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Research Article

Modification of the Mechanical Properties of Ti-Al-V Alloys with Variation of Aluminum

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Abstract: In this study, the development of ternary alloys of titanium, $Ti_{91}Al_5V_4$, $Ti_{90.5}Al_{5.5}V_4$ and $Ti_{89.5}Al_{6.5}V_4$ by Vacuum Arc melting technique was carried out. It was followed by Homogenization in three zone furnace for 16 hours and solution treatment at 1000°C followed by water cooling. Aging treatment at 500°C followed by furnace cooling was carried out and effects of aluminum contents on mechanical properties of Ti-Al-V system were studied. The solution treatments at temperature 1000°C followed by water cooling led to the formation of α′ martensite. Microstructures analyzed in the results confirmed the presence of major alpha Ti and very minute beta-Ti phase. X-Ray Diffraction confirmed the HCP(hexagonal close packed) structure for alpha-Ti phase as the highest peak and BCC (body centered cubic) structure for β titanium as very minor peak. An increasing trend of all mechanical properties (yield strength, tensile strength, toughness, ductility) was found with increase in aluminum content.

Keywords: Microstructure, microscopy, X-ray diffraction

1. INTRODUCTION

Titanium is low density metal as compared to steel and other structural elements and it has very good corrosion resistance and high temperature properties. Due to such properties its different alloys are commonly used in aerospace, automotive, marine, chemical industry, biomedical implants and sports equipments [1]. The mechanical properties and microstructure of titanium alloys are strongly dependent on processing history and heat treatment [2, 3, 4, 5].

In pure titanium, the alpha phase shows HCP crystalline structure while beta phase in pure titanium shows BCC structure. Alpha phase is stable up to 882 ^{o}Cand the beta phase is stable from 882 ^{o}C to the melting point of approximate 1688 ^{o}C [3]. The alloys belonging to the α+β system contain one or more alpha stabilizing or alpha soluble elements together with one or more β stabilizing element. At room temperature equilibrium these alloys usually support a mixture of α and β phases, to an extent depending on the amount and type of β stabilizing elements [2, 3].

One of the most commonly used titanium alloys, which has the greatest commercial importance in the various industries and applications and is being responsible for more than 50% of titanium output in the world, is an alpha-beta type, with 6wt% aluminum stabilizing the α phase and 4wt% vanadium stabilizing the β phase, forming Ti-6Al-4V [7,8]. The most commonly used alloy is Grade 5, Ti6Al4V which covers 80% of aerospace industry. This alloy has wide range of applications in aerospace as well as in marine. This alloy has dual phase structure α +β. The microstructure of Ti-6Al-4V has various types and depends on the cooling rate from the β phase field, prior heat treatment and the chemistry [9, 10, 11]. The properties of α+β alloys can be controlled by heat treatment, which is used to adjust the micro structural and precipitation states of the β component. This leads to the advantage that components with a wider range of mechanical properties can be produced. α+β alloys generally exhibit good fabricability, high room temperature strength and moderate elevated temperature strength [4, 5].

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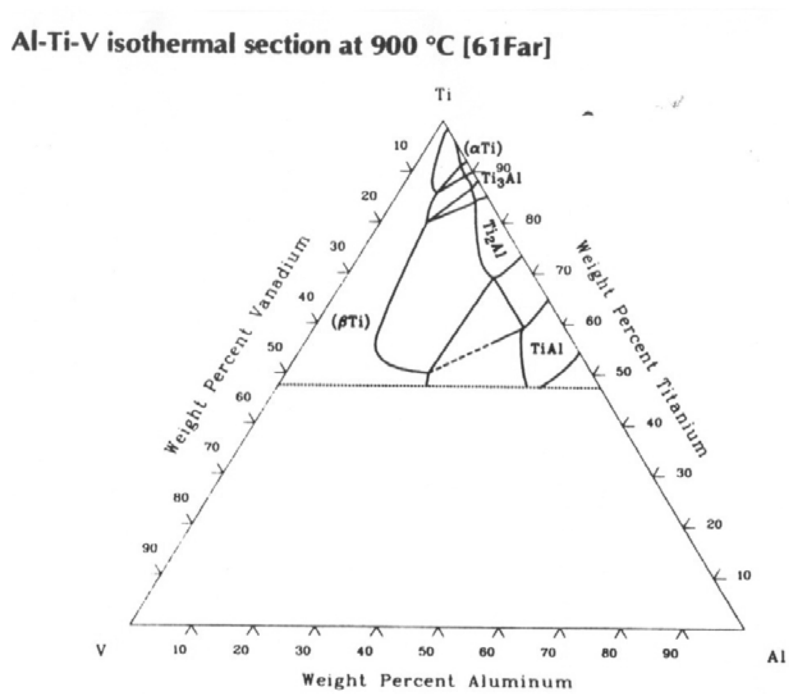


Fig. 1. Al-Ti-V ternary phase diagram.

Ternary diagram of Ti6Al4V is shown above in the Fig. 1 [6]. Individual phases can be clearly identified in the diagram.

In this study, ternary alloys of titanium, aluminium and vanadium were developed with varying wt% content of Al (5%, 5.5%, 6.5% respectively). After development, micro structural and mechanical properties were evaluated of as cast and heat treated specimens. Solution treatment and aging treatment were given to the developed alloys for comparative study of as cast and heat treated specimens. X-Ray Diffraction was performed for phase identification. Then comparison was made between as cast and heat treated specimens.

2. MATERIALS AND METHODS

The experimental work include the procedures of fabrication, sample preparation and characterization techniques.

2.1. Materials

Titanium, aluminium and vanadium were used to develop the ternary alloys of varying compositions. Purity of all three metals used was 99.99%.

2.2. Fabrication

Three alloys of titanium and vanadium with varying wt% contents of alminium were fabricated. Melting was done in vacuum arc melter that was provided with water cooled copper hearth. The melter was evacuated to attain a vacuum of 10^{-5} mbar and flushed with high purity argon several times to ensure oxidation free melts. Each alloy having different composition was kept in molten state for 4 minutes, then allowed to solidify, overturned and re-melted 3 times to ensure the homogeneity. Alloy buttons of different compositions weighing 10 g each were prepared. Weight losses during melting were found to be 1% which lies within the limits of the equipment.

2.3. Homogenization

After melting homogenization was carried out on samples to ensure the mixing of each component element thoroughly. The alloy samples were subjected to homogenization in Nobertherm Three Zone furnace at 800 °C temperature for 16 hours in vacuum environment then were subsequently furnace cooled. Three zone furnace model was RS 50/500/13 and temperature range was 1100 °C or 1300 °C.

2.4. Heat Treatment

The homogenized samples were solution treated at 1000°C followed by water quenching. Then the alloys were aged at 500 °C for 4 hours and were cooled in the furnace.

