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**THE APPLICATION OF FUZZY LOGIC ANALYSIS  
TO ASSESSING THE SIGNIFICANCE OF MIXING PARAMETERS  
FOR THE PM METAL-CERAMIC COMPOSITE\*\***

**1. INTRODUCTION**

The powder metallurgy takes essential place in the group of the material saving technologies. The development of the powder metallurgy take place in directions favouring processes leading to multicomponent materials with good microstructure and high mechanical and functional properties. In many cases, the high quality composites could be obtained only by powder metallurgy methods, for example when the unfavourable chemical reactions between the matrix and the reinforcement phase take place in the melted phase. Automotive, aeronautical and recreational industries are the main consumers of the PM products [1, 2]. The decision to produce the composite material is made always with economical calculations in comparison with this element made using the traditional technology like semi-finished rolled, forged or casting products.

Despite many advantages of the powder metallurgy in production of complex materials like composites the practical applications of this technology cause many problems. An improper solution on given stage of the forming process causes high deterioration of the product's properties and/or makes this process uneconomical. This problem was subject of many studies [3, 4]. In the case of the multicomponent materials the first and crucial stage is properly carried out mixing process [5, 6]. Factors like the kind and shape of components in the mixture, its volume fraction, differences in dimensions and densities, its hardness and other determine the mixing process effectiveness. Rotational speed of mixer, level of components in chamber and mixing time are the most important parameters of the mixing process. Wrong choice of those parameters on this stage of production process practically determines the material properties and makes impossible to obtain right microstructure and

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desired product quality. Next stages of the production process have no further influence and cannot correct it. When time of mixing is too short, it does not assure the static evenness of the components distribution on the other hand, when the mixing time is too long, it leads to extended production time, energy consumption, equipment's wear and tear, and bottleneck in the production process. The mixing of the components in the configuration matrix powder – ceramic fibres makes this problem even more complex. The ceramic fibres have high tensile strength and low resistance on the shear stress and all the mixing time undergo break-up, this reduces ability of the pressure dissipation by produced structural element. In this case the mixing time must be long enough to assure good distribution of fibres in the matrix but not longer. Wrong selection of rotation speed reduces quality of materials as well. When the speed is too low the mixing process takes more time, and below certain speed characteristic for combination of components and equipments, the mixing has no results. When speed of rotation is too high, a centrifugal force immobilises components on the mixer sides. This effect is well known when the mass density of the components differ much. The essential factor having often influence on quality of formed by powder metallurgy parts is a quality control of the mixture. Results in the form of conglomerates or inequality in reinforcement phase distribution are possible to estimate only by the metallographic examinations or by examination of product properties. A wide dispersion of obtained results is the distinct indication of such problems.

An attempt to observe the mixture by microscopy is questionable, because separation of small sample and their placement in the microscope with even small difference of density of components causes its segregation. In practice, the mixing parameters are selected experimentally, each variant is verified using results of the final product examination. However such approach does not guarantee the most advantageous combination of parameters, because confirmation of uniform distribution of components does not mean the most economical choice. The experimental work out of the mixing parameters is valid only for this specific composition of components, each change in the component's proportions spells mixing parameters modifications. This statement is particularly true for diversified components like in the powder particles – ceramic fibres system. In addition, the experimental method of mixing parameters evaluation is time consuming and expensive. For this reasons domain of computer science application is growing, they could be used to estimate mixing parameters and for the mixing process control in real time as well. A particularity of the mixing process is related with difficulties in creation of the mathematical model, even then its applications are limited to the one specific case. In the development of new materials, an estimation of suitable parameters for the technological operations is time consuming process, so the flexibility and simplicity of application in new conditions is very important for the solution. Neural networks are very popular and useful, but in this case with only little learning samples and with large differences between materials they are not the best solution. This tool could be used only on the stage of the mixing control on the production scale [7]. For this reason, the authors decide to use a fuzzy logic as a tool for the computer aided design of composite materials. This method is widely used when the information about the process is partial and/or uncertain, the knowledge and the experience of the design engineer are hard to formulate in exact manner. This approach is at present the subject

of research and it is successful in many domains [7], like analysis of the composites forming process in the powder metallurgy [8]. The authors suppose, the question of the mixing parameters estimation and choice are the one of the possible application of fuzzy logic in the powder metallurgy.

