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Fabrication, Thermo-Mechanical Processing and Characterization of a Ti-6% Al-1.5% V-1.0 Mo-0.5% Zr-0.1% C Alloy with Addition of Ru and Modifications of Small Amounts of V and Mo

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ABSTRACT

Pseudo-α or near-α titanium alloys are being widely used in the power generation industry due to their stability at high temperature service, good mechanical characteristics and corrosion resistance. Particularly Ti-6% Al-1.5% V-1.0Mo-0.5% Zr-0.1% C alloy is mainly used in turbines components, heat exchangers and pipes for steam conduction, among others; these are subjected to critical conditions of temperature, abrasion and corrosive environments. A good performance of such devices depends on the chemistry and of the material processing story.

Effects on microstructure and wear resistance with the addition of Ru and small variation of V and Mo amounts in the Ti-6% Al-1.5% V-1.0Mo-0.5% Zr-0.1% C alloy were analyzed. Three different alloys were melted in a vacuum induction furnace with a cooled copper skull under an argon protective atmosphere for this study

Four alloys were melted "Alloy 1" Ti-6% Al-1.5% V-1.0Mo-0.5% Zr-0.1% C-0.3% Ru, "Alloy 2" Ti-6%Al-0.5%V-1.6%Mo-0.5%Zr-0.1% C-0.3% Ru, "Alloy 3" Ti-6%Al-2.2%V-0.5%Mo-0.5%Zr-0.1%C-0.3%Ru. After melting, all alloys were homogenized at 1200°C for two hours, followed by hot rolling above β transition temperature with a reduction of 50% in thickness.

All alloys were analyzed by using scanning electron microscopy (SEM) and Vickers Micro hardness (HV). Results shown that Mo and V variations modified the micro hardness by microstructure refinement. In contrast, the addition of Ru showed no microstructure modification.

INTRODUCTION

Pseudo-α titanium alloys have been successfully used in geothermal industry due to their adequate characteristics, such as, thermal stability, corrosion resistance and strength-weight ratio; however, part of the efficiency of titanium alloys depends on the microstructure developed during the thermomechanical processing stage. Also, it is well known that some elements have the ability to strengthen some phases, to suppress the formation of secondary phases and/or to refine microstructures [1]. Ti-6%Al-1.5%V-1.0%Mo-0.5%Zr-0.1%C is a weldable pseudo-α alloy, and it is mainly used in devices of steam transport units such as blades, rotor disks, complex castings structures, control systems and fasteners. This alloy has been extensively studied by mechanical means and corroborated by operating experience [2], but there is still lack of information concerning its thermomechanical treatment and the effect of some alloying elements, namely Mo, V and Ru in the mechanical properties.

Molybdenum is the principal β-stabilizer and it is well known that it is the principal hardener element in solid solution of titanium alloys [1]. Vanadium is also a β-stabilizer, and there is evidence that it could increase ductility [3]. Studies of minor additions of ruthenium have shown to increase corrosion protection, but this element also plays a role as a β stabilizer [4]. These three elements have in common the solubility in β phase, since Mo and V have opposite behavior in the mechanical properties, the content of these two elements could develop a more ductile or harder alloy in the integrated microstructure of the α+β alloy, additionally to the developed by the microstructure.

The chemical modification with the increment of molybdenum and reduction of vanadium is expected to increase the hardness, but microstructure is another factor in controlling mechanical properties, and it depends of the history of the thermomechanical process like, temperature, time, and grade of deformation

