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Effect of Radial Forging on the Microstructure and Mechanical Properties of Ti-Based Alloys

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Abstract: Radial forging is a reliable way to produce Ti alloy rods without preliminary mechanical processing of their surface, which is in turn a mandatory procedure during almost each stage of the existing technology. In the present research, hot pressing and radial forging (RF) of the titanium-based Ti-3.3Al-5Mo-5V alloy were carried out to study the specifics of plasticized metal flow and microstructural evolution in different sections of the rods. The structural analysis of these rods was performed using metallography and X-ray diffraction techniques. The X-ray diffraction reveals the two-phase state of the alloy. The phase content in the alloy was shown to vary upon radial forging. Finally, radial forging was found to be a reliable method to achieve the uniform fine-grained structure and high quality of the rod surface.

Keywords: titanium alloys; structure formation; mechanical properties; radial forging

1. Introduction

The need for increasing strength and reliability of constructions, as well as reducing their weight, leads to higher demands for structural materials. In particular, titanium-based alloys that are extensively used in various fields of engineering due to their high specific strength must have high fatigue resistance, corrosion resistance and wear resistance in addition to excellent strength that can be achieved whilst retaining high plasticity [1,2].

According to research conducted over recent decades [3–6], the possibilities of improving the above properties by means of the conventional mechanical and thermal processing methods in order to modify the chemical composition of titanium-based alloys, aimed at introducing alloying elements and varying grain size in the parent material, are almost exhausted. On the other hand, it is evident that strength characteristics along with functional properties of alloys can be noticeably increased via the formation of micro- and submicrocrystalline phases in the bulk of the alloy under severe plastic deformation [7–9].

There is a large number of scientific papers [10–14], in which the processes of evolution of the structure and properties of titanium-based alloys are investigated under deformation by various methods. It is known [15–17] that the formation of structure in a material is largely determined by the degree of deformation, and its scheme and conditions. There is a large amount of experimental data on the effect of deformation on the structural state of titanium-based alloys [18,19]. However, the evolution of the structure of titanium-based alloys during radial forging (RF) has not been studied sufficiently. As is known [20–22], a stressed state is implemented in the dynamic deformation site in the process of compression of a cylindrical rod during radial forging, which is close to the triaxial compression and makes it possible to obtain large degrees of deformation of rods under dynamic influence without the formation of cracks.

According to [3,10,15–17], thermomechanical processing of titanium-based alloys such as Ti-Al-Mo-V and containing Mo and V may lead to the changes in X-ray diffraction patterns owing to texture formation caused by dopant redistribution, forward and backward decomposition of the β -phase, and partial transformation of the α -phase in a metastable α'' -phase. These phenomena may arise individually or overlap with each other. Elucidating the complex redistributions of XRD intensities necessitates a careful analysis of XRD ranges with emerging or disappearing uncombined reflexes from the different phases.

The complex problem of the structural strength of Ti alloys consists in obtaining a homogeneous material with a fine-grained structure, hardened by a highly dispersed phase and a high-quality surface of parts. The fine-grained structure and high-quality surface reduce the effect of stress concentrators and, as a result, increase the resistance to brittle fracture when operating under conditions of alternating dynamic loads [1,2,4].

Traditional methods for making alloys include heating the billet to a temperature above the polymorphic transformation temperature in the β -region, rolling at this temperature, cooling to ambient temperature, heating the rolled stock to a temperature 20–50 °C below the polymorphic transformation temperature, and final rolling at this temperature. In the case of titanium products, such a technological scheme does not provide the necessary manufacturability and quality of titanium material due to its high tendency to grain growth, oxidation and gas saturation during heat treatment and, as a consequence, to loss of plasticity and embrittlement of the material. The temperature of polymorphic transformation (TPT) for the Ti-Al-Mo-V alloy is 840–880 °C, at which phase + recrystallization occurs, which is the basic characteristic for the appointment of heat treatment modes, but it is at TPT and above that catastrophic grain growth in titanium alloys and coarsening of the intragranular structure are observed.

It should be noted that, unlike steels, the coarse-grained structure of titanium materials is not corrected by heat treatment. Therefore, during heat treatment, the hardening temperature is set at 80–150 °C below the TPT of the alloy. However, under these conditions, complete recrystallization does not occur, which does not provide complete hardening and does not correct the heredity of the previous processing, as a result of which the material does not have sufficient quality for such critical parts as bolts and springs. Multiple hot forging and air cooling operations will negatively affect the surface quality of the bar. In addition, the method requires an expensive abrasive operation to remove forging defects and surface substandard layers. As a result, the scrap rate rises and the metal yield decreases, which ultimately leads to an increase in the cost of manufacturing rods.

The problem to be solved by this study is to obtain rods from high quality titanium alloys while ensuring high process productivity.

A promising method for the formation of an ultrafine-grained structure is RF, the use of which in the manufacture of products from titanium alloys is still limited. The use of the radial forging process in the production of pipes from Zr alloys is described in monograph [7]. If the processes occurring in hcp alloys during cold rolling and subsequent heat treatment are well studied, then there is still insufficient reliable information regarding the patterns of structure formation and deformation mechanisms acting during radial forging.

