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PRIMARY CREEP BEHAVIOUR OF TWO-PHASE TITANIUM ALLOY WITH VARIOUS MICROSTRUCTURE

Creep and fatigue properties of two-phase titanium alloys show strong dependence on microstructure, especially morphology of the α and β phases which can be controlled to certain extent by proper selection of hot working and heat treatment conditions. In the paper the creep behaviour of Ti-6Al-2Mo-2Cr alloy (VT3-1) at elevated temperature was modelled. Finite element analyses of primary creep stage were carried out taking into account some microstructural features of the two-phase alloy that were included in the physical model and different properties of α and β phases. In order to verify results of calculations distinct types of microstructure were developed in the alloy by heat treatment and creep tests were carried out at elevated temperature (450°C) at various stress levels. Based on the FEM simulations the effect of changes of some microstructure features on primary creep strain development was estimated.

Keywords: two-phase titanium alloys, microstructure, finite element method, primary creep

1. Introduction

Titanium alloys are very attractive materials for heavily loaded engineering components working in severe environment conditions. The main reason for that is favourable combination of properties like high specific strength, good fracture toughness and corrosion resistance [1-3]. Qualitative relations between these properties and morphology of alloy microstructure are well established. Further enhancement of mechanical properties and performance of titanium alloys through the control of the size, shape and distribution of the grains of various phases, texture, structure and strength of grain boundaries and other microstructural factors requires deeper understanding and quantitative description of the relationships between these microstructural variables and material properties. Functional relations between microstructure parameters and alloy properties can be developed by neural network modelling [4-5]. However this approach requires creation of large dataset containing results of experiments made on various materials with different microstructures generated through heat treatment and thermomechanical processing. It is also very difficult to vary some microstructural features independently during processing to obtain experimental data. Alternative approach is based on application of numerical simulation methods including finite element method. Material behaviour can be analysed at different levels, from individual grains to structural elements, depending on the complexity of the physical model and adopted assumptions. Although three-dimensional, crystal plasticity models enable more realistic representation of alloy microstructure [6-8] they require large number of orientation dependent material data, which can be difficult to determine. In many cases some phenomenological parameters are also introduced to such models. Depending on the pursued information certain simplifying assumptions can be introduced into the material model. In simulations of forming processes or macroscopic deformation behaviour averaged material parameters are usually used [9-10]. In the models taking into account alloy microstructure the phases were often treated as homogeneous and isotropic materials and in certain cases two-dimensional models were elaborated and performed well in the attempts to describe deformation and fracture of structural materials and to estimate the effect of various variables on the material response to loading in various conditions [11-13].

Creep resistance of titanium alloys is of a great concern, especially in aero-engines applications, because they tend to attain high primary creep strains leading to strain accumulation even at relatively low temperature range [3,14]. In the paper finite element analysis of primary creep stage of the Ti-6Al-2Mo-2Cr alloy was carried out taking into account some microstructural features of the two-phase alloy and different properties of α and β phases.

2. Material and experimental

Titanium alloy Ti-6Al-2Mo-2Cr developed in Russia, where it is designated as VT3-1, was subjected to investigation. It is high-strength, martensitic, two-phase α+β alloy containing Al, Cr and Mo as the main alloying elements (Tab. 1).

TABLE 1

Chemical composition of investigated titanium alloy Ti-6Al-2Mo-2Cr (wt%)

