

# Simulation of powder injection moulding conditions using cadmould program

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## Analysis and modelling

### ABSTRACT

**Purpose:** Development of a new generation tool materials on the basis of high speed-steel manufactured by Powder Injection Moulding. To investigate formability of the polymer-powder slurry in which the HS12-1-5-5 (T15) high-speed steel powder was used, as well as the HD-PE polyethylene and paraffin, the „Cadmould” commercial software was employed, developed mostly for simulation of the powder injection moulding of the thermoplastic and composites.

**Design/methodology/approach:** Powder metallurgy, powder injection moulding, sintering, microstructure examination, symulation of injection moulding.

**Findings:** Simulation of powder injection moulding was preceded by the rheological tests, which made obtaining possible of the data indispensable for modelling, pertaining to the polymer-powder slurry viscosity. The portion of particles reinforcing the composite is usually lower than powder portion in mixtures used for forming and next binding agent degradation and sintering. The big powder portion is often the reason for the high viscosity of the mixture and problems with its forming. However, simulation results revealed that the fabricated polymer-powder mixture may be injected, which was confirmed by carrying out powder injection moulding on a typical Arburg injection moulding machine using in the industry.

**Practical implications:** Application of powder injection moulding to manufacturing of high speed steel matrix composites gives the possibility to obtain tool materials with the relative high ductility characteristic of steel and high hardness and wear resistance typical for cemented carbides.

**Originality/value:** Application of symulation of powder injection moulding conditions using cadmould program gives the possibility to reduce cost of expensive injection mould and control the injection conditions.

**Keywords:** Powder injection moulding; Tool materials; Sintering; Simulation

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## 1. Introduction

Forming shapes of ceramic or metal elements fabricated with injection powder forming method is done by employing the classic injection moulding machines used for forming the thermoplastic plastics [1-5]. Most often, the screw surface and

mould cavity of such injection moulding machine are characteristic of a higher abrasion wear resistance. Powder injection moulding is possible thanks to the binding agent used, which is composed mostly from the thermoplastic polymers, and its portion is from 30 to 55%, depending on the powder used, shape of grains, specific surface, wettability, binding agent properties, forming temperature, and many other factors, which

affect properties of the polymer-powder slurry [2]. In powder injection moulding of thermoplastics computer assistance is often used as software making selection possible of forming conditions, mould geometry, injection point, and many other factors, which eliminates the eventual errors and high costs connected with modification of the injection mould [6, 7]. Therefore, employment of the finite elements method for modelling of the injection moulding of thermoplastics is widely known and used in research and industry. In most cases, simulation of injection moulding of the known and readily available thermoplastics is relatively easy because of the known properties of these materials. In this case material testing is not required. However, then the matrix from thermoplastics is reinforced with the solid particles, like fibres or powders, one should always carry out investigation of properties of the polymer-powder mixtures. In particular, rheological examinations of the polymer-powder slurry used in the powder injection moulding make it possible to determine the minimal binding agent portion ensuring the relatively low viscosity and, therefore, enabling injection of the plasticised slurry. Increase of the binding agent portion lowers the slurry viscosity (which is essential for easy injection) but may lead to distortion of the element sintered next. Moreover, using the multicomponent binding agent is recommended, which makes its degradation easier. Therefore, to evaluate the feasibility of powder injection moulding or only its computer simulation, investigation of the polymer-powder slurry properties is necessary because of the multicomponent binding agent and high portion of solid particles.

Investigation results, presented in previous publications, of structure and properties of high-speed steels and cermets fabricated with powder injection moulding method indicate to advisability of employing this technology for manufacturing tool materials [8-11]. Problems during forming the simple shapes are incommensurable with those that which may occur during forming of elements with complex shapes. Therefore, computer assistance in the form of process simulation, making design possible of the injection mould and determining forming conditions, becomes indispensable.

Cadmould 3D-F of a German company Simcon was selected for computer simulation of the polymer-powder slurry injection, which uses the finite elements method. This program makes possible, among others, analysis of the injection point location, analysis of the pressure distribution in the mould cavity, analysis of the material intake system, analysis of filling and loading of the mould cavity, analysis of the cooling system, analysis of contraction and deformation, as well as many other issues [12].

