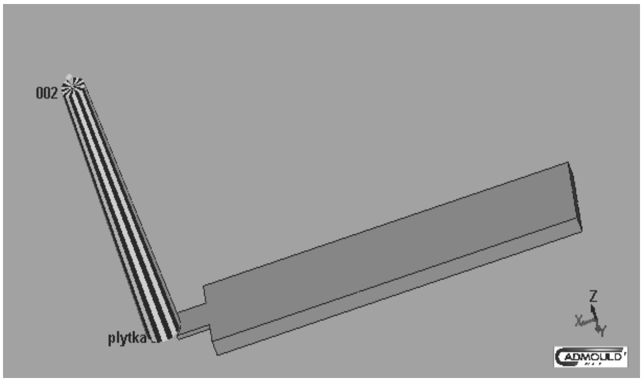

Fig. 4. Real model of the injection machine cavity

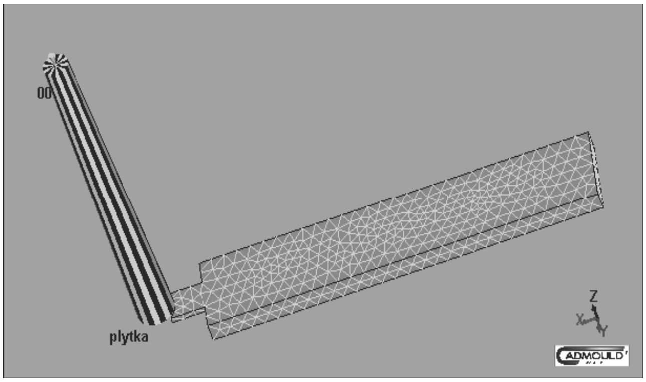

Fig. 5. Model with the finite elements mesh superimposed

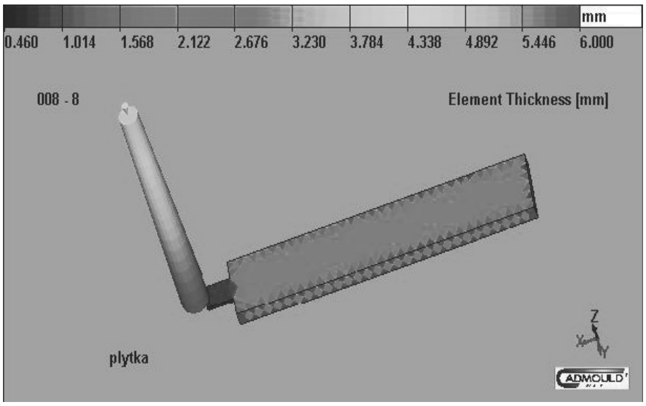

Fig. 6. Screenshot showing thickness of the particular elements whose filling was analysed

3. Investigation results

Modelling was carried out in the work of the injection moulding process of the polymer-powder slurry composed of the M2 (HS6-5-2) high-speed steel powder, paraffin, and polypropylene. Employment of the finite elements method for powders injection moulding modelling is not that commonly used as for simulation of the plastics injection moulding process. This is connected with many problems arising from the injection moulding machine charge properties. Properties of a thermoplastic, e.g., polypropylene, used as a binding agent change after adding the metal or ceramic powder. The volume fraction of the powder, its grain size and shape are very important. Modelling of the powder-polymer slurry flow calls for its previous rheological tests carried out for the slurry with the same chemical composition. Results of modeling carried out for the polymer-powder slurry, i.e., HS6-5-2 high-speed steel with polypropylene as the binding agent, of its injection moulding forming are comparable to the real filling conditions presented in Figure 1.

One should pay special attention to the mould filling time. The filling time is about 0.4 sec both for the real mould filling and in the modelled process. Therefore, we can conclude that the model and filling conditions were selected properly. Detailed analysis of the maximum filling pressure revealed that this pressure is about three times lower in the modelled process (Fig.10) than the real pressure (Fig.1). This was caused undoubtedly by the nominal pressure that was selected by the injection moulding machine operator during filling.