This work aims to characterize the Ti-Al-Mo-V rods with optimal structural and mechanical properties achieved through severe plastic deformation of a Ti-Al-Mo-V alloy using radial forging machines (RFMs). Radial forging is a reliable way to produce Ti alloy rods without preliminary mechanical processing of their surface, which is in turn a mandatory procedure during almost every stage of the existing technology. In order to meet the technical requirements of semiproducts, the development of a new technology needs to solve some important problems such as:

- The choice of thermal treatment modes for forged semiproducts, which meet the technical requirements to the structure and mechanical characteristics;

- The elaboration of algorithms for the deformation of rods and alignment of the RFM tool using data acquired during the analysis of structural and mechanical properties, which obeys requirements to the geometrical sizes and surface quality.

2. Materials and Methods

High and ultrahigh degrees of deformation and the subsequent or concomitant thermal effect lead to the implementation of boundary-substructure and dispersion mechanisms of strengthening. Among the industrial methods that allow us to form a more dispersed structural condition than after hot forming and heat treatment, including quenching and tempering in a wide temperature range, is the technology of RF. The billet material is in overall uniform compression in the deformation center when using four strikers under RF, which leads to the formation of an extremely dispersed and homogeneous structure [7]. It should be noted that the treatment of the billet is implemented at the expense of multiple ultrafast simultaneous compressions. This scheme of deformation allows us to form a high degree of localization of the center of the deformation. Basically, the technology of the radial forging is used to improve the strength, reliability, and durability of the special pipe billets, the main task of which is the long-term operation under normal and extreme conditions.

The investigation of structure and properties of the alloys were performed at various stages of manufacture using mechanical, metallographic, and X-ray diffraction techniques. Samples were rods with diameters Φ of 25 mm, produced from a Ti-Al-Mo-V alloy via hot pressing, as well as rods with diameters Φ 20, Φ 16, Φ 12, Φ 10.5, and Φ 8.5 mm, using the SXP-16 machine of GFM firm (Steyr, Austria). The chemical composition of a Ti-Al-Mo-V workpiece used in testing the technology is given in Table 1.

Table 1. Chemical composition of Ti-Al-Mo-V alloy (wt %).

Ti	Al	Mo	V	C	N	Fe	Si	H ₂	O ₂
base	3.3	4.6	4.5	0.05	0.01	<0.01	≤0.10	0.007	0.014

Radial forging of Ti-Al-Mo-V alloy rods, implemented on a SXP-16 machine of GFM firm (Steyr, Austria), changes their manufacturing technology to a large extent. Radial forging allows one to achieve the better plastic processing of the material, but also to ensure high quality of the rod surface, which enables to avoid facing at intermediate stages of the technological process and to facilitate the process itself. The forging modes applied in this work are given in Table 2. According to the results, the surface roughness of the rod with a diameter Φ of 10 mm was within a range of 3–9 μ m, which met the technical requirements of less than 10 μ m; the ovality of the rod at a length of 2.5 m was below 30 μ m.

Table 2. Forging modes of Ti-Al-Mo-V alloy rods.

Transition	Number of Beats Per Minute	Feed Rate, mm/s
Φ 20→ Φ 16 mm	580	5...7
Φ 16→ Φ 10 mm	580	5...7

The alloy structure in rods exposed to radial forging was inspected in two transition zones—i.e., Φ 20→ Φ 16 mm and Φ 16→ Φ 10 mm (Figure 1).

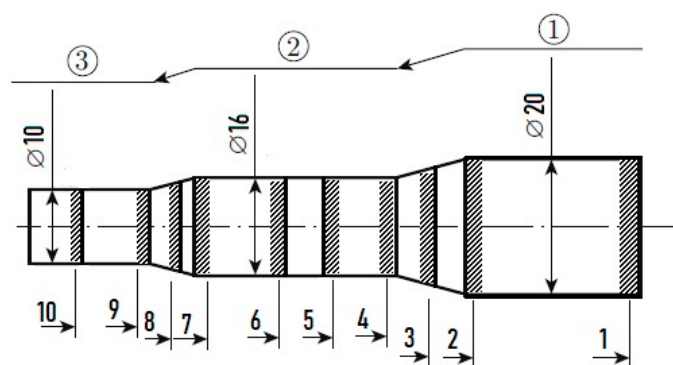


Figure 1. Schematics of cutting-out of samples for metallographic analysis in case of $\Phi 20 \rightarrow \Phi 16$ mm and $\Phi 16 \rightarrow \Phi 10$ mm transitions.

The microstructure of Ti-Al-Mo-V alloy in these zones was probed using a Neophot-21 metallographic microscope equipped with a digital camera (Genius VideoCam Smart 300) and a special software intended for digital image processing. The microstructure of the alloy was determined via chemical etching in a solution of 3% hydrofluoric acid and 3% nitric acid in water [23].

