

Influence of Selected Heat Treatment on Alloy Properties of Ti-6Al-4V Alloy

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Titanium is the polymorphic metal whose recrystallization temperature significantly affects its final properties. The area between 850 °C and 995 °C is a very important area from the point of view of heat treatment of titanium alloys. It is a transition area just below the β transition limit. This article deals with the analysis of the influence of thermal loading on the change in tensile strength and fracture behavior of titanium alloys in comparison with thermally unloaded samples. Monitoring of fracture surfaces and description of the internal structure of the material.

Keywords: Titanium alloy, Heat treatment, Yield strength, Surface, Microstructure, Fractography, Fracture surface

1 Introduction

Titanium alloys are suitable as structural materials due to their physical and chemical properties. High strength, corrosion resistance and good plasticity are particularly important for construction [1]. Pure titanium is very biocompatible, as it does not contain toxic elements such as vanadium and aluminum. However, pure titanium is not used for components that would be exposed to high stress [2, 3]. For structural use, the Ti-6Al-4V alloy was developed originally for the aerospace industry in the 1950s. The alloy, also known as Ti64, Ti Grade 5, is an $\alpha+\beta$ titanium alloy with high strength, low density, excellent corrosion resistance, and has found application in almost all industries. The automotive, energy, chemical, biomedical and aerospace industries fully utilize the good structural properties of this alloy [4, 5, 6]. Ti-6Al-4V is usually an $\alpha+\beta$ alloy with the content of both phases at room temperature. Heat treatment of Ti-6Al-4V alloy is carried out for the purpose of phase transformation and improvement of mechanical properties [7, 16]. When performing operations associated with long-term heating of workpieces and parts made of titanium alloys in an air atmosphere (such as hot deformation, heat treatment), a TiO₂ layer is formed on the surface of the product. In hot-deformed semi-finished products, this layer does not exceed 50-70 μm [4].

The transformation temperature of the β phase is crucial for heat treatment as well as for normal thermal loading. Experimentally, this β transition temperature has been determined above 995 °C in several scientific works [8, 9]. Various industries, especially the aerospace and automotive industries, have adopted several heat treatment methods in engineering the strength of materials used in the industry. Machine components in which Ti-6Al-4V are used are helicopter rotor

blades, turbines, centrifugal pumps, etc. [10]. Rapid cooling is synonymous with lower tensile strength, the higher the annealing temperature, the higher the tensile strength, which is similar to the trend observed in the hardness properties of the alloy. Imam and Gilmore studied the tensile strength of materials heat treated and water quenched at a temperature above the β transition temperature of 985 °C, the samples showed poor ductility, but when processed at 900 °C, the samples showed improvement in ductility [9]. For very slow cooling rates from high temperatures in the $\alpha+\beta$ region or above the β -transition temperature (995 ± 20) °C, the β phase predominantly transforms to the globular α type. Increasing the cooling rate increases the rate of α nucleation at β grain boundaries, thereby increasing the formation and growth of α platelets into the preceding β grains. The length and width of these α platelets are determined by the cooling rate [11]. Ti-6Al-4V alloy is used as a structural material for the production of large-scale welded and prefabricated aircraft structures, is an important alloy for the aerospace industry, and is thermally loaded during the welding process, which affects other mechanical properties and microstructure [12, 13, 14].

The value of 900 °C was chosen as the reference temperature for the study of mechanical properties and microstructural changes. This temperature is below the transition temperature of the β phase (approx. 995–1010 °C), which means that at this temperature there is a partial transformation of the α phase to the β phase, but the two-phase character of the alloy is still preserved. It has been repeatedly stated in the literature that this region is sensitive to significant changes in phase morphology, grain growth and possible coagulation of precipitation particles. Thermal loading at 900 °C can be expected to result in, in particular, an enlargement of the β phase grains, a change in the

shape and volume fraction of the primary α phase, and also a partial reconstruction of the lamellar microstructure. These processes are subsequently reflected in the mechanical properties – typically, there is a decrease in strength and yield strength due to grain coarsening, but at the same time, changes in ductility and toughness can be observed due to a reduction in dislocation density and a decrease in the number of phase interfaces. Studying the thermal loading of Ti-6Al-4V at 900 °C thus allows a better understanding of the sensitivity of this alloy to processes occurring just below the β -trans temperature and provides important insights for optimizing heat treatment and predicting the behavior of the material under real operating load conditions.