Therefore, the main goal of this work is to study the microstructural effects promoted by the variation of elements such as V and Mo under hot-rolled condition. For this purpose, it is important to take under consideration that Ti-6%Al-1.5%V-1.0%Mo-0.5%Zr-0.1%C alloy is a pseudo-α alloy; therefore, the chemical composition must be preserved to maintain this classification. Accordingly, the "Aluminum" and "Molybdenum" equivalents must be calculated to ensure that characteristics and mechanical properties of a pseudo-α titanium alloy prevail [5]; these are calculated by the following formulae:

$$[Al]_{eqv} = [Al] + \frac{[Sn]}{3} + \frac{[Zr]}{6} + 10\,[O_2] + 16.4\,[N_2] + 11.7\,[C] + 3.3\,[Si] \quad (1)$$

$$[Mo]_{eqv} = [Mo] + \frac{[V]}{1.5} + \frac{[Nb]}{3.6} + \frac{[Ta]}{5} + \frac{[W]}{2.5} + 1.25\,[Cr] + 2.5\,[Fe] + 1.7\,[Co] + 1.25\,[Ni] + 1.7\,[Mn] \quad (2)$$

Hardness is the principal parameter that modifies many mechanical properties like wear resistance, commonly the hardest the material the better the wear resistance [2]. The increase of hardness can be aimed by modifying microstructural parameters or by controlling solid solution of the elements in the matrix.

EXPERIMENTAL

Four titanium alloys were obtained, Ti-6Al-1.5V-1.0Mo-0.5Zr-0.1C (Alloy 1), Ti-6Al-1.5V-1.0Mo-0.5Zr-0.1C- 0.3Ru (Alloy 2), Ti-6Al-0.5V-1.6Mo-0.5Zr-0.1C-0.3Ru (Alloy 3), Ti-6Al-2.2V-0.5Mo-0.5Zr-0.1C- 0.3Ru (Alloy 4), (all contents in wt.%); all alloys were made from high purity elements, by the levitation melting method using a cold copper crucible (CCLM), under the protection of argon atmosphere. The ingots were re-melted four times and flipped in each step to improve homogeneity in their chemical composition.

A solubility heat treatment was carried out at 1200°C for 2 hours and cooled down in air, followed by hot rolling at 1200°C (within the β region to form a full lamellar structure) with a thickness reduction of 50% (fig. 1).

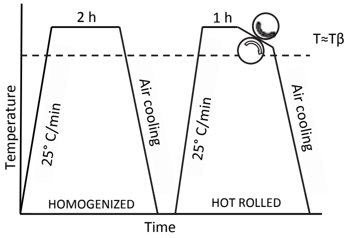

Fig. 1. Heat treatment arrangement.

Microstructural analysis

Samples were sectioned perpendicular and transversal to the rolling direction using a low speed thin abrasive saw with a coolant fluid to obtain the specimens. Samples were grinded and polished using standard metallographic procedures; samples were etched with Kroll´s solution (91 vol% H_2O, 3 vol% HF, 6 vol% HNO_3) for 15 seconds. Characterization was undertaken by Optical microscopy (OM) and Scanning electron microscopy (SEM, JEOL. JSM 7600F).

Vickers microhardness

Microhardness was measured by a micro-indentation test using 500g load for 15 s in a TIME, THV-1D equipment. Ten indentations were done on a polished surface sample of the four alloys fabricated in both conditions (homogenized and hot rolled). The average values of hardness are here reported.

RESULTS AND DISCUSSION

Chemical composition and XRD

The chemical compositions of the alloys were determined in an X-ray fluorescence equipment (Bruker Tiger S8); results are listed in table I

Table I. Chemical composition of titanium alloys, determined via X-ray fluorescence.

	Ti %wt	Al %wt	V %wt	Mo %wt	Zr %wt	C %wt	Ru %wt	Fe %wt	$[Al]_{eqv}$	$[Mo]_{eqv}$
Reference	90.90	6.00	1.50	1.00	0.50	0.1	0.00	0.00	**7.25**	**2.00**
Alloy1	89.20	6.44	1.96	1.12	0.52	-	0.00	0.17	**7.70**	**2.85**
Alloy 2	89.10	6.35	2.02	1.08	0.52	-	0.29	0.19	**7.61**	**2.90**
Alloy 3	89.80	6.21	1.01	1.83	0.52	-	0.25	0.15	**7.47**	**2.88**
Alloy 4	88.50	6.27	2.71	0.57	0.51	-	0.34	0.21	**7.53**	**2.90**

As shown in ref [5] all the obtained alloys have an “Aluminum” and “Molybdenum” equivalent into the range of a pseudo-α alloy; carbon cannot be detected whit this technique.