Table 1.
Mould specification

Total Cavity	
Surface	2009.66 mm
Volume	3311.68 mm^3
Centroid	43.722, 5.951, 62.085 mm
Mass	3g
Part1	
Surface	2009.66 mm
Volume	2277.04 mm^3
Centroid	31.645, 6.00, 54.509 mm
Mass	
Cold Runner	
Volume	1034.63mm^3
Centroid	70.302, 5.842, 78.759 mm
Mass	0.938g

Table 2.
Polymer-powder slurry injection process parameters

Recommended Process Parameters	
Melting Point	240 ^oC
Wall Temperature	30 ^oC
Ejection Temperature	70 ^oC
Process Parameters	
Filling Time	0.4 s
Pressure-Controlled Filling	99%
Melt Temperature	180 ^oC
Wall Temperature	30 ^oC
Ejection Temperature	70 ^oC
Heat Transfer Coefficient Mould (Filling)	Wall Thickness Dependent
Heat Transfer Coefficient Mould (Packing)	1000W/(m,K)
Heat Transfer Coefficient Mould (After Packing)	1000W/(m,K)

Table 3.
Polymer-powder mix specification

Basic Data	
Name	ADSTIF HA740N _od SIMCONA
Type	PP
Manufacturer	BASELL
Carreau Parameters	
P1	233.708 Pas
P2	0.00779182 s
P3	0.660922 s
T0	180 °C
Ts	-35.0613 °C
Fp	0 K/bar
Fp	
Ei	0Pas
Fp	
Fa	8.86
Thermal Data	
Thermal Conductivity	0.16 W/(mK)
Thermal Diffusivity	0.0731342 mm/s
No-Flow Temperature	140 ^{0}C
PVT Parameters	
PS1	48704 bar cmł/g
PS2	1.233 bar cmł/(gK)
PS3	1316.6 bar
PS4	42381 bar
PF1	79729 bar cmł/g
PF2	0.52463 bar cmł/(gK)
PF3	833.3 bar
PF4	73267 bar
PF5	1.63e-009 cmł/g
PF6	0.10053 1/k
PF7	0.000847 1/bar
PK1	179.81 ^{0}C
PK2	0.0063226 K/bar
Density (23^{0}C)	0.9067 g/cmł
Mechanical Data - Young's Modulus	
E0	2958.19 MPa
E1	-54.978 MPa/K
E2	0.4055 MPa/K
E3	-0.0011 MPa/K
Mechanical Data - Poisson Ratio	
N0	0.39
N1	0 1/k
N2	0 1/k
N3	0 1/kł

One should expect that lowering the real filling pressure would not affect development of flaws in the injection moulded green, e.g., like air cavities. However, lowering the filling pressure will reduce the screw and injection moulding machine cavity wear. This is especially important if the injection moulding machine charge is rich in the hard ceramic or metallic powder.

The calculation mesh is shown in Figure 5, on which all numerical calculations are carried out. The mesh is generated by the Cadmould program automatically, however offers the possibility to change the mesh parameters (its refinement) or manual editing, depending on requirements.

Table 4.
Rheological data of the mould charge - – PP+M2 powder.

Filling temperature, ^{o}C	Pressure, Pa	Shear rate, γ,[1/s]	Viscosity, η, Pas
170	4898	10	489.80
	5878	20	293.90
	10780	50	215.50
	18470	100	184.70
	27010	200	135.10
	43380	500	86.77
	59620	1000	59.62
	79770	2000	39.89
	114900	5000	22.98
	152300	10000	15.23
180	7977	10	797.70
	6998	20	349.90
	9797	50	195.90
	17910	100	179.10
	26590	200	133.00
	41710	500	83.41
	55140	1000	55.14
	72070	2000	36.04
	99370	5000	19.87
	124600	10000	12.46
190	7558	10	755.80
	7419	20	370.0
	7838	50	156.80
	10640	100	106.40
	19880	200	99.38
	38210	500	76.42
	52770	1000	52.77
	68590	2000	34.29
	93220	5000	18.64
	115500	10000	11.55

One can observe significant pressure jumps versus filling time (0.4 sec) in the filling simulation results. One can see three mould cavity filling stages on the curve (Fig.18): filling of gating system, filling of constriction, filling of green (plate).