2.5. Metallography

In mounting, the specimen was surrounded by Bakelite which was melted under the temperature range of about 140 °C to 150 °C, pressure of 4200 psi was also applied by a piston. The whole process was carried out in a mounting machine Leco PR-25 and it was completed in 8 minutes. Grinding of samples was carried out using Emery papers of grade 60, 180, 240, 320, 600, 800, 1200 micron. During the process the specimen was rotated at 90 degrees and continuously grinded before changing the direction until all the scratches from the previous grinding direction were removed and then were washed before moving to next paper. Polishing was done by using MECAPOL P260 polishing machine. It began with the 6 micron disc, speed of disc was kept at 450 rpm and samples were held for about 15 minutes on it. Then samples were successively held on 1 micron disc until all the scratches were removed. The etching was done using 10 mL tap water, 1-3 mL hydrofluoric acid, 2-6 mL of nitric acid. Etchant was poured on samples and held for less than a minute.

2.6. Microscopy

Leco™ LX31 Inverted Metallurgical optical Microscope was used to investigate the microstructure. Micrographs were attained on 100X, 200X and 500X magnifications by inclusion-32 software.

2.7. X-ray Diffraction

X-ray diffraction techniques identify the phases present in sample and the physical state of the sample, such as grain size, texture and crystal structure. X-ray diffraction of Ti-6Al-4V samples was carried out by using Burker D-8 equipped with monochromatic Cu k-α radiation having wavelength of 1.54060 Å. JPDS cards were used to interpret the diffraction patterns.

2.8. Mechanical Testing

Hardness and tensile testings were carried out to determine the fitness of the material for a given application. Hardness testing was performed on Rockwell hardness Tester at C scale and the applied load was 150kg. Diamond cone indenter was used for indentation.

Hot rolling was done to make samples for tensile test and XRD. Hot rolling was performed in a manually fed rolling mill. First samples were heated in a Muffle furnace at 800°C and then were passed through the rolls. It was repeated until we got 1mm thickness for tensile samples and 0.5 mm for XRD. The rolling machine was electrically driven.

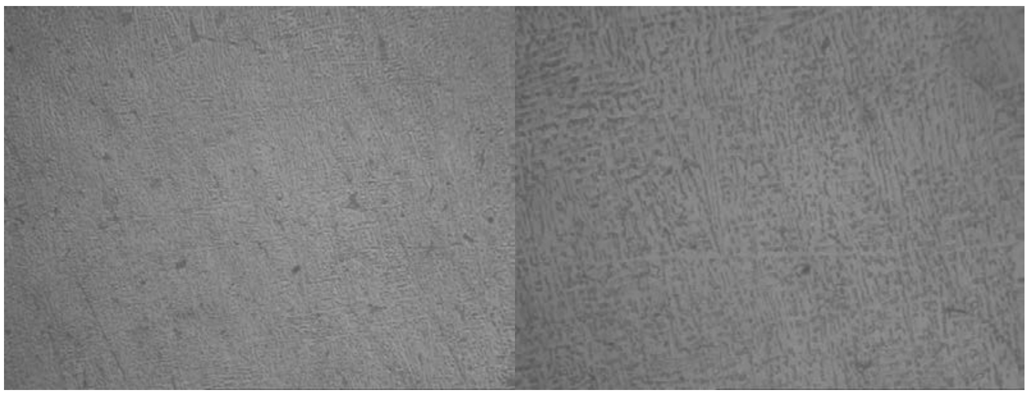
Samples were tested on the machine of universal testing machine the company and the model number of the machine was SHIMADZU AG-IS. Tensile testing was done to determine the mechanical properties of alloys. The samples which are used for tensile testing have 20 mm length, 1 mm thickness and 5-6 mm width.

3. RESULTS AND DISCUSSION

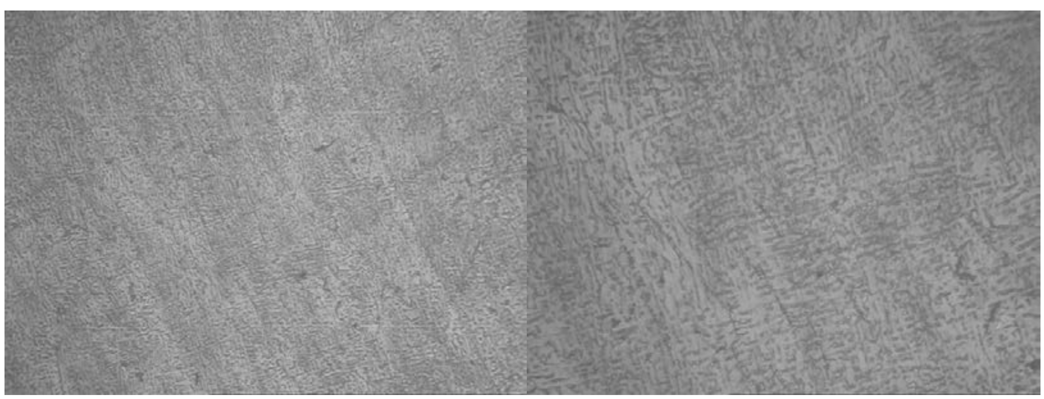
3.1. Microstructures

The microstructures of the cast $Ti_{91}Al_5V_4$, $Ti_{90.5}Al_{5.5}V_4$ and $Ti_{89.5}Al_{6.5}V_4$ alloys are shown in Fig. 2(a, b), (c, d) and (e, f) respectively showing the dual phase microstructure consisting of major α and minor β solid solutions, the α phase is lighter as compared to thin areas of the β phase that is darker in color and then compared with PINKE P., RÉGER M.: Heat treatment of the Casted Ti6Al4V Titanium Alloy. Materials Science and Technology, Vol. 5, 2005. Seong-Tak Oh et al. [11] presented similar results.

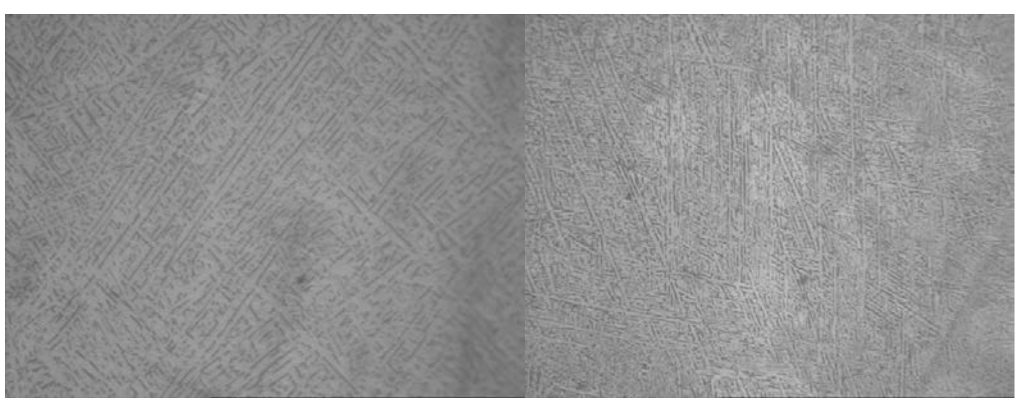
In all the microstructures, β phase is so small that it has not profound effect on overall microstructures of the alloys. All the micro structural results are in good agreement with the standard ternary diagram of Ti-Al-V given in the introduction of the current paper (Fig. 1). The composition of the discussed alloys lies on the upper most central region of the referenced diagram that contains α phase. The discussed alloys also have the α phase as the major phase and the β phase in very small quantity that has not so much effect on the overall micro structures.



