

Characterization of Ti-6Al-2Sn-4Zr-6Mo alloy flow behaviour using Malas's stability criterion

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In the presented study the hot deformation behavior of Ti-6Al-2Sn-4Zr-6Mo (Ti-6246) alloy was investigated by isothermal hot compression tests conducted on the Gleeble 3800 thermomechanical simulator in the temperature range of 800–1100 °C and in strain rate range of 0.01 – 100 s⁻¹ to true strain of 1. For determining the unstable flow regions of the investigated alloy during hot deformation, the processing maps based on the Malas's criterion of plastic flow stability were used. For characterization of the material flow during forming operations, the microstructure analysis of the processed alloy was performed and associated with the processing maps. Basing of this analysis, the results of predicting the flow instability were confirmed, what made possible to understand the mechanical behavior of Ti-6246 alloy in a wide range of strain rates and temperatures.

1. Introduction

In the modern aircraft industry $\alpha+\beta$ titanium alloys are often used for manufacturing turbine engine rotating components. These types of alloys are characterized by the ability of changing the distributions and amounts of untransformed phases by aging or other thermal treatments. The Ti-6Al-2Sn-4Zr-6Mo (Ti-6246) is $\alpha+\beta$ alloy with high tensile strength, especially in β -processed condition, used for the production of compressor disks and blades [1, 2], working at intermediate temperature in the range of about 315 to 400 °C [3]. The high content of β -stabilising elements reduces the intensity of microstructure transformation during processing, and facilitates uniform heat treatment of cross section and uniform property levels.

High strength of this alloy is observed at high strain rates, without significant strain hardening, and decreases significantly with increasing temperature [4]. The initiation of dynamic recrystallization is facilitated by increasing the strain rate and extension of the processing time, but the fully recrystallized microstructure is observed at low strain rates [5, 6]. Some researchers noticed, that the plastic deformation in the range of α phase limits the growth of β phase grains [6]. The influence of the microstructure on the tribological properties of Ti-6246 alloy is shown in [7]. It was shown, that this alloy has one of the lowest value of friction coefficient in comparison with many other types of titanium alloys.

The production of structural components made of Ti-6246 alloy often involves the use of ingots as charge material and hot die forging or isothermal forging for processing. Understanding the mechanical behavior of Ti-6246 alloy in a wide range of strain rates and temperatures is crucial in proper controlling the properties and microstructure of final products. For description of the material flow during forming operations processing maps based upon various criteria, such as Malas's stability



criterion, are successfully used [8-11]. This criterion was proposed by Malas and Seetharaman [12]. This criterion – based on Gegel's criterion - assumes four inequalities (equations 1–4) containing strain rate ($\dot{\epsilon}$) sensitivity m and $m_{\text{criterion}}$ and temperature sensitivity of flow stress s and $s_{\text{criterion}}$ as follows:

$$0 < m \leq 1 \quad (1)$$

$$m_{\text{criterion}} = \frac{\partial m}{\partial (\ln \dot{\epsilon})} < 0 \quad (2)$$

$$s \geq 1 \quad (3)$$

$$s_{\text{criterion}} = \frac{\partial s}{\partial (\ln \dot{\epsilon})} < 0 \quad (4)$$

The sensitivity parameter (s) of flow stress in deformation process can be defined as:

$$s = \frac{1}{T} \frac{\partial \ln \sigma}{\partial (\ln \frac{1}{T})} \quad (5)$$

Where T is temperature and σ is flow stress.

In Malas's criteria with increasing temperature and decreasing strain rate the strain hardening should increase. Besides, with increase in the temperature, the material should exhibit flow softening and the flow stress with respect to strain rate curve must have a convex character [8]. The equations (1) and (2) consider the mechanical stability, (3) and (4) the thermodynamic stability. The four criteria of stability (equations 1–4) determine the stability conditions and in the result of their overlaying the complex map can be developed. The shadowed areas on the complex processing map display the domains of instability.