## 2. Materials and research methodology

Powder of M2 and T15 steels used, made by Sandvik Osprey Ltd., is sprayed with the neutral gas and is characteristic fig of spherical shape. The average grain size does not exceed the value of 20  $\mu\text{m}$ , therefore, this powder is suitable for powder injection moulding. Apart from its shape, distribution of grain size is also an important factor. If the grain size distribution characteristics of the investigated powder is relatively wide, the pores originating between big grains may be filled with small particles, which is attested by the curve slope angle coefficient  $Sw$  [2].

$$Sw = \frac{2,56}{\log\left(\frac{D_{90}}{D_{10}}\right)} \quad (1)$$

Powder with the  $Sw$  coefficient of ca. 2 is most recommended for powder injection moulding. Moulding of powder with the  $Sw$  coefficient equal to 7 is not recommended, as for this powder the grain size distribution characteristics is very narrow. A table is presented below with the particular parameters of powders and computed  $Sw$  coefficients. Powder from the M2 steel is characteristic of the highest value of  $Sw$  coefficient. The calculated  $Sw$  coefficients of the powders used do not exceed value of 4, which attests to their applicability for powder injection moulding [2].

Paraffin (PW) and polypropylene (PP) with portions 50/50% or PW and the high density polyethylene (HDPE) in the same proportions were used as the binding agent which would make powder injection moulding possible. Next, the binding agent with the high-speed steel powder were mixed in the universal high speed mixer Haake Rheomex CTW100p making measurement possible of torque and rotational speed of blades and feedstock temperature. Rheological tests of mixtures of the high-speed steel, carbides, and binding agent were carried out using the ThermoHaake Rheofix capillary rheometer at temperatures of 170, 180, and 190°C. Shearing rates during the tests were in the range from 10 to 10000  $\text{s}^{-1}$ .

Results of the rheological tests and torque as a function of phase composition of the investigated polymer-powder mixtures and time of their homogenisation made it possible to select for the further investigations the mixture characteristic of the relatively low viscosity, high volume portion of powders, good wettability of powders by the binding agent and, therefore, capability for quick homogenisation. Mixture selected in this way was processed further in the Rheomex CTW100p device with the addition of twin-screw extruder, which ensures obtaining the high homogeneity level of the feedstock prepared for the final injection. To determine the temperature of powder injection moulding of the polymer-powder mixture, the melting point was determined of the binding agent used with the differential scanning calorimetry method in the Perkin Elmer device, model Diamond. The device and computer software used make it possible to log the amount of heat, presented as a peak, as the thermal effect of the ongoing process. The thermogravimetric analysis was carried out in the TGA Perkin Elmer Pyris 1 device. Investigations were carried out in the atmosphere of the flowing mixture of gases  $\text{N}_2$ -10% $\text{H}_2$  and Ar. For the powder injection moulding the Arburg 220-s injection moulding machine was used equipped with the single cavity mould for a flat plate with dimensions (63 x 12 x 3 mm).

The commercial Cadmould software was used for the powder injection moulding simulation, using Carreau-WLF (William-Landel-Ferry) or Cross-WLF mathematical models. The Carreau-WLF model was used for simulation. The Carreau P1, P2, and P3 parameters, as well as T0 and Ts temperatures have to be determined using plots showing viscosity versus shearing rate. These values have to be entered into the program. An example of the program window is shown in Fig. 1.

The Carreau P1, P2, and P3 parameters are, respectively, the viscosity for the shear rate of 0  $\text{s}^{-1}$ , shear rate for which shoulder of a curve occurs, i.e., transition from the shearing rate at which

the fluid is Newtonian into the pseudoplastic range, and the coefficient specifying the decrease of viscosity along with the shearing rate growth. The model used for computation in Cadmould software is presented in Fig. 2. The mould cavity model is treated by the program as the thin-walled object, whereas, the so called cold intake channel, supplying the material, the program treats as the thick-walled object. Models of the cavity and supply channel are made in the CAD and Cadmould software respectively. The computational mesh required for simulation is shown on the mould cavity model (beam for bending). The mesh is generated automatically by Cadmould software, however, it makes changes possible of the mesh parameters or its manual editing, depending on the required accuracy of calculations.