(a) 200X (b)500X



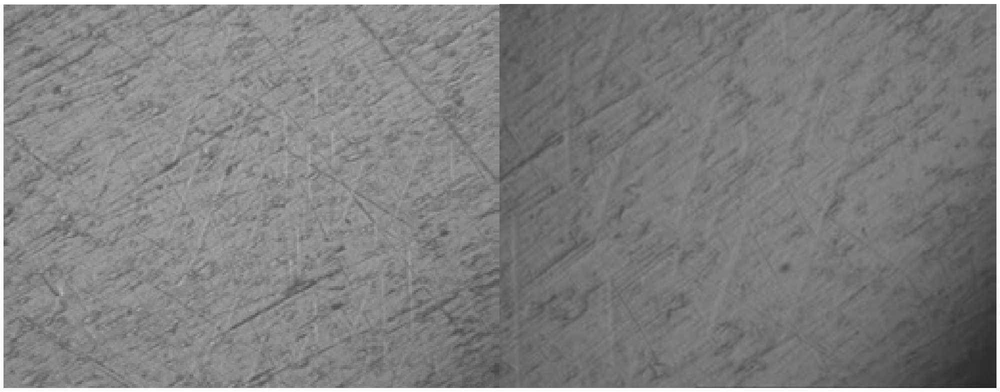
(c) 200X (d) 500X



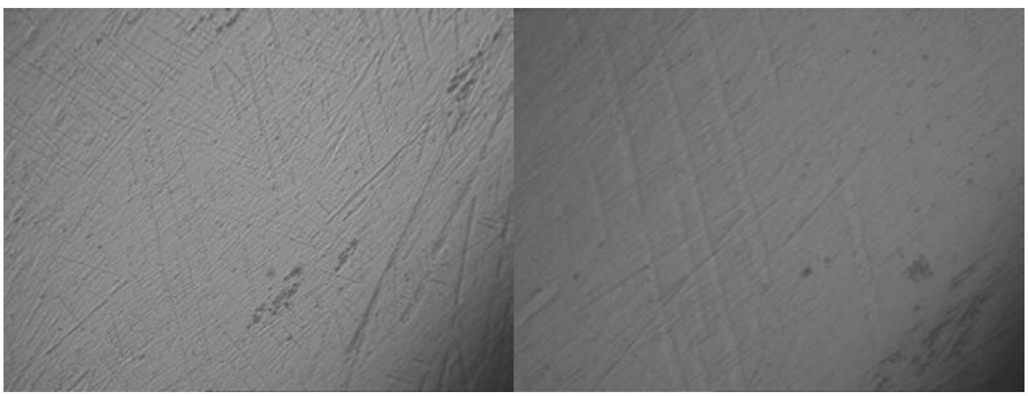
(e) 200X (f) 500X

Fig. 2. The microstructure of as cast $Ti_{91}Al_5V_4$(a, b), $Ti_{90.5}Al_{5.5}V_4$ (c, d), and $Ti_{89.5}Al_{6.5}V_4$ (e, f).

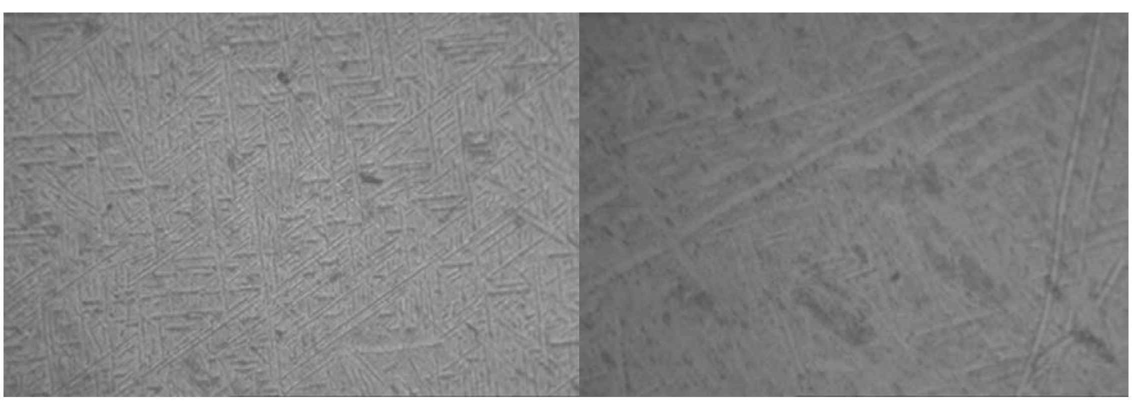
The microstructures of solution treated samples of the alloys $Ti_{91}Al_5V_{4,}$ $Ti_{90.5}Al_{5.5}V_4$ and $Ti_{89.5}Al_{6.5}V_4$ are shown in Fig. 3: (a, b), (c, d) and (e, f). Water quenching of these alloys from 1000°C resulted in a microstructure composed of two phases, acicular α′ martensite and primary α phase (Ti rich phase). The primary α phase did not dissolve in β phase at 1000°C. This is due to the fact that α + β → β transformation takes place at a temperature > 1000°C as reported by DONACHIE M. J., Jr.In: Titanium: A technical guide, ASM International, Metals Park, OH, 1988.



