THE INFLUENCE OF THERMOMECHANICAL PARAMETERS OF BETA-C TITANIUM ALLOY PROCESSING ON ITS THERMOMECHANICAL BEHAVIOR

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Abstract

The influence of thermomechanical processing history on the microstructure and thermomechanical behavior of Ti-3Al-8V-6Cr-4Zr-4Mo titanium alloy was subjected to the analysis in this research. The alloy flow stress curves were elaborated basing on compression tests performed under various temperatures and strain rates. Various criteria of stability and instability of the material flow were taken into account to analyze the material behavior under various thermomechanical conditions. The research shown, that the inhomogeneity of the alloy's microstructure in the initial state is a significant factor affecting the inhomogeneity of deformation. It was also shown, that the processing maps developed using various criteria are an effective tool in predicting flow instability and optimising hot forming parameters. The processing maps clearly showed the set of thermomechanical parameters potentially leading to the formation of adiabatic shear bands and strain localisation during deformation of the investigated alloy, but also enabled identifying optimal conditions for dynamic recrystallisation of the material. The obtained results may have direct applications in the design of thermomechanical processing of the investigated titanium alloy under industrial conditions.

Keywords: Beta titanium alloy, flow curves, processing maps, microstructure analysis

1. INTRODUCTION

Titanium alloys, due to their favourable mechanical properties, high corrosion resistance and low specific gravity, are one of the most important groups of structural materials used in modern industry, including aerospace, automotive and medical applications [1]. In particular, the Ti-3Al-8V-6Cr-4Zr-4Mo alloy is classified as a metastable β-titanium alloy, which is characterized by high strength, good weldability and the possibility of precise control of the microstructure through appropriate thermo-mechanical processes [2].

In technological processes such as forging, rolling or extrusion, it is essential to have a thorough understanding of the rheological properties of the alloy and its behaviour during plastic deformation at elevated temperatures. A key element in this respect is the analysis of the flow curves and the development of so-called processing maps that enable the optimisation of thermomechanical processing parameters [3, 4]. Such maps make it possible not only to predict the behaviour of the material under different processing conditions, but also to identify areas of stable flow, favourable for the formation of a homogeneous microstructure, and zones of potential instability, where shear bands, strain localisation or cracking may occur [5].

One of the most commonly used methods to develop processing maps is the method using the Dynamic Material Model (DMM), which is based on the balance of energy during deformation. Within this model, the total energy input to the deformation process is split into energy stored as heat and energy used for microstructural changes [6]. From a mathematical point of view, the key parameters of the model are the energy dissipation efficiency (η) and the flow instability parameter (ξ). The areas where the parameter ξ takes

values less than or equal to zero are considered potentially unstable, while high values of energy dissipation efficiency contribute to the occurrence of dynamic recovery, dynamic recrystallisation or superplasticity [7].
Semiatin [8], on the other hand, proposed a complementary approach in which more attention is paid to microstructural mechanisms occurring during deformation, such as dynamic recrystallisation, phase transformations or globular structure formation. An integrated approach, combining Prasad's and Semiatin's criteria, allows a more complete characterisation of the material behaviour under different processing conditions and a more accurate determination of appropriate deformation parameters.
The aim of the present study was to analyse the effect of thermo-mechanical treatment history on the microstructure and rheological behaviour of Ti-3Al-8V-6Cr-4Zr-4Mo alloy. For this purpose, compression tests were carried out over a wide range of temperatures and strain rates. Based on the data obtained, flow curves were elaborated and processing maps were developed using stability and instability flow criteria according to the approach of Prasad and Semiatin.
The results obtained showed that the microstructural heterogeneity of the material in the initial state significantly affects the strain localisation and the initiation of unstable rheological phenomena.

2. MATERIALS, METHODS AND EXPERIMENT

The test material was a Ti-3Al-8V-6Cr-4Mo-4Zr alloy with the chemical composition shown in **Table 1**. The starting form of the material was a powder obtained by spraying cast alloy. The morphology of the resulting powder is shown in **Figure 1a**. The powder was then hot-pressed at 950°C for 30 minutes. The microstructure of the compact is shown in **Figure 1b**.

