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The systemic analysis of metal injection moulding

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Summary

The study reported in this paper comprises the making and description of the general model for metal injection moulding (*MIM*) and the analysis of the mentioned process with Rophol's theoretical definitions. The model includes a complex of elements of the metal injection process. The elements are the core of the model and the inputs, outputs and relations it the above mentioned elements. The basic principles of this process and all the phenomena connected with *MIM* are represented by means of inputs, outputs and relations. An exact analysis of metal injection moulding was made using a precise and systematic approach. The analysis could be used for a more detailed recognition of *MIM*, especially for the beginners in this field.

KEY WORDS:
hierarchical, functional and structural concepts
metal injection moulding (*MIM*)
systemic analysis
systemic model of injection moulding of metal particles

KLJUČNE RIJEČI:
hijerarhijski, funkcionalni i strukturni concept
injekcijsko prešanje metalnih čestica (*MIM*)
sustavnosna raščlamba
sustavnosni model injekcijskog prešanja metalnih čestica

Sustavnosna analiza injekcijskoga prešanja metalnih čestica

Sažetak

Načinjen je i opisan opći model injekcijskoga prešanja metalnih čestica s pomoću Ropohlovih teorijskih definicija. Modelom su opisane temeljne funkcije procesa, uključivo ulaze, izlaze i veze među funkcijama (sastavnice sustava). Temeljna načela procesa i svi fenomeni povezani s *MIM*-om predstavljeni su s pomoću ulaza, izlaza i relacija. Svrha je provedene sustavnosne raščlambe bolje razumijevanje procesa injekcijskoga prešanja metalnih čestica, posebno s motrišta početnika.

Introduction

We are surrounded by extremely complicated products, the production of which is very expensive and demanding. The need for such products leads to the emergence of new procedures, whose only point in common is to make a product that will be competitive in the market. A product can be competitive if practical experience and theoretical knowledge are associated in it. The problem is that theoretical knowledge is sometimes being ignored in practice, with a trial-and-error principle being preferred.

The main purpose of this paper is to present the theoretical systemic analysis of metal injection moulding, which can be used as a basis for the recognition of this relatively new technology. The analysis was made on the basis of the article *The systemic analysis of injection molding*[1] and the book the *Systemic analysis of injection moulding of polymers.*[2] In studying the mentioned sources it was found that a large gap prevails in this field of work. In[2], only the basic model of injection moulding of polymers and other substances is presented. Due to this fact, it was decided to make a systemic analysis of metal injection moulding. The systemic analysis includes the making of a basic model for *MIM* and the analysis of this process in the light of Ropohl's theoretical definitions.

Metal injection molding

R. M. German is one of the leading experts in powder injection moulding and has thoroughly described this process in his sources.[3-7] Metal injection moulding is a cyclic process, during which a compound of metal powder and binder is injected into a mould. After the solidification of the binder, a green part with poor mechanical properties is formed. After injection moulding, a debinding process is used to remove the binder from the green part. The debinding can be thermal, catalytic or solvent. The part with has almost all binder removed is the brown part and is very fragile. The firmness of the brown part is achieved through the rest of the binder, which is removed during the sintering process. During sintering, the powder particles are joined together at high temperatures. The size of the pores is reduced and the density of the part reaches from 94 - 99 % of the theoretical density. Because of a highly porous structure the shrinkage can reach up to 30 %. After sintering, mechanical properties are improved, while the chemical and electrical ones undergo certain changes. Furthermore, it is possible to treat the piece thermally or mechanically in order to achieve higher mechanical properties, narrower tolerances and lower surface roughness.

Due to relatively expensive equipment the procedure is competitive, above all, in the field where greater quantities of such complicated products are produced. It is the smaller products that are usually produced because tolerance deviations increase with the size of the product. The greatest advantage of this procedure is that all sintering-suitable (sinterable) materials can be processed. Although this article deals mainly with metal injection moulding it is important to mention that other materials can be processed as well - carbides, silicates, ceramics, etc.

