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FAST ESTIMATION OF FAVORABLE PARAMETERS OF HOT METAL FORMING, USING THE FUZZY LOGIC METHOD

The paper presents an approach based on the use of the fuzzy logic method as a tool for quick estimation of favorable parameters of hot plastic working of selected alloy and for the identification of those combinations of parameters that should be avoided. The idea and basic principles of operation of fuzzy controllers for the selection of thermo-mechanical parameters of hot metal forming were presented. The most important information necessary for a quick analysis based on knowledge engineering has been compiled. An example of the fuzzy controller using the information obtained based on plastometric test data and the results of observation of the microstructure state of deformed samples at various temperature and strain rate variants is presented. For the tested alloy, it was shown that the analysis of the parameters of their plastic processing using the fuzzy logic method, based on properly formulated expert knowledge, leads to obtaining satisfactory results. Thus, it was confirmed that fuzzy logic can be successfully used as a tool for quick estimation of correct or unfavorable thermal and mechanical combinations of hot forging processes.

Keywords: hot plastic working; knowledge engineering; fuzzy driver; plastometric tests; microstructure

1. Introduction

The manufacturing of highly responsible structural components from metals, alloys or composites on metallic matrices by hot forming methods requires a deep knowledge of the deformation behavior of these materials, depending on the thermo-mechanical conditions of the process. To obtain this knowledge plastometric tests-are performed using thermo-mechanical simulators, as well as metallographic tests of deformed samples are commonly carried out [1,2].

The analysis of the flow curves, developed from the compression tests under given conditions (temperature, strain rate, strain value) and their comparison with the microstructure formed under these conditions gives a lot of important information about the response of the material to given parameters. Evaluation of this information by a human expert allows concluding the important conclusions about the phenomena occurring in the material such as strengthening, recovery, recrystallization, or grain growth. It also allows to preliminarily indicate favorable combinations of hot forming parameters of the tested material or to reject unfavorable combinations of parameters. The disadvantage of this approach is that it requires the expert to spend a great deal of time analyzing the data and interpreting it. Therefore, plastometric test data are often processed by analytical or numerical methods. Finite element methods (FEM) and dynamic material modeling (DMM) are commonly used for this purpose. In the application of both mentioned methods, the authors of this publication have experience, confirmed by participation in research works [3,4].

The application of FEM leads to comprehensive knowledge about thermo-mechanical conditions of hot processing. The evaluation of FEM results allows also for the prediction of material properties, such as inhomogeneity of deformation or microstructure evolution. Additionally, it enables to indicate of the zones in the forgings volume, which are potentially exposed to the occurrence of defects. However, the application of this method has its limitations. The most important is the high cost of a license for commercial software of the appropriate quality and access to a material and process database. In addition to the description of the material rheology, the calculation requires knowledge of the friction conditions and thermal properties at the forming temperature, such as density, diffusivity, thermal conductivity or heat transfer coefficients between the deformed material, tools and environment.

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A significant part of the mentioned material data is for alloys that are tested at room temperature or within the temperature ranges in which they operate. In the temperature ranges used during the hot deformation process of these materials, the mentioned data are incomplete or unavailable and their determination requires separate, advanced research. On the other hand, the method of DMM is used mainly to develop sets of thermomechanical parameters of hot deformation that are favorable for a given material. It also allows selecting those combinations of parameters that should be avoided, because their application may cause the formation of defects in the microstructure. However, this method requires complex calculations for its effective use. Additionally, it is advisable to develop distributions of activation energy values of high-temperature deformation. The lack of flexibility of the method is also a problem, which prevents the introduction of detailed information about the process or the consideration of small changes in technology. Some of the disadvantages typical of the above-mentioned methods can be eliminated by using controllers based on expert systems, especially on the fuzzy logic method.

Expert systems are computer programs capable of processing knowledge. They can analyze and solve such problems for which the mathematical model is difficult to define or does not exist. The knowledge needed to solve the problem posed to a system is stored in the system's knowledge base in the form of its representation. A characteristic feature of expert systems is that the knowledge about the problem to be solved is separated from the processing mechanisms. This is the fundamental difference between an expert system and traditional systems, where processing mechanisms are located in a procedural form, as internal parts of the program code. Expert systems are more and more often used in many areas of the economy, including control of devices and technological processes [5]. Currently, expert systems that have great application importance are systems based on the fuzzy logic method. Fuzzy logic is a strict mathematical approach for the description and processing of uncertainties which are themselves strongly oriented by human reasoning, unlike the likelihood theory and statistics. The fuzzy logic method was originally introduced and developed as a tool to control such processes for which the development of a model describing their course is difficult or impossible. Such an approach was proposed, among others, by Zadech, the forerunner of the method [6]. It is among other things used in the control and monitoring of production processes as well as in the optimization of material problems. In the fuzzy logic method the form of knowledge representation are rules, e.g., IF X is ...THEN Y is ..., where X is the premise (simple or complex logical expression) and Y is the conclusion (decision or statement). The reasoning system uses the methods of inference based on the rules. This system is responsible for the processing of the information contained in the knowledge base of an expert system.