To implement the metallographic analysis of metallic state, as well as to assess the efficiency of the used deformation method and to optimize the alignment of strikers of the SXP-16 RFM, the samples were selected from the deformation center. The schematics of cutting-out of samples for metallographic tests are shown in Figure 1.

Table 3 contains information about specimens that were cut from deformation zones in a cross section according to the scheme in Figure 1, so that each sample corresponds to a certain degree of reduction in diameter, which increases with increasing number.

Table 3. Tested samples according Figure 1.

Sample No.	Workpiece Diameter, μm	Location along the Workpiece	Reduction K, %
1	$\Phi 20$	Input (initial state)	0
3	$\Phi 20$	Deformation center (RF)	17
5	$\Phi 16$	output	20
7	$\Phi 16$	Deformation center (RF)	23
8	$\Phi 16$	Deformation center (RF)	38
10	$\Phi 10$	Output (final state)	50

X-ray diffraction measurements of Ti-Al-Mo-V alloy were conducted on a sample with $\Phi 8.5$ mm, obtained from the rod exposed to hot pressing, as well as on sample 6 made by radial forging at a $\Phi 16 \rightarrow \Phi 10$ mm transition (see Figure 1). The data were recorded in the Bragg—Brentano geometry (Θ - 2Θ mode) within a range of angles of $10 \leq \Theta \leq 125$ deg [24] using a DRON-3 (Burevestnik, Russia) diffractometer and $\text{Cu K}\alpha$ radiation with the filtered $\text{K}\beta$ line. The X-ray diffractograms were recorded in a stepwise mode with a step of 0.1 deg; the exposure time was 5 s. The XRD data were processed using a special computational software. The phase analysis was performed in ARFA-7000 software (Russia), including the database for 40,000 compounds.

The mechanical characteristics of Ti-Al-Mo-V alloy were studied on the flat samples, whose working element dimensions were $2 \text{ mm} \times 6 \text{ mm} \times 40 \text{ mm}$. Samples were stretched at room temperature on an Instron-1185 (US) universal testing machine at a rate of $8.3 \times 10^{-5} \text{ s}^{-1}$.

3. Results

3.1. Mechanical Properties of Ti-Al-Mo-V Alloy after Hot Pressing

The mechanical characteristics of Ti-Al-Mo-V alloy were studied on the flat samples for initial state (sample 1) with heads cut off from the center of the workpiece (1), as well as from the surface (2) and transition (3) layers. The appropriate stress–strain diagrams of the tested samples are given in Figure 2. The strength characteristics of all three samples are quite close to each other, as can be seen from the values of strength limit $(\sigma_B)_1 = 1060$ MPa, $(\sigma_B)_3 = 1040$ MPa, and $(\sigma_B)_2 = 980$ MPa. At the same time, the plasticity drastically varies from one sample to the other. So, the uniform elongation (before the formation of the neck) was found to be $(\epsilon_B)_1 = 0.06$, $(\epsilon_B)_2 = 0.08$, and $(\epsilon_B)_3 = 0.105$. The elongation at failure was even more different for each sample, being $\delta_1 = 0.09$, $\delta_2 = 0.11$, and $\delta_3 = 0.16$.

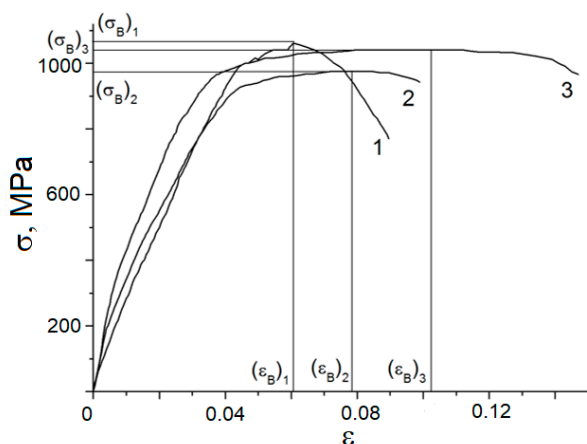


Figure 2. Stress–strain diagrams of Ti-Al-Mo-V alloy: center of the workpiece (1), surface layer (2), transition layer (3).

This is owing to the large cross-sectional heterogeneity of the alloy structure. According to the metallographic data acquired on the cross-section of the workpiece, the phase composition within the scanned area from the center to the surface is presented by a mixture of α and β phases of titanium, where the volume fraction of the α -phase exceeds that of the β -phase (see Figure 3).