Microstructural analysis

Some microstructural features were measured using optical micrographs (fig. 2 a and b), β grains were equiaxed at the homogenization stage with different diameter size for each alloy (see Table II). Grain growth depends on the cooling rate and the elements that act as nucleating agents; the four alloys were cooled down at the same rate and under the same conditions, leading to the same composition and nucleating speed. All four alloys had a mix of primary plates which are thicker than secondary ones (fig.2b). At the beginning of the cooling stage, primary α plates precipitate into the β grains, and as the temperature is decreasing, a secondary set of α plates precipitate between the primary α plates. Alloy 2 showed the less homogeneous plate thickness and a microstructure with sizes from 4μm to 15 μm, with discontinuous primary plates. A similar microstructure was observed for Alloy 4. All alloys showed α grains boundary with similar size of primary plate.

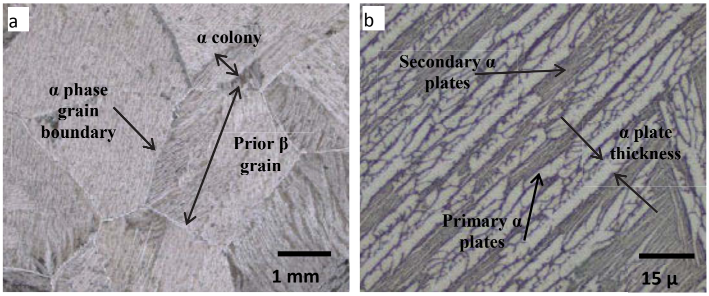

Fig. 2. Lamellar microstructure of the fabricated titanium alloys and its microstructural parameters at homogenized stage (a) Alloy 1 at 50X (b) Alloy 1 at 1000X.

After hot rolling, a finer microstructure, known as basket-wave or widmanstätten shape, was developed (fig. 3 a and b) [7]; the refinement of the microstructure is a typical behavior of a hot deformed titanium alloy processed within the β field by recrystallization [1,6], as mention before, microstructure is the principal parameter controlling mechanical properties, and refinement of microstructure is expected to increase hardness by remarkable interfacial-strengthening effect since grain boundaries act as strong obstacles, but a widmanstätten fine microstructure has different mechanical behavior, this microstructure is desirable to enhance creep resistance notoriously, fine microstructures increase the strength as well as the ductility, since hcp lattice of α phase is harder to deform than bcc β titanium due to the number of slip systems, α phase is surrounded by a larger amount of β phase due to the refinement microstructure, so β phase is easier to deform under micro hardness test.

Former β grains were elongated in the rolling direction showing a similar size increase in all four alloys, with an average of 2.2 ± 0.3 mm in the cross section and 4.5 ± 0.4 mm in the longitudinal section. The finest microstructure after hot rolling was observed for the Alloy 3 with an average α plate thickness of 0.9 ± 0.02 µm. On the other hand, the coarser microstructure was observed for the alloy 2; this feature remained even during the homogenization stage. With the refinement of the microstructure, the grain boundaries seemed to disappear (fig. 3 a). The microstructural parameters of all four alloys are shown in table II.

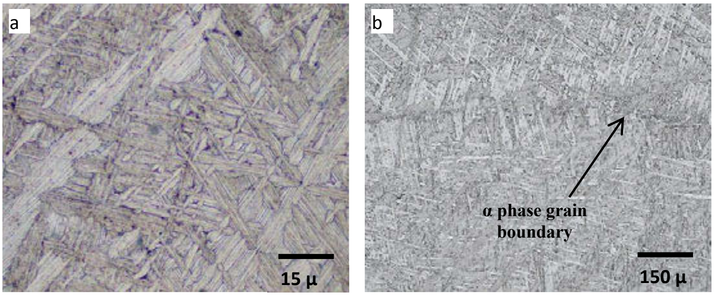

Fig. 3. basket-wave microstructure of the fabricated titanium alloys after hot rolled treatment (a) Alloy 1 at 1000X (b) Alloy 1 at 100X.