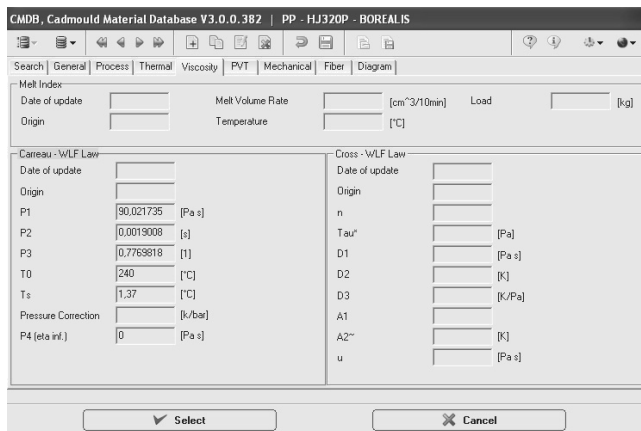


Fig. 1. Dialog window of Cadmould program

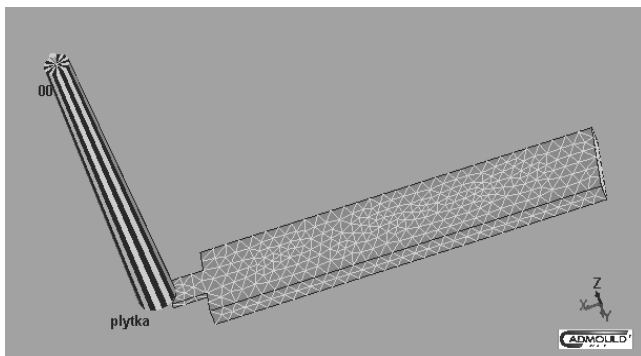


Fig. 2. Model of the channel supplying the material and model of the mould cavity with the superimposed finite elements mesh

### 3. Results and discussion

Results of investigations made in the capillary rheometer and measurements of the torque during mixing the polymer-powder slurry revealed that the portion of metal powder should not exceed 70%. Because of the possibility of paraffin degradation during mixing of the binding agent with the powder, and of the viscosity growth, the powder portion used for the powder injection moulding was assumed to be 68%.

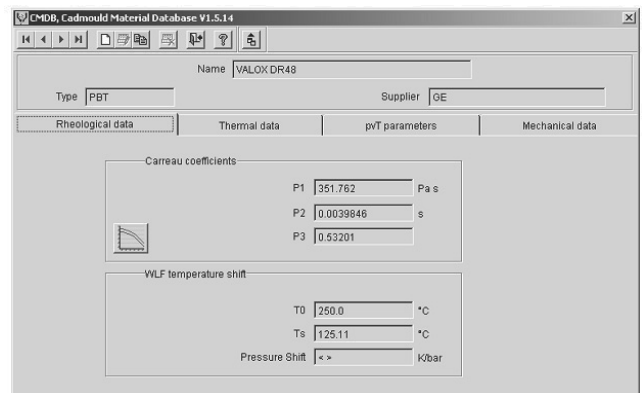


Fig. 3. Carreau parameters and WLF temperature shift calculated for the T15/HDPE/PW mixture

Carreau parameters were determined based on the viscosity curves obtained from rheometer as function of shear rate and using the SimFit program included in the Cadmould program package.

In industry, the shear rates from 100 to 10.000  $s^{-1}$  are used mostly, which is connected with the characteristics of the injection moulding machines operation. Carreau parameters and WLF temperature shift calculated by the program and displayed in the dialogue window are shown in Fig. 3.

