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K. ZYGUŁA[1*], M. WOJTASZEK[1]

THE APPLICATION OF FUZZY LOGIC ANALYSIS FOR THE FAST CALCULATIONS OF PROPER PARAMETERS OF MANUFACTURING TITANIUM ALLOYS FROM POWDERS

This paper presents a method based on the use of fuzzy logic for the rapid selection of optimal induction sintering parameters. The prepared fuzzy controller uses expert knowledge developed from the results of induction sintering tests of Ti-5Al-5Mo-5V-3Cr alloy green compacts produced from a mixture of elemental powders. The analysis of the influence of the applied sintering parameters on the material characteristics was based on the evaluation of the microstructure state and the measurement of the relative density of the samples after sintering. In this way, a universal tool for estimating the sintering parameters of titanium powder-based green compacts was obtained. It was shown that with the help of fuzzy logic it is possible to analyze the influence of the parameters of the manufacturing process of metal powder materials on the quality of the obtained products.

Keywords: fuzzy logic; titanium alloys; powder metallurgy; induction sintering; microstructure

1. Introduction

Powder metallurgy technology is becoming more and more popular in the production of structural elements, particularly from rare or expensive metals [1,2]. A promising approach is the densification of a mixture of elemental powders. This is due to several key advantages of this technology. By using elemental powders, it is possible to be flexible in the designing of the chemical composition of the alloy produced. Powder metallurgy allows the production of near-net or net-shape components, which results in a reduction in the machining process. Moreover, alloying usually occurs during the sintering process, which is carried out at a much lower temperature in comparison to the traditional ingot process, which reduces the final costs of the component.

Materials that are currently attracting great attention are titanium alloys, which characterize a unique combination of low density, high mechanical properties, and corrosion resistance. Nevertheless, the production costs of titanium components are relatively high [3]. The research challenge continues to be to describe the effect of the processing titanium alloys from powders on their homogeneity and strength properties. Typically, a conventional sintering process conducted in a furnace can take up to several hours [4]. This results in excellent homogenization of the chemical composition but leads to significant grain growth, which has a negative impact on mechanical properties. A reduction in sintering time can be achieved by using induction sintering, which involves heating the material to a high temperature using eddy currents that are created in the material while it is in a magnetic field induced by an induction coil [5].

The induction sintering process is considered less costly compared to the conventional furnace sintering, because of the shorter time of the process, as well as equipment that is simpler and easier to maintain. The induction sintering process of titanium usually consists of the preparation of powder compact and sintering in an argon atmosphere, where eddy currents are directly introduced to the material [6]. No additional tooling such as dies is required, and the environment of the heated compact is cold. Sintering with induction heating provides rapid heating and cooling, significantly reduces sintering time, and provides energy efficiency. Due to the advantages of this process, the use of induction sintering is a topic eagerly pursued by researchers. A key aspect in achieving adequate homogenization of the chemical composition and microstructural homogeneity is the proper selection of the sintering parameters. Raynova et al. [7] conducted extensive research on density, microstructure evolution, and mechanical properties of the commercially pure titanium powder compact. Induction heating has been shown to be a fast

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[1] AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF METALS ENGINEERING AND INDUSTRIAL COMPUTER SCIENCE, AL. MICKIEWICZA 30, 30-059 KRAKÓW, POLAND

* Corresponding author: kzygula@agh.edu.pl

and effective way to consolidate Ti powders. By varying the starting density of the compact, temperature, and sintering time, structures with high density and low porosity can be obtained. The process parameters have a strong influence on the degree of consolidation and the properties of the sintered material. It has also been shown that oxygen contamination during induction sintering is slight due to the short exposure to high temperatures. Another example of research in this field is studies undertaken by the authors of this work [8]. In this case, the study involved an alloy with a far more complex chemical composition. It was shown how the temperature of induction sintering affects the kinetics of diffusion bonding and dissolution of the particles that make up the mixture of elemental powders. In addition, it was investigated how initial parameters of the powders consolidation process affect the further hot deformation.

The referenced studies show that the selection of the most favorable combination of sintering time and the temperature usually involves a number of laboratory tests and then determining the effect of the parameters used on the analyzed characteristics of the material, which requires a relatively high cost and time. At the same time, the complexity of the phenomena occurring during sintering significantly complicates the development of a universal model of this process. A method leading to the solution of this problem can be the application of the method of fuzzy logic (FL) as a system supporting the selection of process parameters universally. Based on the expert knowledge introduced in the fuzzy controller and the cause-effect analysis, it is possible to shorten the time of selection of favorable induction sintering parameters and to reduce laboratory tests to a minimum.