The approach of using fuzzy logic as a tool to solve hot processing problems is currently the subject of many research works. The fuzzy model has been successfully applied to predict the flow of material during deformation [7]. Raßbach and Lehnert used the fuzzy logic method to model the functionally gradient materials (FGM) behavior during deformation [8]. Interesting results were obtained by Gronostajski et al. in [9]. They presented the expert system for determining the quantitative contributions of four principal mechanisms (abrasive wear, thermo-mechanical fatigue, deformation and mechanical fatigue) to the degradation of forging tools for selected industrial hot forging processes. Lee and Kopp [10] discussed the application of an adaptive fuzzy controller for a hydraulic forging machine. The paper describes the use of the fuzzy controller with two processes, upsetting, and thixoforging. Moreover, Lin et al. developed the fuzzy expert system to estimate dimensional errors of forging products having a complicated shape, which was presented in [11].

In the opinion of the authors, supported by literature analysis and results of own research conducted in this field, fuzzy logic can be effectively used as a tool for rapid selection of parameters of hot processing of various alloys based on data from compression tests on a Gleeble simulator and observation of the microstructure of deformed samples. This applies not only to materials produced traditionally but also with the use of alternative technologies, such as powder metallurgy (PM). The application of fuzzy controllers for the prediction of parameters of manufacturing processes of powder products has been dealt with by P. Radha et al. [12]. The co-author of this publication also has an experience in knowledge engineering and building fuzzy controllers. The issues he investigated included the estimation of the relationship between the manufacturing process parameters of metal-ceramic composites and their predicted properties [13]. Another example of research conducted in this area was the development of a controller for the rapid determination of favorable parameters of powder mixing, depending on the morphology of individual components of the mixture and the relationship between them [14].

A separate issue that has great potential is the use of fuzzy logic to automatically select the parameters of the metal forming process in real-time. This approach is based on the digital twin technology, which involves taking information about the material during the process, such as current dimensions, temperature, and strain value, and analyzing this data. Based on the measurements, a strategy for further hot forming steps is created in real-time. For example, in the case of free forging, these include the values of strain in subsequent steps, the decision to carry out reheating of the forged material, etc. The development of data for the implementation of this technology requires access to extensive material and process knowledge, including knowledge of the flow curves and microstructure state of the deformed samples. The implementation of such an approach must be based on methods of rapid data analysis, such as fuzzy logic, neural networks, or systems combining the aforementioned methods. Such an approach is currently being developed by the authors within the M-ERA.NET 2 Call 2020 (2021-2024). The content of this paper presents selected aspects of such an approach.

2. Aim and scope of study

The aim of this research was to develop a fuzzy logic-based controller as a tool to quickly indicate favorable hot forging parameters, based on a database developed from plastometric tests and observations of the microstructure of samples deformed in these tests.

As the material used as the basis for the development of the fuzzy controller Ti-6Al-4V alloy obtained from elemental powders was adopted. To produce the alloy, the mixing process of titanium, vanadium, and aluminum powders as well as hot pressing of the mixture were used. Hot compression tests of this alloy were performed using different variations of temperature and strain rate. The relationships between the parameters of the hot compression tests, flow curves and microstructure of the deformed specimens were analyzed. Input and output variables were then identified, and ranges of their values were defined. The relationships between the variables were presented in the form of cause-and-effect relationships in such a way that they could be processed by the computational system. The resulting relationships were the equivalent of human expert knowledge. They were used to develop a fuzzy controller used to quickly identify favorable or unfavorable combinations of hot forging parameters of the alloys under study. The Fuzzy Logic Toolbox module of the Matlab package was used to develop the controller. The controller was tested, and necessary rule corrections were made. At the last stage, the results of the fuzzy analysis were compared with the results of previous test alloys to verify the correctness of the controller.

3. Methodology

Plastometric tests were performed on the Gleeble 3800 thermo-mechanical simulator. Cylindrical specimens of dimensions 10 mm × 12 mm were resistively heated to the assumed temperature, held at this temperature for 10 seconds, and then compressed at a constant strain rate. The compression tests were carried out using strain rates in the range of 0.01-10 s^{-1}, at temperatures in the range of 800-1000°C up to a strain value of 1,0. Immediately after the deformation, the samples were cooled using compressed air. The specimens were ground and polished with the standard metallographic procedure. Etching was performed in two stages: first stage: 6% HF + 96% H_2O, second stage: 2% HF + 2% HNO_3 + 96% H_2O. Metallographic studies were performed on a Leica DM4000M optical microscope.

4. Results and discussion

4.1. Plastometric tests

Fig. 1 summarizes the stress-strain relationships developed based on plastometric tests of the investigated alloy carried out at different temperature and strain rate variants.