2. Material and experimental procedures

Ti-6246 alloy of chemical composition presented in Table 1 was used in this study. The cylindrical specimens of 10 mm in diameter and 12 mm high were cut out from Ti-6246 alloy rod along its axis. The isothermal hot compression tests were carried out on the Gleeble-3800 thermomechanical simulator under vacuum atmosphere. The specimens were heated up at the heating rate of 2.5 °C/s and kept at given temperature for 10 s. The samples were deformed in compression at the temperatures of 800, 900, 950, 1000, and 1100 °C, and at the strain rates of 0.01, 0.1, 1, 10, and 100 s⁻¹. A graphite foil was used to reduce the friction effects. The specimens were deformed to the true strain of 1. After the plastic deformation samples were quenched in compressed air. The microstructure of the processed materials was observed on the optical microscope LEICA DM4000M.

Table 1. Chemical composition of Ti-6246 alloy (weight %)

C	Si	Mo	Al	Fe	Sn	Zr	Ti
0.01	0.09	6.18	6.13	0.09	1.8	3.8	Bal.

Figure 1 shows the microstructure of initial material used for testing, observed on optical microscope (a) and on SEM (back scattered electron SEM-BSE micrographs) (b) at transverse cross-section of Ti-6246 alloy rod. The microstructure consists of equiaxed α grains and precipitations of α phase needles in β phase matrix.

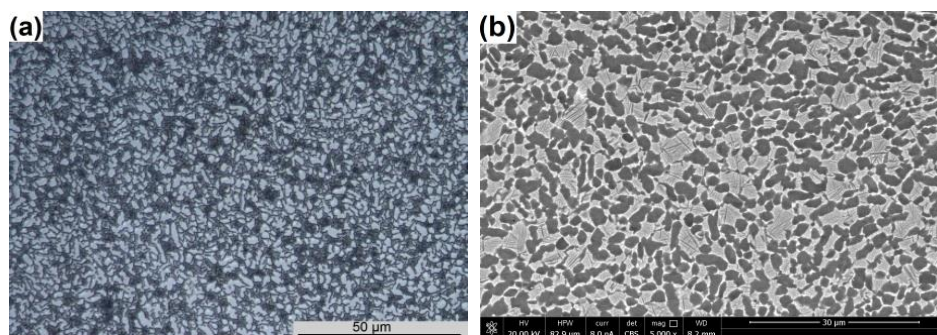


Figure 1. The optical (a) and SEM-BSE images (b) of the microstructure of the investigated Ti-6246 alloy at transverse cross-section of Ti-6246 alloy rod.

3. Results and discussion

3.1 Stress–strain behavior

True stress - true strain curves for Ti-6246 alloy were obtained in compression tests performed in temperature range from 800 °C up to 1100 °C and strain rate range of 0.01-100 s⁻¹ are partly shown in Figure 2. As can be seen from the curves, higher temperature and lower strain rate reduce the flow stress. The flow stress curves (Figure 2a) exhibit a moderate to extensive flow softening at all strain rates. As can be seen in Figure 2a, the softening is less remarkable with decreasing strain rate. The curves obtained from the compression tests performed at the deformation temperature of 1100 °C (Figure 2b) are characterized by the insignificant drop in the flow stress at the beginning of hot deformation and further, almost constant, flow stress level signifying no visible flow softening mechanisms.