(a) 200X (b) 500X



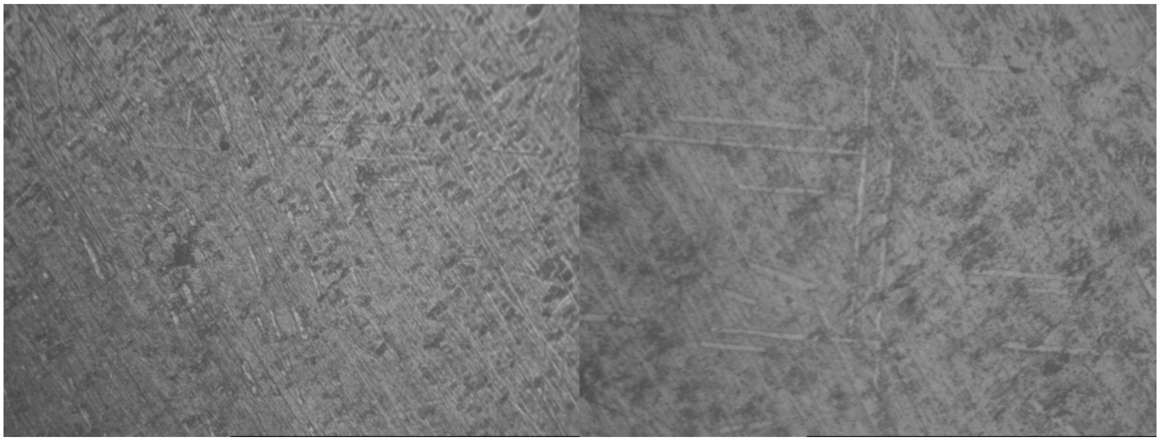
(c) 200X (d) 500X



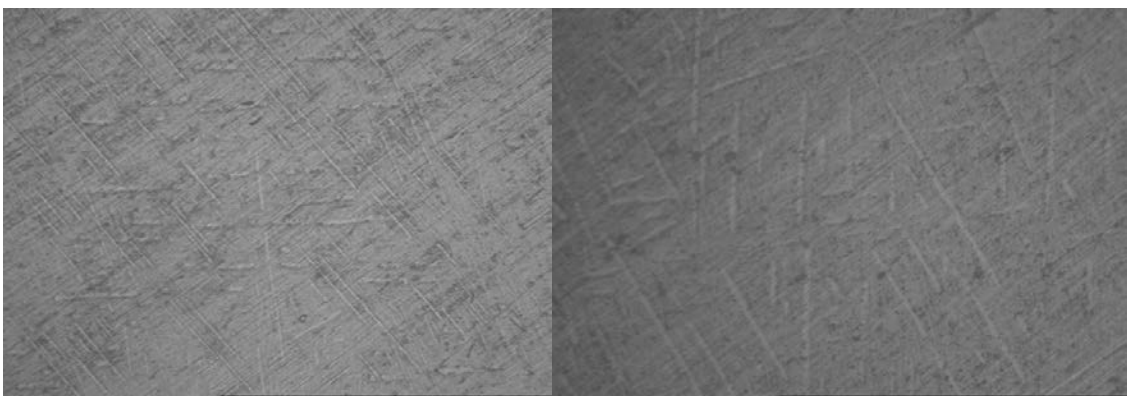
(e) 200X (f) 500X

Fig. 3. The microstructure of solution treated $Ti_{91}Al_5V_4$ (a, b), $Ti_{90.5}Al_{5.5}V_4$ (c, d) and $Ti_{89.5}Al_{6.5}V_4$ (e, f).

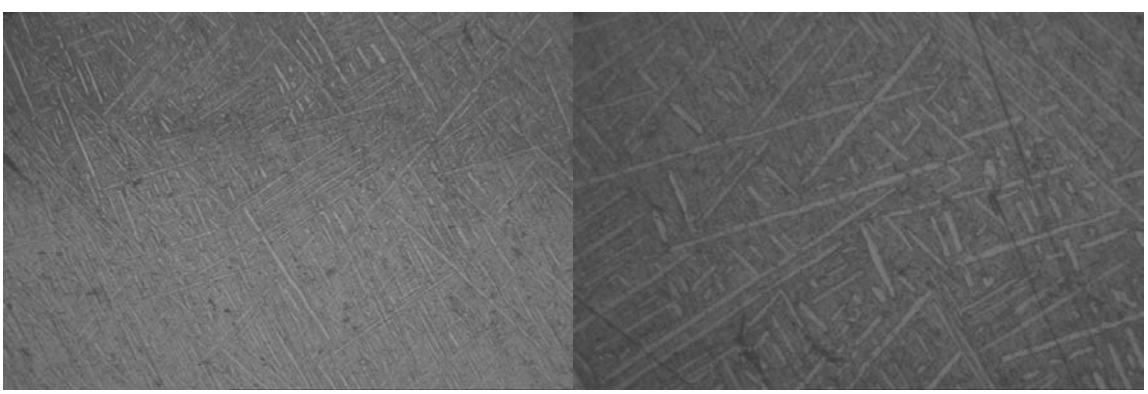
Aging treatment of 4 hours at 500°C was carried out after each solution treatment process followed by furnace cooling. The microstructure that formed after solution treatment remained unchanged even after this ageing treatment shown in Fig. 4(a, b), (c, d) and (e, f).



(a)200X (b) 500X



(c) 200X (d) 500X



(e) 200X (f) 500X

Fig. 4. The microstructures of aged $Ti_{91}Al_5V_4$ (a, b), $Ti_{90.5}Al_{5.5}V_4$ (c, d) and $Ti_{89.5}Al_{6.5}V_4$ (e, f).

3.2. Hardness

Hardness testing was carried out to investigate the effects of the applied heat treatment processes on the mechanical properties of the specimens and compared with DONACHIE M. J., Jr. In: Titanium: A technical guide, ASM International, Metals Park, OH, 1988.

Table 1. Comparison of hardness values in HRC scale.

Compound	$Ti_{91}Al_5V_4$	$Ti_{90.5}Al_{5.5}V_4$	$Ti_{89.5}Al_{6.5}V_4$
As cast	30.22	33.74	33.81
Solution Treated	37.22	40.28	40.30
Aged	39.28	40.27	40.31

Hradness values of all three compositions in as cast, solution treated and aged conditions are tabulated in the above table. An increasing trend of hardness values was recorded in all three compositions in all three states. With the increase in aluminum content, hardness of the specimens was found to increase. Similarly hardness values in solution treated state were found to be higher than in as cast state. In the same way hardness values in aged state were on higher side than in solution treated state.

After quenching of solution treated samples from 1000 °C, an obvious change in microstructures was observed. Rapid cooling from 1000 °C led to the formation of acicular α′ martensite that was the main reason for increase in hardness. In the aged state, the martensite structure became more prominent that's why hardness increased to some more extent.

A comparison of Rockwell Hardness values of as cast, solution treated and aged samples was made and is shown in Fig. 5. The hardness values of this work is comparable with the values shown in B. Baufeld and O. Biest // Science and Technology of Advanced Materials 10 (2009).

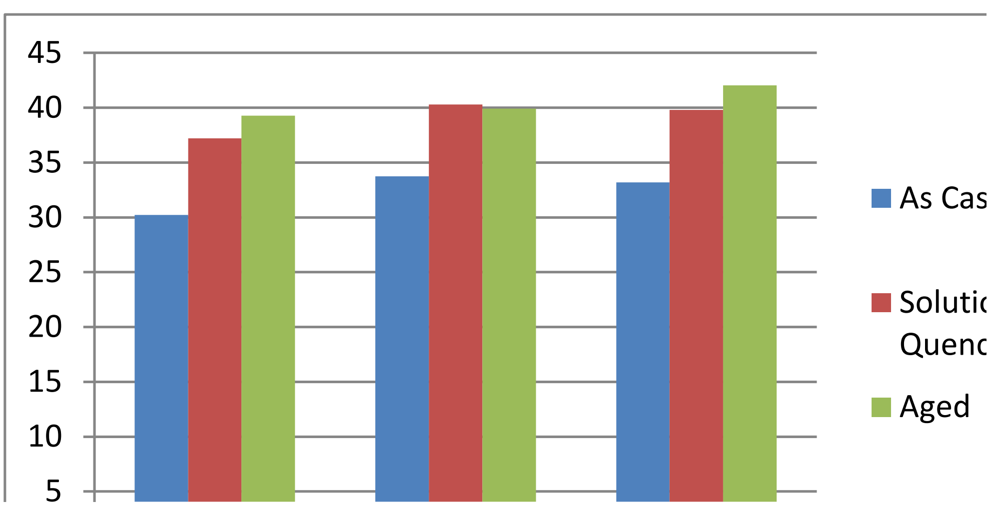


Fig. 5. Comparison of hardness in HRC scale.