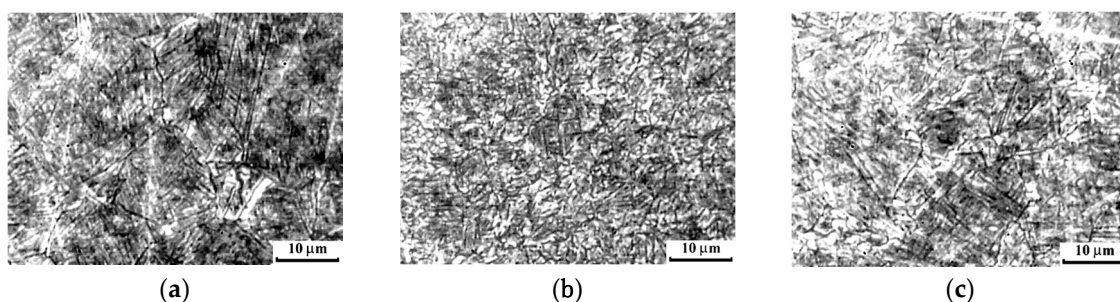


Figure 3. Microstructure of Ti-Al-Mo-V alloy in the initial state before radial forging: center of the workpiece (a), surface layer (b), transition layer (c).

Meanwhile, the average grain size of the α -phase near the surface is ~ 2.7 μm , which is almost five times lower than in the center, as seen in Figure 3 for initial state before radial forging. The finest grains attributed to the α -phase were detected in the 3-mm-thick surface layer. However, their size gradually increased while moving toward the center, attaining a value of ~ 16.5 μm , which is consistent with that for pristine workpieces. Hence, a pronounced difference in plasticity of samples cut off from the different parts of the alloy seems to be due to structural heterogeneity of Ti-Al-Mo-V, which persists under hot pressing of rods.

The microhardness of the alloy was measured in the indicated zones using a PMT-3M (Russia) hardness tester at a load of 1 N. In comparison with a central part of the sample, the microhardness near the surface is slightly reduced and continues to decrease from 1750 to 1690 MPa while going away from the center. The reason of such a change in structure and properties can be surface layer disordering caused by degassing of surface layers during processing.

3.2. Structure of Ti-Al-Mo-V Alloy after Radial Forging

Radial forging allows one to suppress porosity that is usually present in axial sections of rods obtained via hot pressing. According to the experimental data, the highest pore concentration was found in sample 1 ($\Phi 20$ mm) (see Figure 4). The pores at the central part of the sample form the axial porosity. The surface pores have the round shape. The pores at the workpiece outlet ($\Phi 20 \rightarrow \Phi 16$ mm) (sample 5) and at the inlet ($\Phi 16 \rightarrow \Phi 10$ mm) (sample 6) may form the small linear clusters. The smallest density and pore sizes were observed in sample 10 (with the outlet of $\Phi 16 \rightarrow \Phi 10$ mm). Figure 4 shows the presence of pores for the initial state (sample 1) and after radial forging (final state, sample 10).

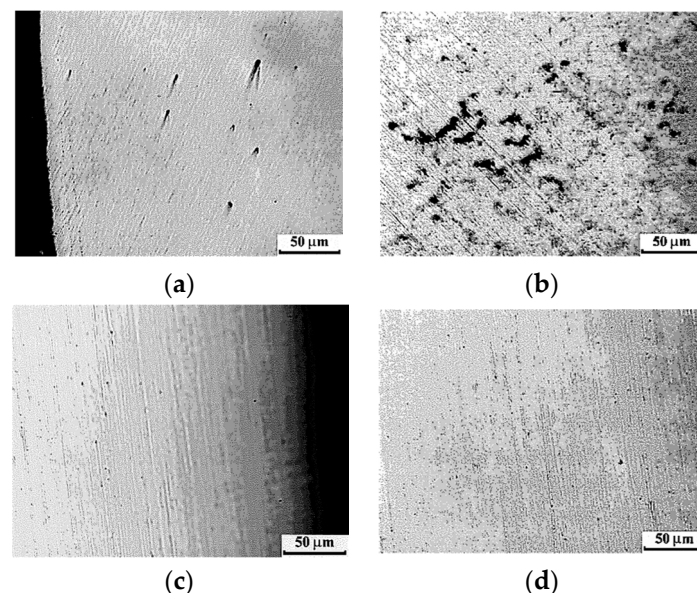


Figure 4. Microstructure of Ti-Al-Mo-V alloy in the initial state before radial forging—sample 1 (a,b) and after radial forging in sample 10 (c,d). From left to right: surface layer (a,b), center of the workpiece (b,d).

Table 4 presents data on the change in the parameters of the structure depending on the reduction.

Table 4. Porosity and grain size (in points) depending on the degree of reduction.

Ti-Al-Mo-V Sample No.	Pore Density, mm^{-2}		Maximum Pore Size, μm		Grain Score (in Points)	
	Center of the Workpiece	Surface Layer	Center of the Workpiece	Surface Layer	Center of the Workpiece	Surface Layer
1	771	325	18	3,5	6	4
3	542	274	9	3	5-4	3
5	362	244	2.5	3	4	3-2
7	297	202	2	2	3-2	2-1
8	183	149	1.5	1	2	1
10	102	98	<1	1	2	1

The metallographic data are illustrated in Figures 5 and 6 for subsequent $\Phi 20 \rightarrow \Phi 16$ mm and $\Phi 16 \rightarrow \Phi 10.5$ mm transitions. A comparative analysis of images reveals that noticeable structural changes at the deformation center of the workpiece during the $\Phi 20 \rightarrow \Phi 16$ mm transition are manifested by the grain refinement near the surface and close to the axis of the workpiece.