The process of injection moulding of metals is very similar to that of polymers.[8] Differences can be seen in the individual segments of the mould, while the injection moulding machine for this procedure requires a different screw and cylinder. The metal powder is extremely abrasive, which requires the surface of the screw and cylinder to be wear resistant. Moreover, the core of the screw itself must be tough.[4]

The size of the powder particles ranges between 1 μm and a few of 100 μm. The most appropriate size of an individual particle for the process of metal injection moulding is smaller than 30 μm, the average size of a particle being approximately 6 to 7 μm. The powder particles can be of various shapes, although the desired shape is a round one. In this way, it is possible to overcome certain anisotropic characteristics of a product while shrinking.

The binder performs several different functions: it enables the flow of a compound and contributes to the firmness of the green and brown parts during the process of debinding and sintering. The binder must fulfil a number of criteria - enabling a quick debinding; sufficient strength after the process of solidification of the green part; a low enough viscosity for the process of injection; the structure of short molecules in order for a binder to penetrate the narrow voids, etc. There are many kinds of binders, viz. the ones based on polymers (PP, PE, POM, PA, PS), organic binders, for example, agar (a mixture of seaweed, mostly algae,[5,6] paraffin wax and beeswax, thermoset (rarely used)[3] etc. It is possible to add various additives in order to lubricate the powder; supplements for joining different binders; lubricants; supplements for lowering viscosity.

The binder and the powder need to be compounded to an extent such as to produce a highly homogeneous structure. The binder must surround the powder particles evenly in order to avoid different defects while injecting, debinding and sintering. It is often the case with small particles that powder agglomerations occur. This leads to a poorly lubricated surface and, thus, to a mixture which is not homogeneous. These mentioned agglomerates must be crumbled during the process of mixing.

In industry, it is only in the last couple of years that this procedure has gained ground and it is only now that various possibilities made possible by the procedure are becoming known. Many different materials and binders are appears on the scene, the process of debinding is getting shorter; narrower tolerances are being achieved; micro-products of high precision are emerging and the products themselves are getting more complex. It is possible to make products consisting of several components, with negative angles, outer and internal threads, etc.

Systemic analysis of injection molding

The following section is based on the article *The systemic analysis of injection molding*[1] and the book *Systemic Analysis of Injection Moulding of Polymers*.[2,9]

In observing certain problems, objects or phenomena it is important to be systematic, which facilitates dealing with the matter on the whole and, at the same time, pointing at individual segments of which a certain phenomenon or object consists.

In producing a general model, three concepts have been used – hierarchical, functional and structural (Figures 1-3). It is typical of a hierarchical concept that a certain system consists of several subsystems (e.g. mould, thermolater etc.). At the same time each subsystem must fulfil all criteria to be systems themselves (Figure 1).[2,10]

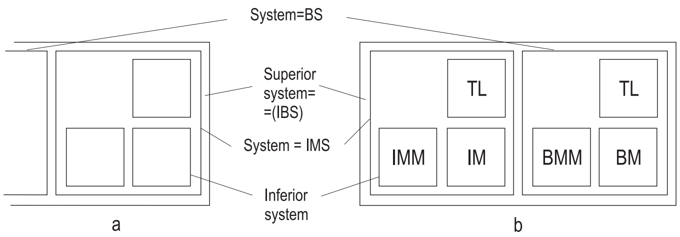

FIGURE 1. The hierarchical concept of the injection moulding system: BS – blowing system, IMS - injection moulding system, IBS – injection blowing system (super system), IMM - injection moulding machine, IM - injection mould, TL - thermolater, BMM – blow moulding machine, BM-blow moulding mould[2,9]

The functional concept concentrates on the functioning and reaction of substances (Figure 2). The concept represents inputs, outputs and the state of a system. Inputs and outputs are divided into material, energy and information.