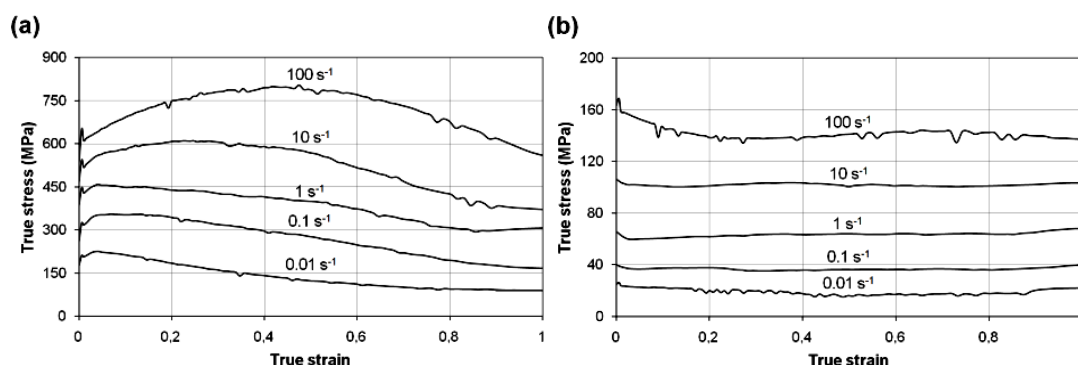


Figure 2. True stress-strain curves of Ti-6246 alloy at the temperature of: a) 800 °C and b) 1100 °C.

3.2 Microstructural validation and application of Malas's criterion

The contour maps of Ti-6246 alloy for the true strain of 1 at the temperature range of 800–1100 °C and for the strain rate range of 0.01 – 100 s⁻¹, describing the criteria of stability in accordance with Malas are shown in figure 3. As can be seen from the distribution of $m_{\text{criterion}}$ parameter (Figure 3a), the area of mechanical instability (shaded area) is in the range of high strain rates of deformation (from 5 s⁻¹ to 100 s⁻¹) and temperature range of 800 °C – 990 °C. Figure 3b shows the contour map describing $s_{\text{criterion}}$ parameter distribution with one area of flow instability for the temperature range from 800 °C to 975 °C, and the strain rate range of 0.01 – 0.4 s⁻¹. It should be taken into account, that such structural instability areas can be characterized by the occurrence of microstructural banding or slip bands. From the distribution of temperature sensitivity of flow stress s (Figures 3c), the thermodynamic instability of the process at high temperatures (1030 – 1100 °C) and high strain rates (from 6 to 100 s⁻¹) can be noticed. The distribution of the strain rate sensitivity m (Figures 3 d) did not reveal the areas of instability in the investigated temperatures and strain rate range.