Figure 7 presents filling pressure during mould cavity filling. One can observe the most significant pressure jump with the feed channel completely filled, when the material commences passing through the constriction (Fig.8). The gray zone is the zone that is still not filled with the material. The pressure keeps on growing in the next filling process phases (Figs. 9, 10) but sudden jumps do not occur any more, and the pressure increase may be qualified as linear.

Simulation presented in Figure 11 in which filling the particular zones of the mould cavity is shown in time is essential in case of the analysis of a system of two elements whose volumes vary – the correct design of the feed channels guarantees the simultaneous filling of both elements in the mould cavity.

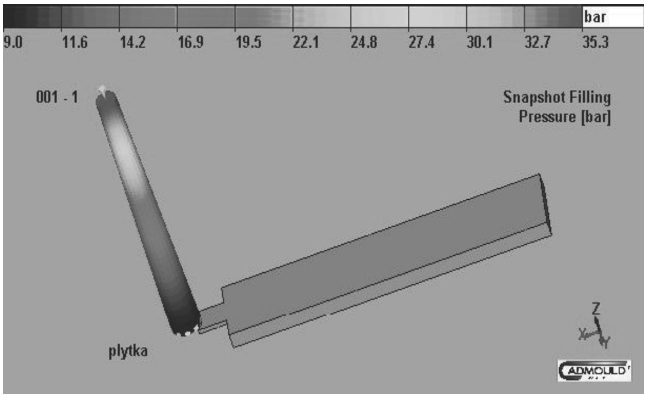

Fig. 7. Screenshot showing filling pressure during the injection mould cavity filling (space filling – 31%)

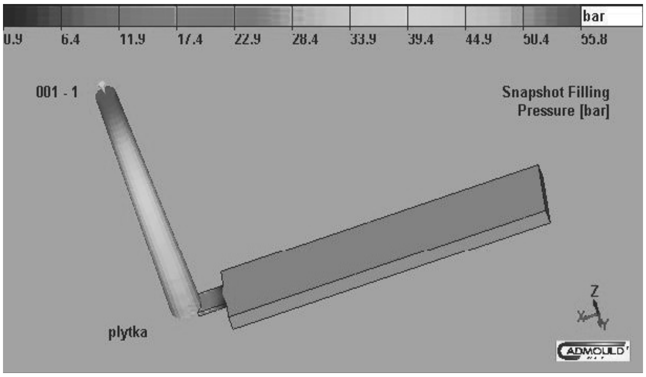

Fig. 8. Screenshot showing filling pressure during the injection mould cavity filling (space filling – 33 %)

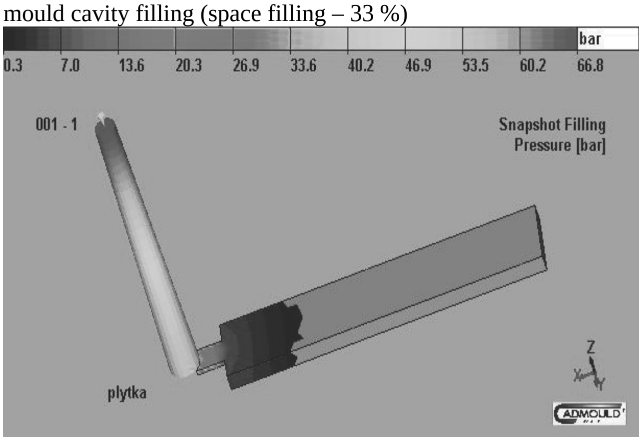

Fig. 9. Screenshot showing filling pressure during the injection mould cavity filling (space filling – 50 %)

One can observe in Figure 13 that the material flow rate grows significantly in the constriction zone, which leads often to the binding agent temperature growth, its degradation, and to development of gas cavities in the green volume. Is the undesirable effect and one should consider possibility of increasing the constriction transverse area.