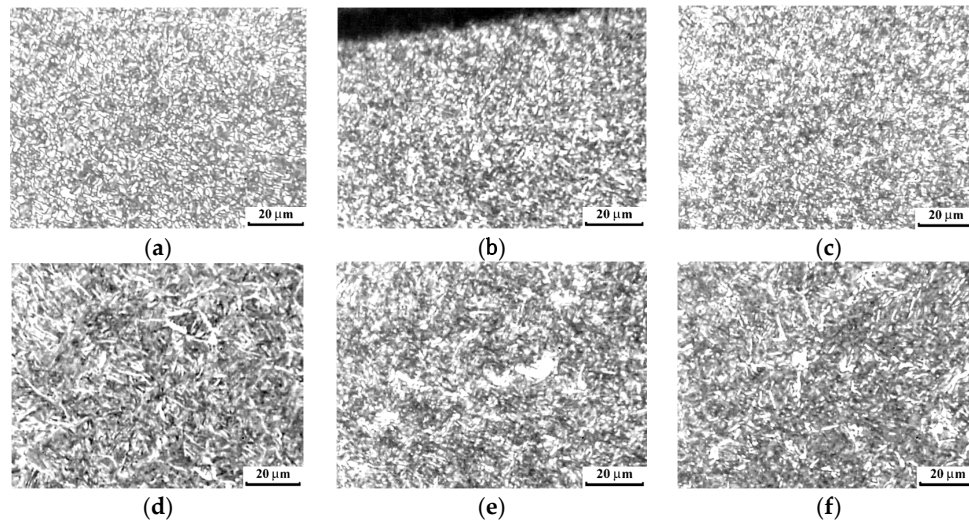


Figure 5. Microstructure of Ti-Al-Mo-V alloy at the $\Phi 20 \rightarrow \Phi 16$ mm transition. From left to right: samples 1, 3, and 5 (see Figure 1); (a–c) surface structure; (d–f) structure at the central part of the rod.

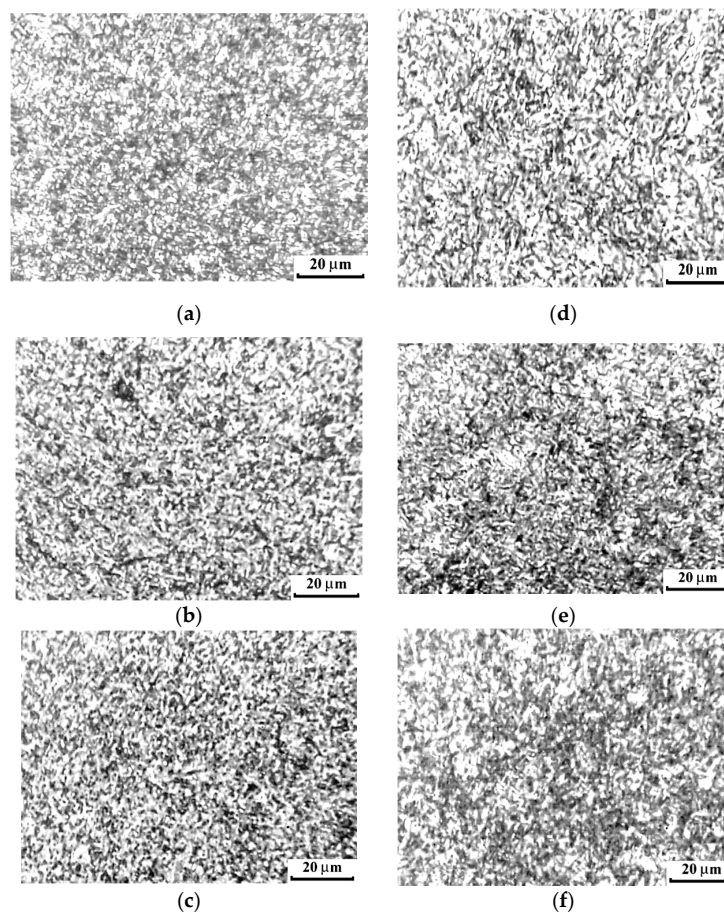


Figure 6. Microstructure of Ti-Al-Mo-V alloy at the $\Phi 16 \rightarrow \Phi 10$ mm transition. From top to bottom: samples 6, 8, and 10 (see Figure 1); (a–c) surface structure; (d–f) structure at the central part of the rod.