The fuzzy logic method was originally introduced as a tool to control processes for which the development of a model describing their course is difficult or impossible. The approach was proposed by Zadech, the forerunner of the method [9]. This method eliminates the typical limitations of classical logic. According to classical logic, the analyzed element either belongs to a certain set of values fully or does not belong to it in any way. Such a defined membership either is true and takes the value of 1 or false and is equal to 0. However, this state occurs only under certain conditions. Apart from these specific conditions, the degree of membership is partial and defined by real values greater than 0 and lesser than 1. Thus, it can take any value in this range and can be described by the membership function $l(x)$.

Fuzzy logic is an analytical method for to process knowledge and experience into a form that can be analyzed by a dedicated computing system. Knowledge is formulated in the form of a rule base that defines cause-and-effect relationships between input and output variables. Individual variables are defined, and the characteristics of their changes are presented using mathematical functions. The system works on a principle similar to the way humans think, which significantly increases its flexibility compared to other control techniques. This approach does not require knowledge of the model of the analyzed issue. It also allows analysis of incomplete and imprecise knowledge, which for many issues is a great advantage [10,11].

The approach of applying knowledge engineering to support the processes of obtaining products from powders is currently the subject of many ongoing research works. The application of fuzzy controllers as tools for analyzing processes based on powder metallurgy has been handled, among others, by P. Radha et al. [12]. They demonstrated that the fuzzy logic method can be effectively applied to control production processes. Ramanathan et al. [13] studied the deformation behavior of composites produced by powder metallurgy. They fabricated aluminum matrix composites reinforced with silicon carbide particles and then subjected them to a compression test at different strains, strain rates, and temperatures. The fuzzy logic method was successfully applied by the authors to predict the effect of test parameters on the flow stress values. Based on the obtained results, the authors developed the processing map that allows the selection of favorable variants of thermo-mechanical parameters of the tested material and avoids unfavorable combinations.

The fuzzy logic method can also be used to estimate the properties of materials produced by powder metallurgy technology. Examples of this include the results presented by Balasubramanian et al. [14]. They made an interesting attempt to build an expert system based on the fuzzy logic method for analyzing the mechanical strength of samples produced by selective inhibition sintering (SIS). For this purpose, they developed a fuzzy rule model based on the Mamdani approach. A comparative study showed that the average result of the tensile and flexural strength characteristics obtained from the fuzzy system calculations agreed with the experimental results. Based on this, the authors demonstrated that the fuzzy system can be successfully used in automated manufacturing environments to reduce the complexity of process planning activities. Kalyon et al. [15] studied the effect of phase composition on the microstructure and wear of Inconel 718 alloy produced by powder metallurgy. They developed a fuzzy controller for predicting weight loss after wear tests, the use of which led to estimated results consistent with test results. In this way, they demonstrated that the fuzzy logic method can be successfully used as a tool for predicting the results of the wear tests of alloys obtained from powders.

The application of the fuzzy logic method can also cover the problem of controlling selected parameters of the sintering process. Examples of this include the results of the work of Li and Gong [16]. The authors noted that since the sintering mixture moisture control system has time-varying and nonlinear characteristics, it is difficult to develop a mathematical model for it. As an alternative solution, they designed a self-tuning fuzzy controller that sets process parameters based on sintering furnace design features and performance requirements. Based on operational results, they showed that the fuzzy controller they made improved the system's performance, stabilized the moisture content of the sintering mixture, improved sintering production conditions, and increased production efficiency.

The co-author of this work also has experience in the field of knowledge engineering and the design of fuzzy controllers for both the analysis of manufacturing processes of powder products and the estimation of the properties of the resulting products.

An example of his research in this field was the development of a fuzzy controller for the rapid determination of favorable parameters for mixing powders, depending on the morphology of the individual components of the mixture and the relationships between them [17]. The work carried out by the co-author also concerned the application of knowledge engineering to the rapid analysis of the relationships that occur between the parameters of the manufacturing processes of metal-ceramic composites and their properties [18].