3.3 TENSILE TESTING

3.3.1. $Ti_{91}Al_5V_4$

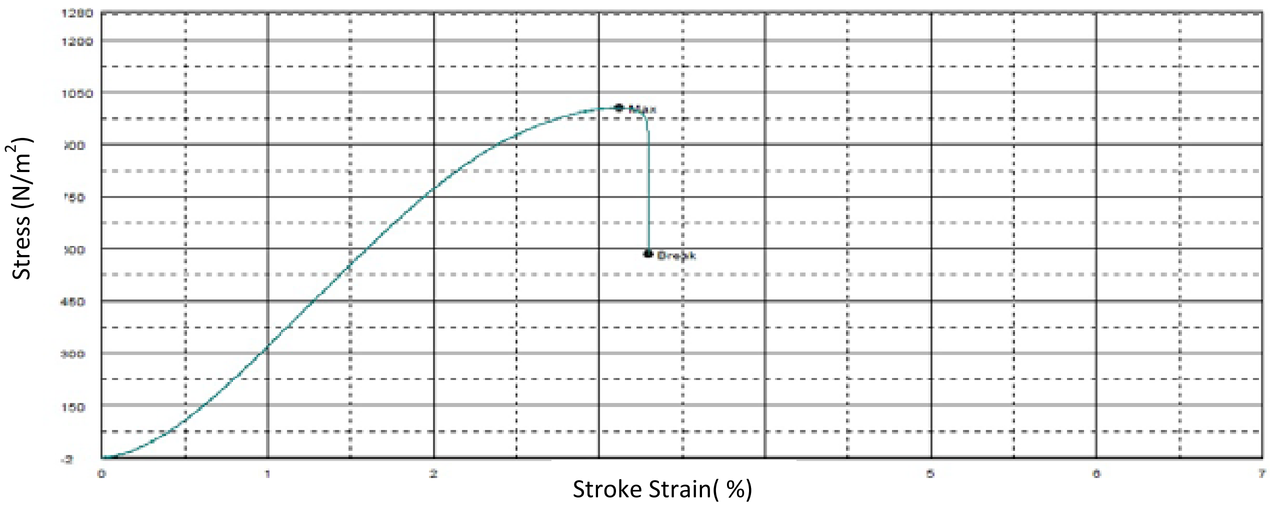


Fig. 6 (a). Tensile testing graph for$Ti_{91}Al_5V_4$.

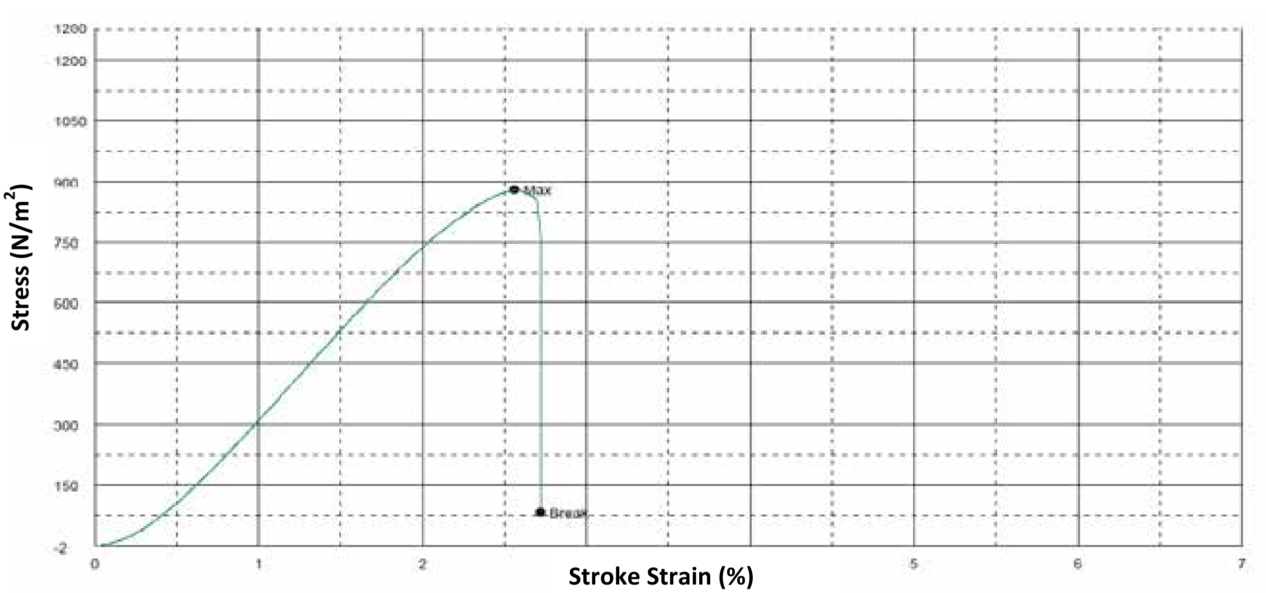


Fig. 6 (b). Tensile testing graph for $Ti_{91}Al_5V_4$.

The tensile testing was done on samples and the results of testing is shown in Table 2.

3.3.2. $Ti_{90.5}Al_{5.5}V_4$

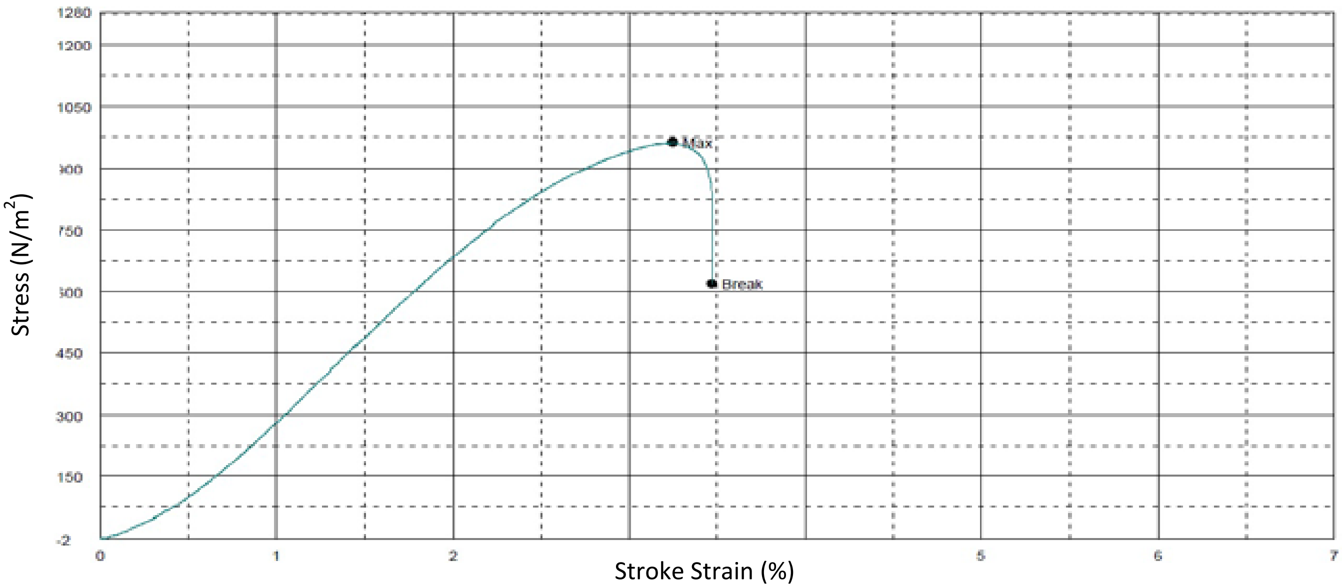


Fig. 7(a). Tensile testing graph for $Ti_{90.5}Al_{5.5}V_4$.

