APPLICATION OF ALEXANDER-MALAS CRITERION OF PLASTIC FLOW STABILITY FOR ESTIMATION OF PM Ti-6Al-2Sn-4Zr-6Mo ALLOY FORGING CONDITIONS

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Abstract

Ti-6Al-2Sn-4Zr-6Mo (Ti-6-2-4-6) is a high strength titanium alloy having low density and good corrosion resistance. The primary commercial applications of this alloy are forgings designed for working at intermediate temperature turbine engine rotating components. Currently the most common charge for forging is cast material. However, a promising alternative for producing such stock can be powder metallurgy (PM). This approach gives the opportunity to receive high quality products with fine microstructure and profitable mechanical properties. An application of Alexander-Malas criterion of plastic flow stability in reference to the investigated material makes possible to predict the material flow behaviour during hot processing as well as can be used as the basis for selection of the profitable parameters of forging.As the initial material for the investigations Ti-6-2-4-6 alloy compacts were used. The characteristics of hot deformation behaviour of Ti-6-2-4-6 alloy was studied using processing maps obtained on the basis of flow stress data, generated in compression tests performed at the temperature range of 800 - 1100^{o}C and at the strain rate ranging from 0.01 s^{-1} to 10 s^{-1}. The microstructure of selected samples after deformation was observed. Based on elaborated criteria of plastic flow stability, the processing maps for constant value of strain were developed. Complex processing maps, describing the areas of flow instabilities and processing window, were also developed.The determined domains were interpreted taking into account criteriadescribingmechanical and microstructural stability of thermomechanical processing.

Keywords: Titanium alloy, plastic flow stability, processing maps, powder metallurgy

1. INTRODUCTION

Titanium alloys are nowadays widely used for the production of structural parts mainly in automotive, marine and aircraft industry [1, 2]. This is due to the advantageous properties of titanium, which include low density, high strength, high toughness, high fatigue strength and good corrosion resistance. The disadvantages of titanium and its alloys include low thermal conductivity, difficulties with machining [3-6], and high costs of the production [7].Ti-6Al-2Sn-4Zr-6Mo (Ti-6-2-4-6) alloyis a two phase $\alpha+\beta$ alloy. It is mainly applied for the production of parts rotating at elevated temperature conditions, like the components of engine turbines. Die forging or isothermal forging is most commonlyused for processing of this alloy.In reference to this particular alloy, these processes must be performed under precisely controlled conditions [3].Titanium alloy ingots are mostly used as charge material for the production of structural parts, however, an increasing number of the research works is carried out on the use of such materials produced by powder metallurgy (PM) methods.In this respect, many processing methods can be applied for example as compacting and sintering [7, 8], hot pressing, including hot isostatic pressing [9, 10], and other methods. These techniques allow manufacturing of final products or semi-finished products used for further processing, mainly by rolling or forging.Such technology can be applied without a necessity of modifying existing production lines [11]. However, proper description of the material flow during forming operations at various strain-strain rate-temperature conditions is very important. From that point of view, complex processing maps, elaborated on the basis of plastometric tests, can be very helpful in determining the most advantageous parameters of processing.From this respect, Alexander-Malas criterion of the stability of plastic flow [12-15], can successfully be used.This criterionmeets he four inequalities (equations 1-4), which highlight the significance of the parameters of the strain rate ($\dot{\varepsilon}$) sensitivity m and $m_{criterion}$, and also the temperature sensitivity of flow stress in the process of deformation s and $s_{criterion}$. The stability criteria based upon Alexander-Malas approach are:

$$0 < m \leq 1 \tag{1}$$

$$m_{criterion} = \frac{\partial m}{\partial(\ln\dot{\varepsilon})} < 0 \tag{2}$$

$$s \geq 1 \tag{3}$$

$$s_{criterion} = \frac{\partial s}{\partial(\ln\dot{\varepsilon})} < 0 \tag{4}$$

These four criteria of stability determine the conditions necessary for avoiding the instabilities and have metallurgical basis. The first two inequalities are associated with the mechanical stability and the other two - with thermodynamic stability. In presents study, a complex map was developed as the result of overlaying these four criteria of stability in accordance with Alexander-Malas. The shadowed areas on the elaborated processing maps reflect the domains of instability determined with the application of the equations given above. The temperature (T) sensitivity parameter (s) of flow stress (σ) of material is given in equation 5:

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

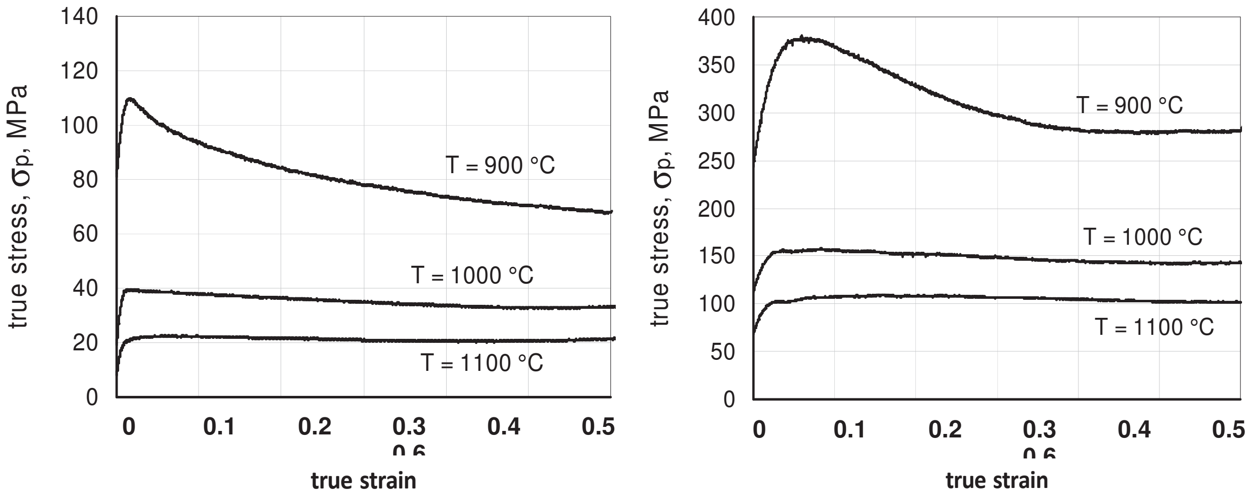
It should be pointed out, that in Malas's flow instability criteria, the flow stress with respect to strain rate curve should be convex in nature and the material should exhibit flow softening with increasing temperature [14].

The aim of the study was evaluation of the most advantageous parameters of hot forging of Ti-6-2-4-6 alloy compacts, based on the Alexander-Malas criterion of the stability of plastic flow. Flow stress curves, determined in plastometric tests, were used for this analysis. The criteria of the stability of plastic flow were elaborated based on these flow stress curves and processing maps were developed for chosen values of strain. Moreover, a complex processing map including the areas of flow instability and processing windows for successful thermomechanical treatment was also elaborated. Determined in such way domains were interpreted towards forging processes, taking into account the criteria describing the mechanical and structural stability of the processed materials.

2. MATERIAL FOR THE RESEARCH AND EXPERIMENTAL PROCEDURE

Ti-6Al-2Sn-4Zr-6Mo compacts were used as a starting material for this research. Titanium powder and the powders of the alloying elements (Al, Sn, Zr and Mo) were mixed in quantities required for obtaining the assumed chemical composition of the investigated alloy.Next, the mixture of the powders was compacted under argon atmosphere (test stand by Thermal Technology Inc.) during 3 hours at the temperature of 1200 °C, and under pressure of 25 MPa.

Compression tests of Ti-6-2-4-6 alloy compacts were performed at the Metal Forming Institute of TU Bergakademie Freiberg inGermany, on MDS 830 (Bähr) metal forming processes simulator.The tests were carried out on cylindrical samples having diameter of 10 mm and height of 12 mm. The samples were heated up to the test temperature at heating rate of 2.5 $K\cdot s^{-1}$, held at that temperature for 10 s, and subsequently deformed in compressionat the assumed strain rate.Compression tests were performed at the temperatures of: 800, 900, 950, 1000, and 1100 °C at the strain rates of: 0.01, 0.1, 1.0, and 10 s^{-1}. After testing the samples were cooled down to room temperature at cooling rate of 100 °C/s. Based on these plastometric tests, flow stress curves for Ti-6-2-4-6 alloy were determined. Exemplary true stress-true strain curves for the samples deformed at strain rate of 0.1 s^{-1} and 10 s^{-1} were shown in **Figure 1**.



a) b)

Figure 1 The influence of the temperature on true stress-true strain curves obtained in compression tests performed on Ti-6-2-4-6 compacts. Strain rate: a - 0.01 s^{-1}, b - 10 s^{-1}.