2. Experimental methods

The characteristics of the starting material, the preparation of the elemental powder mixture, and the manufacture of compact in the cold pressing process are described in detail in the paper [8]. Obtained compacts were subjected to the induction sintering process using Bähr MDS 830 Multi-Directional Deformation Simulator. This device has a chamber that makes it possible to perform the process under a vacuum and use controlled cooling with inert gas, in this case, argon. The heating rate was 100 K/s and the cooling rate was 25 K/s. The temperature was controlled with a thermocouple welded to the surface of the sample. Four temperatures of sintering (1000°C, 1100°C, 1200°C, and 1300°C) were used. The holding times were determined experimentally. Pre-sintering was performed at 1000°C and a time of 900 s. It was shown that after about 420 s, the shrinkage rate of the sample during sintering decreases, and further dimensional change can take place due to microstructure remodeling rather than material compaction. Based on these results, a baseline sintering time of 450 s was selected. Then, in order to determine how the different stages of indention sintering at a given temperature affect the dissolution of alloying elements and the development of the microstructure, 25%, 50%, and 75% of the base time were calculated, which were 112.5 s, 225 s, and 337.5 s, respectively. The diameter of the sample during the process was controlled by laser detectors. The sample was positioned between two pressing ceramic anvils in such a way that the expansion in height during the process can be neglected.

The relative density of the samples after sintering was determined by measuring geometry dimensions. Samples for microstructure observations were prepared with the standard grinding and polishing procedure, followed by etching with Kroll's reagent (2% HF + 6% HNO_3 + 92% H_2O). Microstructural analysis was carried out using Leica DM4000M optical microscope. Hardness measurements were performed using a Struers Duramin-40 testing machine. Distribution maps were prepared in Surfer 17 software using the Kriging gridding method. The fuzzy controller was built using The Fuzzy Logic Toolbox module of the Matlab package.

3. Result and discussion

3.1. Densification during the sintering process

The average density of the as-compacted sample was 82.7 ± 1.7% (with respect to the theoretical density of the Ti-5553 alloy, which is 4.68 g/cm^3). Fig. 1 shows maps of density and sintering shrinkage as a function of process parameters. For most combinations of induction sintering conditions, the density of the material increased. Only for samples sintered with a short time values are slightly lower than the average density of green compact. This may be due to the lower density after hot pressing of individual samples. Therefore, it was assumed that a short time generally does not affect the relative density after sintering. However, it should be noted that the differences between individual samples are not significant. This is due to the relatively high density of the material after the cold compaction process. If a time of 337.5 s or longer is used, the distribution of density is uniform.

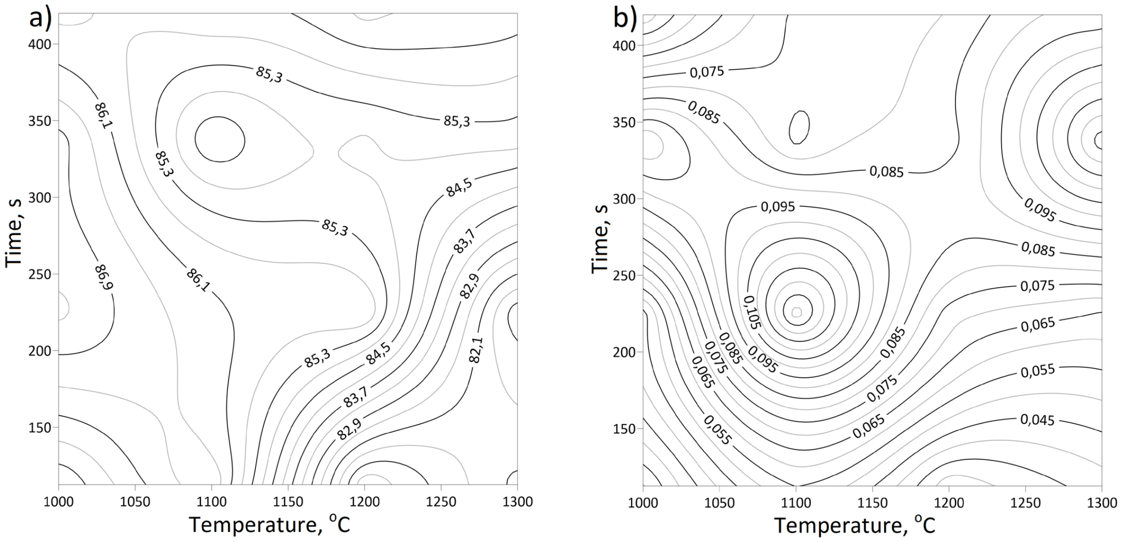

Fig. 1. The relationship between a) density, b) shrinkage, and parameters of the induction sintering process of a Ti-5553 alloy green compact in the form of distribution maps

Measurement of the diameter during sintering allowed calculation of the sample's shrinkage during isothermal holding. This approach made it possible to analyze effects related to sintering only. The phenomena occurring during rapid heating and cooling, mostly thermal expansion, which is reversible, were neglected. It was shown that as the temperature increases, longer holding at the set temperature slightly affects the shrinkage of the sample. With the selection of an appropriate temperature, it is possible to reduce the sintering time by up to 25% and achieve similar results.