Al	Cr	Mo	Fe	Si	Ti
6.1	2.1	1.94	0.3	0.15	balance

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It is widely used for structural elements operating at room and elevated temperature – up to 450°C. By proper heat treatment high creep resistance and fracture toughness of the alloy can be obtained [1,2,15]. The alloy was delivered in the form of rolled bars, 16 mm in diameter in mill-annealed condition. In this state its microstructure consisted of stable, globular and fine-grained α and β phases (Fig. 1). Additional heat treatment consisting of annealing at 1000°C (β phase range) and controlled cooling at the rate of 0.06 °C·s⁻¹ was applied in order to obtain lamellar microstructure (Fig. 2).
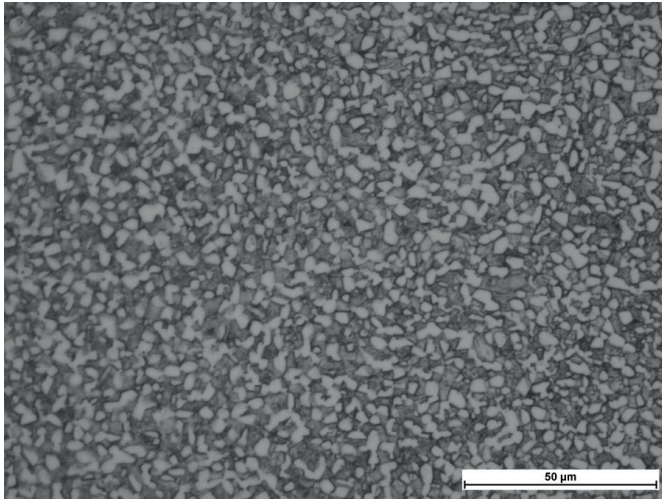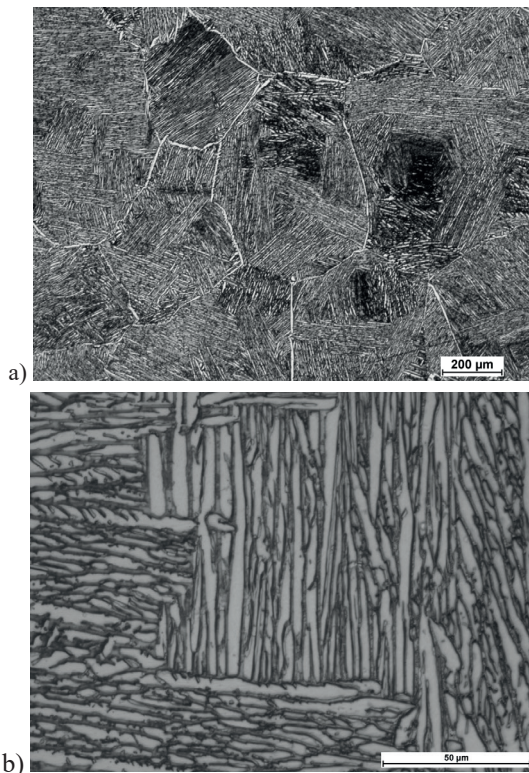

Fig. 1. Globular microstructure of Ti-6Al-2Mo-2Cr alloy

Fig. 2. Lamellar microstructure of Ti-6Al-2Mo-2Cr alloy: a) primary β-phase grains, b) colonies of α-phase lamellae

Microstructure of the alloy was examined using light microscope Nikon Epiphot 3 equipped with DS-1 camera and image analysis software Aphelion. Following quantitative parameters were determined for lamellar microstructure:
- diameter of primary β phase grains,
- diameter of the colony of α phase lamellae,
- thickness of a lamellae,
- volume fraction of β phase,

For globular microstructure volume fraction of α phase and average diameter of equiaxed grains were determined.

Creep tests were carried out at the temperature of 450°C and at the constant initial stress in the range of 450-600 MPa. The tests were interrupted after about 100 hours, when indications of constant strain rate stage were identified.

3. Finite element model

Finite element model was developed taking into account following features of titanium alloy microstructure:
- different properties of individual phases (modulus of elasticity, yield strength, strain hardening rate, creep properties),
- different volume fraction of α and β phases,
- size, shape and distribution of α and β phase grains.

The aim of calculations was to determine the effect of selected microstructural factors on the primary stage of creep process in Ti-6Al-2Mo-2Cr alloy.

The finite element model applied was two-dimensional in order to reduce computational effort required. Eight-node, isoparametric, strain based elements were used throughout all analyses.