In the case of the tested material, the flow curves obtained for specimens deformed at 10 s^{-1} indicate an intense strengthening process of the material in the initial phase of deformation, regardless of the test temperature. In the case of the compression at 800°C, this effect can be observed up to a true strain value of

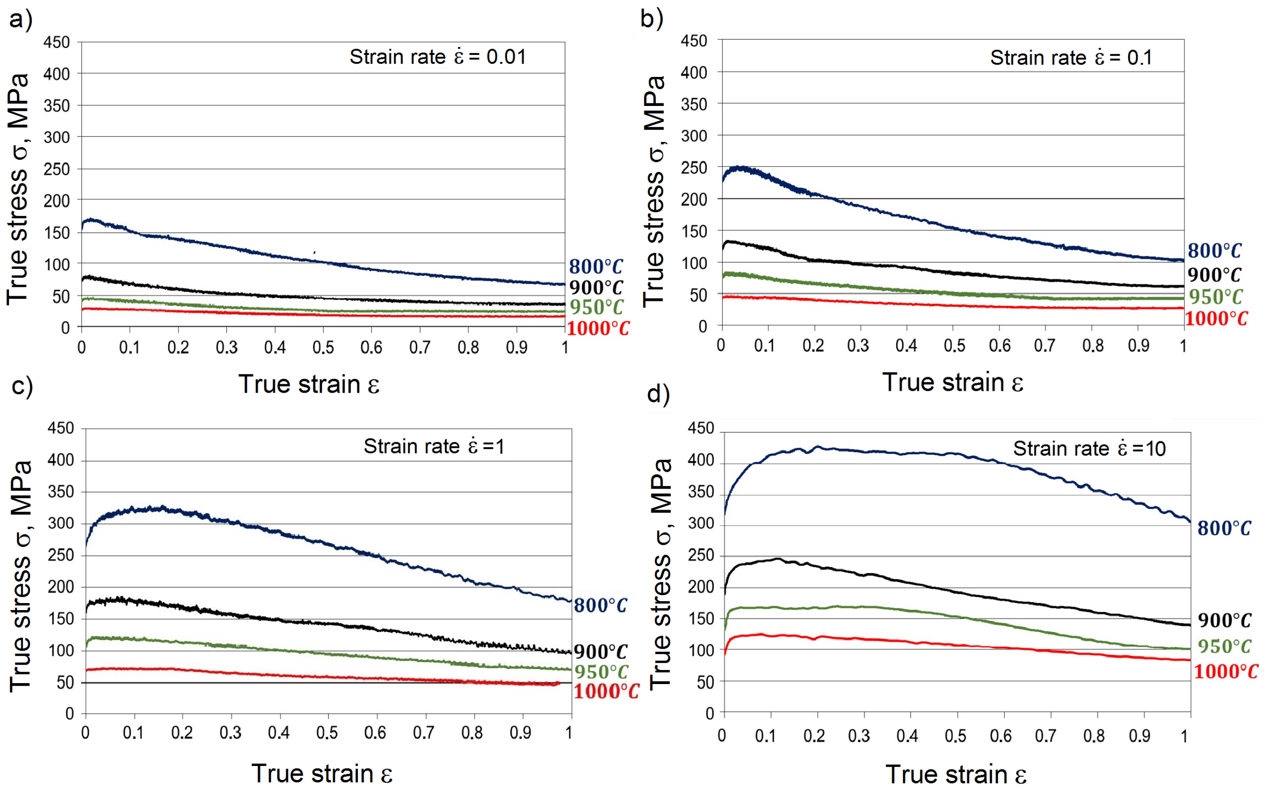

Fig. 1. The influence of strain rate and temperature used during plastometric tests on the character of the curves: true stress – true strain of Ti-6Al-4V alloy obtained from powders. Strain rate: a) – 0.01, b) – 0.1, c) – 1 and d) – 10

about 0.6, thus over a much wider strain range compared to the flow curves at higher temperatures. It should be assumed that the decrease in true strain beyond the maximum value may be a consequence of stress relaxation due to the dynamic recovery of the material. A similar effect of stress increases at the initial stage of deformation, indicating the strengthening of the material at this stage, is also visible for the specimens deformed at 1 s^{-1} at 800°C and, to a small extent, at 900°C. The flow curves developed from the compression tests at a strain rate of 1 s^{-1} at higher temperatures (950°C and 1000°C) show a decrease in the true stress values with an increasing true strain to the value of 0.5. The same effect is also seen for specimens deformed at lower strain rates of 0.1 s^{-1} and 0.01 s^{-1} over the full temperature range. At values of true strain higher than 0.5, a steady-state flow is observed. The strain increment under these conditions occurred at constant or slightly decreasing values of true strain. The flow curves obtained as a result of the applied combination of deformation parameters do not show the effect of strengthening and are similar in their course as a function of strain. Hence, they differ only in the values of flow stress. A comparison of the courses of the different flow curves shows that the material is very sensitive to strain rate at lower temperatures. With increasing temperature, the sensitivity to changes in the strain rate decreases.

The flow curves obtained from the plastometric tests describe the material's behavior during hot deformation under different conditions, but the obtained information as a result of such tests needs to be verified. Therefore, the analysis of the flow curves and their interpretation should be related to the observations of the microstructure. Fig. 2a shows a microstructure of a sample not subjected to deformation, Fig. 2b-2f summarizes images of the microstructure of specimens deformed on the Gleeble simulator, at representative variations of temperature and strain rate.