3.2. Microstructure observations

During the observations, special attention was paid to the presence of undissolved particles of alloy powders included in the mixture, the size and morphology of the pores, the degree of bonding of individual powder particles, and the homogeneity of the microstructure. Microphotographs for each combination of parameters are shown in Figs. 2-5.

Microstructural analysis showed a significant effect of the sintering parameters on the degree of homogenization of the chemical composition and the development of the microstructure. Observations of the microstructure at different stages of sintering showed that, regardless of the temperature, at the initial stage of the process there is an initial bonding of powder particles, and the diffusion of alloying elements has not yet occurred (especially at a temperature of 1000°C) or is at a very early stage. It is possible to distinguish individual particles of titanium powder with a microstructure consisting mainly of fine grains of the α phase. Around the particles, a reaction layer is visible through which diffusion of alloying elements takes place. The increase in sintering time is associated with the increasingly better chemical homogenization of the alloy. Due to the presence of alloying elements in the mixture that stabilize mainly the β phase, its share in the microstructure increases in

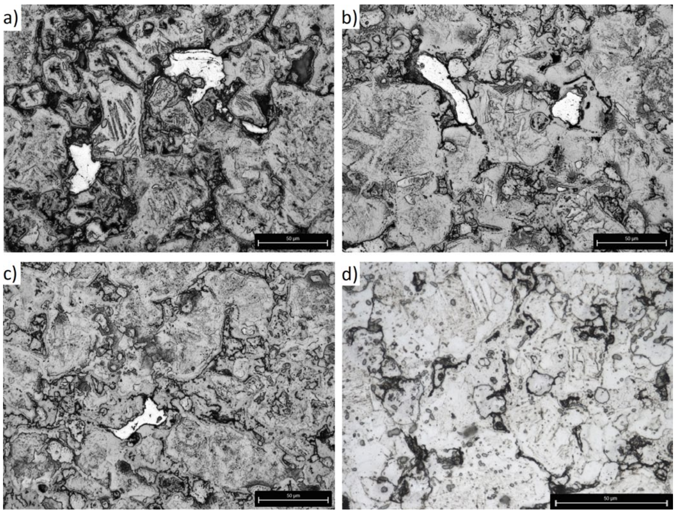

Fig. 2. Microstructures of Ti-5553 alloy induction sintered at the temperature of 1000°C and time of a) 112,5 b) 225 s, c) 375,5 s, d) 450 s

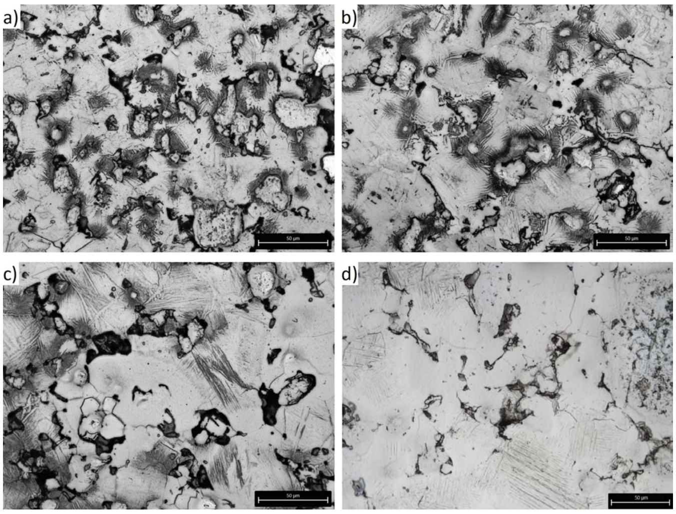

Fig. 3. Microstructures of Ti-5553 alloy induction sintered at the temperature of 1100°C and time of a) 112,5 b) 225 s, c) 375,5 s, d) 450 s