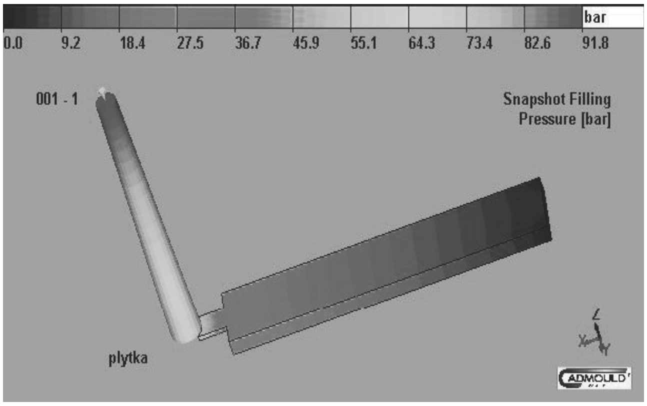

Fig. 10. Screenshot showing filling pressure during the injection mould cavity filling (space filling – 99 %)

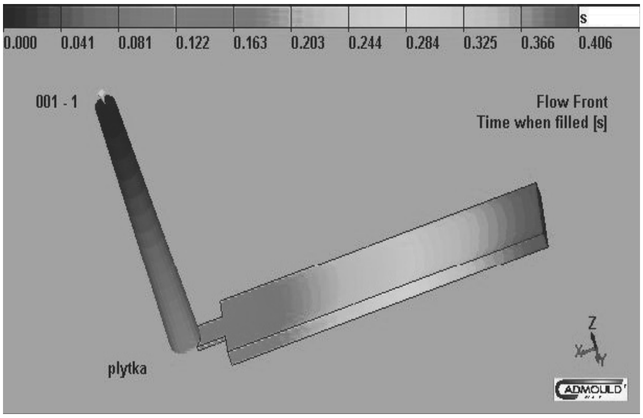

Fig. 11. Screenshot showing mould cavity filling rate

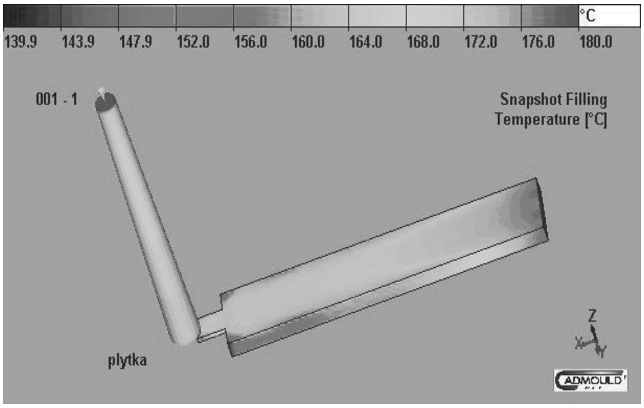

Fig. 12. Screenshot showing temperature on the test piece surface, immediately after filling the mould cavity

Modelling of the green cooling phase in the mould revealed that cooling time (Figs. 14, 19) depends mostly on the wall thickness (being proportional to the square of the wall thickness). As one can see, cooling time will be the longest for the feed channel and the shortest for the constriction. Figure 12 presents temperature at the test piece surface right after filling the mould cavity, and in Figure 15 one can observe volume shrinkage being very important for the process, as well as locations where surface breakdowns may occur (Fig. 16).