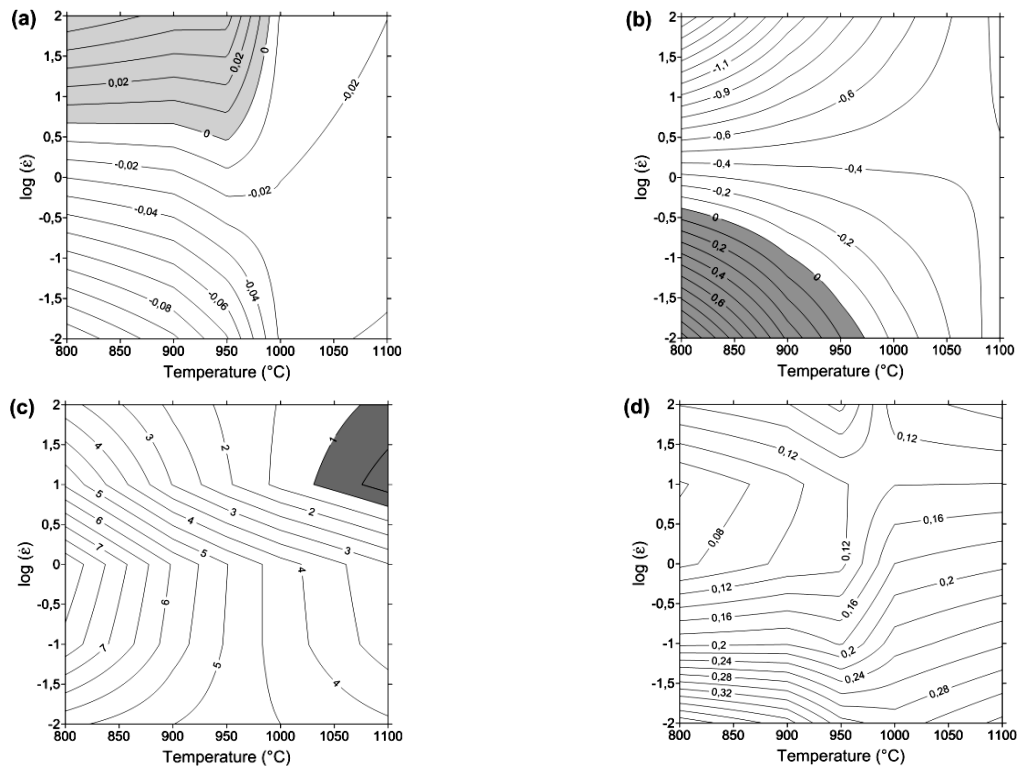


Figure 3. Contour map of Ti-6246 for the $m_{\text{criterion}}$ (a), $S_{\text{criterion}}$ (b), for the temperature sensitivity of flow stress s (c) and strain rate sensitivity m (d).

The processing map of Ti-6246 alloy created by superimposing of the four criteria of flow stability based upon Malas's stability criterion for the true strain of 1 is shown in Figure 3. This map makes it possible to identify areas providing a stable flow (white area) and the areas of flow instability (shadowed areas). In this case, there are three characteristic stability regions enabling determination of processing windows. The first window is in the range of low strain rates (from 0.01 to 0.4 s^{-1}) and high temperature range ($975 \text{ °C} - 1100 \text{ °C}$). A wide range of processing temperatures ($800 - 1100 \text{ °C}$) and processing strain rates ($0.4 - 6 \text{ s}^{-1}$) for the investigated alloy are characterized by the second processing window. This area is suitable for die forging on hydraulic-mechanical or hydraulic presses. The last window describes the processing parameters in narrow temperature range (from $990 \text{ °C} - 1030 \text{ °C}$) and strain rate range of $6 - 100 \text{ s}^{-1}$.

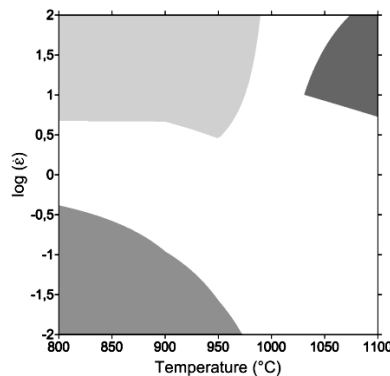


Figure 4. Processing map for Ti-6246 alloy based on Malas's stability criterion.

The typical microstructures of the specimens deformed under processing parameters corresponding to the instability area at the temperatures of 950 °C and 1100 °C , at the strain rates of 0.01 s^{-1} and 100

s^{-1} are shown in Figures 5a and 5b. As can be seen from these figures, in both cases only a partial recrystallization of the material could be observed. The microstructures consisted of the mixture of the original coarse grains and small recrystallized grains, what could result in unstable plastic flow and decreasing in the formability of the investigated alloy. Consequently, the hot deformation of Ti-6246 alloy in the instability area is not recommended.

