INFLUENCE OF THERMOMECHANICAL PROCESSING AT TEMPERATURES ABOVE β-TRANSUS ON THE MICROSTRUCTURAL AND MECHANICAL CHARACTERISTICS OF THE Ti-6246 ALLOY

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The microstructure evolution and tensile strength test of The Ti-6246 alloy were investigated in the present study. Ten samples have been modified by using different thermo-mechanical processes (heat-homogenization process, hot plastic deformation, and solution heat treatment) in the β-field range. The tensile test parameters were also investigated for all samples. The results revealed that the phase transformations and compositional changes induced by thermo-mechanical processes have a significant influence on the microstructural and mechanical characteristics. It was concluded that all samples present different crystallographic structure/lattice and morphologies. The mechanical properties have improved in the solution heat treatment in comparison with hot deformation processes.

Keywords: Ti-6246, titanium alloys, microstructure evolution, tensile test

1. Introduction

Titanium (Ti) is an allotropic element that has low-density and can be strengthened greatly by alloying and deformation processing. Ti and its alloys have different microstructures. Generally, Ti exists in more than one crystallographic form [1]. The Ti-6Al-2Sn-4Zr-6Mo (Ti-6246) alloy belongs to a wide class of titanium alloys known as ‘‘α + β alloys’’ since this alloy exhibits a microstructure based on two main phases stable at room temperature [2, 3]. The Ti-6246 alloy is somewhat more β-stabilized than the Ti-64 which classified as α + β alloy, thus, more β phase exists at equilibrium at ambient temperature. Therefore, The Ti-6246 alloy can be closer to the near-β alloys. However, there is some confusion in the literature because this alloy is sometimes referred as an α + β alloy [4-6] or a near- β alloy [7-9].

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The coexistence of the two phases depends on the temperature with the relative amount of the alloying elements, from room temperature to a specific transition temperature, called β-transus temperature [10].

Furthermore, the mechanical properties of Ti-6246 can be extremely reduced by oxidation leading to decrease in ductility and fracture toughness. This can be one of the main disadvantages [11, 12]. On the other hand, the advantage of this alloy over the other alloys such as Ti-6Al-4V (Ti-64) and Ti Grade 5 is that the Ti-6246 can be heat treated in larger sections having high strength without any compromises on the excellent corrosion resistance properties [11, 12].

Ti and its alloys have been widely used in different industries such as the aerospace, automotive and biomedical applications because of their high strength to weight ratio, excellent corrosion resistance and superior biocompatibility [13].

Titanium and its alloys have been extensively studied in the literature. Numerous studies have been carried out to explore the influence of thermo-mechanical processes on the microstructure and mechanical properties of Ti alloys [14-17].

Usually, the thermo-mechanical processing of (α + β) and near-β alloys comprises two stages. The first one, performed in the β field (at temperatures above β-transus), in order to achieve high-degrees of deformation during thermo-mechanical processing, to obtain a semi-finished geometrical shape for processed material. The second stage, performed in the α field (at temperatures below β-transus), in order to obtain the finished geometrical shape for processed material and to generate the desired mechanical properties of the processed material.

In the present work, Ti-6246 alloy was subjected to thermo-mechanical processing in the β-field. The microstructure and the mechanical test were investigated to analyse the influence of thermo-mechanical processing conditions on the microstructure evolution and mechanical strength.

2. Materials and Methods

Ti-6246 alloy was chosen for this study (β-transus: 940ºC ±5ºC) [4, 8, 18]. The chemical composition of Ti-6246 alloy (as-received) is Ti-6Al-2Sn-4Zr-6Mo (wt. %) which obtained by Vacuum Arc Remelting (VAR) at S.C. Zirom S.A. of Giurgiu, Romania. Ten samples were studied for the microstructure and the tensile strength test; sample I (as-received), sample II (heat-homogenization process), samples from III to VI (hot plastic deformation in β-phase field at a temperature range 950°C - 1100°C) and samples from VII to X (solution heat treatment with a fixed temperature at 950°C). The samples have been obtained from an ingot which was cut into four parts by using a precision cutter device model Metkon Micracut 200. The dimension of these parts was approximately 18 mm, 27 mm and 4.8 mm. The secondary work was the heat-homogenization

process at temperature 950ºC (duration time, 3h) in the β-field to ensure the physico-chemical homogeneity throughout the alloy then cooled in water.

Thermo-mechanical processes

Thermo-mechanical treatment processes consist of two processes. The first is the hot plastic deformation process which conducted through upsetting (forging) to obtain a higher degree of deformation without destroying the microstructural integrity of the alloy. This process includes deformation in the β-phase field at different temperature ranges from 950ºC to 1100ºC (duration time, 10 mins) and direct cooled at ambient temperature; this process includes the samples from III to VI. The final process is the step solution heat treating at specified temperature 950°C (duration time, 10 mins), followed by water quench for finalizing the microstructure deformation; this process contains the samples from VII to X.