Table 1 Chemical composition of Ti-3Al-8V-6Cr-4Mo-4Zr alloy

Element	C	V	Cr	Mo	Zr	Al	Fe	O	N	Y	Ti
Content (wt%)	0.014	8.19	6.41	4.17	4.15	3.46	0.08	0.08	0.009	0.005	Rest

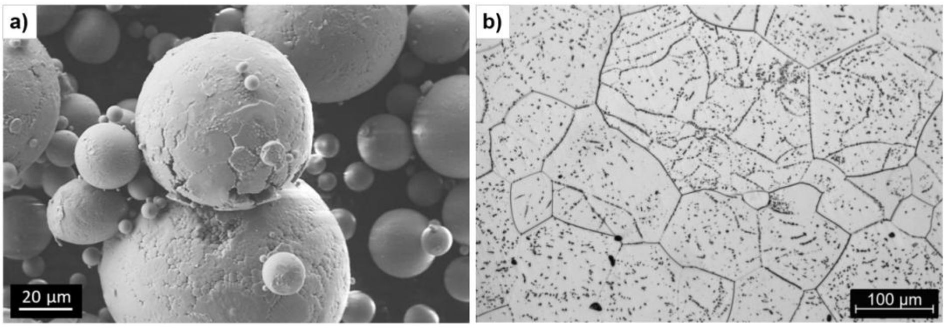

Figure 1 Powder morphology (a) and microstructure after hot pressing (b) of Ti-3Al-8V-6Cr-4Mo-4Zr alloy

Plastometric tests were carried out on a WUMSI thermomechanical simulator (TU Freiberg). For this purpose, specimens with a diameter of 10 mm and a height of 18 mm were prepared and heated in an furnance to the temperatures in the range of 800 - 1000°C and then compressed in the strain rate range of 0.1 - 10 s^{-1}. Flow curves were created from the plastometric tests data (**Figure 2**).

As shown in **Figure 2**, a decrease in stress levels is observed as the strain temperature increases and the strain rate decreases. The initial increase in stress at all temperature conditions analysed is due to strain hardening, while its subsequent decrease is related to material softening processes, indicating an increase in dislocation density during the initial deformation phase [9]. The decrease in stress at a later stage may result from the activation of mechanisms such as dynamic recrystallisation (DRX), dynamic recovery (DRV) or superplasticity [10], although the contribution of flow instability cannot be excluded.

A detailed analysis and examination of the microstructures was carried out, with a particular focus on verifying the processing maps. The microstructure was analysed using a Leica DM4000M light microscope. The subsequent state of the specimen, resulting from deformation tests under different thermomechanical parameters, was then analysed. The microstructures of the test specimens were observed in the central region of the specimen cross-sections, on a plane aligned with the compression direction.

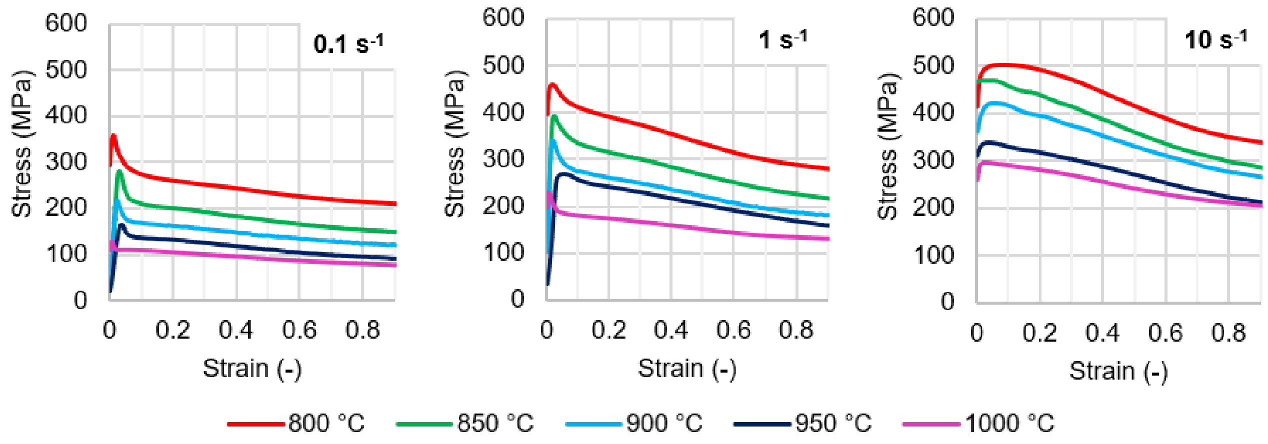

Figure 2 Flow curves of Ti-3Al-8V-6Cr-4Mo-4Zr alloy deformed in compression at the temperature range of 800–1000 °C under the strain rates of 0.1, 1 and 10 s^{-1}

Accurate determination of metal forming parameters is crucial as it affects the mechanical properties and microstructure of the product. In the hot deformation process, it is essential to control the microstructure and predict the material's response to the processing temperature, strain rate and strain amount. The energy dissipation efficiency (η), presented in a map, shows how energy is consumed in microstructural transformations - higher η values indicate more favourable processing conditions. In turn, the analysis of the flow instability parameter allows the creation of instability maps, and their combination with the η map gives a comprehensive processing map. Negative values of this parameter indicate a risk of instability, such as high local deformation or cracking.