The observations of the microstructure of the samples tested in compression were performed using light microscope (LEICA DM 400M). **Figure 2** shows exemplary microstructures of the samples deformed at chosen strain rate and temperature.

a) b) c) d)

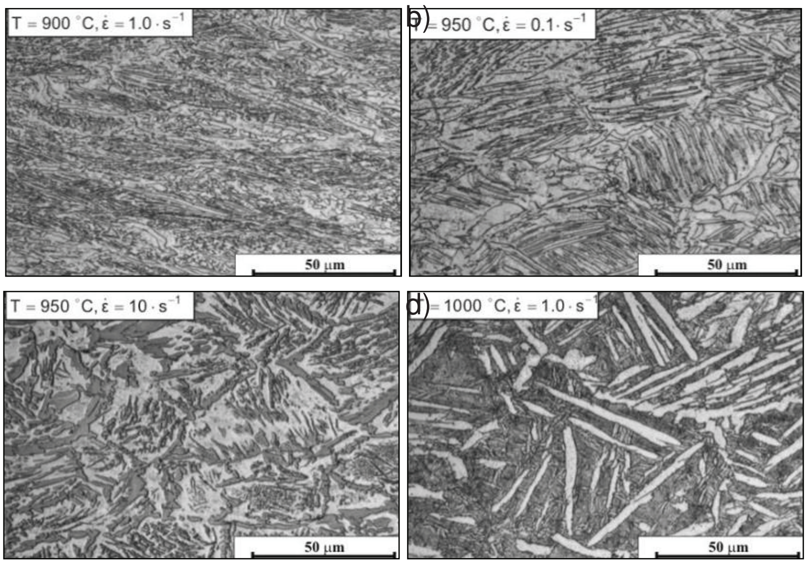


Figure 2 The influence of plastometric tests conditions on the microstructure of PM Ti-6-2-4-6 alloy samples. Cross-sections at the center of the samples.

The observed microstructures are of lamellar or necklace type, however, those types of microstructure vary in size, depending on the testing conditions. In the case of the sample deformed at the temperature of 900 °C and at the strain rate of 10 s^{-1} (**Figure 2a**), the areas of directed flow can be noticed. Bigger lamellas, with smaller ones between them, can be noticed in the microstructure of the sample deformed at the temperature of 1000 °C as compared to the microstructure of the samples at lower temperatures. **Figure 2c** shows fine or coarse-grained necklace type of microstructure, formed in the result of compression at the temperature of 950 °C at the strain rate of 1.0 s^{-1}.

3. THE APPLICATION OF ALEXANDER-MALAS CRITERION

Figure 3 shows the contour maps of changes in the parameters describing the criteria of stability in accordance with Alexander-Malas for the investigated alloy at the temperature range of 800-1100 °C and for the strain rate range of 0.01-10 s^{-1} for the true strains of 0.4 and 0.6.