The aim of the presented article is to analyze the effect of thermal loading on the change in tensile

strength and fracture behavior of titanium alloys in comparison with thermally unloaded samples.

2 Materials and methods

The titanium alloy Ti-6Al-4V, supplied in the form of rolled bars, was used for the experiment. Currently, titanium is preferred mainly for its physico-chemical properties, mechanical strength and good corrosion resistance. It is the most widely produced and used titanium alloy. It has a wide range of applications in all sectors of industry. This alloy is easily hardenable, formable and, if an inert gas or vacuum is used, it can also be welded [14, 15]. The chemical composition according to AMS 4928 of the titanium alloy is given in Tab. 1.

Tab. 1 Chemical composition of Ti-6Al-4V alloy according to AMS4928

Chemical el.	O	N	C	H	Fe	Al	V	Ni	Ti
wt [%]	0.20	0.05	0.08	0.015	0.40	5.80	3.70	-	90.12

2.1 Sample preparation

Rolled bars of this alloy with a diameter of 12 mm were machined on a lathe into the shape of test specimens for static tensile testing. The specimens were prepared by machining to the required dimensions and surface roughness to meet the ČSN EN ISO 6892-1 standard. See Fig. 1 for samples after turning.



Fig. 1 Machined samples

The prepared samples were then thermally loaded in an electric resistance furnace. The prepared samples were thermally treated in an electric resistance furnace with a heating rate of 5 °C/min up to 900 °C, followed by holding at this temperature for 2 hours and subsequent furnace cooling. Fig. 2 shows the surface of the samples after heat treatment.



Fig. 2 Samples after heat treatment

After heat treatment, a static tensile test was performed according to the ČSN EN ISO 6892-1 standard on the universal tensile testing machine Inspekt 250. During the test, data was recorded - yield strength, tensile strength, relative elongation.

The experiment was also focused on the evaluation of the fracture surface in order to compare the fracture morphology and the behavior of the material at the point of rupture. Fractographic analysis of the fracture surfaces was performed on a Vega3 Tescan electron microscope and EDS analysis was performed using the Esprit program. The fracture surfaces formed after the static tensile test were analyzed.

For the analysis of the microstructure of the heat-treated material and the base material without heat treatment, metallographic sections were prepared by wet grinding using sandpaper with a grain size of 320, 500 to 1200 μm . Subsequently, the metallographic sections were polished using a 9 μm polycrystalline diamond suspension and a 0.1 μm colloidal silicon suspension Eposil F. Grinding and polishing were performed on a SAPHIR 360 machine with a wheel speed of 150 and subsequently 450 rpm. After subsequent etching with a Kroll etchant mixture, the material structures were observed using light microscopy on a LEXT OLS 5000 confocal laser microscope from Olympus.

Tab. 2 Samples “S”, static tensile test – selected values

	R_{p0.2} [MPa]	R_m [MPa]	A [%]	At [%]
$\emptyset$	851.1	929.7	22.0	29.3
σ	3.7	3.6	0.6	0.6

Tab. 3 Samples “S9”, static tensile test – selected values

	R_{p0.2} [MPa]	R_m [MPa]	A [%]	At [%]
$\emptyset$	781.4	840.1	20.2	27.4
σ	4.5	3.0	0.6	0.8

The measured values show a decrease in strength characteristics. It was found that after thermal loading, the yield strength R_{p0.2} decreased from (851.1 $\pm$ 3.7) MPa to an average value of (781.4 $\pm$ 4.5) MPa. The same trend was also observed in the strength limit after heat treatment of the alloy, where the average value R_m decreased by more than 89 MPa. The values also changed in the plasticity characteristics, when the ductility of the material was evaluated. However, the difference in ductility between the unheated and heat-loaded material is not significant. To explain the changes, it is necessary to perform a microstructural and fractographic analysis. Fig. 3 shows a comparison of all tensile tests performed in a tensile diagram, which confirms the statement above.