The processing maps were created according to the Prasad criterion for true strain ranging from 0.1 to 0.9 (**Figure 3** shows selected maps). The isolines on the processing map illustrate the distribution of the power dissipation efficiency parameter η (1) based on the strain rate sensitivity parameter m (2):

$$\eta = \frac{2m}{m+1} \quad (1)$$

$$m = \left(\frac{\partial \log \sigma}{\partial \log \dot{\varepsilon}}\right)_{T,\varepsilon} \quad (2)$$

where: σ – stress, $\dot{\varepsilon}$ – strain rate, T – temperature, ε – strain.

The shaded areas represent instabilities associated with a negative value of the flow instability parameter ξ (3).

$$\xi(\dot{\varepsilon}) = \frac{\partial \log\left(\frac{m}{m+1}\right)}{\partial \log \dot{\varepsilon}} + m \leq 0 \quad (3)$$

The distribution of the isolines suggests that a decrease in strain rate correlates with an increase in power dissipation efficiency. It can be observed that the maximum values of energy dissipation efficiency are concentrated in the areas with the lowest analyzed strain rates at high temperatures. Areas with high values of the energy dissipation efficiency parameter (η) are often considered to describe favourable parameters of the material processing, as they are characterized by the occurrence of dynamic recrystallization (η = 30-50%), dynamic recovery (η = 20-30%) and superplasticity (η > 60%).

The processing maps prepared according to the Prasad criterion, for all values of true strain, generally look similar with slight deviations in the values of temperature and strain rate parameters for η and ξ parameters. The maximum values of energy dissipation efficiency (η = 38-50%) are concentrated in the areas of lowest strain rate (0.1 s^{-1}) and temperature above 920 °C. The isoclines of the η parameter have a similar course, with a small amplitude of change in deflection in the direction of increasing strain rate, which may indicate some stability of the material flow during processing in this parameter range. Partial dynamic recrystallisation occurs in this area, reflected in differences in grain sizes. The low strain rates favour homogenisation of the structure, but also the grain growth tendencies due to the long material exposure time at high temperature.