## **2. EXPERIMENTAL PROCEDURE**

An attempt to implement the fuzzy logic to aid the selection of correct mixing parameters in the aluminium powder – ceramic fibres system, based on the knowledge uncertain and partial was the purpose of these researches. The numerical development of charge preparation parameters for the forming technology, which use together the powder metallurgy and the plastic working methods to obtain in correctly guided process the materials with possibly high properties was the expected effect. The domain of the researches includes the experimental part and supported by obtained results numerical analysis using the Matlab's Fuzzy Logic toolbox.

The analysis was carried out for the aluminium powder – ceramic fibres system, with variable proportions of components. The input parameters for the numerical calculations were divided in two groups. The first one was data obtained from experiments determining influence of the variable factors on the specific properties of the product. For the quantitative analysis the volume fraction of the reinforcing phase was singled out. It was assumed, that on constant mixing parameters and following forming of composites using powder metallurgy techniques the microstructure and the properties of the material depend on the volume fraction of the fibres in the matrix. Obtained results of the structural investigations will show the correctness of chosen parameters for the given proportion of components. The second group of data was considered as an expert's knowledge came from his knowledge and his experiences, it was formulated using linguistic variables and rules or presented in the form of the trend diagrams. The output data consist in experimental data (density, tensile strength) and qualitative observations of the microstructure (distribution uniformity of the reinforcement phase in the matrix, conglomerate of fibres) formulated as the linguistic variables.

### **2.1. Material for experiments**

The material for the matrix was obtained by gas spattering of aluminium. Aluminium powder had particle density  $2700 \text{ kg/m}^3$  and the particles size was beneath  $40 \text{ }\mu\text{m}$ . As the reinforcement phase, the ceramic fibres with the trade name Belcotex (94.5%  $\text{Al}_2\text{O}_3$ , 4.5%  $\text{SiO}_2$ , others  $< 1$ ). The mass density was  $2100 \text{ kg/m}^3$ . The diameter of the fibres was between  $8$  and  $10 \text{ }\mu\text{m}$  and initial length between  $10$  and  $12 \text{ mm}$ .

### **2.2. Preparation of mixtures**

Three mixtures were prepared with three ratios of the reinforcement phase in the matrix: 2.5, 5.0 and 10.0%. Suspended solids of aluminium powder in methanol ( $\text{CH}_3\text{OH}$ ) and the fibres were introduced into the double cone mixer. The mixing parameters were constant

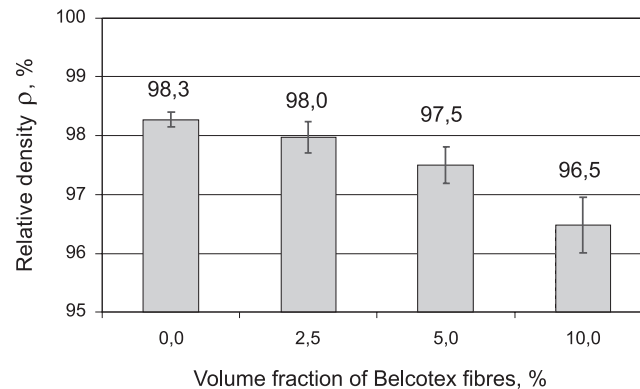
for each composition: time 30 min., rotational speed 55 r.p.m. and mixer packing below half of its volume.

### 2.3. Preparation of samples to examinations

For the evaluation of a mixing influence on the product properties, the samples for examinations were prepared using the same procedure with exactly the same parameters. To obtain the reference point a non reinforced material was also prepared. The prepared mixtures and the powder without fibres were pressed in the ambient temperature. Based on densification curves a unit-thrust was chosen, which permits to obtain P/M compact with the relative density about 80% of the density of a solid material with equivalent chemical composition. Prepared in this way blank were heated up to a temperature 500°C and coextruded in the isothermal conditions, with coefficient of extrusion  $\lambda=13.3$ . The extruded materials were cooled on the air. For evaluation of obtained material quality, the porosity and the tensile strength were examined. The distribution uniformity of reinforcement phase in the matrix was determined by the fractography analysis of a rupture surface created in a tensile test.