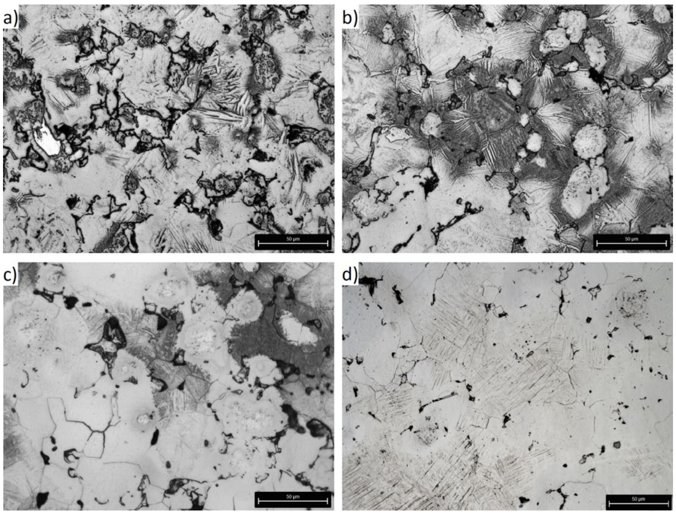

Fig. 4. Microstructures of Ti-5553 alloy induction sintered at the temperature of 1200°C and time of a) 112,5 b) 225 s, c) 375,5 s, d) 450 s

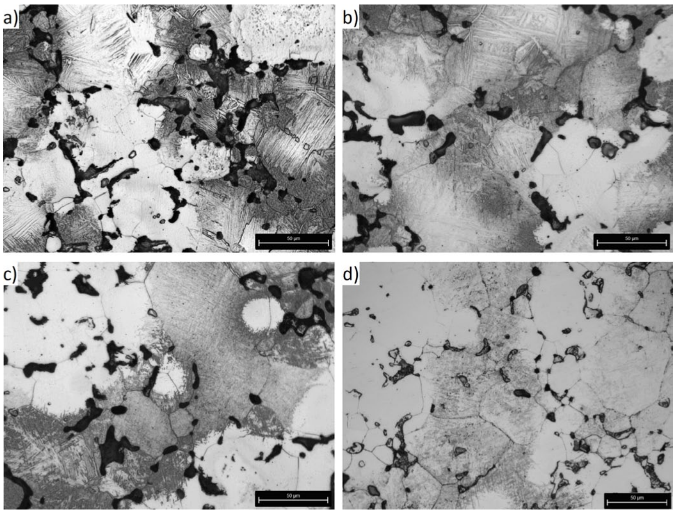

Fig. 5. Microstructures of Ti-5553 alloy induction sintered at the temperature of 1300°C and time of a) 112,5 b) 225 s, c) 375,5 s, d) 450 s

the subsequent stages of sintering. The number of undissolved particles of alloying elements also decreases.

The number and morphology of the pores change slightly during the subsequent stages of sintering. Regardless of the sintering time, closed spherical pores and open channel pores were observed. Only for the two highest temperatures, closed pores predominate, which may have a more favorable effect on the strength properties of such material [19].

The effect of temperature on the evolution of the microstructure, as well as its homogeneity, is significant. It was observed that the higher the temperature of induction sintering, the faster the fusion of individual powder particles and the dissolution of alloy powder particles occurs. Samples sintered at lower temperatures and for a short time show a higher proportion of needle-like α phase. This is because Al as a stabilizer of the α phase dissolves already at the lowest sintering parameters due to the low melting point of aluminum. This results in the formation of areas rich in the α phase. Increasing time and temperature allows gradual dissolution and diffusion of high-melting alloying elements (Mo, V, Cr), which stabilize the β phase. Therefore, for high sintering parameters, a much higher proportion of equiaxial grains of the β phase is observed. For the samples sintered at 1200°C and 1300°C, a homogeneous microstructure consisting of equiaxial grains of the β phase and needle-like precipitations of the α phase was already formed at the sintering time of 337.5 s. For a temperature of 1200°C, only single undissolved particles are present, probably molybdenum, which has the highest melting point of all alloying elements [20]. For samples sintered at 1100°C, only after a time of 450 s was it possible to achieve a relatively homogeneous microstructure. At 1000°C it is possible to distinguish individual powder particles regardless of the sintering time.