Morphology of the α and β phases was modelled based on the images of actual alloy microstructure obtained after heat treatment. First model represented globular microstructure of the alloy (Fig. 3a). In this case the grains of regular, hexagonal shape and equal size were included in the model. Total number of grains in the analysed model amounted to approximately 1000. Individual grains were assigned to α or β phases randomly to obtain volume fraction of the phases corresponding to the value determined experimentally. In further analyses volume fraction of α phase was varied to determine its influence on primary creep strain.

Second model geometry represented lamellar microstructure of the alloy (Fig. 3b). Primary β phase grains morphology was generated using Voronoi tessalation method. Subsequently these grains were filled with randomly oriented lamellae colonies, for which characteristic dimensions were assigned based on metallographic examination results. In that case in further analyses values of stereological parameters describing phase morphology were varied to determine their effect on primary creep response of the alloy.

Precise estimation of mechanical properties of individual phases is very challenging task. Anisotropy of elastic properties, especially of the hexagonal α phase, should be taken into account. Further, grain orientation dependence of their plastic deformation behaviour is also important. Finally rheological properties are also influenced by grain orientation factor, especially in the case of dislocation glide involved. However, inclusion of all those relations in physical model would lead to its increased complexity and would require

additional information about the material, concerning grain orientation distribution.
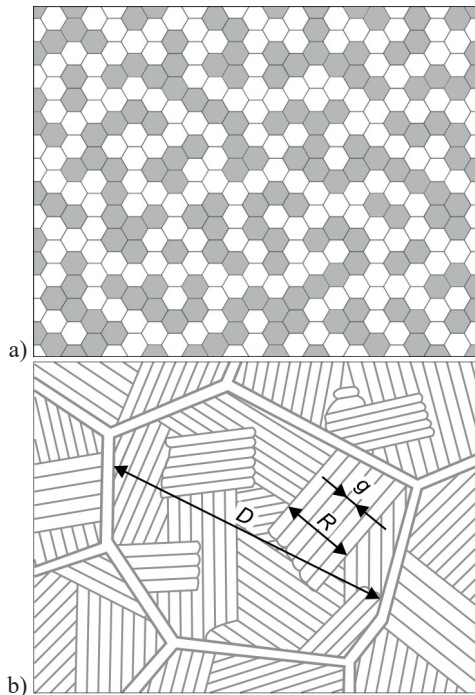

Fig. 3. Geometry models of two-phase alloy adopted in finite element calculations: a) globular, b) lamellar

In current investigation, alternative approach was employed, based on certain simplifying assumptions. For both phases which were treated as isotropic, plastic-creep material model was adopted and creep strains were calculated using power law [16]:

$$\varepsilon = A \cdot t^n \qquad (1)$$

where: ε - creep strain, t – time, A, n – material constants.

It was assumed that if sufficiently large number of grains was included in the model the influence of the phase anisotropy on the global deformation behaviour of the alloy would be significantly reduced and the results of simulations would represent real material response, especially for the case when there was no pronounced texture in it. Averaging the phase properties reduces the number of variables in the model which in turn can be advantageous in analysis of the influence of the morphological features of alloy microstructure on its deformation behaviour.

Different mechanical properties were assigned to α and β phases. Time independent properties of the phases usually vary in certain range due to some chemical composition variations resulting from diffusional processes. All main alloying elements dissolve both in α and β phases, but to the different extent. Aluminium content in α phase tends to be slightly higher than in β phase and in turn chromium and molybdenum content in β phase is about twice as high as in α phase [17]. Because it is not feasible to estimate precisely contribution of alloying elements to solid solution strengthening of individual phases, their strength properties were set based on analysis of properties of single phase α or β alloys and generally observed trends for higher elastic modulus and lower yield stress of α phase comparing to β phase.

Young's modulus and yield strength of α phase at 450°C were assumed to be equal 80 GPa and 300 MPa respectively. Corresponding values for β phase were: 60 GPa and 700 MPa. Poisson ratio v=0.3 was assigned to both phases in all analyses. Two phase titanium alloys exhibit low strain hardening and are frequently modelled even as elastic-perfectly plastic material [18]. In current analysis tangent modulus related to strain hardening equal to 5 GPa was assumed for both phases.