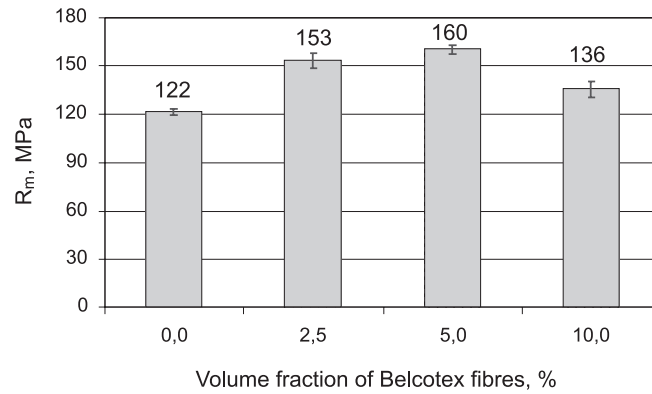
### 2.4. Result of properties examinations

The density of the samples was determined using Archimedes method. The Figure 1 shows the results. The introduction or increase the fraction of the ceramic fibres into the matrix results in decrease of its relative density.



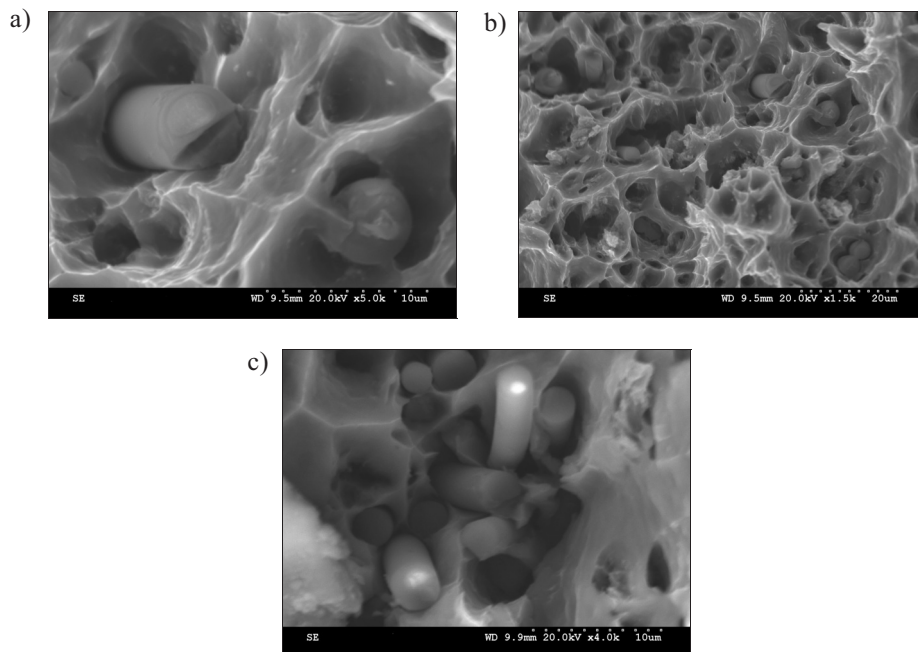
**Fig. 1.** Influence of the chemical composition on the relative density of materials prepared by hot extrusion of compacts (RAL-1 aluminium powder and RAL-1 based composites reinforced with Belcotex fibres)

The tensile tests were carried out using a testing machine Instron 4502, in an ambient temperature and with speed 5 mm/min. The results of the tensile strength  $R_m$  are presented on the Figure 2. Introduction into the matrix 2.5% (by volume) fibres and increase this volume to 5% results in an improvement of the  $R_m$  value. Further increase of the volume fraction of fibres from 5 to 10% produces the tensile strength reduction.



**Fig. 2.** Influence of the chemical composition on the tensile strength of materials prepared by hot extrusion of compacts (RAL-1 aluminium powder and RAL-1 based composites reinforced with Belcotex fibres)

The examinations of fractures arising in the tensile strength test were carried out using a scanning electron microscope Hitachi S3500. The Figure 3 shows fractographies of samples surfaces for the samples with the volume content of the fibres 5% and 10%.



**Fig. 3.** Fracture surface of hot extruded Al-Belcotex fibre composite. Extrusion temperature 500°C, extrusion ratio 13.32, mixing time 30 min., rotations speed 55? r.p.m. Mixing in analytically pure methanol (CH<sub>3</sub>OH). Fraction of the fibres in the matrix: a), b) 5%; c) 10%

On the base of the fracture observations it was found that applied mixing parameters were correct for the composite with fibres volume fraction 5%, the Figures 3a and b. A ruptures of fibres were just in the same plane as the matrix. The fibres adhered strictly to the matrix material as it shows a higher resolution picture on the Figure 3b. The increase of the fibres volume fraction led to creation of conglomerates. Holes formed by broken-out the fibres are visible on the Figure 3c. Being in direct contact fibres in the conglomerate did not transmit forces fully and they did not participate in the composite reinforcement, that was confirmed by the tension strength tests.