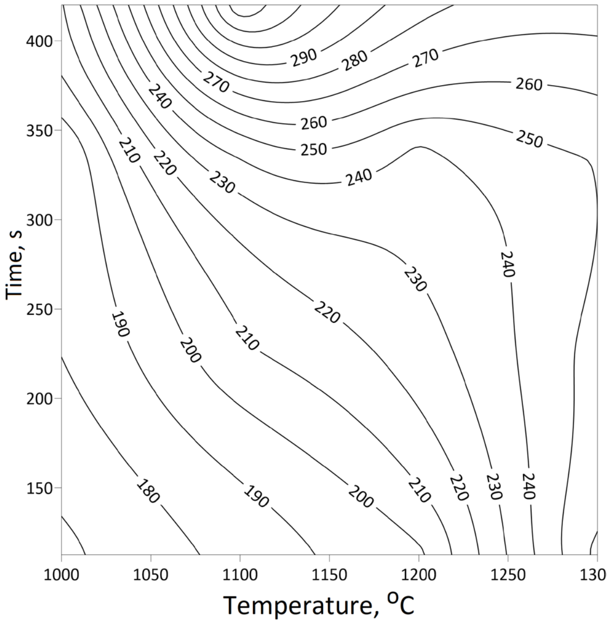

Fig. 6. Map of sample average hardness as a function of sintering temperature and time

3.3. Hardness measurements

Changes in the hardness of the sintered Ti-5553 alloy with respect to the temperature and time of the sintering process are presented in Fig. 6. Two main trends can be observed in the changes in hardness as a function of process parameters. As the sintering time increases, the hardness increases. It was also noted that when using a sintering time in the range not exceeding 375 s, increasing the sintering temperature also led to an increase in HV. The results correlate well with the microstructure observations. At low temperatures and short times, the degree of diffusion bonding of powder particles is low, so the hardness of the material is low. An increase in sintering time achieved qualitatively better particle bonding, making the material more compact and harder. The highest average HV value was recorded for a temperature of 1100°C and a time of 420 s (328 HV1). When this sintering time was used, increasing the temperature resulted in a decrease in hardness, which is inconsistent with the trend observed for the other, shorter sintering times. This may be related to the faster grain growth of the β-phase since the sintering was carried out well above the β-tranus temperature.

3.4. Fuzzy logic

The design of the fuzzy controller used to analyze the parameters of the sintering process was carried out in the Matlab Fuzzy Toolbox package. A diagram of the various blocks of the package's computational system is shown in Fig. 7.

A fuzzy controller consists of four main blocks [21]. These include fuzzification block, rule base unit, rule processing unit (fuzzy interface engine), and defuzzification block. The fuzzification block is the first stage of a fuzzy processing system. Precise data entering the system is fuzzified in it by changing the scale. Each piece of knowledge is assigned a membership

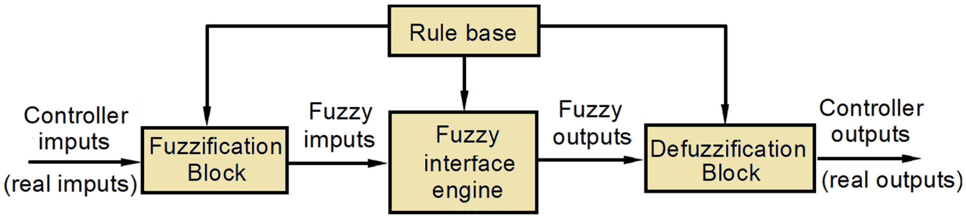

Fig. 7. The block diagram of a simple fuzzy logic controller

function at this stage and transformed into a linguistic structure. Data processed in this way is then sent to the rule processing unit, where it is combined with the existing rule base. The rules define the relationships between this information and the values of the output variables. In the final stage, the results of the inference are sent to the defuzzification block, where ranges of values of output variables are processed into strictly defined values.

An inference process was designed for two input variables and three selected output variables. The "*Temperature*," expressed in °C, and the "*Time of sintering*," defined in seconds, were defined as input variables. Three representative values were selected as output variables, which could be characterized based on the test results and based on knowledge of the main phenomena and relationships occurring during sintering. The variable "*Microstructure homogeneity*", expressed as a percentage, was defined based on microstructural analysis of induction sintered samples. Evaluating the microstructure in terms of the description of this variable, special attention was paid to the presence of undissolved particles of alloy powders included in the mixture, the degree of bonding of individual powder particles, and similarities and differences in the microstructural state. The "*Densification level*" variable reflects qualitatively and quantitatively the level of densification. This variable was defined based on an in-depth analysis of three factors, which were relative density, shrinkage value, and qualitative pore characteristics determined from microstructure observations. This factor included both a comparative assessment of the number of pores and the uniformity of their distribution, as well as a determination of the type of porosity, distinguishing between open and closed pores. The output variable "*Hardness*" was defined based on the results of HV hardness measurements.