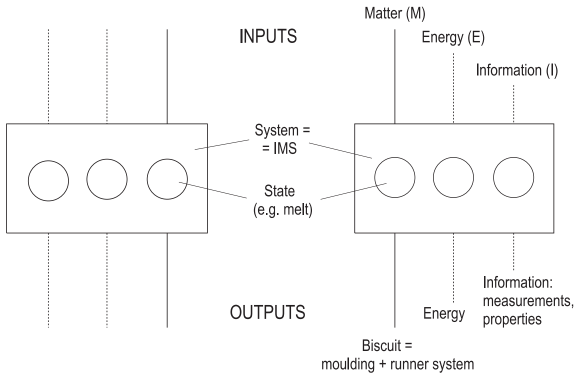

FIGURE 2. The functional concept of an injection moulding system[2,9]

The structural concept represents a system as a whole made up of several mutually related elements (subsystems), where the whole does not act as a mere sum of individual parts, but also of the relations among those parts (Figure 3).

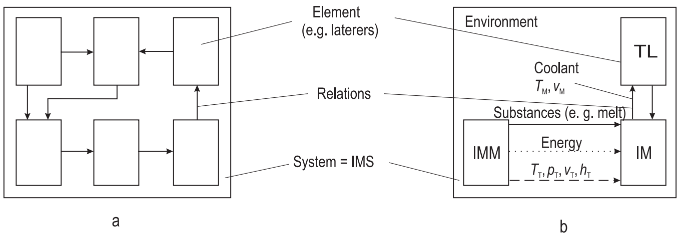

FIGURE 3. Structural concept: IMS - injection moulding system, IMM – injection moulding machine, IM – injection mould, TL – thermolater[2,9]

To establish inputs, outputs and relations between the elements, it is important to define a means of characterization, represented in Figure 4.

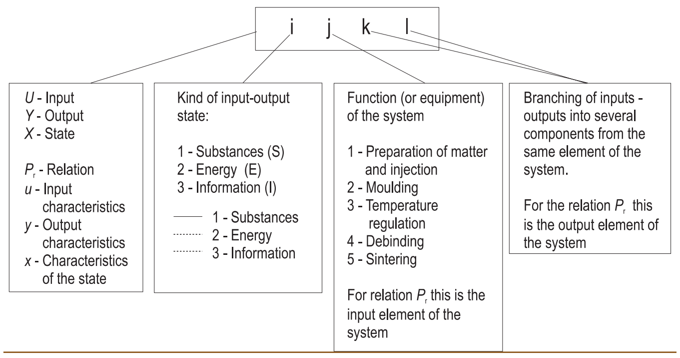

FIGURE 4. Simbolic representation of metal injection moulding system[9]

General model of *MIM*[9]

The *MIM* system is divided into 5 subsystems (Figure 5):

- preparation of substances and injection of melt
- moulding
- temperature regulation

– debinding
– sintering.

The first two subsystems refer to the process of injection moulding itself, while the last two represent the additional subsystems typical of powder injection moulding only. The temperature is regulated in all the subsystems. The subsystems are made up of the following elements: injection unit; mould; element for debinding and sintering furnace.

With the expansion of the Čatić-Rujnić model[2] an additional relation between the subsystems of sintering, debinding and temperature regulation was established. In the following section only the main differences among the general model of injection moulding described in[1,2] and metal injection moulding will be put out.

The main difference among the above-mentioned systems are two additional elements for sintering and debinding. In both processes extra outputs, inputs and relations occur. In both, the atmosphere is used, while in debinding combustion gases and solvents are used.

Two intermediate phases of the final product are typical of *MIM* – green and brown part. The green part can be a final product only in the case of plastic bonded magnets. With the green part the information about injection moulding is transferred to the element of debinding. After debinding the brown part is produced whose possible errors, structure and properties, give the information about the process of debinding.

With an informational close-loop the flow rate of gases at debinding is determined so as to measure the gas composition when exiting the element. The process is controlled with the help of the output information on the basis of which the system is regulated. In order to correctly determine various parameters, the regulation of all the processes with informational relations is of high importance.

Certain energy relations within the system are in practical work often disregarded although they do represent an important part of the process. When debinding and sintering an exothermic reaction occurs, which causes problems in temperature regulation. In all the elements of the system the heat transfer is carried out by means of convection, radiation, conduction, and also by exit and combustion of gasses.

One needs to take into account the fact that a narrower and broader environment, which is connected with the system by inputs and outputs, surrounds every system. Narrower or technical environment, influence the system through temperature, humidity and pressure, which results in debinding with drying.