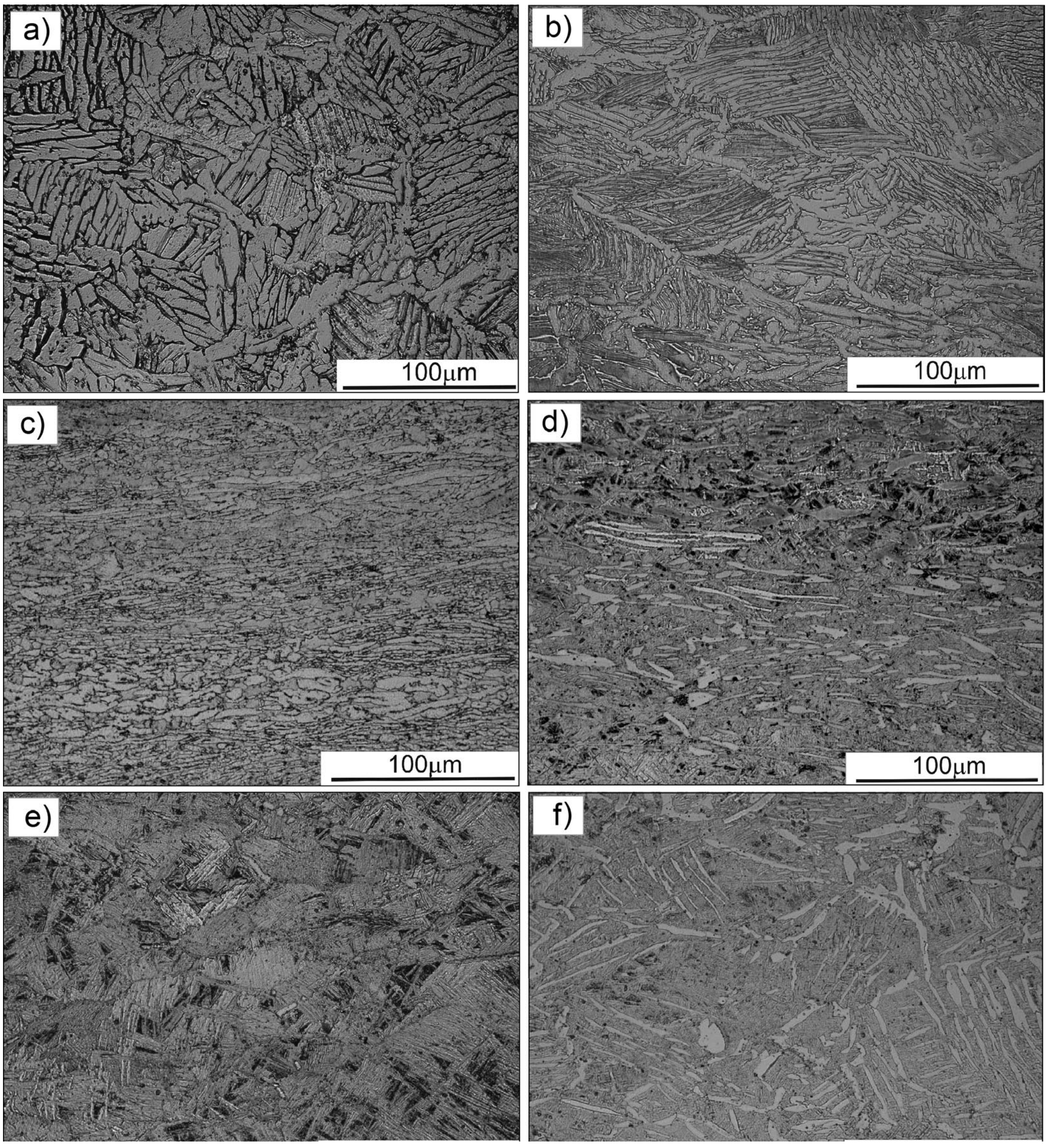

Fig. 2. Influence of the hot compression test conditions on the microstructure of the Ti-6Al-4V alloy compact: a) – initial material and b-f) samples deformed during the test under the following conditions: b) – temperature 800°C, strain rate 1 s^{-1}, c) – temperature 900°C, strain rate 0.1 s^{-1}, d) – temperature of 950°C, strain rate 1 s^{-1}, e) – temperature of 1000°C, strain rate 0.01 s^{-1}, f) – temperature of 1000°C, strain rate 10 s^{-1}. Metallographic examination in longitudinal section etched. Images in the center zone of the sample

The microstructure of a sample not subjected to deformation has a lamellar character and consists of massive α phase plates (light phase visible at low magnification) in a β phase matrix (darker phase) and continuous α phase precipitations present on the former boundaries of the phase grains β.

It was found that recrystallization did not occur during deformation at 800°C (Fig. 2b). These observations were related to the α and β phases. For the samples deformed at 900°C and strain rates no higher than 0.1 s^{-1}, undeformed grains of both phases were observed, which indicates the occurrence of partial recrystallization. Increasing the strain rate to 1 s^{-1} caused this effect to be observed for samples compressed at temperatures above 950°C (Fig. 2d). At the highest strain rate of 10 s^{-1}, the microstructure showed the effect of partial phase recrystallization only at 1000°C (Fig. 2f). At this temperature, the α phase contribution to the β phase matrix was negligible. As the test temperature increased at a constant strain rate, an increase in the proportion of the β phase was observed as a result of the phase transformation (Fig. 2b,d). These observations explain the high sensitivity of the investigated alloy to the deformation temperature demonstrated during the analysis of the flow curves. Since the efficiency of sliding systems of the α phase with hexagonal crystallographic lattice is much lower compared to the β phase with body-centered cubic lattice, therefore, in the case of the tested material decreasing the amount of the α phase with increasing temperature affects the increase in the plasticity of the alloy.