Table II Microstructural parameters of the four alloys fabricated in homogenized and hot rolled condition

Specimen	Prior β grain size (mm) Homogenized condition	α plate thickness (µm) Homogenized condition	α plate thickness (µm) Hot rolled condition
Alloy 1	1.45 ± 0.3	3.54 ± 1.1	1.1 ± 0.23
Alloy 2	1.4 ± 0.3	15.20 ± 5.1	1.4 ± 0.03
Alloy 3	2.1 ± 0.6	4.02 ± 0.9	0.9 ± 0.02
Alloy 4	1.2 ± 0.2	7.42 ± 4.2	1.3 ± 0.25

The hot rolling within the β field allows a fully plastic deformation; this means that no residual stresses remain in the microstructure, and nucleating elements get more distributed refining the microstructure when alpha precipitates.

Micro-hardness analysis

Figure 4 shows the micro-indentations marks in the four alloys ((a),(c),(e) and (g) in the homogenized condition, and (b),(d),(f) and (h) in the hot rolled condition. From these images, it is easy to note the microstructural size and refinement after the hot rolling explained above. Microhardness results are shown in Fig. 5 and values are shown in table III.

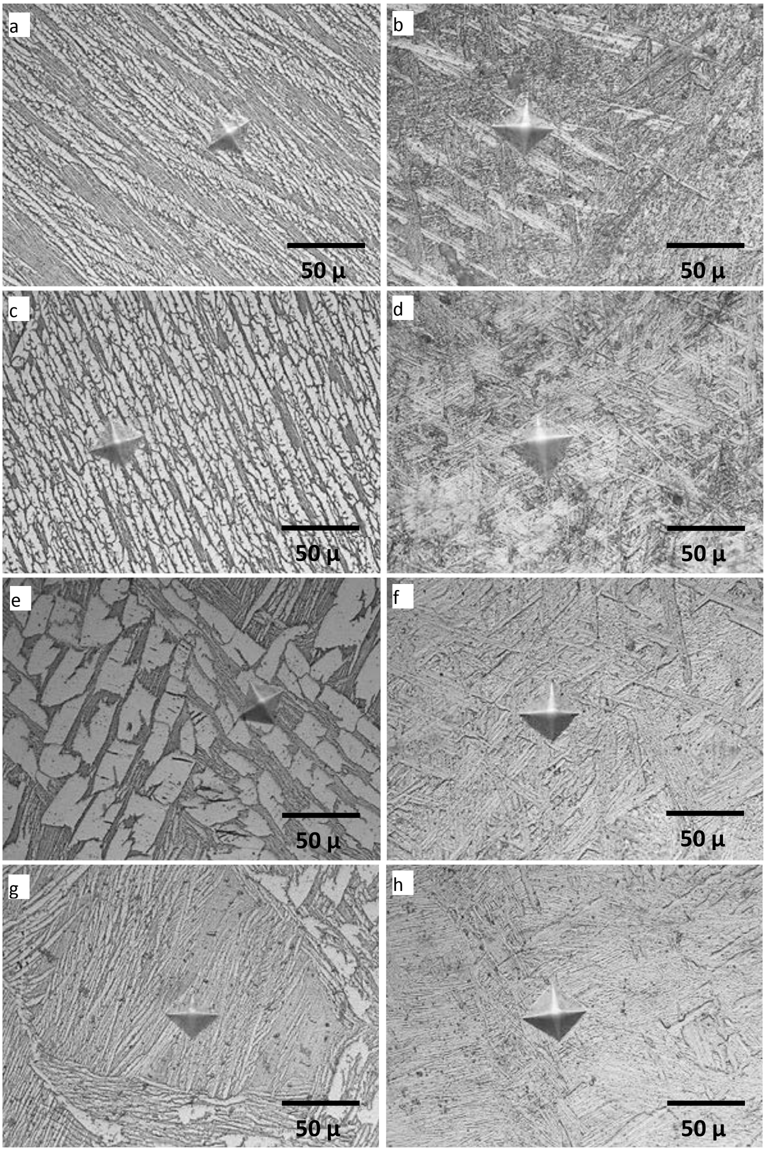

Fig. 4. OM of microhardness indentations in the four alloys fabricated (Alloy 1 (a), Alloy 2 (c), Alloy 3 (e) and Alloy 4 (g) in homogenized condition) and (Alloy 1 (b), Alloy 2 (d), Alloy 3 (f) and Alloy 4 (h) in hot rolled condition).

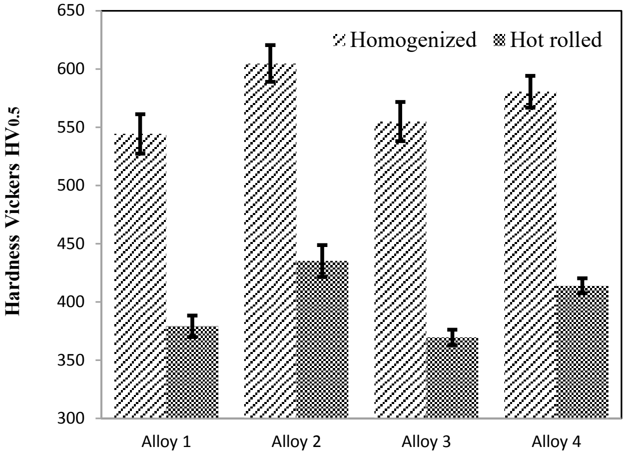

Fig. 5. Hardness Vickers values for four alloys fabricated in homogenized and hot rolled condition.