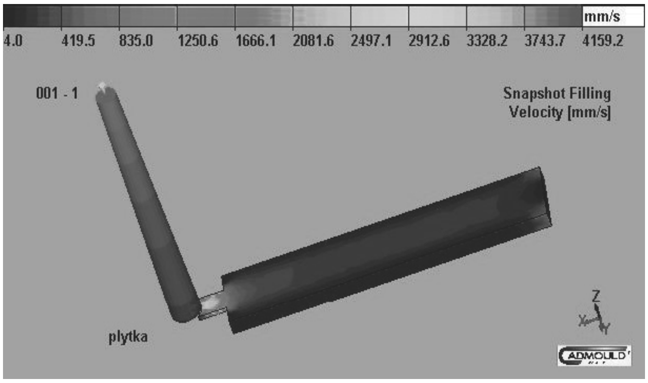

Fig. 13. Screenshot showing the filling velocity during filling the mould cavity

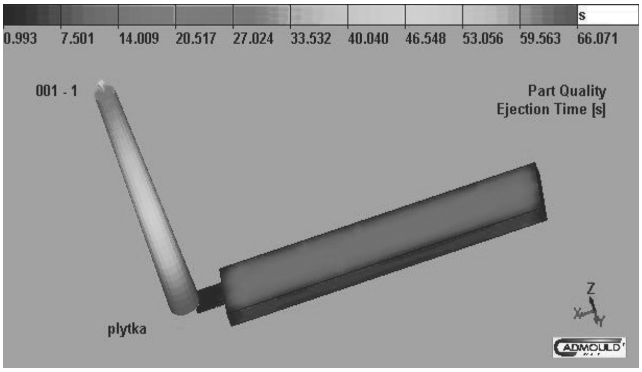

Fig. 14. Screenshot showing cooling time

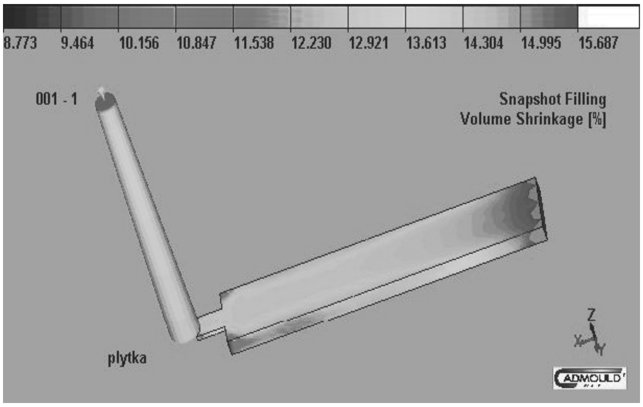

Fig. 15. Screenshot showing volume shrinkage

Analysis of filling the plate alone was also carried out within the framework of the filling simulation. It was found out that the pressure required to fill the system without the feed channel and constriction is more than three times lower than for the complete system (Fig. 17).

The optimum filling point found automatically by Cadmould program is shown in Figure 17. Shortening the filling path reduces the filling pressure more than twice. Pressure distribution in the mould cavity in the filling- (F) and compacting (P) phases is shown in Figure 20.

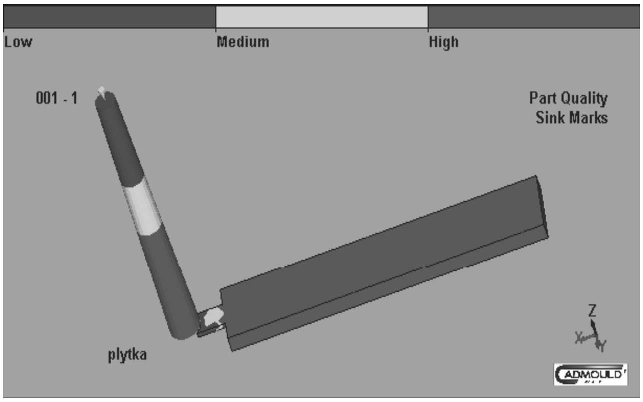

Fig. 16. Screenshot showing locations where sink marks may occur

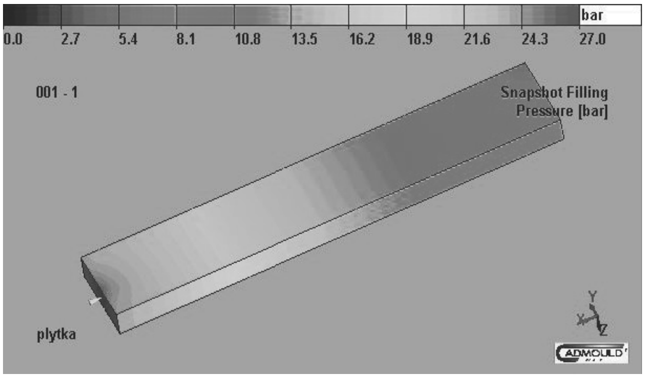

Fig. 17. Screenshot showing filling pressure from the shorter side (without the feed channel and constriction)