### 3. APPLICATION OF FUZZY LOGIC TO MIXING PROCESS ANALYSIS

For the testing implementation of this solution the Fuzzy Logic Toolbox from the Matlab package was chosen, because of its simple graphical interface making possible the quick testing of hypothesis. Such solution could be implemented in the final application using Matlab's or others programistic libraries. In the fuzzy logic usually, the input and output parameters are defined by linguistic variables like *Mixing\_Time*, for this parameter following values was defined  $\{Too\_Short, Short, Medium, Long, Too\_Long\}$ .

**Table 1.** Values of the linguistic variable *Mixing\_Time* with associated membership functions

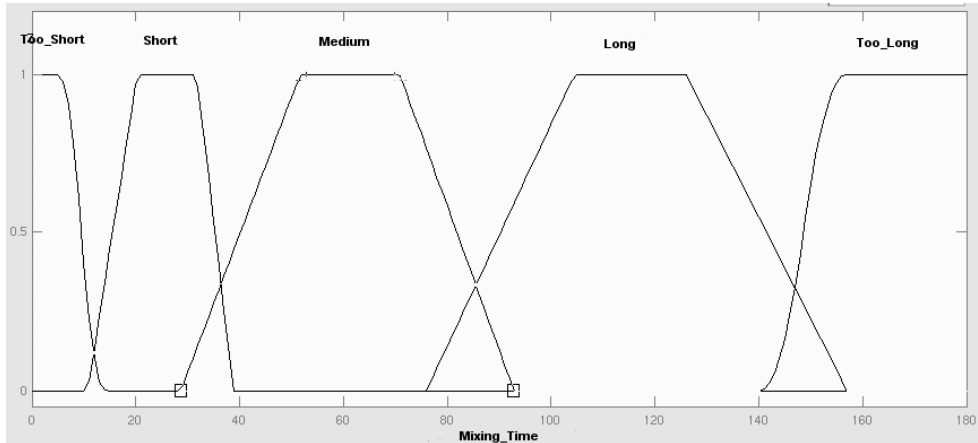
Values of linguistic variables	Membership function values, min	Type of membership function
Too_Short	[5 14]	$\mu$ - zmf
Short	[10 20 31 38]	$\mu$ - trapmf
Medium	[28 51 64 84]	$\mu$ - trapmf
Long	[76 112 121 157]	$\mu$ - trapmf
Too_Long	[147.2 164.8]	$\mu$ - smf

Table 1 and Figure 4 present the fuzzy set with assigned linguistic variables and membership functions. For those imprecise descriptions, the membership functions  $\mu_{A_i}(x_i)$  are defined. A FIS fuzzy system can be considered to be a parameterised non-linear map, called  $f(1)$ .

$$f(x) = \frac{\sum_{l=1}^m y^l (\prod_{i=1}^n \mu_{A_i^l}(x_i))}{\sum_{l=1}^m (\prod_{i=1}^n \mu_{A_i^l}(x_i))} \quad (1)$$

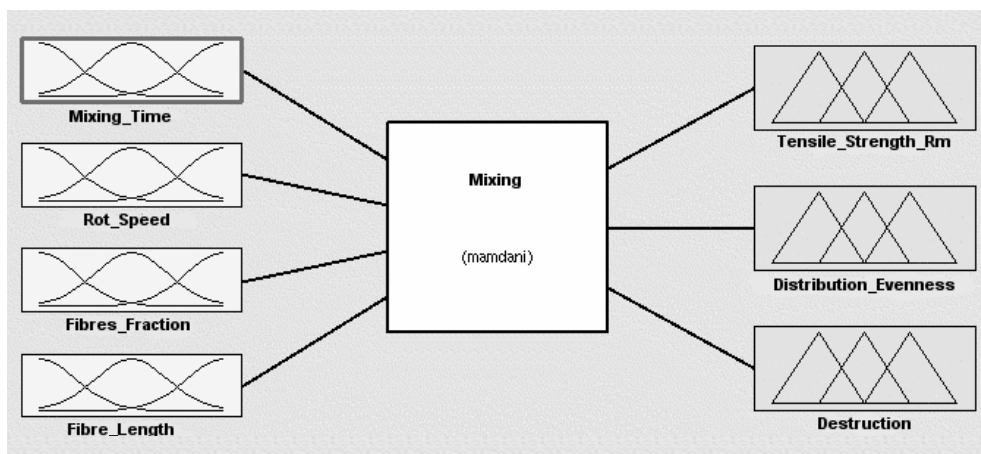
where:

- $y^l$  – place of output singleton,
- $\mu_{A_i}(x_i)$  – corresponds to the input  $x=[x_1, \dots, x_n]$  of the rule  $l$ .