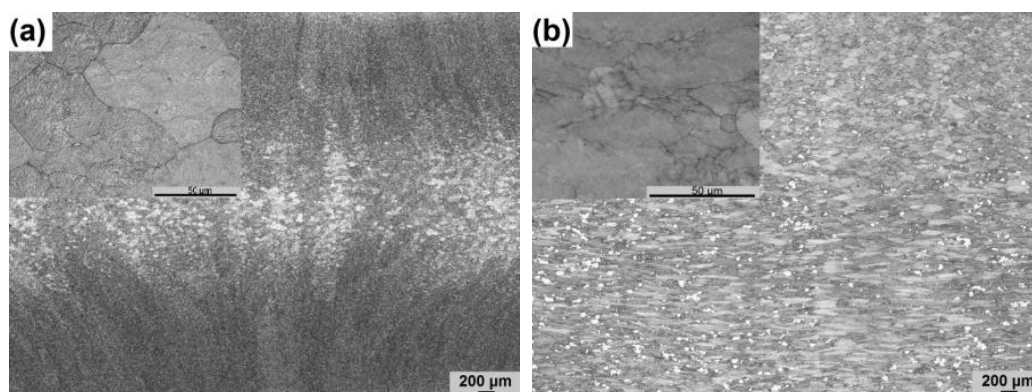


Figure 5. The microstructures of Ti-6246 alloy specimens deformed in instability area at the temperature and strain rate of: a) 950 °C / 0.01 s^{-1} , b) 1100 °C / 100 s^{-1} .

On the other hand, the microstructures of the specimens deformed in stability area at the strain rate of 0.1 s^{-1} and temperatures of 950 and 1000 °C (Figure 6) did not contain visible deformation defects such as internal cracks or shear bands, showing the stability and good quality of such structures. It should also be noted, that as it was also noted earlier [6], the presence of secondary precipitations of α phase in the microstructure, affects the final grain size and this fact should be taken into account in designing the hot working parameters for Ti-6246 alloy processing.

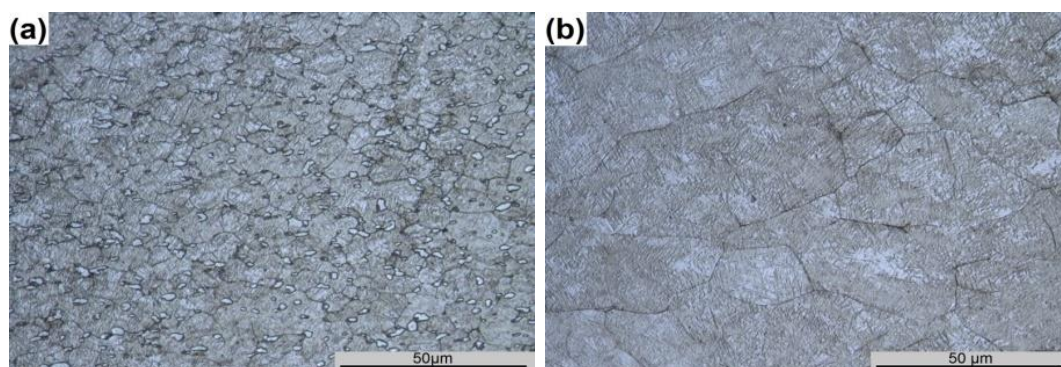


Figure 6. The microstructures of the specimens deformed at the processing parameters corresponding to the stability area - strain rate of 0.1 s^{-1} and temperatures of 950 (a) and 1000 °C (b).

4. Concluding remarks

The behavior of Ti-6246 alloy during forming operations has been studied based upon Malas's stability criterion. The true stress-strain curves were obtained in the isothermal hot compression tests performed to the true strain of 1 at the temperature range of 800–1100 °C, and at the strain rate range of 0.01 – 100 s^{-1} . The processing maps for the investigated alloy were created by superimposing four criteria of flow stability. According to the elaborated processing map (shown in Figure 4), stable processing of the investigated alloy should be assured in a wide range of the temperature and average strain rates in the range of 0.4 - 6 s^{-1} . At lower strain rates (below 0.4 s^{-1}) and at high temperatures (>950 °C), processing of this alloy should also be successful. Moreover, processing in the temperature range of 990 °C – 1030 °C and strain rate range of 6 – 100 s^{-1} should result in good quality Ti-6246 alloy products, too. The microstructure analysis confirmed the results of predicting the flow instability

of Ti-6246 alloy, making possible understanding the mechanical behavior of Ti-6246 alloy at a wide range of strain rates and temperatures.

Acknowledgements

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