For specimens deformed at higher temperatures decreasing the strain rate led to an increase in the exposure time of the specimen to the temperature used during the test. The result of this was an increase in the proportion of the β phase in the microstructure. The varying phase contribution may be one of the factors causing the high sensitivity of the investigated alloy to the change in strain rate at higher temperatures, as shown during the analysis of the flow curves. Observations of the microstructure showed differentiated fragmentation of α phase plates within individual grains. This effect is due to the different orientations of the plates inside the grains. When the orientation of the α phase plates was perpendicular to the direction of force applied during deformation, significant fragmentation occurred. This was particularly evident for samples compressed at 800°C (Fig. 2b), or higher strain rates (Fig. 2f). The arrangement of the plates parallel to the direction of the force during compression led to their deformation. Observations of the microstructure of the sample deformed at 1000°C show that the higher the strain rate at this temperature, the higher the proportion of the α phase (Fig. 2e,f). For low strain rates of no more than 0.1 s^{-1}, the contribution of this phase was negligible. (Fig. 2e). In summary, the observations of the deformed specimens indicate that by using different combinations of temperature and strain rate, it is possible to introduce controlled changes in the microstructural state of the Ti-6Al-4V alloy compacts.

4.2. Assumptions made in the development of the controller

At this stage, it should be assumed that the phenomena observed during plastometric and metallographic tests are specific to the alloy under analysis or materials with similar chemical composition and properties. Within the assumed range of thermo-mechanical parameters, different types of phenomena, such as the precipitation dissolution characteristic of high alloy steels or valve steels, will lead to the different behavior of these materials during their deformation. The phenomena occurring under such conditions are individual and must be interpreted properly. Therefore, the results obtained can be used as a basis for the construction of fuzzy controllers for rapid analysis of favorable plastic processing parameters only for the tested materials or those with similar deformation responses. However, in the opinion of the authors of the paper, the idea of the proposed method, which is to use data from plastometric tests and the results of observations of the microstructure after deformation as the basis for the development of fuzzy controllers, will also apply to other groups of materials. The procedure for developing a fuzzy controller for an engineering material other than the one adopted in the paper, based on well-developed and properly interpreted knowledge of the material, can be essentially similar.

4.3. Development of a fuzzy controller

The Matlab Fuzzy Toolbox package was used to develop a controller based on the fuzzy logic method. A diagram of the various blocks of the package's functioning system is shown in Fig. 3.

As shown in the diagram, the fuzzy controller consists of four main blocks [15]. These are the fuzzification interface, interface engine, knowledge base (rule processing) unit, and defuzzification interface. Their operation divides the computation process into sequences. The Fuzzification interface is the first sequence of the computational process based on the fuzzy logic method. The input data in the form of input variables is defuzzified in the system by rescaling. At this stage, each knowledge

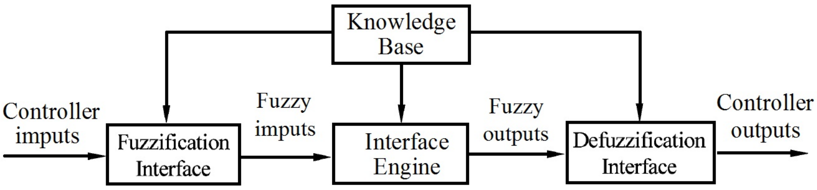

Fig. 3. Fuzzy controller system

item is assigned a membership function and transformed into a linguistic structure that can be processed by the computing system. The processed data is then sent to the interface engine unit, where in the next sequence it is combined with the developed knowledge base. The rules posted in this block define the relationships between these data and the values of the output variables. Operations on fuzzy sets are implemented by logical sum, logical product, or negation. In the last sequence of the computational procedure, the results of the inference are sent to the defuzzification block, where the ranges of values of the output variables are processed into strictly defined values. This is implemented, for example, through the center average defuzzification method or the center of gravity method. At this stage, the strictly defined value of the output variable is determined, which is the result of the calculations

Input and output variables were defined. The inference process was run for two input variables and four selected output variables. Temperature and strain rate – expressed as logarithm o this value – were used as input variables. Four values were selected as output variables, reflecting the knowledge of the investigated alloy, obtained from the analysis of plastometric test results, supported by the evaluation of the microstructure of deformed samples. The variable "flow stress" determines the effect of the parameters of the compression test on the value of the stress necessary for the initiation of plastic deformation. The variable "hardening effect" characterizes the increase in the value of the actual stress in the first stage of deformation. The variable "softening effect" reflects the intensity of the decrease in the value of real stress at the advanced stage of deformation. The "recrystallization intensity" variable, which characteristics were defined based on flow curve analysis and microstructure observation, determines the degree of recrystallization as a function of temperature and strain rate.