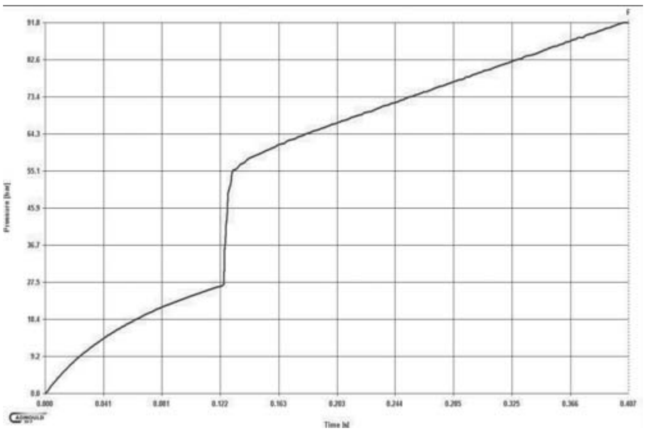

Fig. 18. Screenshot showing pressure versus time (0.4 sec)

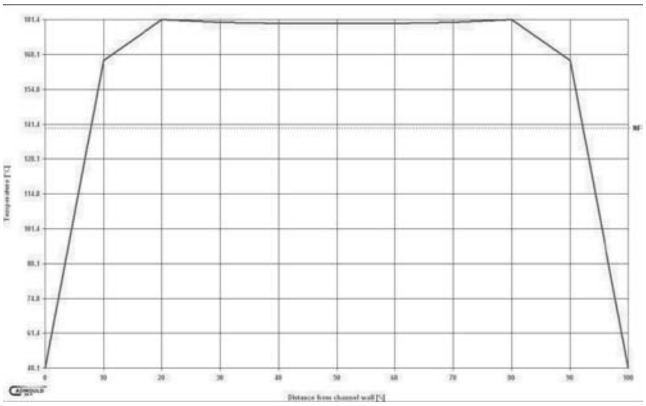

Fig. 19. Screenshot showing temperature distribution versus wall thickness

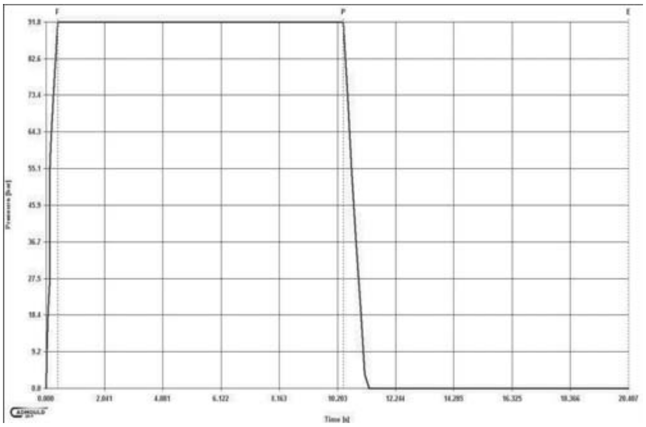

Fig. 20. Screenshot showing pressure distribution in the mould cavity during the filling (F) and packing (P) phases

4. Conclusions

The dynamic development of new techniques and fabrication technologies of greens formed from powders has made them competitive to the manufacturing techniques used to date. The new methods eliminate often the costly plastic forming and machining, being limited to finishing grinding only which is advantageous both because of the economic- and ecological aspects.

The main goal of the simulation is obtaining such feed filling system parameters that will ensure obtaining the lowest mould clamping force and lowest filling pressure values while retaining 100% filling and maximum use of the charge. This research goal is reduction the mould load level and reduction of the deformation effects. Designs resulting from simulation often costly experiments on the injection moulding machine and in the presented work they proved correctness of the injection moulding carried out.

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References

[1] R.M. German, A. Bose, Injection Molding of Metals and Ceramics, MPIF, 1997, Princeton, NJ.

[2] K. Wilczyński, Rheology in plastics processing, WNT, Warsaw, 2001 (in Polish).

[3] E. Bociąga, Special methods of plastics injection moulding, WNT, 2008 (in Polish).

[4] R.M. German, A-Z of Powder Metallurgy, Elsevier, 2005, Ltd.