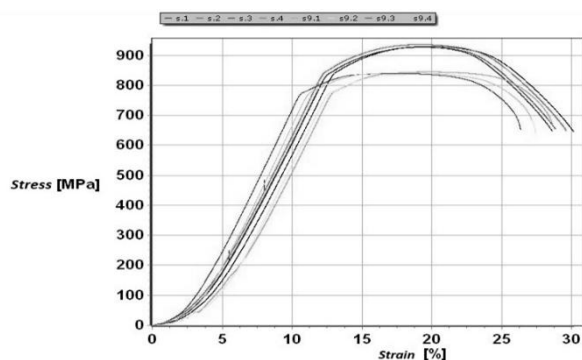


Fig. 3 Elongation curve as a function of stress, static tensile test

3.2 Microscopic analysis

Microscopic analysis of the Ti–6Al–4V alloy without heat treatment is documented in Fig. 7. This alloy

3 Results

3.1 Static tensile test according to ČSN EN ISO 6892-1

The static tensile test was performed on two sets of samples. The first set, which was the reference set, was a set of samples without thermal loading. These were samples of Ti–6Al–4V alloy machined for the static tensile test. The samples were labelled as “S”. The second set of samples for the static tensile test was loaded with a temperature of 900 °C. The samples were labelled as “S4”. Each set consisted of 4 samples. The values obtained for the “S” samples are given in Tab. 2 and for the “S9” samples in Tab. 3.

is characterized by a heterogeneous, two-phase structure formed by a solid solution of $\alpha + \beta$. Fine light grains of the α phase are surrounded by the β phase, which is darker. The grains are distributed evenly and without clusters of one or the other phase. The larger white grains of the α phase have a more regular shape. The β phase is stabilized by vanadium in this alloy.

The microstructure of the heat-treated material is shown in Fig. 4. The microstructure is formed by larger grains, where the α phase is again evenly surrounded by β phase grains. However, the β phase grains also increase in size and bring about greater homogeneity of the structure, which is caused by the transformation of α to β at high temperatures.