Individual variables were defined by assigning their ranges of values and by describing their course, using an appropriate number of shape functions. These functions were described with linguistic terms, such as "lack," "small," "very large," etc. To enable the system to analyze and interpret the data, the relationships between input and output variables were defined using a set of fuzzy rules, based on conditional sentences of the IF...THEN type. The rules introduce data into the system in a manner analogous to the way inference of a human expert analyzing data from an experiment proceeds. An example of a rule may be in the simplified form: IF "temperature" is " high" AND "strain rate" is "very low" THEN "flow stress" is low AND "hardening effect" is "lack" AND... In this way, a linguistic model was prepared, on which the functioning of the system is based. The rule database was developed not only based on the results of the experiment but also using expert knowledge. These include information defining the effects of various phenomena accompanying deformation under certain conditions, such as strengthening or recrystallization, on the way the material flows, and on the microstructural state of the deformed samples. Deffuzification was carried out using the center of gravity method.

4.4. Example results of fuzzy logic analysis for hot forging parameter selection

Examples of the relationships between the input and output variables adopted in this work are summarized in Fig. 4. The presented graphs show the trends resulting from the way the variables are defined, the rules entered into the expert system, and the interactions between them. This database is the basis for the working of the fuzzy controller. The values of the variables in Fig. 4a-c are derived from the analysis of the flow curves, while the variable "recrystallization intensity" was developed from the analysis of the flow curves and the evaluation of the microstructure state of the deformed samples. The trends seen in Fig. 4 are qualitatively consistent with the knowledge of the effect of changes in temperature and strain rate on the behavior of Ti-6Al-4V alloy during its deformation in the range of these parameters adopted for analysis. The quantitative data were determined by analyzing the changes in the values on the stress-strain curves and evaluating the changes in the microstructural state depending on the test conditions. Based on such analysis, measurable ranges of values for individual linguistic terms, such as "very high", "low", etc., were determined. The correct operation of the fuzzy controller was verified by inserting the tested variants of temperature and strain rate as input variables. The obtained values of the output variables were consistent with the tests results. This approach allows assuming that the data obtained correctly reflects the behavior of the material during hot deformation.

The developed fuzzy controller allows rapid estimation of the material's response to changes in the combination of temperature and strain rate, making it possible to select favorable process parameters or reject unfavorable variants. Input data to the controller can be entered manually or through automatic real-time measurement of process parameters. In the latter case, the speed of the controller's response is significantly increased, which is an advantage of the method. For this reason, a developed controller can be useful as a tool for rapid evaluation of the feasibility of hot forging processes in industrial conditions. Entering input data into the system, such as the strain rate, which is derived from the dimensions of the charge and the speed of movement of working parts of the machine, and the temperature of the feedstock makes it possible to estimate the forces required to carry out the process or to predict the occurrence of effects such as hardening or softening during forging. Another advantage of the controller is that the proposed solution does not require knowledge of mathematical models describing the process. An approach based on the way of inference as a human expert allows revealing unusual effects that a standard model may miss. As noted by Stendal et al. [16], the deformation behavior of the alloys during hot deformation is dependent on a wide range of interconnected phenomena, such as hardening, softening, dynamic recovery, dynamic or meta-dynamic recrystallization, and generation of heat. These phenomena can all occur simultaneously and influence each other. The behavior varies with process temperature, applied strain rate and strain value.