[5] G. Herranz, G. Matula, R. Alonso, I. Sánchez, G. Rodríguez, Metal lnjection Moulding of Carbides Reinforced M2 HSS, Powder lnjection Moulding-Compounds & Composite Parts, (2009) 99-104.

[6] G. Matula, T. Jardiel, B. Levenfeld, A. Várez, Application of powder injection moulding and extrusion process to manufacturing of Ni-YSZ anodes, Journal of Achievements in Materials and Manufacturing Engineering 36/1 (2009) 87-94.

[7] G. Matula, L.A. Dobrzański, G. Herranz, A. Várez, B. Levenfeld, J.M. Torralba, Influence of Binders on the Structure and Properties of High Speed-Steel HS6-5-2 Type Fabricated Using Pressureless Forming and PIM Methods, Materials Science Forum 534-536 (2007) 693-696.

[8] L.A. Dobrzański, G. Matula, G. Herranz, A. Várez, B. Levenfeld, J.M. Torralba: Metal injection moulding of HS12-1-5-5 high-speed steel using a PW-HDPE based binder, Journal of Materials Processing Technology 175 (2006) 173-178.

[9] G. Matula, L.A. Dobrzański, G. Herranz, A. Várez, B. Levenfeld, J.M. Torralba, Structure and properties of HS6-5-2 type HSS manufactured by different P/M methods, Journal of Achievements in Materials and Manufacturing Engineering 24/2 (2007) 71-74.

[10] G. Matula, L.A. Dobrzański, G. Herranz, A. Várez, B. Levenfeld, J.M. Torralba, Comparison of structure and mechanical properties of HS12-1-5-5 type high-speed steels produced by PIM method and heat treated, Proceedings of the 7th International Tooling Conference Tooling Materials and their applications from research to market, Torino, Italy, 2006, 417-422.

[11] G. Matula, L.A. Dobrzański, G. Herranz, A. Várez, B. Levenfeld, J.M. Torralba, Influence of atmosphere and temperature of debinding on microstructure of HS6-5-2 HSS parts produced by Powder Injection Moulding, Processing and Fabrication of Advanced Materials 2 (2005) 752-761.

[12] G. Matula, G. Herranz, A. Várez, B. Levenfeld, J.M. Torralba, L.A. Dobrzański, Microstructure and mechanical properties of T15 high-speed steels parts produced by powder injection moulding using a polyethylene based binder, Proceedings of the Powder Metallurgy World Congress (2004) 469-475.

[13] E. Bociąga, T. Jaruga, Visualization of melt flow lines in injection moulding, Journal of Achievements in Materials and Manufacturing Engineering 18 (2006) 331-334.

[14] T. Barriere, J.C. Gelin, B. Liu, Experimental and numerical investigations on properties and quality of parts produced by MIM, Powder Metallurgy 44 (2001) 228-234.

[15] S.V. Atre, S. J. Park, R. Zauner, R.M. German, Process simulation of powder injection moulding: identification of significant parameters during mould filling phase, Powder Metallurgy 50 (2007) 76-85.

[16] P. Suri, R.M. German, J.P.de Souza, S.J. Park, Numerical analysis of filling stage during powder injection moulding: effect of feedstock rheology and mixing conditions, Powder Metallurgy 47 (2004) 137-142.

[17] M. Dutilly, O. Ghouati, J.C. Gelin, Finite-element analysis of the debinding and densification phenomena in the process of metal injection molding, Journal of Materials Processing Technology 83 (1998) 170-175.

[18] S. Łączka, Introduction to the ANSYS Finite element system, Cracow Technical University Press, 1999.

[19] O.C. Zienkiewicz, Finite elements method, 2000.

[20] M. Kupczyk, Technological and functional quality of cutting tool flanks with the anti wear coatings, Poznan 1997, (in Polish)

[21] T. Chmielewski, H. Nowak, Computer-aided CAD CAM, WNT –Warsaw, 1996.

[22] F. Bernal, G. Herranz, M. Kindelan, B. Levenfeld, L. Bonilla, J.M. Torralba, Numerical Simulation of Powder Injection Moulding (PIM) Process of Metal-Loaded Polymers Into a Shallow Cavity, Proceedings of European Powder Metallurgy Conference, Valencia, Spain, 2003, 187-192.