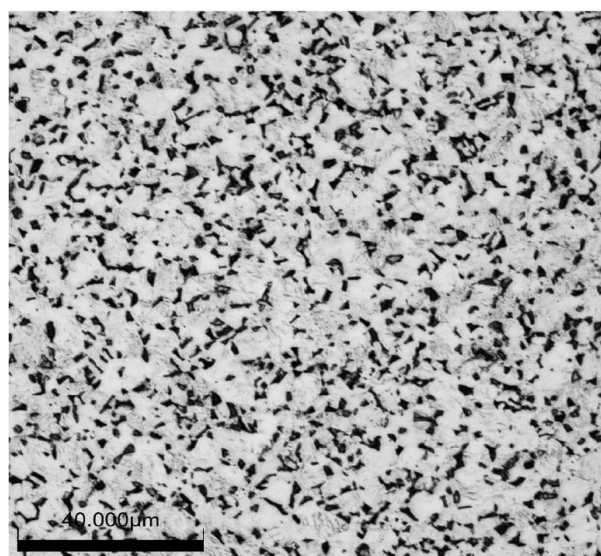


Fig. 4 Microstructure of the sample without HT

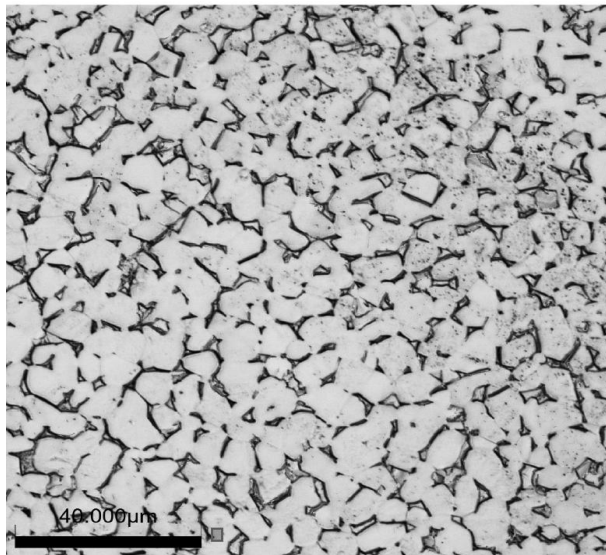


Fig. 5 Microstructure of the sample after HT

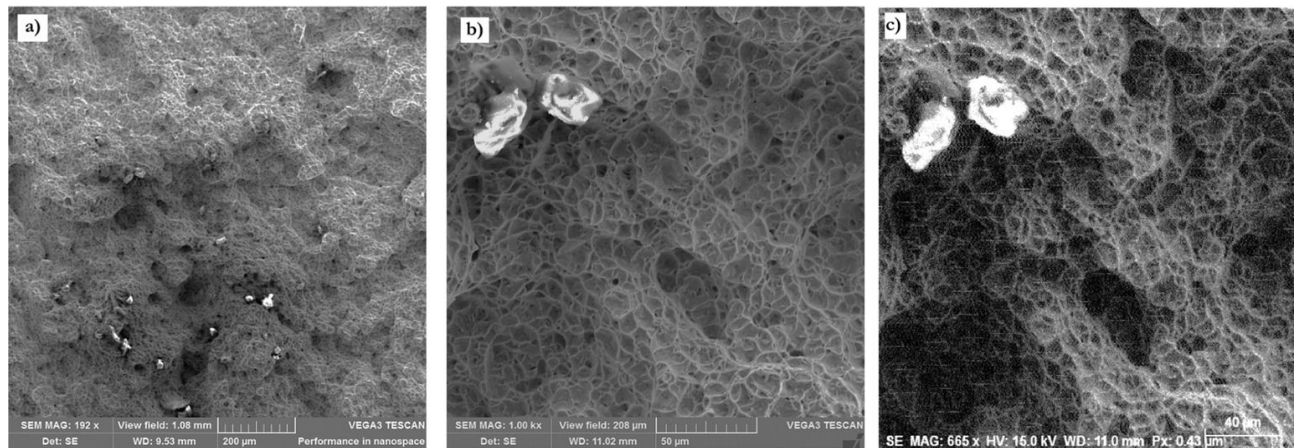


Fig. 6 a) Central area, inclusions; b) Central area, inclusions – detail; c) Spot EDX analysis

Tab. 4 Point composition analysis

Element	wt [%]	at [%]
Oxygen	53.53	69.18
Titanium	29.09	12.56
Nitrogen	6.94	10.24
Silicon	3.55	2.61
Sodium	2.74	2.46
Sulfur	1.98	1.27
Aluminium	2.18	1.67
In total	100	100

We can observe a fragmented fracture profile in the alloy after heat treatment S9, as shown in Fig. 7a. The crack did not propagate perpendicularly to the direction of tensile stress, but at an angle of about 45°. The fracture surface was formed by a ductile fracture with a pitting morphology. In the central part of the

3.3 Fractographic analysis

Fractographic analysis of fracture surfaces was performed on a Vega3 Tescan electron microscope and EDS analysis was performed using the Esprit program. The analyzed fracture surfaces were the result of a static tensile test, where standardized test specimens were subjected to static stress.

The fracture surface of the “S” alloy without heat treatment is formed by a ductile fracture with a pitted morphology, Fig. 6a. The pits are uniform and equiaxed, which is typical for uniaxial tensile stress of the material, Fig. 6b. The fracture surface shows a number of inclusions, especially in the central part of the test sample, Fig. 4 a, b. Spot EDX analysis confirmed that the phases present are intermediate phases based on titanium, oxygen and nitrogen, Fig. 6c.

fracture, pronounced plastic ridges are visible, Fig. 7b, c, which are related to the direction of the slip bands. The pits around the ridge are uneven, elongated and deformed by the influence of the load. Unevenly distributed sharp-edged inclusions were also observed in this alloy (Fig. 7b, d).