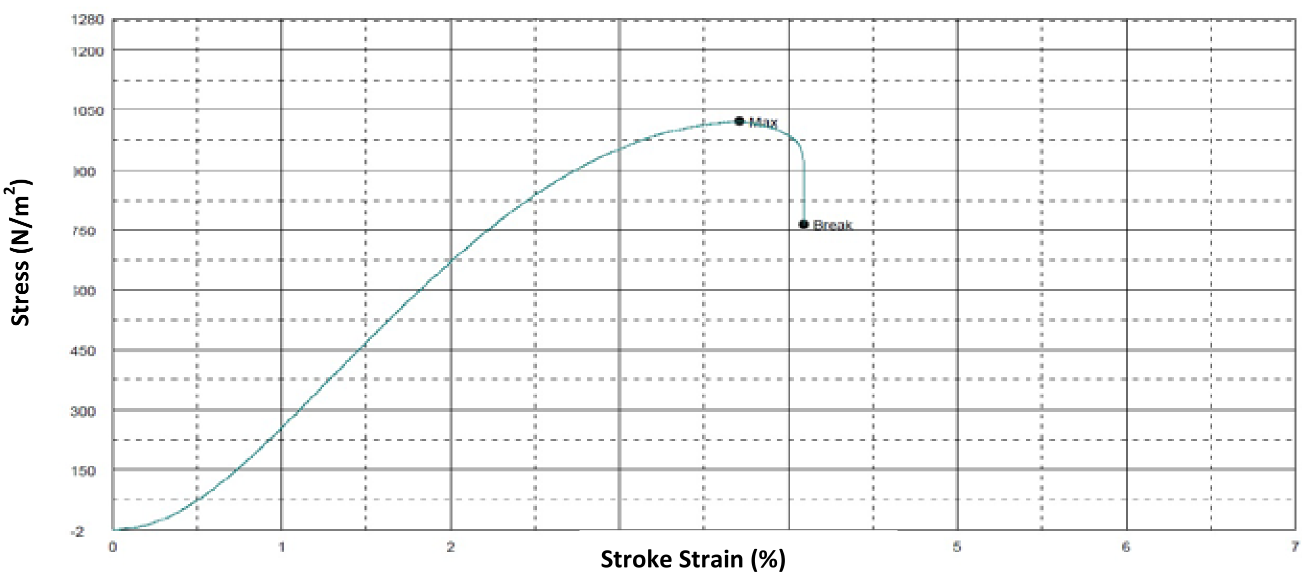


Fig. 7(b). Tensile testing graph for $Ti_{90.5}Al_{5.5}V_4$.

The tensile testing was done on samples and the results of testing are shown in the Table 2.

3.3.3. $Ti_{89.5}Al_{6.5}V_4$

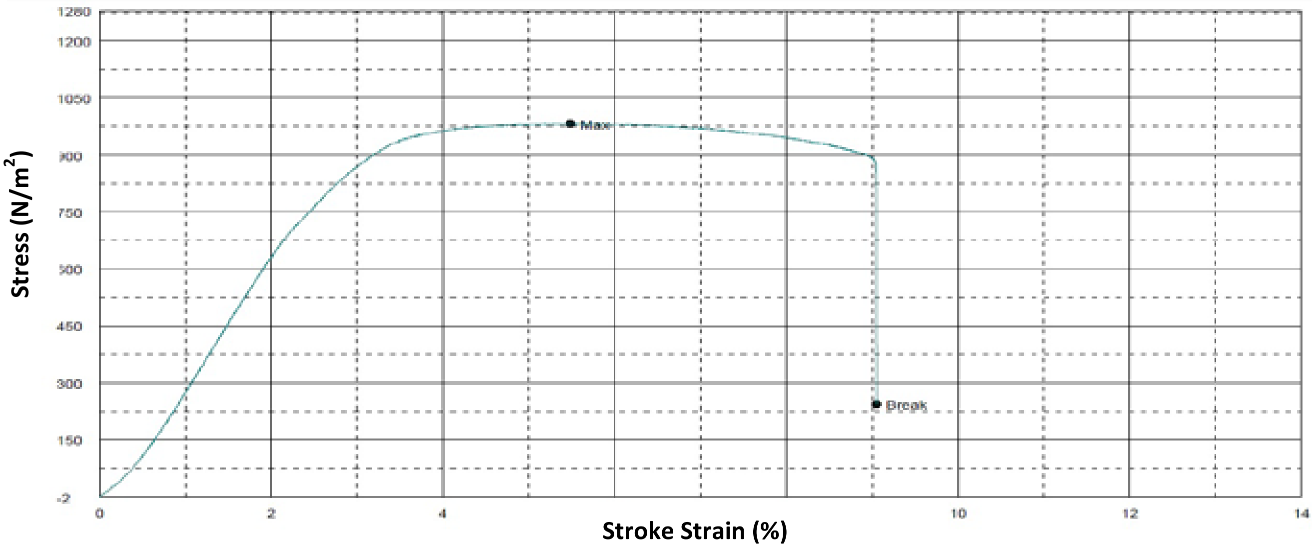


Fig. 8 (a). Tensile testing graph for $Ti_{89.5}Al_{6.5}V_4$.