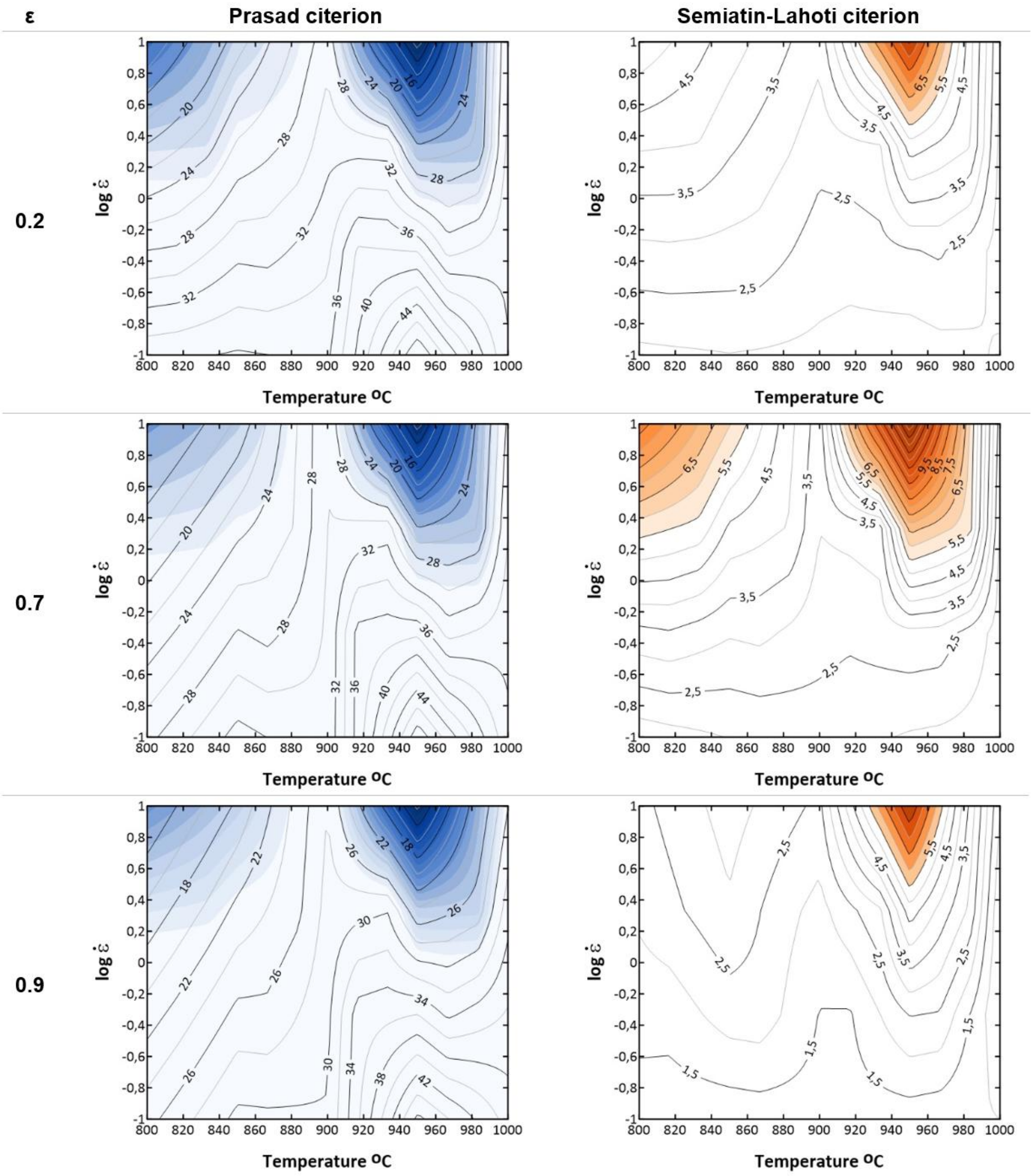

Figure 3 The processing maps of the Ti-3Al-8V-6Cr-4Mo-4Zr alloy developed for the true strain 0.2, 0.7 and 0.9 using the Prasad and the Semiatin-Lahoti criterion based upon flow localisation criterion with shadowed instability areas

For each processing map, two areas of instability are visible, that are areas where the parameter $\xi < 0$. First area includes parameters: T = 800-885 °C, $\dot{\varepsilon}$ = 1.3 – 10 s^{-1}, while the second area includes the parameters: T = 905-995 °C, $\dot{\varepsilon}$ = 1.1 – 10 s^{-1}. The shape and position of these areas may indicate heterogeneous deformation with varying levels of stress and resistance to plastic deformation. However, these areas do not cause negative flow instability effects in the material. It can be seen that the amount of strain has a significant effect on the identified areas of instability. This may be due to the continuous development of the microstructure during thermomechanical processing.

Characterization of the material instability in the thermomechanical deformation of the investigated titanium alloy was achieved by analyzing the flow localization parameter α for true strain of 0.1 to 0.9. The parameter *α* expressed in equation (4) is based on the normalised flow softening factor *γ* (5) and the strain rate sensitivity parameter m.

$$\gamma = \frac{1}{\sigma}\frac{\partial\sigma}{\partial\varepsilon} = \frac{\partial\ln\sigma}{\partial\varepsilon} \quad (4)$$

$$\alpha = -\frac{\gamma}{m} \quad (5)$$

Figure 3 shows maps of the distribution of α, based on Semiatin's and Lahoti's concepts of flow localization, for the cases where $\alpha > 5$ and for true strain 0.2, 0.7 and 0.9. For the strain $\varepsilon = 0.2$, there is only one area of instability. The area is located in the contour showing the parameters: T = 920-975 °C, $\dot{\varepsilon}$ = 3.2 – 10 s^{-1}.The map of the flow localization parameter for $\varepsilon = 0.7$ shows two areas where instability can occur. First area is in the parameter range: T = 800-860 °C, $\dot{\varepsilon}$ = 1.9 – 10 s^{-1}, and the second area includes parameters: T = 910-980 °C, $\dot{\varepsilon}$ = 1.4 – 10 s^{-1}. For a true strain of 0.9, one area of possible instability is visible in contour indicating the parameters: T = 928-967 °C, $\dot{\varepsilon}$ = 3.2 – 10 s^{-1}. Observations of the distribution of the processing maps isoclines indicate that the material does not deform uniformly across the cross-section during the process. The shape and arrangement of the isoclines of the analysed parameter α shows insufficient ductility of the material for high strain rate values in the range of the indicated process temperatures. The areas of instability are reflected by dense isoclines with an arc shape in the direction of decreasing strain rate. The epicentre of instability corresponds to the areas of instability determined according to the Prasad approach. Analysis of the nature of this instability leads to the conclusion that there is no flow softening of the metal, and the nature of this instability reveals a significant amount of deformation in the microstructure and accumulation of strain energy.