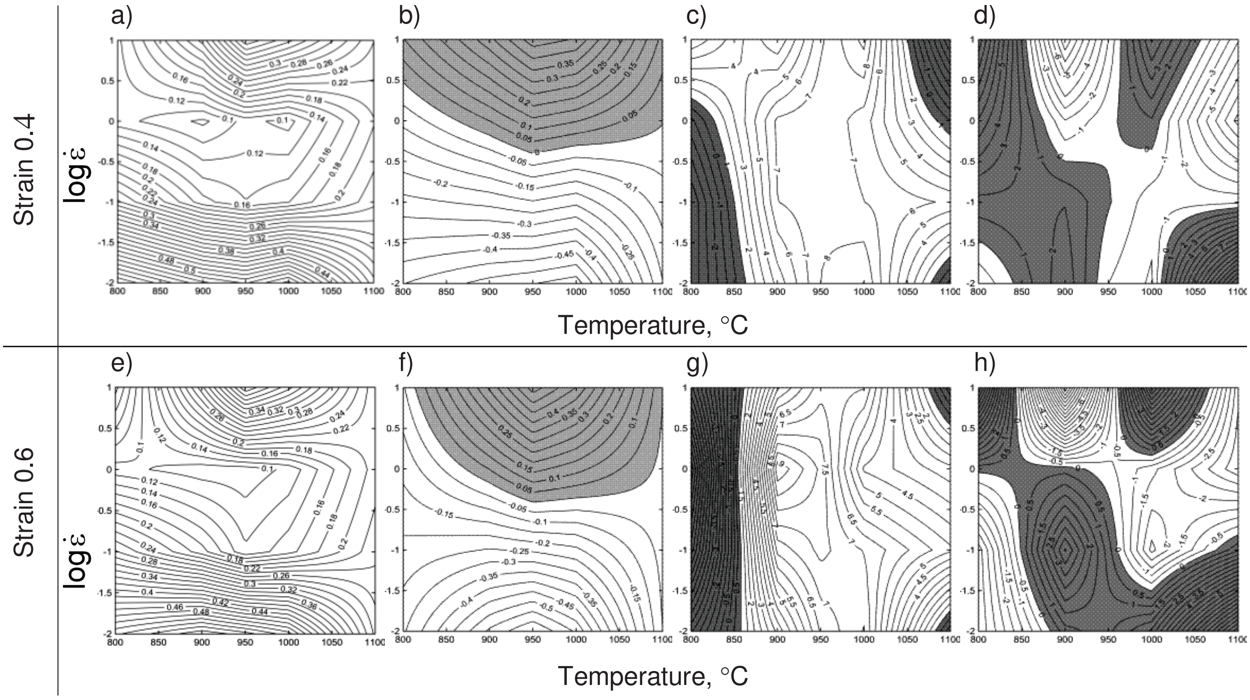


Figure 3 The contour maps for PM Ti-6-2-4-6 alloy at different true strains. The shaded areas indicate the flow instability

Figures 3a and **3b** show contour maps of the changes of strain rate sensitivity of stress in relation to the temperature and strain rate for two values of strain rate: 0.4 and 0.6 respectively. Three areas of *m* parameter changes can be distinguished on those maps: area I, area II, and area III. Area I is characterized by low strain rates from 0.01 s^{-1} to 0.1 s^{-1}. Isoclines of *m* parameter form the area of uniform and constant changes. Along with decrease of compression strain rate, sensitivity of the processed material to the strain rate increases. For the strain of 0.6, and temperature range of 875-925 °C, and strain rate of 0.01 s^{-1}, the highest value of *m* parameter can be noticed, but for the temperatures higher than 950 °C the values of this parameter decrease. The characteristic feature of area II is the occurrence of the lowest value of parameter m = 0.1 for the temperature range of 825 - 1000 °C and for the strain rate range of 1 - 0.56 s^{-1}. Area III covers the high values of strain rate (from 2 to 10 s^{-1}). The temperature of 950 °C can be considered as the contractual point of the isoclines distribution symmetry. From this processing temperature *m* parameter also increases with increasing strain rate. In the entire range of temperatures (800 -1100 °C) and strain rate (0.01 - 10 s^{-1}), the strain rate sensitivity parameter *m* (**Figures 3a**, **3b**) does not show the areas of instability. Taking into account the distribution of $m_{criterion}$ parameter (**Figures 3c**, **3d**), one area of mechanical instability, for almost whole range of the analyzed temperatures and for the strain rate in the range of 0.4 - 1 s^{-1}, can be noticed. Contour maps (**Figures 3e**, **3f**) describing the distribution of parameter *s* (the temperature sensitivity of flow stress) show three areas of flow instability. For the temperature lower than about 860 °C, the lowest value of *s* parameter occurs, and the highest thermodynamic instability of the process can also be noticed. The highest values of *s* parameter can be observed for the temperature range of 900 °C to 1000 °C. Contour maps (**Figures 3g**, **3h**) describing $s_{criterion}$ parameter distribution for strain of 0.6 show two areas of flow instability and for strain 0.4 - three areas. In these areas structural instability can occur in a form of slip bands or microstructural banding.