Metallographic Analysis

The ten samples were cut for metallographic investigation. The samples were prepared with a very good surface finish using a precision cutter Metkon Micracut 200. Subsequently, all samples were hot mounted using a Buehler SimpliMet mounting press within the cylindrical sampler. Thereafter, all samples were subjected to grinding and polishing using a Metkon DIGIPREP Accura (advanced high-end grinding and polishing system). Ultimately, the microstructure was examined using scanning electron microscopy (SEM) device, model TESCAN VEGA II–XMU. The alloy chemical composition and alloying elements dispersion within microstructure was determined by Energy Dispersive Spectroscopy using a BRUKER xFlash 6/30 EDS detector mounted into (SEM).

Mechanical testing (Tensile Strength Test)

All the samples were mechanically investigated through the tensile strength test. This test was carried out using a mechanical testing machine module Deben MICROTEST-2000 - mounted inside SEM. The samples were cut into small rectangular slides shape of approximately 2: 35 mm length, 2 mm width and 0.6 - 0.7 mm thickness. Ultimate Tensile Strength (UTS), Yield Strength (YS) and the Fracture Elongation (ε_f) were estimated.

3. Results and Discussions

Alloying element's dispersion

Fig. 1 shows alloying element's dispersion within microstructure for the as-received sample. One can see that SEM-BSE image shows a microstructure consisting of alternate α-Ti lamellar colonies with β-Ti phase dispersed between α-Ti lamellar. The higher content of Ti is observed within α-Ti lamellar (Fig. 1.b), as well as Al (Fig. 1.c), due to α-Ti phase stabilizing the effect of Al [19, 20]. The higher content of Mo is observed in the space between α-Ti lamellar (Fig. 1.f),

stabilizing the β-Ti phase [19, 20]. As observed, Sn and Zr (Fig. 1.d-e) shows uniform dispersion within the entire microstructure, both having a neutral character in the stabilization of α-Ti and β-Ti phases [19, 20]. The EDS spectra of Ti6246 as-received sample (Fig. 1.g) shows the presence only of Ti, Al, Sn, Zr and Mo, no other relevant EDS lines being observed.