Meanwhile, the structural changes at the central part of the workpiece are less pronounced. At a small rod diameter during the $\Phi 20 \rightarrow \Phi 16$ mm transition it observes the drastic refinement of the structure and the variation in grain morphology. The structure near the rod surface is 80% globular. The average grain size at the axis of the workpiece is much greater and the amount of globular grains achieves a value of 50–60%. As follows from the metallographic study of samples cut off from the $\Phi 16 \rightarrow \Phi 10$ mm transition, the alloy structure at this stage of deformation gradually transforms from a duplex (globular-lamellar) state with a high degree of inhomogeneity (sample 6) to a more uniform globular (sample 10) state. However, there is still partial heterogeneity: while the surface of sample 10 exhibits the uniform and globular structure, the central part of the rod contains up to 25% lamellar grains, which results in a stronger structural heterogeneity. Nevertheless, the central porosity in samples obtained by radial forging is less pronounced in comparison with the porosity near the axis of hot-pressed Ti-Al-Mo-V rods. Figure 7 shows the porosity and grain score (in points) depending on the degree of reduction.

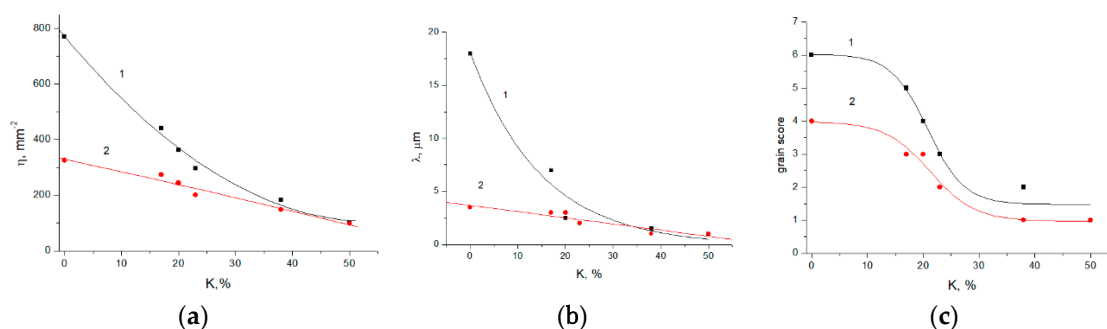


Figure 7. Changes in pore density (a), maximum pore size (b), and grain score (c) depending on the degree of reduction in radial forging: 1—center of the workpiece; 2—surface layer.

The results of transmission electron microscopy showed that in the initial state (sample 1) in the initially inhomogeneous microstructure, there is a deformation-induced bending of the alpha-plates and beta-interlayers, as well as the process of destruction of colonies of the alpha and beta phases with dispersion of the structure. Solid solutions disintegrate inside the structural elements. At a reduction of 20%, the mixture of alpha and beta phases occupies most of the near-surface layer. The average transverse dimension of the structural elements was $\sim 0.3 \mu\text{m}$. The microstructure formed after radial forging as a result of a strong deformation effect is noticeably dispersed, homogeneous, and is a mixture of alpha and beta phases with a size of $0.05\text{--}0.3 \mu\text{m}$.

3.3. X-ray Diffraction Analysis of Ti-Al-Mo-V Alloy

X-ray diffraction measurements of Ti-Al-Mo-V alloy were conducted on a sample with $\Phi 8.5$ mm, obtained from the rod exposed to hot pressing, as well as on sample 6 made by radial forging at a $\Phi 16 \rightarrow \Phi 10$ mm transition (see Figure 1). Figure 6 displays the X-ray diffractogram that is characteristic of a biphas alloy, as seen from the presence of reflexes from the coexisting hcp α -phase and bcc β -phase.

The X-ray diffractogram of sample 6 after radial forging at a $\Phi 16 \rightarrow \Phi 10.5$ mm transition (after the $\Phi 20 \rightarrow \Phi 16$ mm transition) is given in Figure 8. The observed pattern is strongly different from that for a hot-pressed sample. First of all, there are the differences between the intensities of the main peaks attributed to the α -phase and those associated with a quantity of the β -phase. Moreover, the (002) and (004) reflexes of the α -phase vanish, indicating the emergence of anisotropy in the properties along various crystallographic directions, which is due to the alloy processing.