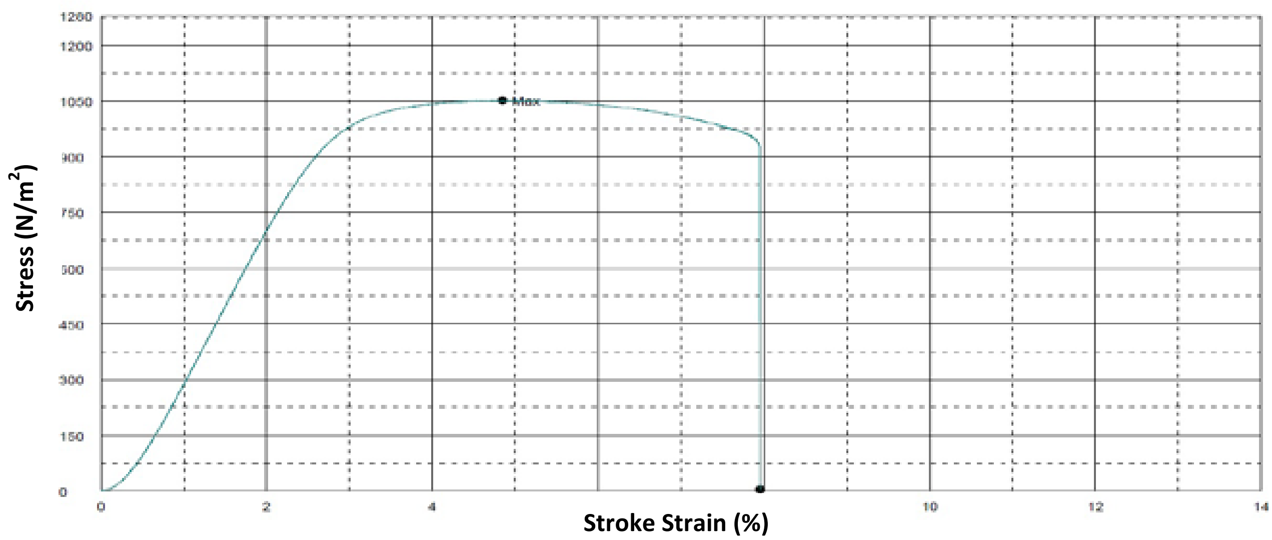


Fig.8 (b). Tensile testing graph for $Ti_{89.5}Al_{6.5}V_{4.}$

Table 2. Mechanical Properties of alloys developed.

Sr. #	Property	$Ti_{91}Al_5V_4$	$Ti_{90.5}Al_{5.5}V_4$	$Ti_{89.5}Al_{6.5}V_4$
1	Yield strength (MPa)	918	888	999
2	Toughness (MJ/m^3)	26.95	34.605	52.40
3	Young's modulus (MPa)	33300.26	28606.93	19813.78
4	Percentage elongation	2.84	3.475	5.165
5	Tensile strength (MPa)	942.72	992.77	1017.28

All mechanical properties improved with an increase in aluminium content.

Tensile Strength

The comparison of tensile strengths values of cast $Ti_{91}Al_5V_4$, $Ti_{90.5}Al_{5.5}V_4$ and $Ti_{89.5}Al_{6.5}V_4$ are shown in Fig. 9. The trend shows that as the Al content increases in the alloys, the strength also increases.

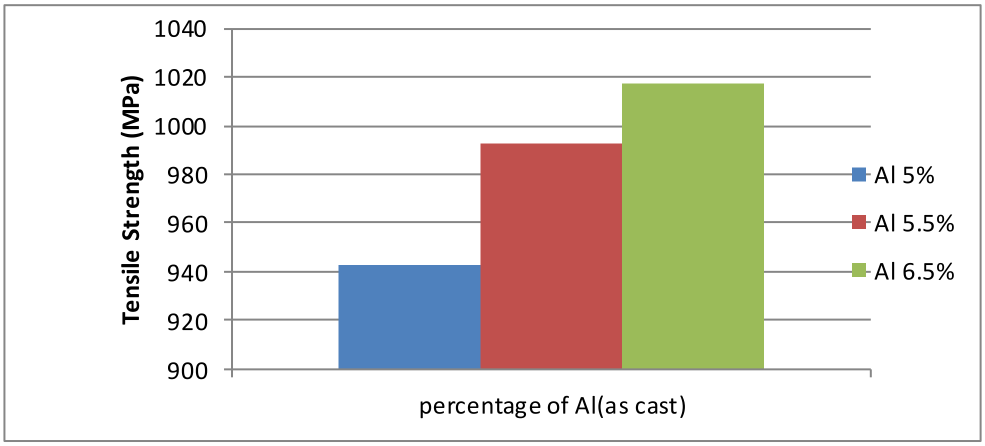


Fig. 9. Comparison of tensile strength in MPa.

3.4. Ductility

The comparison of ductility of cast $Ti_{91}Al_5V_4$, $Ti_{90.5}Al_{5.5}V_4$ and $Ti_{89.5}Al_{6.5}V_4$ are shown in Fig. 10. The trend shows that as the Al content increases in the alloy the ductility also increases. As the hardness values of the alloys increase, ductility values decrease respectively. y. Similar results were obtained by Jovanovic et al. [11] who stated that the effect of α′ and α was the major reason for these kind of trends.

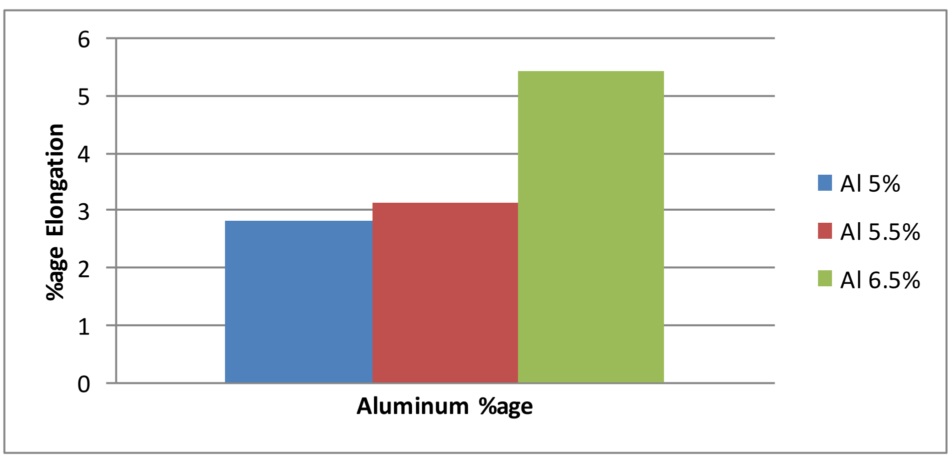


Fig. 10. Comparison of ductility (%age elongation).

3.5. X-Ray Diffraction (XRD)

X-Ray diffraction examination was carried out to identify the phases in $Ti_{91}Al_5V_4$, $Ti_{90.5}Al_{5.5}V_4$ and $Ti_{89.5}Al_{6.5}V_4$ alloys; There is a minute difference in Al content, number of peaks are observed in all three compositions and the crystalline analysis performed by XRD showed that only the phase α-Ti is clearly identified, it has the highest major peaks and β-Ti phase is also identified but it has very small peaks that can be neglected. Seong-Tak Oh [10] reported similar type of observations.

The results of x-ray diffraction are in good agreement with the results of optical microscopy that also showed α phase as the major phase and very minute β phase.

Lattice parameters of the α-Ti and β-Ti were calculated from available JCPDS data cards Sailer, R. McCarthy, G. North Dakota State University, Fargo, North Dakota , USA, ICDD Grant-in-Aid, (1993) and J.H de Boer, W. G. Burgers, and J. D. Fast: Proc. Acad. Amsterdam (1936). Table gives the lattice parameters along the structure of α-Ti and β-Ti.