Systemic analysis of *MIM*

Systemic analysis of injection moulding of substances, based on Ropohl's theoretical definitions[10] is described in.[1,2] Therefore, only the main differences between *MIM* and polymer injection moulding will be pointed out.

Ropohl for description of general systemic theory used 24 definitions. For description technical system of things he used additional 16. For starting description, we need from general system theory definitions 4 to 6 and 22 to 24. For description of technical system of things, definitions 28 to 33 are necessary.

Definition 4 to 6 and 22 to 24 deals with functions and actions .In injection moulding of substances definitions 28 to 33 we found following functions: change (Df28) transport (Df29), accumulation (Df30), change of state (Df31) and preservation of state (Definition 32). Df33 give answer on question, injection moulding system is navigable (open loop) system.

The *MIM* system contains the class change function F_C which is divided into two sub-functions: the manufacturing function F_{CM} and the processing function F_{CP} (D28). One of the functions, that of manufacturing is the function of primary shaping ($F_{CM, ps}$) which is present in all the processes. There are also two functions of structuring, viz. the function of primary structuring (creating the primary structure) on the supramolecular level $F_{CP, pss}$ and the function of restructuring (changing of the primary structure) on the molecular level $F_{CP, rsm}$. These two functions describe molecular orientation, internal stresses and the degree of crystallinity of semi-crystalline thermoplastics, and thermal decomposition of the binder. The $F_{CP,pss}$ function appears in debinding and sintering since the geometry of the part changes.

In some cases the function of primary shaping on the molecular level $F_{CP, psm}$ also occur. In powder injection molding it is present at debinding and sintering. During these procedures certain chemical reactions take place. These reactions cause the decomposition of the molecules or reduction of certain elements. The reactions appear among the atmospheres, solvents and binders, or among the powder particles and the atmosphere (reduction of the oxide with nitrogen). All the remaining functions are described in.[1]

In definition Df15, a system of goals on condition that the observed system contains a group of functions in the subsystems (σ) and a group of relations (π) is defined. In powder injection moulding there is a subsystem of the following functions: preparation of substances (C_{11}) and injection (C_{12}) (C_{11} in $C_{12} = C_1$), moulding (C_2), temperature regulation (C_3), debinding (C_4) and sintering (C_5). Debinding can be carried out in different ways: with drying (C_{41}), with solvent (C_{42}), in the furnace with heat (C_{43}); with catalyst (C_{44}). There are two functions of heating in the sintering furnace: debinding of the remaining binder (C_{51}) and the particle joining (C_{52}). The main aims of the temperature regulation system are to regulate the temperature of the injection unit (C_{31}), mould (C_{32}), debinding (C_{33}), and sintering furnace (C_{34}). First, the starting temperature field (C_{321}) in the mould is achieved and after a certain number of cycles a quasi-stationary temperature field (C_{322}) is reached. The group of functions of subsystems is:

$$\sigma_s = \{C_{11}, C_{12,} C_2, C_3, C_4, C_5\} \tag{1}$$

In *MIM* the following groups of relations emerge: the relation of indifference, the relation of competition, the relation of instrumentation, and the relation of preference.

$$\pi = \{P_{Idfm}\} \cup \{P_{Kkrm}\} \cup \{P_{Ismm}\} \cup \{P_{Prfm}\} \tag{2}$$

According to definition Df16 there are two relations of indifference:

$$P_{Idf2}\,(C_{31}, C_{321}) \;<=>\; \dashv C_{31} \mid \dashv C_{321} \tag{3}$$

The meaning of equation (3) is that it is not important whether the prescribed temperature of the injection unit or the necessary temperature field in the mould is reached first.