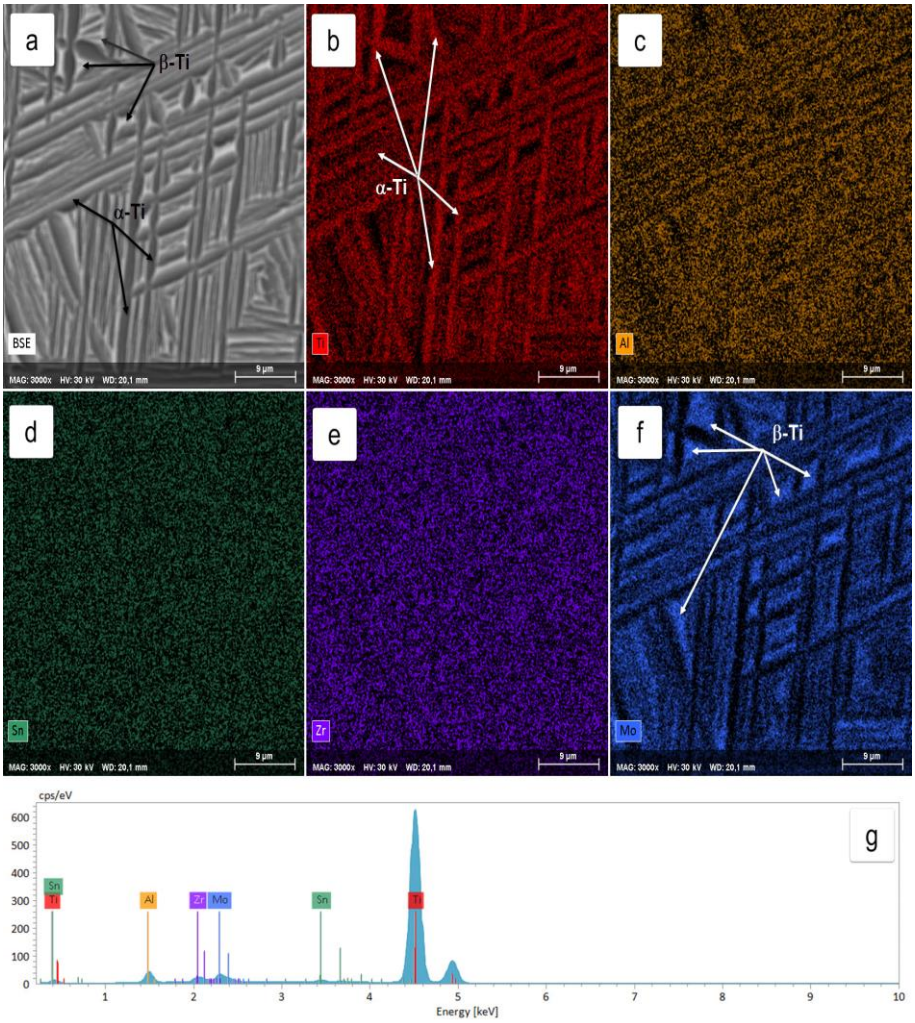

Fig. 1. Alloying element's dispersion within as-received sample (obtained at S.C. Zirom S.A. Giurgiu, Romania); a) high magnification BSE image of as-received sample microstructure; b) Ti dispersion; c) Al dispersion; d) Sn dispersion; e) Zr dispersion; f) Mo dispersion; g) EDS spectra of as-received sample.

In order to compute the chemical composition, five random microstructural images were acquired and EDS analyzed. Resulted chemical composition data were statistically analyzed and shown in Table 1.

Table 1

Statistical data on the chemical composition of the Ti-6246 alloy

Components of the alloy	Contents of the alloy (wt. %)
Ti	82.07 ±0.32
Al	5.72 ±0.54
Sn	1.88 ±0.12
Zr	4.02 ±0.28
Mo	6.11 ±0.21

Metallographic Analysis

The results of the microstructure of sample I (as-received) are shown in Fig. 2. It can be seen from the Fig. 2.a, that there are three areas were selected for one grain to be investigated. Area 1 represents the β-phase (black color), area 2 indicates the α-phase (white color) and the area 3 represents the grain boundary zone. The areas 1, 2 and 3 are shown in Fig. 2.b, Fig. 2.c and Fig. 2.d respectively with magnification factor (X) equal to 250. It was observed that the microstructure of this sample contains α-Ti lamellar with β-Ti inter-lamellar morphology.

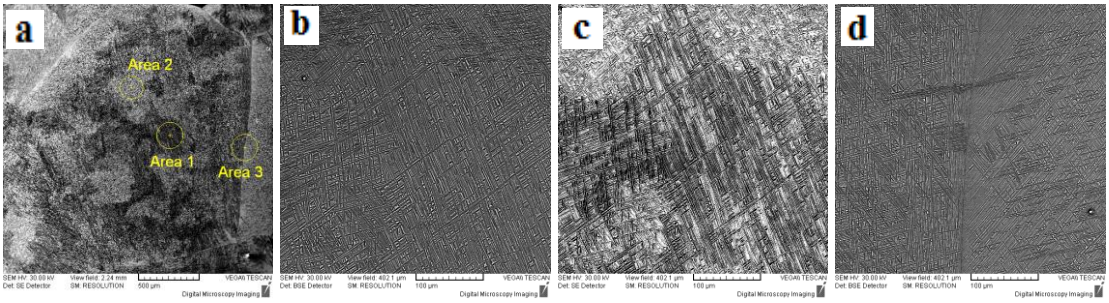

Fig. 2. SEM microstructures of sample I (as-received), a) the positions of selected areas with X 70; b) area 1 with X 250; c) area 2 with X 250; d) area 3 with X 250.

The results of the microstructure for the sample II (after homogenization) are shown in Fig. 3. Three areas were also investigated within one grain (Fig. 3.a). It was observed that the micrograph of the sample after homogenization process (Figs. 3.b, 3.c and 3.d) become more pronounced α-Ti lamellae (thin lamellae) with more β-Ti as matrix phase. As a result of homogenization process in the β-phase field, the β-Ti matrix phase is growing [21, 22]. Moreover, the microstructure of sample II became more homogenous and compact.

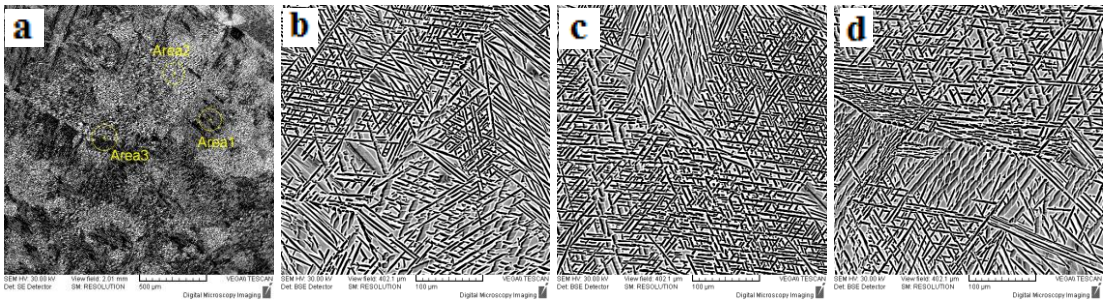

Fig. 3. SEM microstructures of sample II (after homogenization process at 950°C), a) the positions of selected areas with X 70; b) area 1 with X 250; c) area 2 with X 250; d) area 3 with X 250).