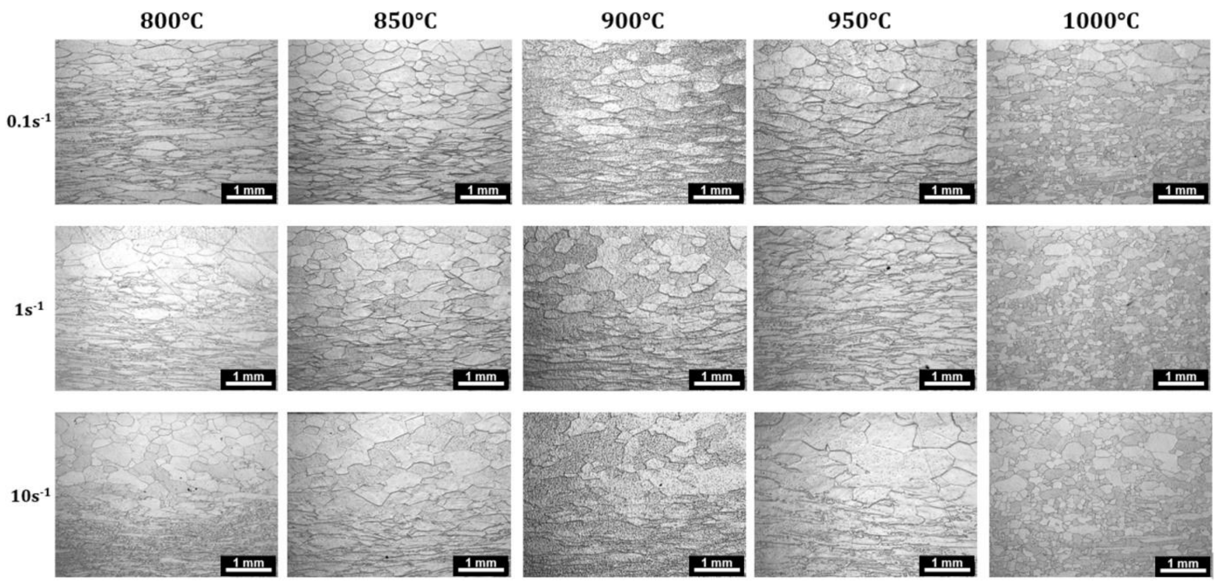

Figure 4 Microstructure of the Ti-3Al-8V-6Cr-4Mo-4Zr alloy after deformation in the temperature range of 800-1000 °C and strain rate in the range of 0.1 – 10 s^{-1}

A thorough examination of the microstructure of the samples tested in compression reveals significant recrystallization occurring at the temperatures higher than 950 °C. Furthermore, it has been observed that the grains exhibit an elongation in direction perpendicular to the applied compressive force. This phenomenon is most pronounced in the central region of the sample. In the samples subjected to deformation at elevated temperatures the orientation of the grains is mostly caused by the processes of microstructure development that occur (e.g. dynamic recrystallization).

3. CONCLUSION

The presented research results lead to the following conclusions:

- The study confirmed the hypothesis that higher strain temperatures (above 950 °C) facilitate recrystallisation of the microstructure of the investigated material, as evidenced by the formation of new grains. It was found that the most homogeneous microstructure was obtained for the strain rates of 1 s^{-1} and temperature of 1000 °C. The use of higher strain rates leads to inhomogeneity of the microstructure in the sample volume.
- The processing maps developed using both the Prasad and Semiatin – Lahoti criteria were found to be effective in predicting flow instability and optimising hot forming parameters. The maps highlighted regions of strain localisation, while also identifying optimal conditions for dynamic recrystallisation and material softening.
- The comparison of the processing maps developed on the basis of Prasad criterion and Siemiatin-Lahoti showed, that they were generally similar, with some differences in maps developed for lower strains (0.2), but also for higher strain levels (0.9). The verification of the correctness of the developed maps will be possible through deformation tests of the investigated alloy under industrial conditions.

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