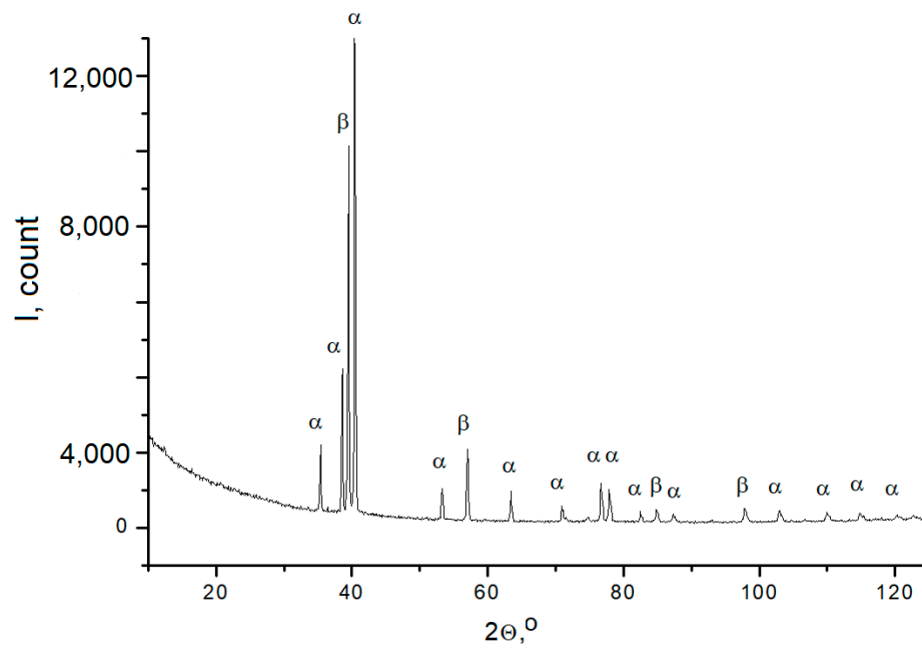


Figure 8. X-ray diffraction of a hot-pressed biphas Ti-Al-Mo-V alloy.

To confirm these changes, the X-ray diffractograms from Figures 8 and 9 were merged in Figure 10. One can see that $(002)_{\alpha}$ line is almost absent in the case of sample 6 after forging.

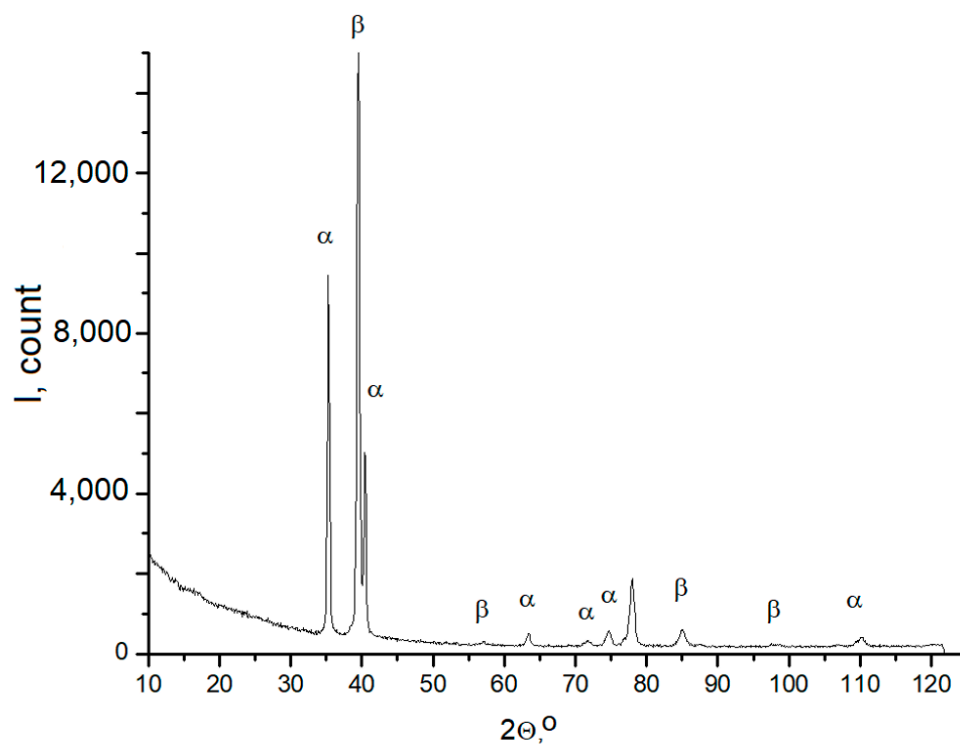


Figure 9. X-ray diffraction of sample 6 of Ti-Al-Mo-V alloy (see Figure 1).