Fig. 4 shows the scheme of the thermo-mechanical process in which the sample before deformation processing is shown in Fig. 4.a, whereas the sample after hot deformation processing (forging) is shown in Fig. 4.b. In the hot deformed samples, three areas were selected to investigate the sample's microstructure. The locations of the selected investigation areas are shown in Fig. 4.c. It can be noted that area 1 and 3 were selected on the edge of the sample while area 2 in the middle of the sample. In this work, the β-phase field was studied with a different set of temperature (950°C - 1100°C).

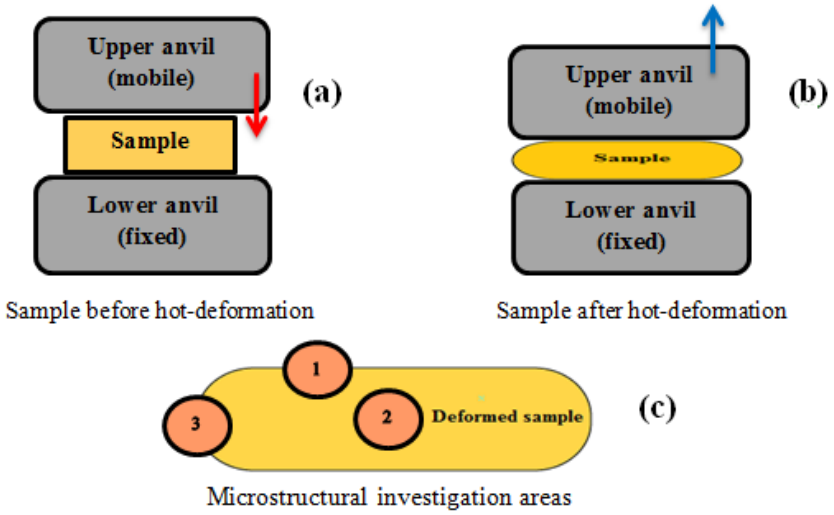

Fig. 4. The hot-deformation processing; a) before the hot-deformation; b) after the hot-deformation; c) the positions of the selected investigation areas.

For sample III, the hot deformation process was conducted at a temperature of 950°C. The microstructure results of this sample in the case of areas 1, 2 and 3 are presented in Fig. 5. It can be seen that the microcracks were observed in area 1 due to the relatively high deformation degree (Fig. 5.a). In area

2, it can be noticed that the flow direction of the grains boundaries became thinner due to the grains elongation (Fig. 5.b). In area 3, it can be seen a fragmented distribution of α-Ti lamellae within the β-Ti matrix (Fig. 5.c).

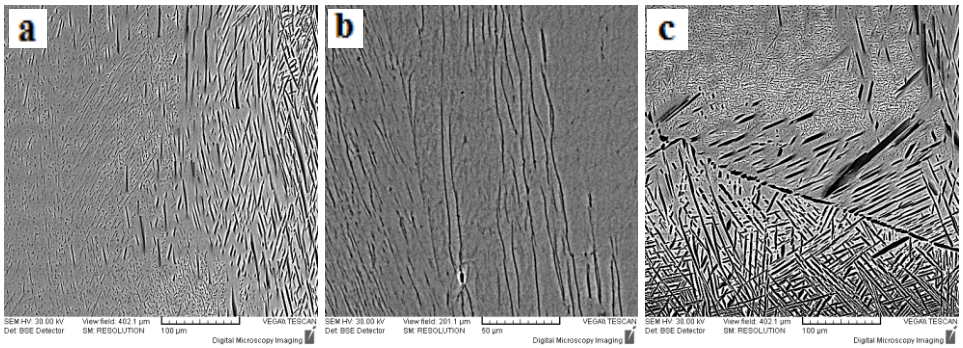

Fig. 5. SEM microstructures of sample III (hot-deformed at 950°C), a) area 1 with X 250; b) area 2 with X 500; c) area 3 with X 250).

In sample IV, the hot deformation process was conducted at a temperature of 1000°C. The microstructure results of this sample for area 1, 2 and 3 are shown in Fig. 6. It was observed that when the temperature increases, the deformation in area 1 (Fig. 6.a) became more intensive in comparison with area 1 of sample III. In area 2 (Fig. 6.b), it was observed that the flow direction of the grains boundaries is quite clear in comparison with area 2 of sample III. Furthermore, elongation and dynamic recrystallization in the grains, containing α-Ti plates within the β-Ti matrix, due to the higher temperature, led to change in the microstructure from α-Ti lamellar to (α + β) lamellar microstructure. In area 3 of sample IV, it can be seen a fragmented distribution of α-Ti lamellar within the β-Ti matrix (Fig. 6.c).