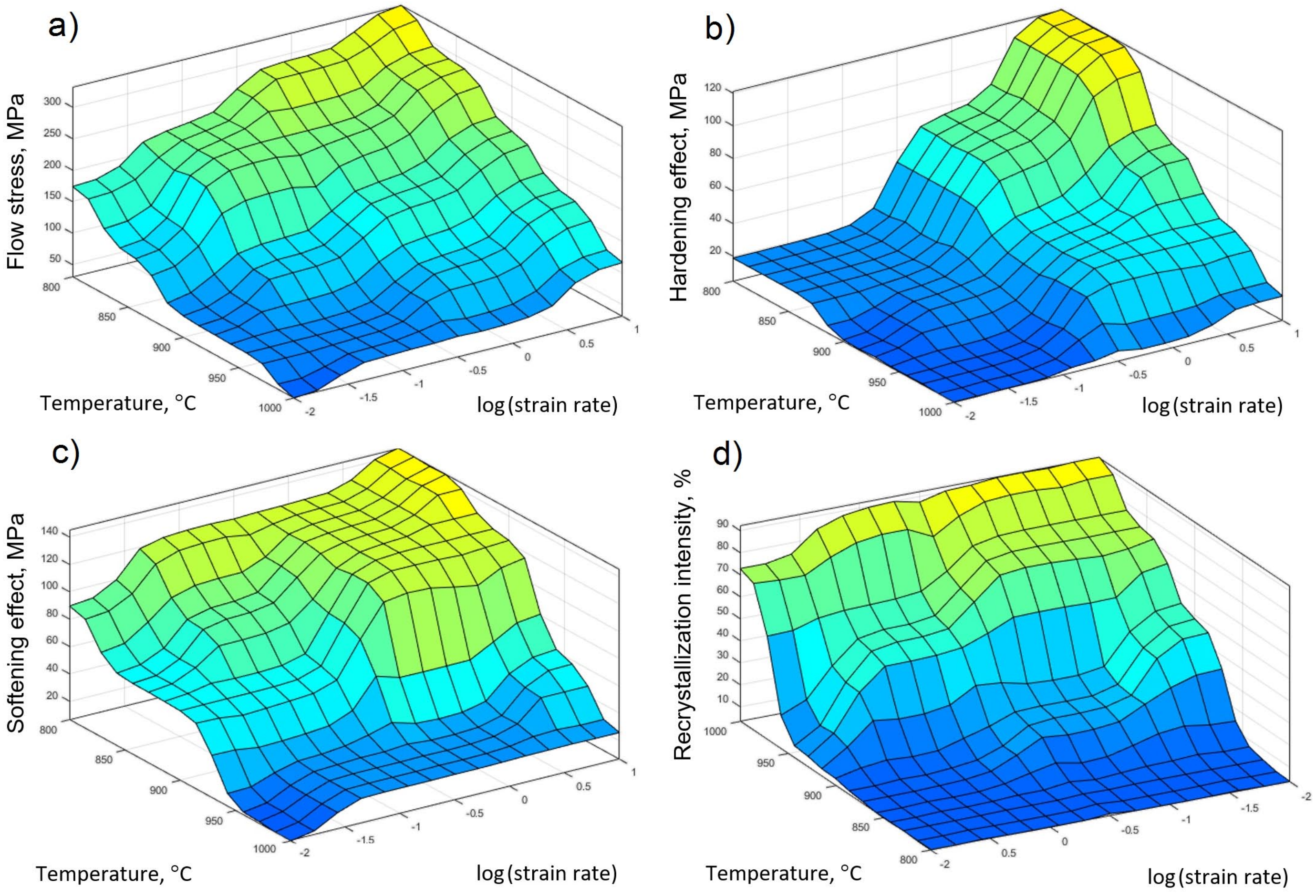

Fig. 4. Developed by the fuzzy logic method, the effect of temperature and strain rate on the change of the example output variables: a) flow stress, b) hardening effect, c) softening effect, and d) recrystallization intensity

Therefore, a high-quality fuzzy controller based on the analysis of flow curves and microstructure can contain large amounts of information. In addition to rules describing obvious relationships (IF "temperature" is "very high" AND "strain rate" is "very low" THEN "flow stress" is low), it was possible to introduce into the analysis and inference those relationships that are subtle in nature and indicate, for example, the occurrence of recrystallization. Often, these rules describe tendencies that are typical of the particular chemical composition of the alloy or of the method of producing the feedstock for hot processing. For this reason, proposed method is very well suited for analyzing the behavior of materials during their hot forming.

4.5. Verification of the controller

The correctness of the fuzzy controller was verified. For this purpose, a hot compression test of a Ti-6Al-4V alloy sample was performed, assuming an example variant of temperature and strain rate. The results obtained from the experiment were compared with the results of calculations carried out using the fuzzy controller. The compression test of the Ti-6Al-4V alloy sample was carried out at 900°C and an average strain rate of 1 s^{-1}. It was assumed that the test results obtained with such a combination of parameters can be additionally useful as data for characterizing the compression process of the studied alloy under industrial conditions. Samples with a diameter of 5 mm and a height of 8 mm were used. The relatively small dimensions of the samples were due to limitations in the linear speed of the traverse on the available compression stand. The surfaces of the samples were coated with graphite lubricant. The sample was placed in a heat-resistant steel container, closed with a punch, to protect it from cooling too quickly. The container and the sample were heated in a furnace to 900°C, transported to the press, and compressed at a linear speed of 5 $mm \cdot s^{-1}$, which, with the dimensions of the sample used, allowed an average strain rate of about 1 s^{-1}. During the test, the force required for deformation and time were measured. The measurement was carried out at a frequency of 40 Hz. The results are shown in Fig. 5a.

After the deformation, the sample was removed from the container and cooled in air. The true stress – true strain curve was developed. The curve was then corrected for the value of the friction coefficient. This was necessary because the curves used as a basis for designing the controller were developed in the same way. For the lubricant used in the test, the value of the coefficient of friction was assumed to be 0.14, which was determined based on separate tests. The curves obtained from the test and after correction are shown in Fig. 5b. From the cor-

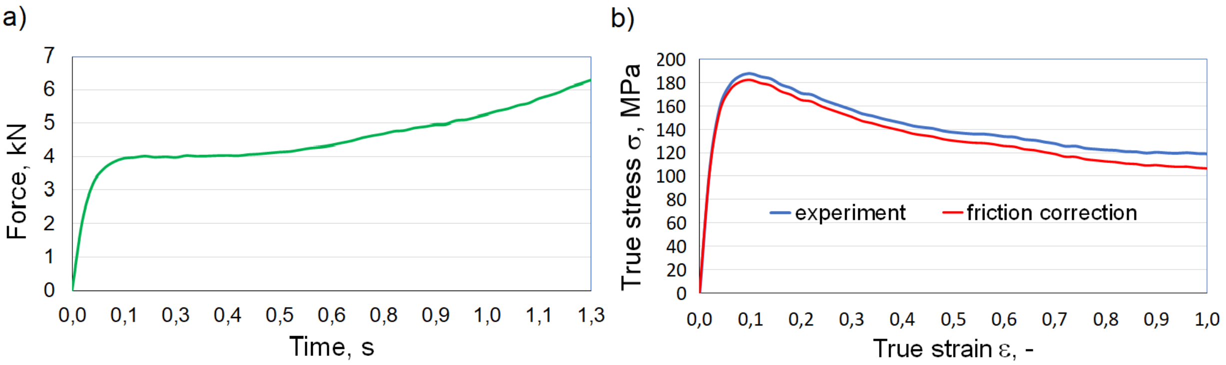

Fig. 5. Obtained from the compression test at 900°C and with an average strain rate of 1 s^{-1}: (a) – force as a function of time and (b) – true stress – true strain curves