Apart from the rheological properties, specific heat of the moulded composite and its thermal conductivity were taken into account for the powder injection moulding process simulation. Moreover, it is necessary to determine the minimal and maximal injection temperatures. The minimal temperature determined with the differential calorimetry method is 127°C. The maximum injection temperature may not exceed the degradation temperature of any of the binding agent's components. In this case, paraffin is subjected to degradation at the lowest temperature. It was found, based on thermogravimetric tests, that start of thermal degradation of paraffin occurs at the temperature of 198°C. Finally, the temperature which was used for simulation and next for the powder injection moulding was 170°C. Simulation results of the powder injection moulding of the T15/HD-PE/PW polymer-powder mixture revealed that it may be used for moulding in the injection moulding machines, in spite of the high powder portion. Comparing moulding conditions of the investigated polymer-powder mixture (Fig. 4) with other composites or polymers alone (Fig. 5) one should state that pressure required to fill the cavity and the mould clamping force are lower than in case of moulding other composites or pure high-density polyethylene. Detailed simulation results for various polymers, composites, and the investigated material are presented in Table 1. Mechanical properties of the HS12-1-5-5/HDPE powder injection moulded materials are poor. Bending strength does not exceed the value of 25 MPa. It is the effect of the excessive powder portion, which causes decrease of the mechanical properties, therefore, that high portion of the reinforcing particles is not used in composites. In case of the powder injection moulding, mechanical properties of the moulded shape are not that important because the moulded element is subjected next to thermal degradation and sintering, after which it attains the high mechanical properties. Bending

strength of the HS12-1-5-5 steel sintered at the temperature of 1260°C in the nitrogen-hydrogen atmosphere is about 1200 MPa. The structure examination results revealed that the shape made with powder injection moulding is homogeneous and does not have gas cavities.

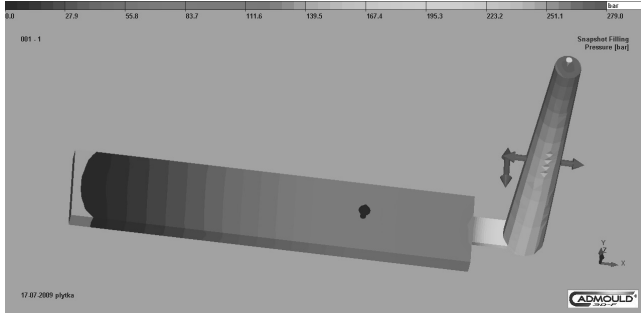


Fig. 4. Screenshot showing pressure distribution after 98% filling of T15/HD-PE/PW composite

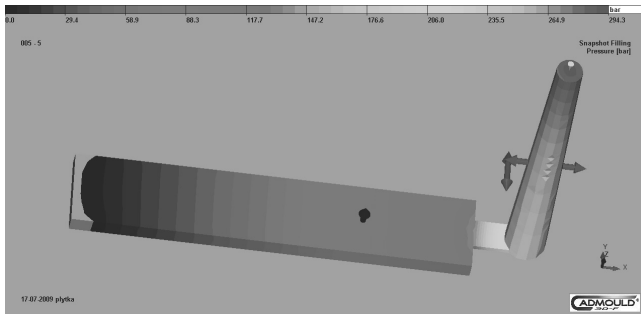


Fig. 5. Screenshot showing pressure distribution after 98% filling of difficult flowing HD-PE

Table 1. Simulation results of powder injection moulding

Material	Injection temperature, °C	Wall temperature filling, °C	Ejection temperature, °C	Simulation result of samples without sprue and gate			Simulation result of samples with sprue and gate		
				Filling time, s	Pressure of injection slot, bar	Clamping force, kN	Filling time, s	Pressure of injection slot, bar	Clamping force, kN
68% of T15, 16% HD-PE, 16% PW	170	40	45	0.158	121.8	4.8	0.193	285.2	6.8
PA 6 + 30% glas fiber	277.5	85	185	0.159	67.1	2.8	0.194	269.9	5.4
PA 6 + 60% glas fiber	250	60	185	0.159	158.1	6.1	0.194	361.6	8.4
PBT + 30% glas fiber	245	90	200	0.159	144.2	5.6	0.194	388.9	8.4
HD-PE (difficult flowing)	225	50	95	0.160	130.5	5.1	0.195	299.1	7.2
HD-PE (free flowing)	250	30	90	0.158	80.9	3.4	0.193	235.4	5.4
PA 6	257.5	65	162	0.160	22.5	1.0	0.195	113.0	2.1
PBT	255	45	180	0.160	95.0	3.7	0.195	272.7	5.7