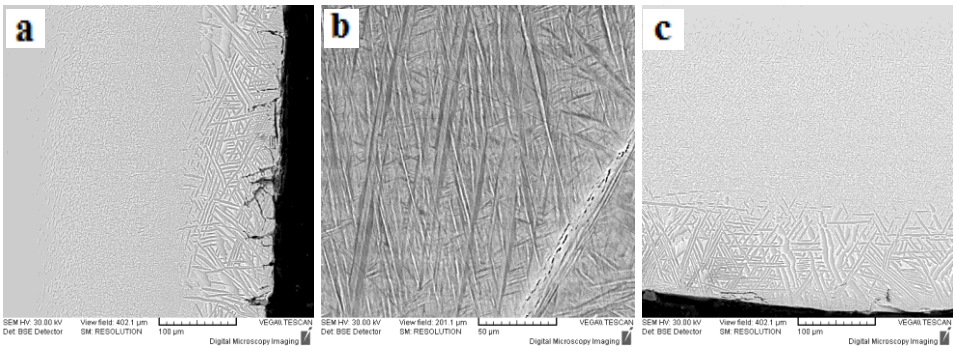

Fig. 6. SEM microstructures of sample IV (hot-deformed at 1000°C), a) area 1 with X 250; b) area 2 with X 500; c) area 3 with X 250).

In sample V, the hot deformation process was conducted at a temperature of 1050°C. The microstructure results of this sample for area 1, 2 and 3 are shown

in Fig. 7. In area 1, it was observed that the α-Ti plates are slightly bigger in comparison with previous samples (Fig. 7.a). In area 2, complete elongated grains were observed in comparison with the previous samples (Fig. 7.b). In area 3 of this sample, the deformation micro-cracks seem large and extended (Fig. 7.c).

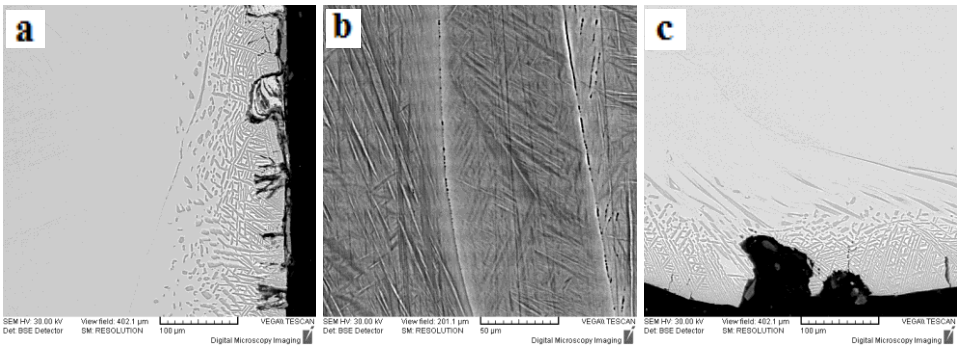

Fig. 7. SEM microstructures of sample V (hot-deformed at 1050°C), a) area 1 with X 250; b) area 2 with X 500; c) area 3 with X 250).

In sample VI, the hot deformation process was conducted at a temperature of 1100°C. The microstructure results of this sample for area 1, 2 and 3 are shown in Fig. 8. The area 2 shows less deformed grains in comparison with samples III, IV, and V, due to the high temperature which promotes the dynamic recrystallization of deformed microstructures. The microstructure of the grains in area 2 shows large grains (Fig. 8.b), due to the occurrence of recrystallization from the middle of the sample, which changes the morphology of the microstructure from the large lamellae to polygonal type. In area 3, same observations can be made as in the case of previous samples (Fig. 8.c).

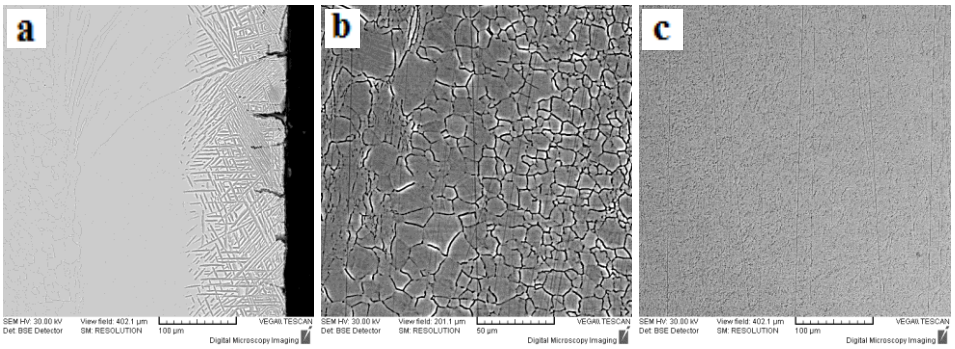

Fig. 8. SEM microstructures of sample VI (hot-deformed at 1100°C), a) area 1 with X 250; b) area 2 with X 500; c) area 3 with X 250).