Table 3. Structure and Lattice Parameter of the α-Ti and β-Ti detected in $Ti_{91}Al_5V_4$, $Ti_{90.5}Al_{5.5}V_4$ and $Ti_{89.5}Al_{6.5}V_4$.

Compound	Structure	Lattice Parameter (a*C) (A^0)		Lattice Parameter (a**c) (A^0)		Reference
		a	c	a	c	
α Ti	Hexagonal (HCP)	2.935	4.723	2.95	4.68	Sailer, R. Mc Carthy, G. North Dakota State University, Fargo, North Dakota , USA, ICDD Grant-in-Aid, (1993)
β Ti	Body centred cubic (BCC)	3.250	_	3.282	_	J.H de Boer, W. G. Burgers, and J. D. Fast: Proc. Acad. Amsterdam (1936)

(*) Calculated in this investigation
(**) Reported in the literature

3.5.1. $Ti_{91}Al_5V_4$

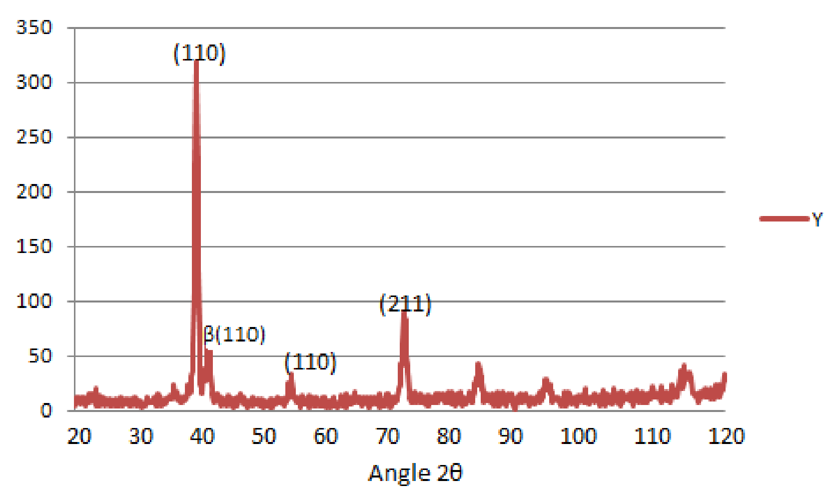


Fig. 11. XRD pattern of $Ti_{91}Al_5V_4$.

3.5.2. $Ti_{90.5}Al_{5.5}V_4$

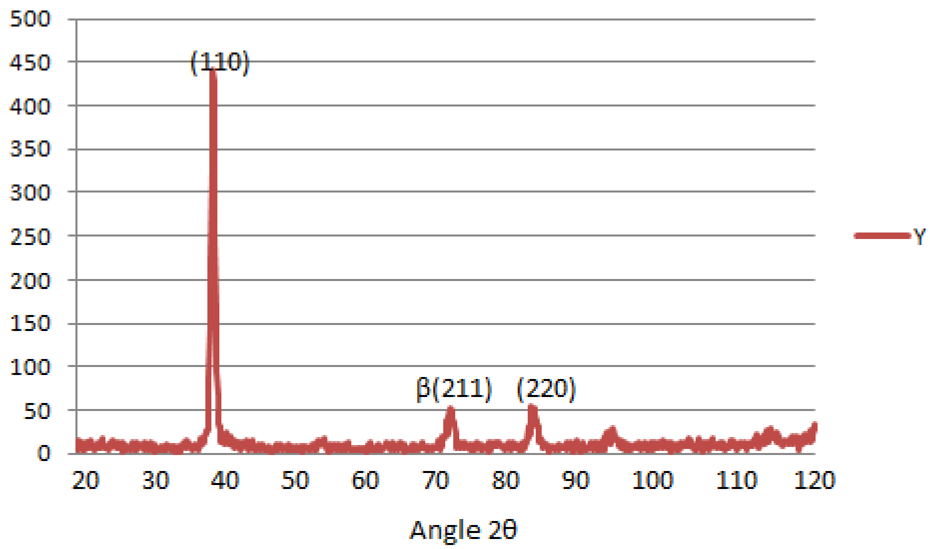


Fig. 12. XRD pattern of $Ti_{90.5}Al_{5.5}V_4$.

3.5.3. $Ti_{89.5}Al_{6.5}V_4$

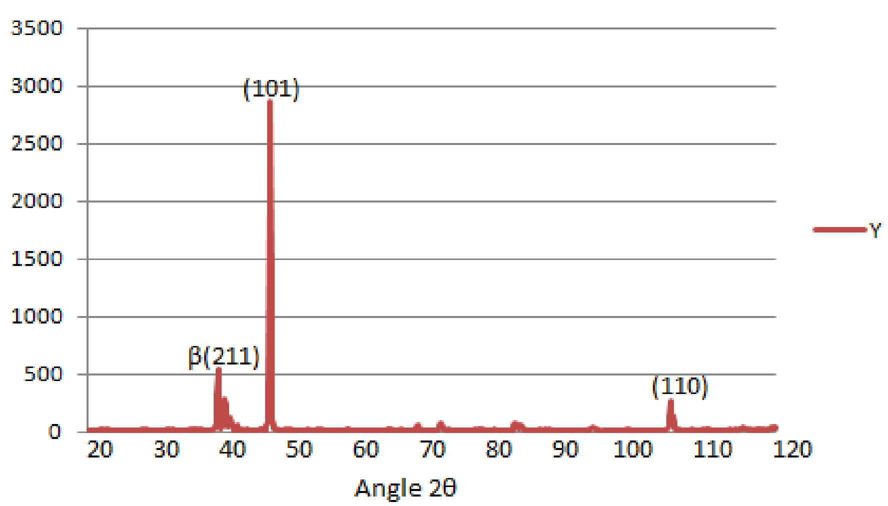


Fig. 13. XRD pattern of $Ti_{89.5}Al_{6.5}V_4$.

4. CONCLUSIONS

Alloys of the compositions $Ti_{91}Al_5V_4$,$Ti_{90.5}Al_{5.5}V_4$ and $Ti_{89.5}Al_{6.5}V_4$ were successfully developed in this work. Mechanical properties (Yield Strength, Tensile Strength, Ductility, Toughness and Hardness) were studied and all were found to increase by the increase in aluminum content.

The results obtained from XRD examination showed the structure of major α-Ti as HCP and β-Ti as BCC. The results obtained from as cast $Ti_{91}Al_5V_4$, $Ti_{90.5}Al_{5.5}V_4$ and $Ti_{89.5}Al_{6.5}V_4$ alloys showed dual α+β phase in which α phase dominates. The results obtained from experimental heat treatment of as cast $Ti_{91}Al_5V_4$, $Ti_{90.5}Al_{5.5}V_4$ and $Ti_{89.5}Al_{6.5}V_4$ alloys showed that after water cooling from the solution-treatment at 1000°C an acicular α′ martensite structure is formed . The resulted microstructure has not changed basically after the aging treatment at 500°C but α′ martensite structure became more prominent. An increase of hardness after aging treatment was compared with the solution treated state. So the alloy with highest aluminum content in the aged condition showed the best results.

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