**Fig. 4.** Graphical representation of the *Mixing\_Time* parameter as an linguistic variable

In the same way, the others input and output parameters were defined: rotational speed – *Rot\_Speed*, fibres volume fraction in the matrix – *Fibres\_Fraction*, *Fibre\_Length*, *Effective\_Porosity*, *Tensile\_Strength\_Rm*, *Distribution\_Evenness* and *Destruction* (Fig. 5).



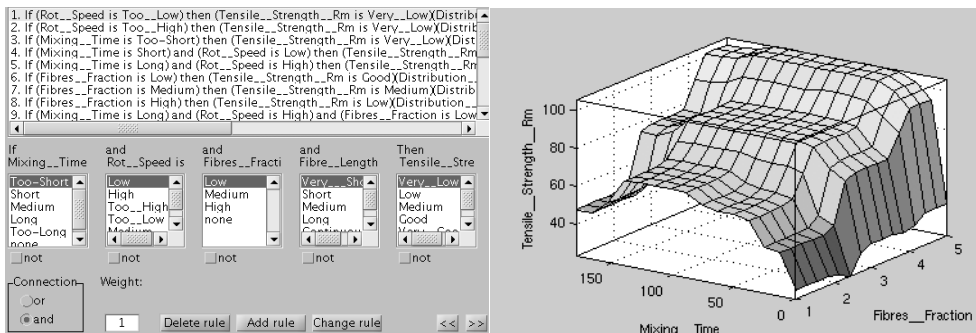
**Fig. 5.** An example of implementation in the Matlab's Fuzzy Logic toolbox

This consideration shows, that by use fuzzy logic rules, the flexibility of the process descriptions is increased. This flexibility is obtained with loose of precision, indeed. However in many applications, linguistic variables manipulation is fully satisfying. In a reasoning process, the three most important blocks could be distinguished: fuzzyfication, inference and defuzzyfication.

The inference system use fuzzy rules in the form of conditions IF/THEN defined on the base of experts' knowledge and literature data [6] as follows:

- 1 If (Rot\_Speed is Too\_Low ) then (Tensile\_Strength\_Rm is Very\_Low)  
(Distribution\_Evenness is Very\_Bad)
- 2 If ( Rot\_Speed is Too\_High) then ( Tensile\_Strength\_Rm is Very\_Low)  
(Distribution\_Evenness is Very\_Bad)
- 3 ...

The implementation of rules in Matlab and their graphical representation are presented on the Figure 6.



**Fig. 6.** Some rules in the FIS Editor and their graphical presentation (Mixing\_Time in minutes, Fibres\_Fraction and Tensile\_Strength\_Rm in percent)

A defuzzification is the last stage, which delivers usable output parameters. In the presented system for this operation a centre of gravity method was used. In the presented configuration four input and three output parameter was used but with only little modification, an arbitrary configuration could be used for example an opposite direction of reasoning could be implemented. In presented researches a satisfying compatibility between experimental data and the calculated ones was achieved.

#### 4. SUMMARY

- 1) Proposed parameters of the mixing give the best results for the volume fraction of fibres equal 5%. Further increase of the fibres fraction had negative influence on the material properties. This was proved by the SEM examinations of the specimens made from composites after the tensile test and the results of the tensile strength tests. The conglomerates of the fibres. Being in direct contact fibres in the conglomerate did not transmit forces fully and they did not participate in the composite reinforcement.
- 2) After the experiments carried out, it was found that the parameters of mixing process must be selected individually for each composition and the application of proposed system was helpful for.
- 3) For the process analysis using the fuzzy logic method there are no need to know the qualitative knowledge of all parameters and their influence on the mixture quality. Chosen description of the process using linguistic variables and fuzzy rules is sufficient to obtain a good result.



- 4) In the considered case of mixing: the aluminium powder – ceramic fibres use the Matlab's Fuzzy Toolkit has allowed to obtain good quality of the mixture, and then the final product with good characteristics.
- 5) The preliminary analysis shows, that the application of the proposed method permits an limitation of time consuming and excessive technological trials.
- 6) With a little modification of the fuzzy rules, the configuration of the input and output parameters could be changed at will.

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