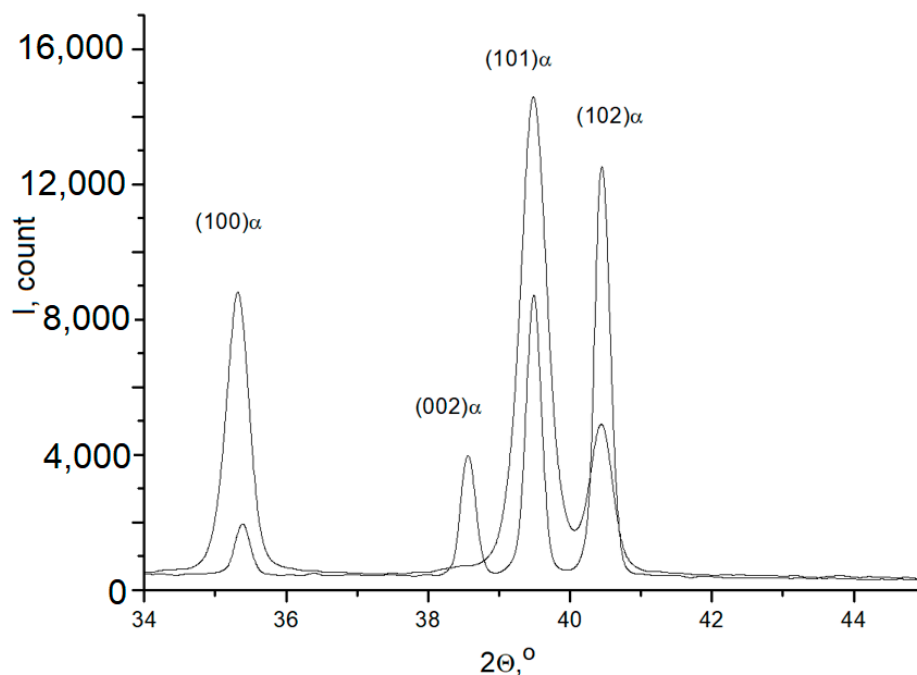


Figure 10. Merged X-ray diffractions from Figures 8 and 9.

4. Discussion

As established via X-ray diffraction with regard to the behavior of the fcc β -phase during radial forging, there was no decrease in its reflex intensity, but an increase for all samples. This evidences the absence of the $\beta \rightarrow \alpha$ transformation. The analysis of other XRD peaks reveals that some lines from the β -phase become larger during the processing and lose their intensity as compared with the initial state. This testifies to a decrease in crystallite size of the β -phase in the VT16 alloy undergoing plastic deformation during radial forging.

An important phenomenon that arises under severe plastic deformation in radial forging can be the $\beta \rightarrow \alpha''$ martensitic transformation, because, as found, there is a small amount of the martensitic α'' -phase in all samples. However, in the case of the initial state, there is also a high content of a stable α -phase. The amount of the α -phase is lower in forged samples, where the parent phase is a metastable α'' -phase. At the same time, the α -phase has a nonstoichiometric composition, as follows from its lattice parameter values. Moreover, it appears from the XRD data that the lattice parameters of the hcp α -phase of Ti-Al-Mo-V alloy are $a = b = 0.29487$ nm and $c = 0.46857$ nm, whereas the lattice parameter of a metastable β -phase of titanium (bcc) is $a = 0.3231$ nm [1,2].

The most significant change in the phase composition of the alloy caused by radial forging is the change in the volume fraction of the beta-phase shown in the Figure 11 during this process. It is calculated from the ratio of the experimentally determined intensities of the lines (102) of the alpha phase and (200) of the beta phase for various degrees of compression. As can be seen, at the beginning of radial forging with a reduction of up to 20% by volume, the bulk content of the beta phase remains at a level of $\sim 1/3$, and then the proportion of the beta phase decreases to $\sim 1/4$ at a final reduction of 50%. In the process of radial forging, there is a gradual change in the texture formed during hot pressing. With an increase in the degree of reduction, the ratio of the intensities of the diffraction maxima approaches the ratio for a fine-grained material after annealing.

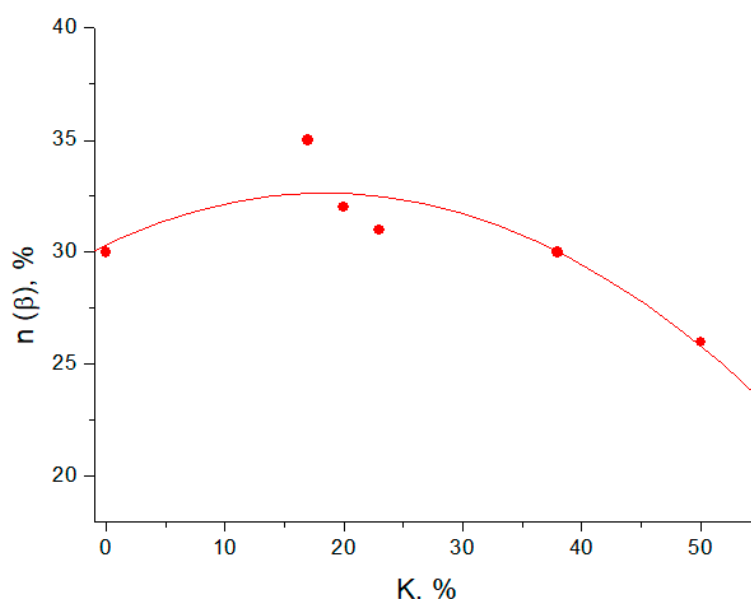


Figure 11. Change in the volume fraction of the beta phase depending on the degree of reduction in radial forging.

5. Conclusions

- Radial forging of Ti-3.3Al-5Mo-5V alloy workpieces leads to the structural refinement and the changes in grain morphology from predominately lamellar to uniform globular, as well as the variations in phase composition of the alloy and the suppression of powder formation.
- The methods of rod deformation and alignment of the RFM working tool, applied in this work, ensure fulfillment of technical requirements to geometrical sizes and surface quality.
- Radial forging is found to allow one to produce semiproducts from titanium-based Ti-Al-Mo-V alloys without using multiple mechanical processing of workpieces and rods.

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Conflicts of Interest: The authors declare no conflict of interest.

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