Data to determine the cause-and-effect relationships between input and output variables were developed using the results of measurements and metallographic tests, but additional relationships, representing expert knowledge, were also considered. It was assumed that too short a sintering time does not lead to favorable results, regardless of the temperature at which the process is carried out. It was also assumed that the presence of open porosity is a significantly less favorable factor than the presence of evenly distributed closed pores.

The variables adopted were assigned in ranges of values and defined descriptions of their course, using shape functions. These functions were described with linguistic terms, such as "*low*" "*quite good*", "*medium*", "*very high*", etc. Relationships between input and output variables were defined in a form that could be processed by the computing system, using rules based on conditional sentences of the *IF...THEN* type. This approach allows the system to perform the inference procedure in a way that simulates the thinking of a human expert when he compares and analyzes data from an experiment. Calculations were carried out using the Mamdani approach. The sharpening operation was performed using the center of gravity method. Fig. 8 summarizes examples of the relationship between input and output variables, which are the result of the inference carried out by the designed fuzzy controller.

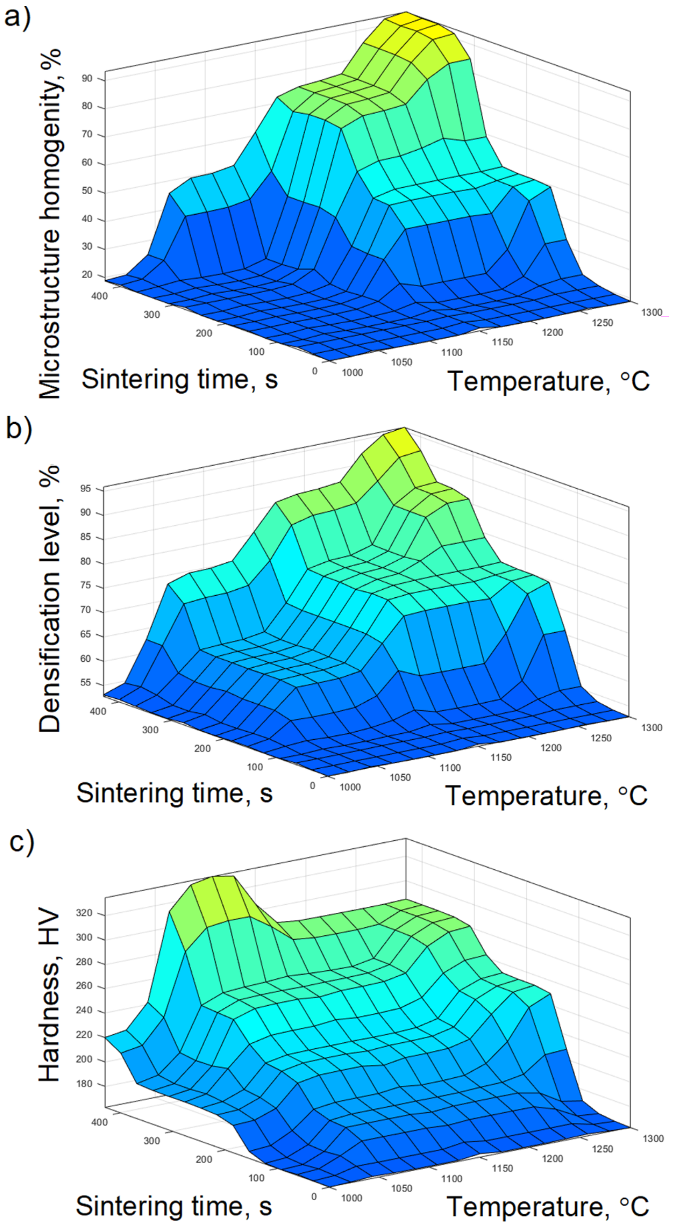

Fig. 8. The fuzzy controller developed using the effect of temperature and sintering time on changes in the example output variables: a) "*Microstructure homogeneity*", b) "*Densification level*", c) "*Hardness*"