According definition Df17 there are three relations of competition. Because individual procedures of debinding (drying, solvent or catalytic debinding) are not mutually related the relation of competition occurs. Which type of debinding will be carried out depends mainly on the type of the binder. When debinding a certain part only one of the following two types of debinding can be used (solvent or drying):

$$P_{Kkr1}\,(C_{41}, C_{42}) \;\dashv C_{41} \mid \dashv C_{42} \tag{4}$$

The same can be said of the catalytic debinding, where only one of the debinding process occurs:

$$P_{Kkr2}\,(C_{44}, C_{42}) \;\; \dashv C_{44} \;|\!\dashv C_{42} \text{ in}$$

$$P_{Kkr3}\,(C_{41}, C_{44}) \;\; \dashv C_{41} \;|\!\dashv C_{44} \qquad (5)$$

According to definition Df18 there are 13 relations of instrumentation. Before preparing the substances it is important to heat the injection unit to the appropriate temperature.

$$P_{Ism1}\,(C_{31}, C_{11}) \;\; \dashv C_{31} \rightarrow \dashv C_{11} \qquad (6)$$

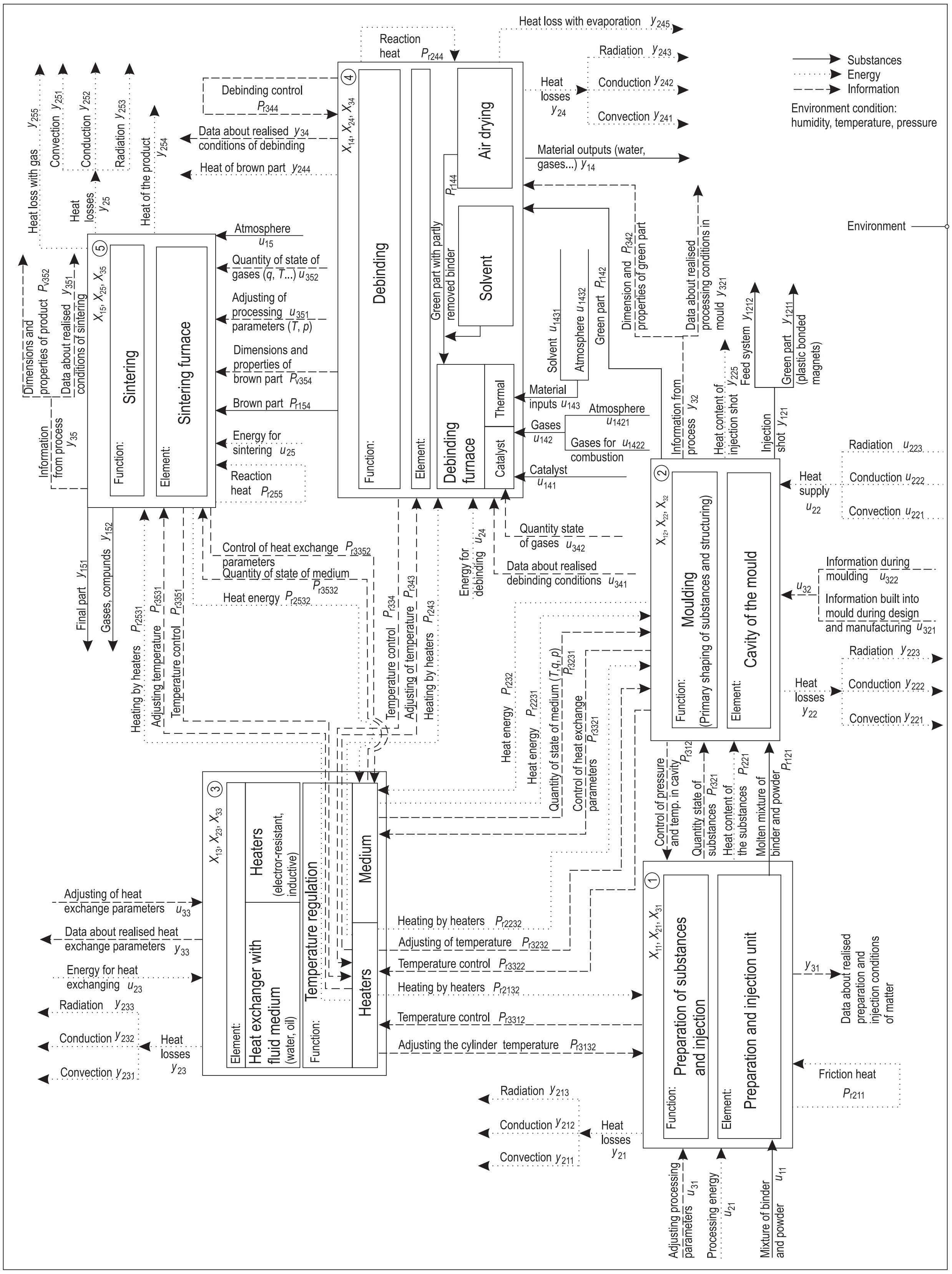

FIGURE 5: General model of *MIM*

This is also a preliminary condition for injection:

$$P_{Ism2}\ (C_{31},\ C_{12})\ \Dashv C_{31} \rightarrow \Dashv C_{12} \tag{7}$$

Before the first injection the mould needs to be heated to the starting temperature field in which the green parts of poor quality are made. The relation of instrumentation is thus:

$$P_{Ism3}\ (C_{321},\ C_{12})\ \Dashv C_{321} \rightarrow \Dashv C_{12} \tag{8}$$

Before the injection the substances needs to be prepared – it needs to be melted, compressed, mixed and transported. All these functions are performed by a screw and, indirectly, by a temperature regulation system. The relation of instrumentation is thus:

$$P_{Ism4}\ (C_{11},\ C_{12})\ \Dashv C_{11} \rightarrow \Dashv C_{12} \tag{9}$$

Before performing the function of moulding, the function of injection must be determined:

$$P_{Ism5}\ (C_{12},\ C_{2})\ \Dashv C_{12} \rightarrow \Dashv C_{2} \tag{10}$$

After the injection the quasi-stationary temperature field is reached:

$$P_{Ism6}\ (C_{2},\ C_{322})\ \Dashv C_{2} \rightarrow \Dashv C_{322} \tag{11}$$

Creating the quasi-stationary temperature field is a function of great importance since the quality products can be produced under certain conditions only. After the moulding, the debinding of the green part takes place:

$$P_{Ism7}\ (C_{2},\ C_{4})\ \Dashv C_{2} \rightarrow \Dashv C_{4} \tag{12}$$

Individual processes of debinding can be mutually combined so as to achieve temporal and qualitative optimal conditions. Before thermally debinded, the green part needs to be dried.

$$P_{Ism8}\ (C_{41},\ C_{43})\ \Dashv C_{41} \rightarrow \Dashv C_{43} \tag{13}$$

After solvent debinding, a thermal one takes place:

$$P_{Ism9}\ (C_{42},\ C_{43})\ \Dashv C_{42} \rightarrow \Dashv C_{43} \tag{14}$$

The furnace is heated with the velocity of a few degrees kelvins per minute. When a certain temperature is achieved the function of debinding through chemical reaction or evaporation is performed. This is illustrated in the following relation of instrumentation:

$$P_{Ism10}\ (C_{33},\ C_{43})\ \Dashv C_{33} \rightarrow \Dashv C_{43} \tag{15}$$

After debinding, sintering occurs:

$$P_{Ism11}\ (C_{4},\ C_{5})\ \Dashv C_{4} \rightarrow \Dashv C_{5} \tag{16}$$

A sintering furnace always performs two functions, viz. removing the rest of the binder and the particle joining. First, the binder is removed, after which joining takes place:

$$P_{Ism12}\ (C_{51},\ C_{52})\ \Dashv C_{51} \rightarrow \Dashv C_{52} \tag{17}$$

A starting temperature at which debinding occurs, must be achieved:

$$P_{Ism13}\ (C_{341},\ C_{51})\ \Dashv C_{341} \rightarrow \Dashv C_{51} \tag{18}$$

The second temperature point represents the beginning of the particle joining. The smaller the ratio between the volume and area of a particle, the lower the temperature. This is illustrated by the following equation:

$$P_{Ism13}\ (C_{342},\ C_{52})\ \Dashv C_{342} \rightarrow \Dashv C_{52} \tag{19}$$