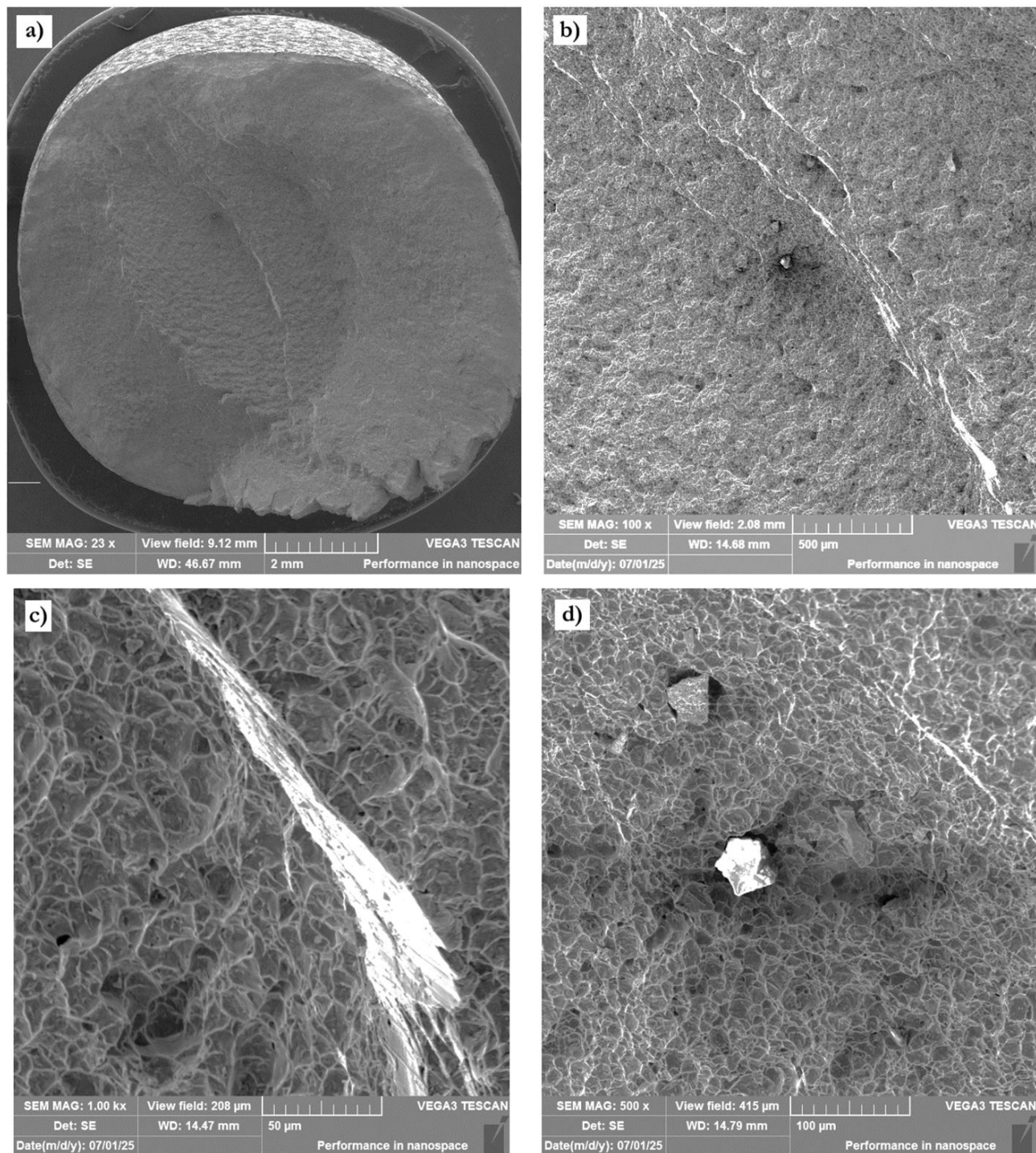


Fig. 7 a) Macroscopic observation; b) Center of the surface, plastic ridges; c) Center of the surface, plastic comb, detail; d) Center of the surface, inclusions

Tab. 5 Point composition analysis

Element	wt. [%]	at. [%]
Oxygen	49.68	63.53
Aluminium	45.19	34.27
Titanium	5.13	2.19
In total	100	100