The variable "*Microstructure homogeneity*" (Fig. 8a) depends strongly on the sintering parameters. The low values of this variable obtained for short sintering times are due to the fact that diffusion of alloying elements at the initial stage of the process does not occur or is at a very early stage. This is confirmed by observations of the microstructure of samples sintered under these conditions, where single particles of titanium powder and a reaction layer can be distinguished, through which diffusion of alloying elements takes place. This effect is only slightly compensated by increasing the sintering temperature. Increasing the sintering time is associated with better chemical homogenization of the alloy. Reflecting this trend, the gradual increase in the value of the variable in the graph is because the higher the sintering temperature, the faster not only the bonding of powder particles but also the dissolution of alloying element powder particles occurs. The significant increase in the value of the "*Microstructure homogeneity*" variable at higher values of temperature and time, seen in Fig. 8a, is due to the fact that only such a combination of induction sintering parameters results in effective dissolution and diffusion of the high-melting alloying elements, i.e., chromium, molybdenum, and vanadium.

Based on sintering tests, it was shown that the values of relative density increased with the increasing temperature and time of the induction sintering process. However, the differences between the values obtained for individual samples were insignificant, due to the small size and possible differences in the relative density of the compacts before sintering. Deviations from the trends of change described above were also observed (Fig. 1a). As a result, it should be assumed that based on the density measurements no relationships were obtained, allowing to determine the influence of the sintering parameters on the density of the sintered samples. Additional information on this matter can be obtained based on the analysis of the value of material shrinkage during sintering, which indicates lower or higher densification of the studied alloy during this process. It should also be noted that the number and morphology of the pores change during the successive stages of sintering. Depending on the sintering parameters, closed spherical pores or open channel pores and more or less uniform distribution of pores were observed. For example, only for the two highest temperatures closed pores predominate, which is important information for a correct description of the densification of the material. Therefore, only combining the data obtained from density and shrinkage measurements during sintering, as well as conclusions derived from observations of the shape and distribution of pores, allows for assessing the actual relationships between the sets of induction sintering parameters adopted during the study and the quantitative and qualitative effect of compaction. The combination of the above-mentioned factors and their introduction into the inference system was made possible by using the fuzzy logic method. The adopted output variable "*Densification level*" (Fig. 8b) comprehensively determines the actual trends between sintering parameters and material densification.

The graph showing the "*Hardness*" output variable reflects the trends determined based on the results of hardness measurements of the samples for each process variant. The performance check of the controller was executed for this variable, which involved adjusting as output values the sets of parameters adopted during the tests. It was confirmed that the HV results obtained from the fuzzy system calculations were consistent with the experimental results. Thus, the correctness of the functions adopted to describe this variable, and the ranges of their values and rules were confirmed.

An evaluation of the analysis of induction sintering showed that the effects occurring during sintering and the resulting material properties change significantly during the successive stages of the process, and their effectiveness is very much influenced by temperature. These changes are nonlinear, so it is difficult to develop a mathematical model of the analyzed process. This problem was solved using the method of fuzzy logic, which made possible to analyze the predicted effects of sintering based on a combined cause-and-effect relationship evaluation of several variables, imitating the work of a human expert. This approach is particularly important when using mixtures of elemental powders as the initial material for compacts, which makes it significantly more difficult to control the homogenization of the chemical composition. The proposed fuzzy controller can be used as a tool for rapid estimation of the sintering process parameters necessary to achieve the required effects in the microstructural state and properties of the Ti-5Al-5Mo-5V-3Cr alloy. It can be also used to fast control the possibility of obtaining the mentioned effects under industrial conditions, using heating equipment available on the processing line.

4. Conclusions

1. The study of the induction sintering process allowed the identification of the phenomena occurring at different stages of the process and in relation to temperature. At the same time, it was shown that the phenomena occurring during the analyzed process have a complex character and are often difficult to interpret.
2. The effect of the combinations of sintering parameters on the homogenization of the chemical composition, the level of compaction, the state of microstructure, and the hardness of the material was determined. This information was the foundation for the development of a fuzzy controller, based on knowledge engineering and the fuzzy logic method.
3. The designed fuzzy controller makes it possible to analyze the progress of densification and homogenization of the chemical composition of material depending on the temperature and stage of the process based on the simultaneous analysis of several variables.
4. The proposed fuzzy controller can be useful as a tool for fast estimation of those parameters of the induction sintering process that are sufficient to achieve the assumed effects in the microstructure state and property requirements of sintered Ti-5Al-5Mo-5V-3Cr alloy.

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