Time dependent properties of the α and β phases were assumed to be described also by power creep law (Eq. 1). The values of A and n constants were selected from available literature data concerning single phase titanium alloys with the chemical composition as close as possible to the composition of individual phases of two-phase alloy (Tab. 2) [17,19-20].

TABLE 2

Power creep law constants used in FEM calculations

Phase	A	n
α	0.051	0.18
β	0.072	0.31

4. Results and discussion

Lamellar microstructure obtained by β annealing and slow, controlled cooling was characterized by following average values of stereological parameters:
- diameter of primary β phase grains – 430 mm
- diameter of the colony of α phase lamellae – 48 mm
- α lamellae thickness – 2.1 mm
- volume fraction of β phase – 7.6 %

Globular microstructure in mill-annealed condition can be described by average values of following parameters:
- average diameter of α phase grains – 3.5 mm,
- volume fraction of α phase – 62 %

Results of the creep tests showed that for all values of test temperature and initial stress levels lamellar microstructure exhibits superior behaviour manifesting itself in lower primary creep strain and lower constant strain rate which was approached at the end of primary creep stage (Fig. 4).
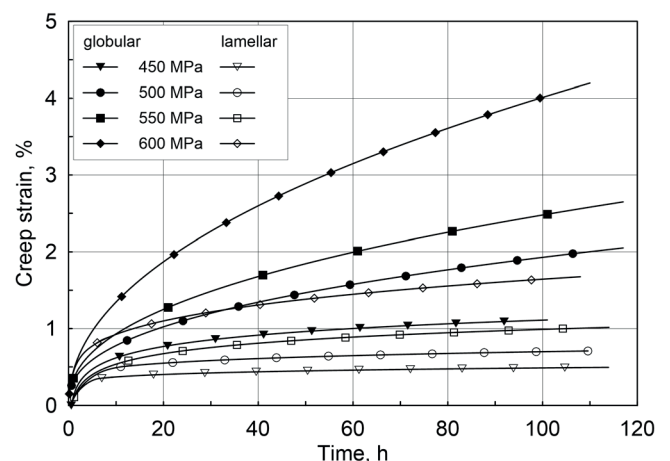

Fig. 4. Primary creep curves of Ti-6Al-2Mo-2Cr alloy with lamellar and globular microstructure at 450°C

Results of finite element analyses indicate that coarsening of the lamellar microstructure leads to reduction of creep resistance on the primary creep stage (Fig. 5 and Tab. 3). Although it was not verified experimentally in the course of current studies this finding is consistent with the data available for two-phase titanium alloys [2]. This proves that the numerical model developed can adequately reflect the effect of the morphological changes on the creep behaviour of the alloy.

TABLE 3

Lamellar microstructure parameters used in FEM calculations

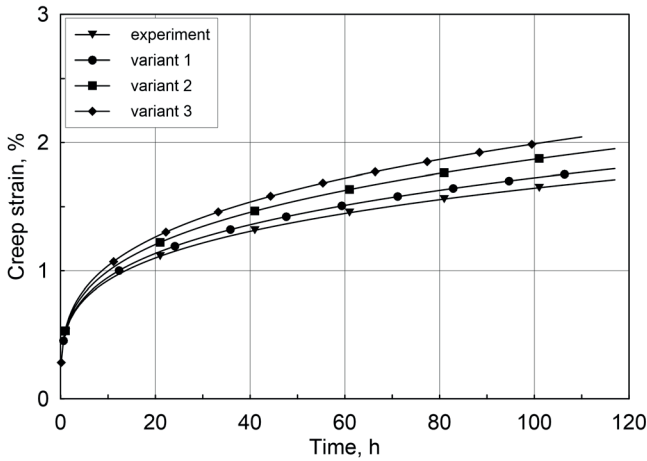| Variant no.	Primary β grain diameter, μm	Diameter of colonies of α lamellae, μm	Thickness of α lamellae, μm
1	480	60	2.5
2	540	80	3.2
3	600	100	4.0