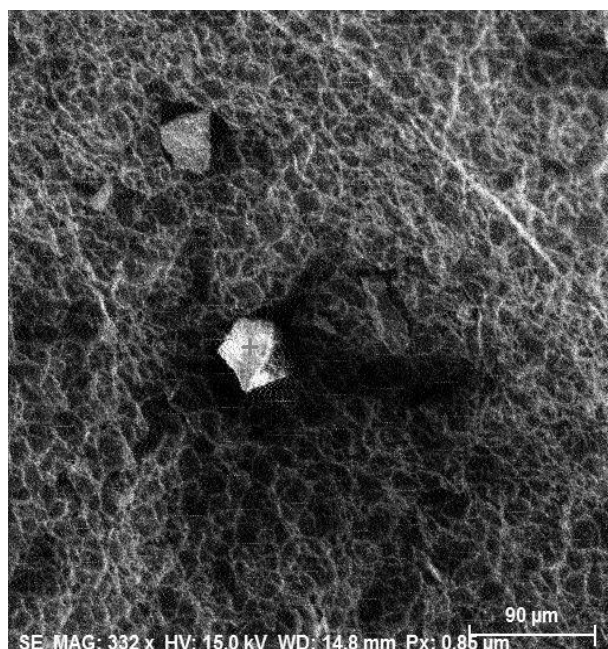


Fig. 8 Point EDX analysis, phase

In this case too, the heterogeneous phase analyzed is based on oxygen, aluminum and titanium. It is sharp-edged and relatively incoherently connected to the underlying matrix, which generally affects the way the crack propagates and subsequently the formation of the fracture surface.

4 Discussion

The results of the tensile test clearly show that thermal loading of the Ti-6Al-4V alloy at a temperature of 900 °C for 2 hours leads to a decrease in mechanical properties. The values of the yield strength $R_{p0.2}$ decreased by approximately 70 MPa and the tensile strength R_m by more than 89 MPa compared to the reference samples without thermal loading. The decrease in strength characteristics can be explained mainly by microstructural changes - the enlargement of the α and β phase grains and the homogenization of the structure. The coarser grain reduces the number of boundaries that act as obstacles to the movement of dislocations, which leads to a weakening of the material.

The ductility of the material decreased only slightly (approximately 2%), indicating that the alloy retained its ductile fracture behavior even after thermal loading. Fractographic analysis confirms this conclusion. The samples without heat treatment exhibited ductile pitting fracture with uniform morphology, while after thermal loading, plastic ridges and shear bands were observed, indicating a more complex crack propagation mechanism. The presence of inclusions and heterogeneous phases based on Ti, O, N and Al played a significant role in crack initiation, but did not lead to major brittle failure.

Microscopic analysis revealed that the thermally stressed samples exhibit coarser grain size and a higher proportion of β phase, which is consistent with the changes described in the literature during heating near the β -trans temperature. These structural changes are directly related to the measured decrease in strength. The results thus confirm the sensitivity of the Ti-6Al-4V alloy to thermal stress in the region just below the β transformation temperature and emphasize the need for precise control of heat treatment parameters.

5 Conclusion

The article dealt with the influence of thermal loading of the Ti-6Al-4V alloy on selected properties of the alloy. The results of the tensile test showed a slight decrease in strength and a decrease in ductility in the heat-treated material. Everything points to the influence of the microstructure, especially the coarser grain after heat treatment and the enlargement of the β phase grains. The values and curves from the diagrams confirm the weakening of the strength characteristics of the Ti-6Al-4V alloy as a result of approaching the β transformation temperature, since the selected temperature of 900° is the limit and was deliberately chosen before the next experiment. It is also clear from the tensile diagram that in both cases the material is without a significant yield strength. The decrease in the average value of the tensile strength by almost 90MPa and the decrease in ductility by almost 2% is an important finding from the design point of view.

The fractographic evaluation shows that the alloy without heat treatment undergoes ductile fracture with pitting morphology. It was also confirmed by the presence of inclusions and intermediate phases on the Ti layer. In the heat-treated alloy, the fracture profile is more fragmented with crack propagation at an angle of 45° to the direction of tensile stress. Ductile fracture with plastic ridges in the central part of the sample is evident.

Further research will focus on monitoring changes when the β transition temperature, determined above 995°C, is exceeded.

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