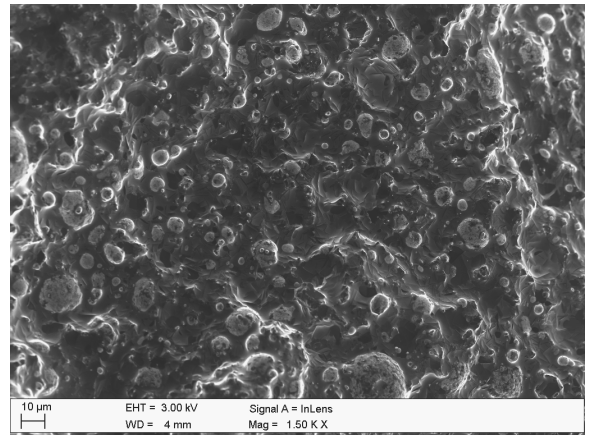


Fig. 6. Microstructure of HS12-1-5-5/HDPE after injection moulding and bending test

Grains of the high-speed steel powder do not form agglomerates and are wrapped with the tightly adhering binding agent. Fracture of the shape after the powder injection moulding is presented in Fig. 6.

The HS12-1-5-5 high-speed steel sintered at the temperature of 1260°C is characteristic of fine dark precipitations rich in V and N with spherical shape and size which does not exceed 2µm and bright carbides rich in W with the maximum size of 20µm (Fig. 7). These precipitations were identified with the EDS method. Steel structure does not display the band-like segregation typical for the cast and plastic formed high-speed steels.

Specimens after powder injection moulding and sintering are shown in Fig. 8. The sintered material is characteristic of the big linear contraction of 14% which results from the binding agent degradation and subsequent consolidation of the powder during sintering.

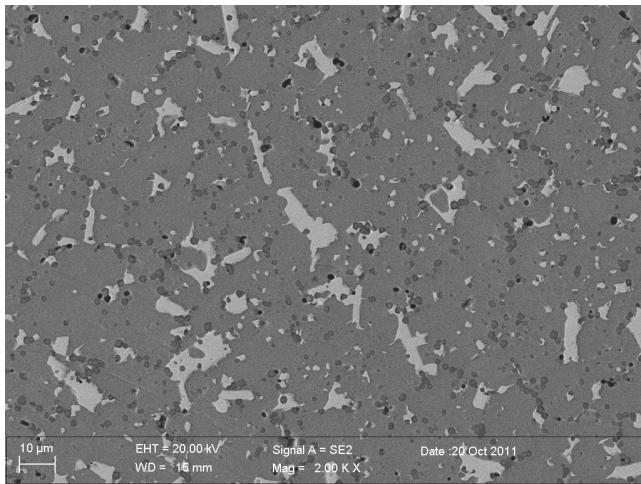


Fig. 7. Microstructure of HS12-1-5-5 high-speed steel sintered at the temperature of 1260°C



Fig. 8. View of samples after moulding and sintering at the temperature of 1260°C

#### 4. Conclusions

Injection simulation is possible, based on the precise data pertaining to the polymer-powder mixture properties, using the finite elements method, and observation of the process of filling the mould with the polymer-powder slurry at the successive injection steps. One should stress in particular the practical aspect of injection modelling, as it may partially substitute the costly technological tests. Results of the rheological tests and of the computer simulation carried out of the powder injection moulding using the CADMOULD program revealed that the fabricated polymer-powder mixtures may be injection moulded, which was confirmed by carrying out the powder injection moulding on typical injection moulding machines used in the industry. The injection moulding conditions, and in particular the real time of filling the cavity is comparable with the time which is presented

by the computer simulation. The investigated polymer-powder slurry is characteristic of better technological properties compared with the HD-PE high-density polyethylene or composite PA 6 + 60% glass fibre and PBT + 30% glass fibre. The moulded shape after thermal degradation and sintering is characteristic of the 30% linear contraction. Results of structure examinations revealed that the powder injection moulded and sintered at the temperature of 1260°C high-speed steel is characteristic of fine precipitations of carbides and carbonitrides in ferrite matrix and does not display the band-like segregation typical for the cast and plastic formed high-speed steels.

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