Fig. 5. The effect of stereological parameters of lamellar microstructure on calculated creep strain of Ti-6Al-2Mo-2Cr alloy at 450°C

Detailed analysis enabled determination of the effect of individual parameters of lamellar microstructure on the values of creep power law constants. It was found that the size of colonies of α-lamellae had generally more significant effect on the creep curve character than thickness of α-lamellae (Figs 6 and 7). Increase of α-lamellae thickness resulted in accumulation of larger creep strains reflected in higher values of both A and n constants. The influence of colonies size was more pronounced in the lower part of analysed range and consisted in lowering of n value and increase in A value with growing colony diameter. This is related to increasing creep strain but with faster primary creep strain exhaustion.
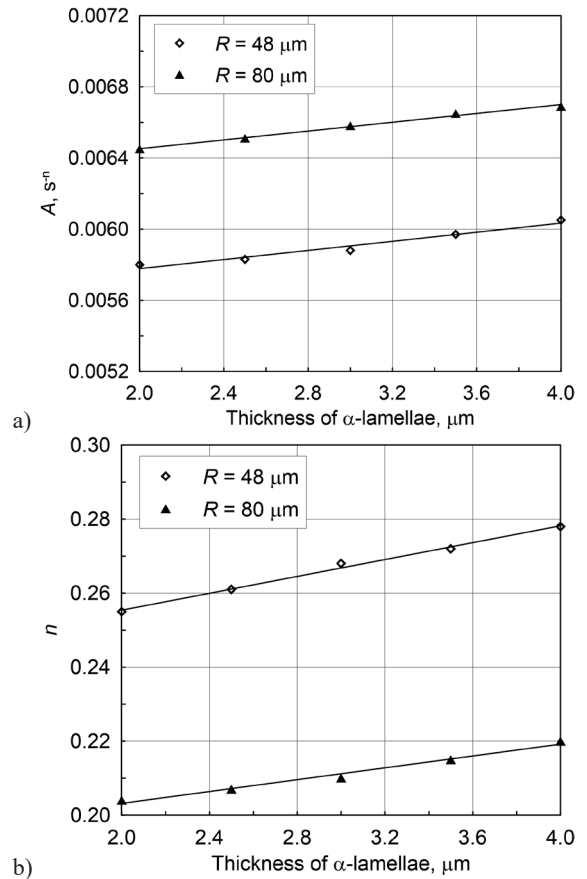

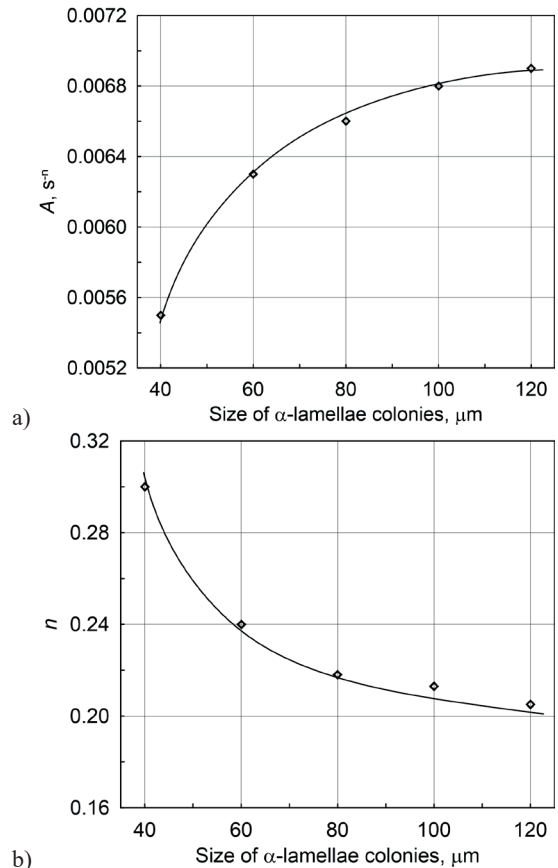Fig. 6. Sensitivity of creep power law constants to α lamellae thickness: a) A, b) n (R - average diameter of α lamellae colonies)