rected curve, the values of "flow stress", "hardening effect" and "softening effect" were read. To evaluate the "recrystallization intensity" parameter, the microstructure of the sample after deformation and cooling in the air was tested. The microstructure is included in Fig. 6.

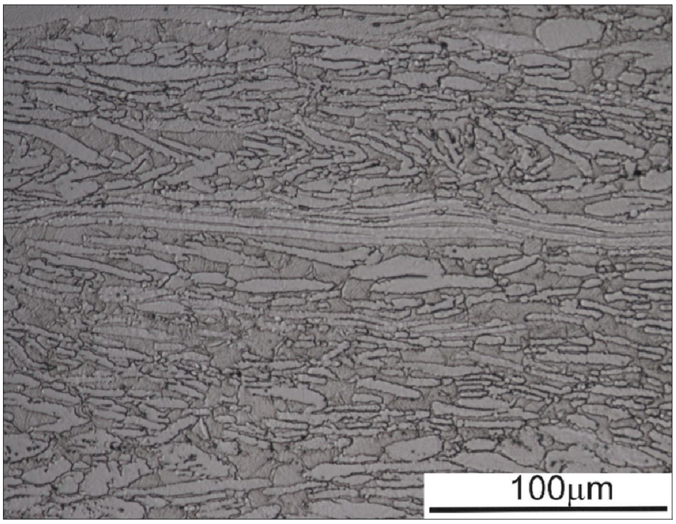

Fig. 6. Microstructure of a Ti-6Al-4V alloy sample after compression at 900°C and an average strain rate of 1 s^{-1}

The microstructure of the sample deformed under the adopted conditions consists of massive plates of α phase and colonies of thin α + β plates located between them. Fine, undeformed grains of the β phase were observed sporadically, indicating a slight level of recrystallization in this phase. A significant part of the microstructure consists of α-phase plates, deformed and oriented during compression according to the flow direction of the material. Some plates were fragmented during compression. The state of the microstructure indicates that the degree of dynamic recrystallization was insignificant and recrystallization occurred mainly after the compression test, and during the cooling of the sample. Therefore, adopting the ranges introduced in the fuzzy controller, the degree of recrystallization was assumed to be low. The values of temperature and strain rate used during the compression test were entered as input data into the fuzzy controller and calculations were made. A summary of the test results and calculations is provided in TABLE 1.

The greatest difference was found for the „hardening effect" variable, but it is the most difficult to define clearly in the controller, due to the large differences in this value for the base curves. Increasing the accuracy of calculations for this variable requires more data. On the other hand, a fairly good quantitative agreement was found for the values of the variables „flow stress", „softening effect" and qualitative agreement for the variable „recrystallization intensity". Taking into account the fact that a fuzzy controller is a tool for rapid estimation of similar values of the adopted variables, it should be assumed that its operation is correct.

5. Conclusions

1. Plastometric tests provided the basis for describing the behavior of the studied alloy during its hot processing in the assumed range of temperature and strain rate. These data were extended by the results of observations of the microstructure of the deformed alloy.
2. The designed fuzzy controller allows rapid estimation of the material's response to specific combinations of temperature and strain rate in the analyzed ranges of these parameters. It also allows predicting the effect of the adopted forging

TABLE 1

Comparison of the results of the compression test and calculations made with the fuzzy logic controller for variables: "flow stress", "softening effect", "hardening effect" and "recrystallization intensity"

	Flow stress, MPa	**Softening effect, MPa**	**Hardening effect, MPa**	**Recrystallization intensity, –**
Compression test	156	76	37	low
Fuzzy logic controller	161	83	27	20.5% (low)

conditions on the nature of changes in the state of the microstructure, resulting from the occurrence of such phenomena as dynamic or meta-dynamic recrystallization.

3. The proposed controller can be useful as a tool for rapid assessment of the feasibility of hot forging processes in industrial conditions. Introducing machine speed and feedstock temperature characteristics into the system makes it possible to estimate the values of forces required for the process or to predict the material's response to given deformation conditions.
4. The speed of response of the fuzzy controller can be significantly increased by automatic real-time measurement of process parameters and their direct input into the fuzzy logic-based computing system. This data can be read in real-time from sensors, such as thermal cameras or thermocouples. In this way, the results of an expert analysis of the issue can be obtained in an immeasurably shorter time than is possible by way of analysis conducted by a human expert. These results can be automatically entered as data for process control.

Acknowledgments

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