Correlation graphs show that the hardness behavior is directly related to the α plate thickness (fig. 6). A sample with coarse microstructure has higher hardness values than a sample with a finer microstructure. It has been also observed that a finer microstructure in titanium alloys show a higher ductility values; therefore, it can be concluded that the decrease in the hardness via microstructure is due to the microstructural refinement [1].

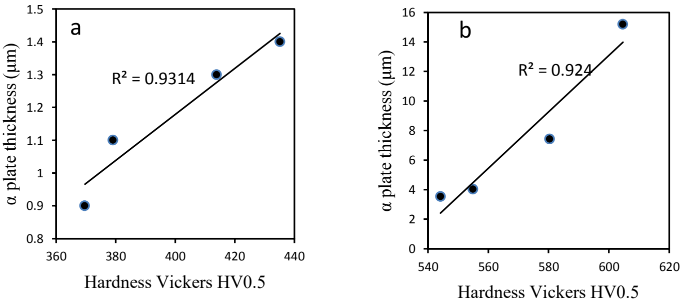

Fig. 6. Correlation graphs, Hardness Vickers vs α plate thickness for four alloys fabricated in homogenized (a) and hot rolled condition (b).

Table III Mechanical properties of the four alloys in hot rolled condition.

Specimen	H, $HV_{0.5}$ (homogenized)	H, $HV_{0.5}$ (hot rolled)
Alloy 1	544.2 ± 16.9	379.11 ± 9.3
Alloy 2	604.7 ± 15.8	435.21 ± 13.7
Alloy 3	554.9 ± 16.7	369.61 ± 6.7
Alloy 4	580.4 ± 13.5	413.90 ± 6.5

CONCLUSIONS

1.- The two alloys with the lowest percentages of Mo and high percentages of V produced thicker α primary plates regarding to the secondary ones leading to a harder microstructure.

2.- Hardness were reduced in a similar proportion in all alloys after the hot rolled treatment.

3.- Ru seems to have no influence in the microstructure in both thermal treatments.

4.- Hardness behavior has been proved to be directly proportional to α plate thickness due to the soft β phase surrounded the α plates.

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