In sample VII, after hot deformation processing at 950°C a solution treatment was performed at a temperature of 950°C for 10 min and water quenched. The microstructure results of this sample for areas 1, 2 and 3 are shown in Fig. 9. It was noticed that an oxidized layer has appeared in area 1 and 3 on the

sample surface. Moreover, in area 2, the microstructure of the sample changes to "basket weave" type, the α-Ti lamellae and β-Ti matrix being well defined.

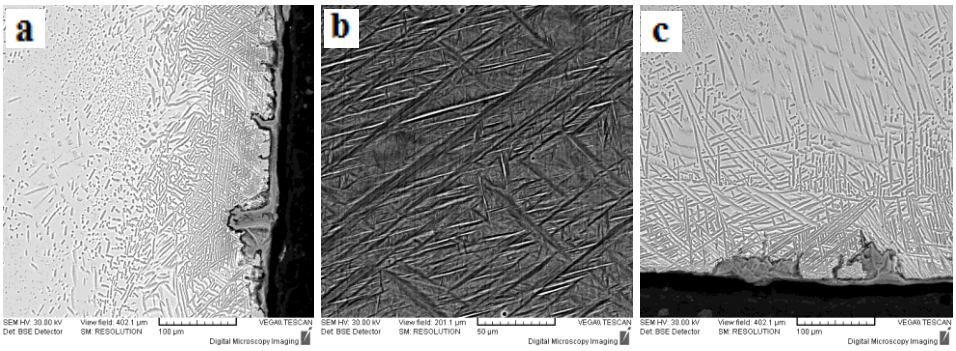

Fig. 9. SEM microstructures of sample VII (hot-deformed at 950°C and solution treated at 950°C), a) area 1 with X 250; b) area 2 with X 500; c) area 3 with X 250).

In sample VIII after hot deformation processing at 1000°C, a solution treatment was performed at a temperature of 950°C for 10 min and water quenched. The microstructure results of this sample for areas 1, 2 and 3 are shown in Fig. 10. Same observations as in the case of sample VII can be made. Must be mentioned that in the case of area 2 (Fig. 10.b) one can observe that the α-Ti lamellae become thinner within the β-Ti matrix.

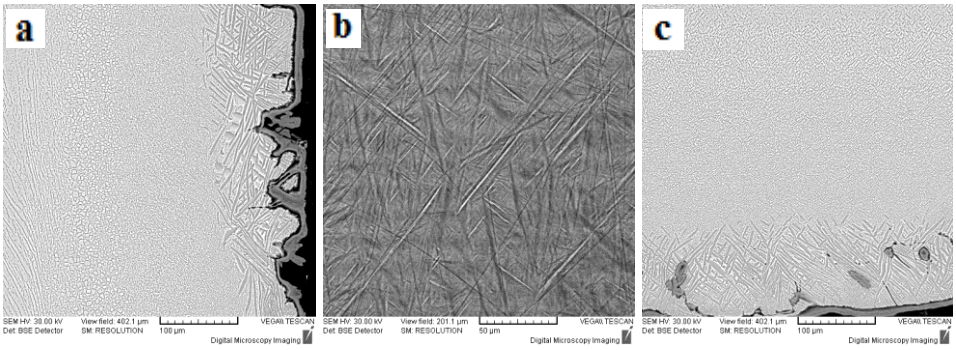

Fig. 10. SEM microstructures of sample VIII (hot-deformed at 1000°C and solution treated at 950°C), a) area 1 with X 250; b) area 2 with X 500; c) area 3 with X 250).

In sample IX, hot deformation processing at 1050°C a solution treatment was performed at a temperature of 950°C for 10 min and water quenched. The microstructure results of this sample for areas 1, 2 and 3 are shown in Fig. 11. In comparison with sample VII and VIII, one can observe that the solution treatment process tends to improve the microstructure, especially area 2 (Fig. 11.b) due to the refining of α-Ti lamellae within the β-Ti matrix.

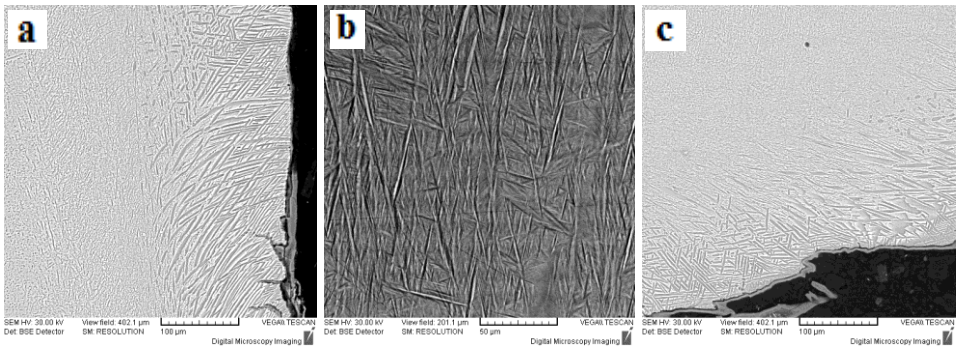

Fig. 11. SEM microstructures of sample IX (hot-deformed at 1050°C and solution treated at 950°C), a) area 1 with X 250; b) area 2 with X 500; c) area 3 with X 250).