Superimposition of the four criteria of flow stability based upon the Alexander-Malas approach allows developing complex processing maps for the analyzed amount of deformation (**Figure 4**). The shaded areas indicate the flow instability, and white area indicatesthe processing conditions enabling stable flow.

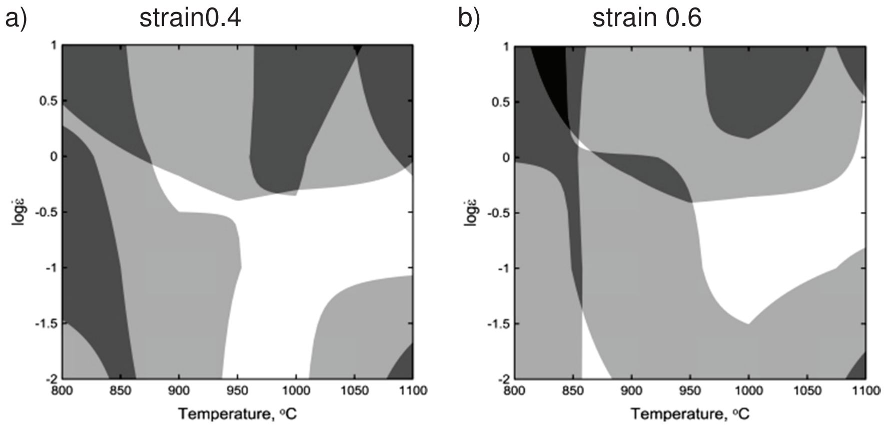


Figure 4 The complex processing maps based upon Alexander-Malas stability criterion of Ti-6-2-4-6 alloy at different true strains. The shaded areas indicate the flow instability

Two domains, having the most advantageous parameters in Alexander-Malas criterion, assuring stable flow of the investigated material during deformation can be identified for strain equal to 0.6.Processing window for forging in isothermal conditions was located in those domains (processing window for the temperature range of 950 - 1100 °Candstrain rate range of 0.01 - 0.05 s^{-1}) andfor forging in conventional conditions (processing window for the temperature range of 860 - 890 °Candstrain rate range of 0.03 - 5.6 s^{-1}). Processing window for forging in isothermal conditions shows the parameters for die forging of small forgingson hydraulic presses or on hydraulic-mechanical presses. Processing window for the conventional forging shows the parameters for die forging, that can be performed on many forging machines (e.g. hydraulic-screw presses, mechanical presses, and even hammers). For lower value of strain (0.4), complex processing map shows one domain of stable flow of the investigated alloy. In this case also two processing windows can be determined. One of them shows the parameters for die forging of small forgings in isothermal conditions on mechanical or hydraulic-screw presses (temperature range of 875 - 930 °C and strain rate range of 0.3 - 1 s^{-1}). The rest of this domain can be treated as processing window showing the parameters for conventional forging (temperature range of 930 - 1100 °C and strain rate range of 0.01 - 0.8 s^{-1}).

4. CONCLUSIONS

The flow stress curves for PM Ti-6-2-4-6 alloy, obtained from plastometric tests, were applied for determining the most advantageous parameters of its forging.In the result of the performed analysis, domains for the assumed values of strain (0.4 and 0.6), having the most profitable configuration of the criteria parameters describing stable flow of the investigated alloy, were determined. Processing windows for isothermal forging were determined for both assumed strain levels. Based on the analysis performed for the strain level equal to 0.6, the possibility of forging the investigated alloy in conventional conditions was also proved. Despite the fact, that in this case forging such alloy is possible only in the narrow range of processing temperatures (860 - 890 °C), a wide range of strain rates can be used, what still enables processing on many kinds of forging machines.Much wider range of possible temperatures of conventional forging were determined in the case of the analysis performed for the strain level equal to 0.4 (930 - 1100 °C), but possible strain rates were identified in narrow range of 0.01 - 0.8 s^{-1}.

Elaborated processing windows can be used in designing forging technology of Ti-6-2-4-6 alloy. They can also be applied for estimating the possibility of processing such alloy in technological conditions already existing in commercial companies producing structural parts from titanium alloys.

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