The relation of preference is present in injection moulding of thermoplastic melts, as well as in *MIM*. Injection can be carried out even if the stationary temperature field in the mould is not created, while it cannot be carried out until certain criteria for injection are met. The following relation of preference describes this:

$$P_{Pfr1}\ (C_{12},\ C_{322})\ \Dashv C_{12} > \Dashv C_{322} \tag{20}$$

According to definition Df20 a chain of goals can be defined:

$$L_{CS} = (P_{Ism1},\ P_{Ism2},\ldots,P_{Ism13}) \tag{21}$$

A chain of goals is a sequence of relations of instrumentation, which describe the process of *MIM*. There are more such relations in *MIM* than in polymer injection moulding, which is due to debinding and sintering. If one would like to describe the process in detail the subsystems would have to be treated as systems themselves and general models would have to be created. Furthermore, analyses according to Ropohl's theoretical definitions should be made.

Conclusion

Mastering a certain product or process begins on a theoretical level and then continues on the practical one. But what is essential in a theoretical part is that this knowledge can be further used in practical work. The making of a general model of metal injection powder moulding and the evaluation of this procedure according to Ropohl's theoretical definitions is exactly the knowledge which broadens one's horizons and contributes to better practical work. Systemic analysis is important because through a systemic approach the general rules, better understanding of the procedures, and the appropriate foundation for further work are established. When dealing with a certain problem questions arise, which otherwise would not arise. In this paper an element of mixing was not included. Nowadays many companies make feedstock, so the mixing is not necessary, although in some cases it is still used.

For a discussion of the *MIM* system in detail would be necessary to create general models for each individual subsystem, by means of which a more thorough image of this complex procedure would be created. Also a subsystem of mixing should be included. Thus, work in this field is certainly not finished yet.

Abbreviations

F_C - class change function
F_{CM} - manufacturing function
F_{CP} - processing function
σ - group of functions
π - group of relations
C_{11} - preparation of matter
C_{12} - injection
C_2 - moulding
C_3 - temperature regulation
C_{31} - regulate the temperature of the injection unit

C_{32} - regulate the temperature of the mould
C_{321} - the starting temperature field
C_{322} - a quasi-stationary temperature field
C_{33} - regulate the temperature of debinding furnace
C_{34} - regulate the temperature of sintering furnace
C_{4} - debinding
C_{41} - debinding with drying
C_{42} - debinding with solvents
C_{43} - debinding in furnace with heat
C_{44} - debinding with catalyst
C_{5} - sintering
C_{51} - debinding of the remaining binder
C_{52} - particle joining
P_{Idfm} - relation of indifference
P_{Kkrm} - relation of competition
P_{Ismm} - relation of instrumentation
P_{Prfm} - relation of preference

REFERENCES

1. Čatić, I., Rujnić-Sokele, M.: *The systemic analysis of injection molding*, Polimery, 47(2002)1, 15-21.
2. Čatić, I. Razi, N., Raos, P.: *Systemic Analysis of Injection Molding of Polymers,* Društvo plastičara i gumaraca, Zagreb, 1991.
3. German, R. M.: *Powder injection molding*, Metal Powder Industries Federation, Princteon, New Jersey, 1990.
4. N. N.: *Company research*, ARBURG GmbH, 2003.
5. LaSalle, J. C., Burlew, J., Sesny, S., Stevenson, J., Fanelli, T.: *Analysis of a 17-4PH component made using the agar based binder system*, PM^{2}TEC 2000, New York, USA, 195-203.
6. Powers, J. D. Matic, M. M., Behi, M.: *Aqueous injection molding of advanced ceramics*, PM^{2}TEC 2000, New York, 129-135.
7. R. M. German, A. Bose, *Injection molding of metals and ceramics,* Metal powder industries federation, Princteon, New Jersey, 1997.
8. Čatić, I., Johannaber, F.: *Injekcijsko prešanje polimera i ostalih materijala* (*Injection moulding of polymers and other materials*), Društvo za plastiku i gumu, Zagreb, 2004, 114-119.
9. Berginc, B., Čatić, I.,_Kampuš, Z.: *The systemic analysis of metal injection molding*, Conference proceedings ANTEC 2005, Boston, 610-614.
10. Ropohl, G.: *Eine Systemtheorie der Technik, zur Grundlegung der Allgemeinen Technologie*, Carl Hanser Verlag, München 1979.

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VIJESTI

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