In sample X, hot deformation processing at 950°C a solution treatment was performed at a temperature of 1100°C for 10 min and water quenched. The microstructure results of this sample for areas 1, 2 and 3 are shown in Fig. 12. In comparison with sample VII, VIII and IX one can conclude that the solution treatment process improves the microstructure, especially area 2 (Fig. 12.b) due to the refining of α-Ti lamellae within the β-Ti matrix.

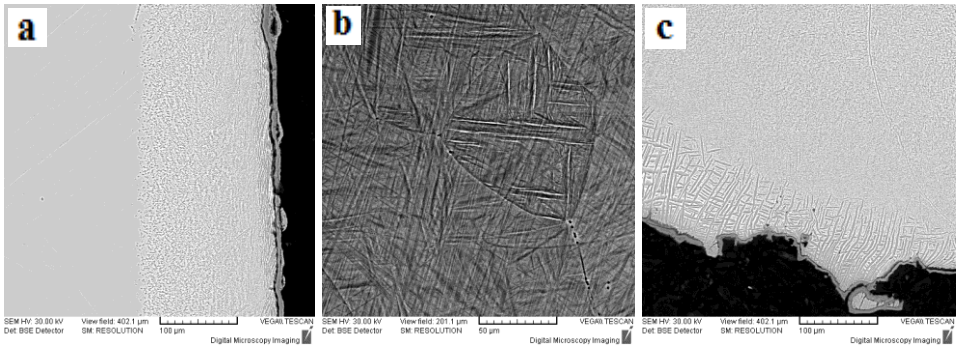

Fig. 12. SEM microstructures of sample X (hot-deformed at 1100°C and solution treated at 950°C), a) area 1 with X 250; b) area 2 with X 500; c) area 3 with X 250).

Mechanical test (tensile strength test)

The resulted morphologies in the present paper are distinguished by different features as discussed above. Therefore, the mechanical properties of Ti-6246 alloy are extremely relying on its microstructure. All the samples (I - X) were subjected to mechanical investigation through the tensile strength test. For each sample, the tensile test parameters: Ultimate Tensile Strength (UTS), Yield Strength (YS), and Fracture Elongation (ε_f) were given in Table 2. The results obtained for the specified mechanical test are shown in Figs. 13 – 15. It was observed that the sample I has the best mechanical properties in which UTS, YS and ε_f were higher than other samples. The elongation of this sample was typical.

Table 2

Mechanical properties of Ti-6246 alloy

Samples	UTS, (MPa)	YS, (MPa)	ε_f, (%)
Sample I	900.97	843.39	6.47
Sample II	612.72	621.42	3.49
Sample III	680.70	680.83	3.22
Sample IV	609.37	634.39	5.56
Sample V	580.85	638.84	2.59
Sample VI	583.55	568.17	2.54
Sample VII	678.24	697.16	3.47
Sample VIII	637.18	602.54	4.02
Sample IX	682.83	599.97	4.22
Sample X	658.59	630.31	3.48

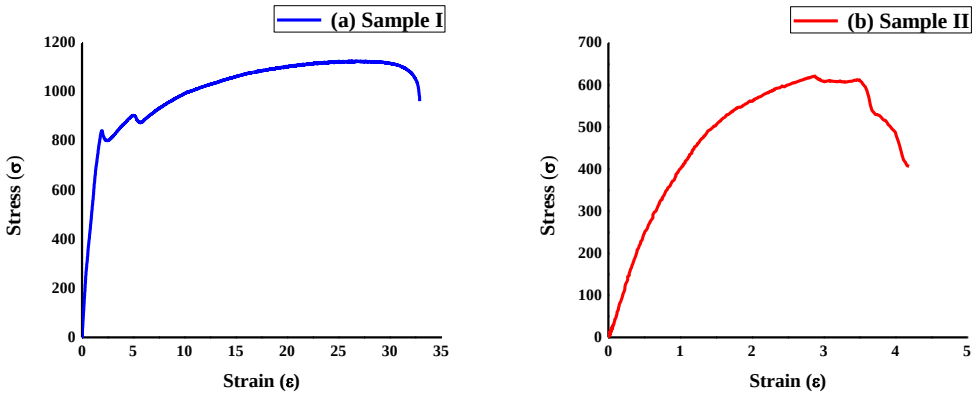

Fig. 13. Tensile stress-strain curves, a) sample I (as-received); b) sample II (after the heat-homogenization process at 950°C).