Fig. 7. Sensitivity of creep power law constants to the size of α lamellae colonies: a) A, b) n

Considering globular microstructure increase in volume fraction of α phase has beneficial effect on the primary creep response resulting in reduced strain at this stage of the process (Figs 8 and 9) and lower estimated strain rate at the secondary creep stage.
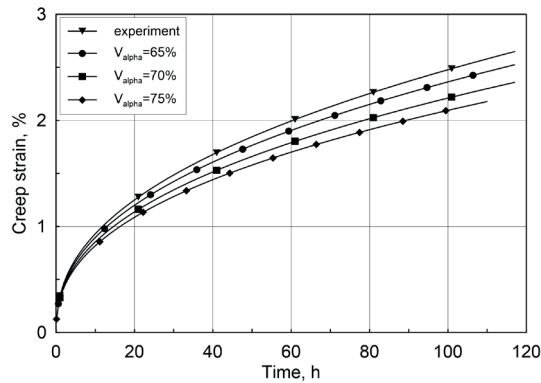

Fig. 8. The effect of the volume fraction of α phase on calculated creep strain of Ti-6Al-2Mo-2Cr alloy at 450°C
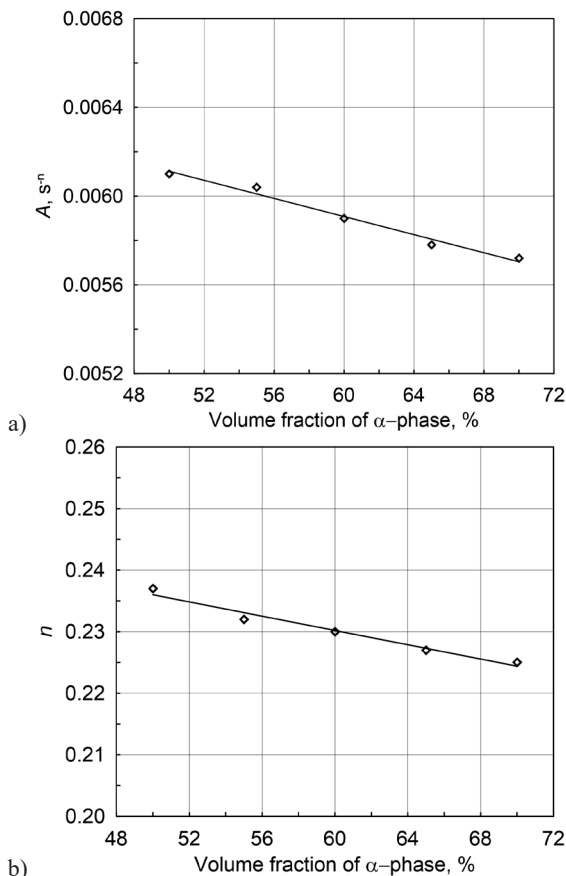

a)

b)

Fig. 9. Sensitivity of creep power law constants to volume fraction of α phase in globular microstructure: a) A, b) n

5. Summary

Morphology of the microstructure of two-phase titanium alloy Ti-6Al-2Mo-2Cr have pronounced effect on its creep behaviour. It was found that lamellar microstructure obtained by controlled cooling at the rate of 0.06 °C·s^{-1} provides the lowest creep strain on the primary creep stage and the lowest creep strain rate at the beginning of secondary creep stage. Coarsening of lamellar microstructure leads to increase in primary creep strain. For globular microstructure increase of α phase volume fraction leads to enhancement of creep behaviour that manifest itself in lower primary creep strain.

Two-dimensional finite element model taking into account morphology and properties of the individual phases is capable to predict the behaviour of the alloy on the primary creep stage depending on selected microstructural factors.

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