In sample II, the tensile test parameters (YS, UTS and ε_f) and the elongation were less in comparison with the sample I due to the oxidation on the surface sample which makes the sample more brittle. In the case of samples from III to VI, it was noted a relative decrease in the tensile test parameters. The higher the temperature above the β-transus temperature, the mechanical resistance reduced. The samples from VII to X have a relative increase in the tensile test parameters due to the mechanical properties improvement. This because the temperature is equal or very close to β-transus temperature (i.e. α-phase field). These samples have better elongations than samples of hot deformation process.

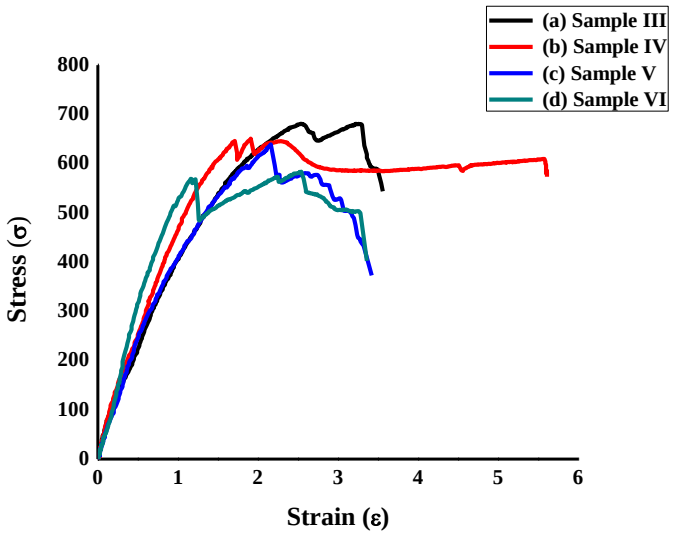

Fig. 14. Tensile stress-strain curves (hot-deformation process), a) sample III at 950°C; b) sample IV at 1000°C; c) sample V at 1050°C; d) sample VI at 1100°C.

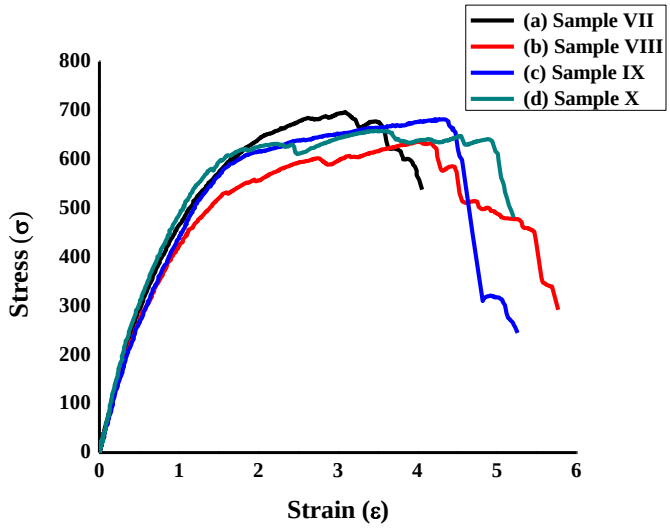

Fig. 15. Tensile stress-strain curves, a) sample VII (hot-deformed at 950°C and solution treated at 950°C); b) sample VIII (hot-deformed at 1000°C and solution treated at 950°C); c) sample IX (hot-deformed at 1050°C and solution treated at 950°C); d) sample X ((hot-deformed at 1100°C and solution treated at 950°C).

The present results of this paper were consistent with Sebastien et al. [23] regarding the morphologies of the microstructures. They have found that the Ti-6246 alloy that subjected to the thermo-mechanical processes (in the beta field) resulted in different morphologies. On the other hand, the results of this paper

were inconsistent with Sebastien et al. [23] regarding the forging process. They have found a slight improvement in the mechanical properties of the Ti-6246 alloy whereas, no improvement was observed in the current work. The reason may be due to the different duration time of the samples embedded in the furnace.

6. Conclusions

In the present work, the main aim was to examine the effect of the microstructure and mechanical characteristics of the Ti-6246 alloy during the thermo-mechanical processes. It was found that the microstructure for all samples exhibits different morphologies from lamellar to basket weaves types. The solution heat treatment, applied after hot deformation, improves the microstructure especially in the middle area of the samples in comparison with the selected areas on the edges of samples.

According to the tensile testing, it was found that the as-received material (Ti-6246) has the best mechanical test parameters (YS, UTS and ε_f) and elongation in comparison with other samples. In the case of hot deformation processing, it was observed that the higher the temperature of processing above the β-transus the less the mechanical strength is obtained, while in the case of solution treatment processing applied after hot deformation, a relative increase of mechanical strength is noticed. Despite, the sample as-received has the best mechanical properties than other samples. However, these samples may be useful to certain applications and can be examined in the future researches.

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