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Combined Effect of Cold Rolling and Heat Treatment on the Mechanical Properties of Al-Ti Alloy

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***Abstract*—**This study investigated the combined effect of cold rolling and heat treatment on the mechanical properties of Al-Ti alloy. Samples of the alloy are cast in metal mould to obtain 0.94-2.19wt% mixes of titanium. These samples are grouped into untreated (as-cast) and those that are cold rolled to fifty percent reduction, homogenized at 500^0C and soaked for one hour. The cold rolled and heat treated samples are normalized (RT_n) and quench-tempered (RT_{q-t}) at 100^0C. All these samples are subjected to tensile, micro-hardness and microstructural evaluation. Results show remarkable improvement in the mechanical properties of the cold rolled and heat treated samples compared to the as-cast. In particular, the RT_{q-t} samples containing titanium in the range of 1.7-2.2% demonstrates improve tensile strength by 24.7%, yield strength, 28%, elastic modulus, 38.3% and micro-hardness, 20.5%. The Al_3Ti phase being the most stable precipitate in the α-Al matrix appears to have been responsible for the significant improvement in the alloy's mechanical properties. It is concluded that quench and temper heat treatment is an effective method of improving the strength-strain ratio of cold rolled Al-.0.9-2.2%Ti alloy.

***Keywords*—**Aluminum-titanium alloy, heat treatment, mechanical properties, precipitate.

I. Introduction

PURE aluminum has low strength and cannot be readily use in applications where resistance to deformation and toughness are essential, hence, other relevant elements are usually added to enhance performance. This paper seeks to establish an efficient processing method for achieving significant improvement in the mechanical properties of aluminum-titanium alloy meant for structural application.

The application of aluminum alloy as structural members at either high or moderate temperature requires microstructure containing fine, homogeneous and stable distribution of precipitates. The most stable intermetallic phase in Al-Ti-Ca system is the Al_3Ti crystals with solution heat treatment time greater than 4 hours for effective solubility of titanium and calcium in the Al matrix solid solution [1]. Mechanical alloying and Ti content have been found to increase the hardness of AA7050 aluminum based alloy in both as-extruded and heat treatment conditions [2]. Titanium in the alloy is found to be effective at retarding the coarsening kinetics of the precipitates while the low levels of titanium substitution result in only modest hardness increases over the binary Al–0.06wt%Sc alloy [3]. This accounts for preference for high melting point intermetallic such as Al_3Ti with a melting point of about 1350°C with a relatively low density, 3.3g/cm^3 [2]. Recently developed aluminum based alloys, especially with titanium, are becoming more useful for high temperature applications due to their excellent properties [4].

The development of fine microstructure is another means of achieving improved mechanical characteristics of aluminum alloys. Reference [5] established that salt containing weight ratio of 22.2Ti:1B has the best refining effect on the purity of aluminum with the finest structure and the best mechanical properties. The refining effect of the salt increases with increasing Ti and B contents in the melt occasioned mainly by increase precipitation of heterogeneous nuclei of fine Al_3Ti precipitates that are evenly dispersed in the melt. Grain refinement being one of the major techniques for property enhancement often plays important roles in determining the ultimate properties of aluminum alloy products. It improves tensile strength, plasticity, and reduces the tendency of hot tearing and porosity in castings [6]. Additional benefits of grain refinement include improve fluidity and a reduce tendency for shrinkage formation in casting [7]. On reduction of grain size, the morphology of the spaces available for pores is modified, resulting in an improved fatigue life for casting [8]. According to [9] this technique can be employed to halt incidents of mechanical properties impairments observed in plate products for structural application when a uniform as-cast grain size is not achieved. The grain refinement of aluminum by titanium is due to the occurrence of a peritectic reaction at the aluminum-rich end of the aluminum-titanium phase diagram [10].

In addition to the foregoing, several classical empirical studies have shown that the mechanical properties of aluminum alloys can be improved through the combination of deformation and the introduction of appropriate solute atom. This approach is employed in this study with a modification which consists in the introduction of selected forms of heat treatment combined with cold rolling and addition of varying amounts of titanium in aluminum.

II. Experimental Procedure

The development of the material used for the study involved melting and diluting the as-received rod containing 1XXX aluminum alloy to produce aluminum-titanium alloy samples having 0.94-2.2%Ti as shown in Table I.

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TABLE I
CHEMICAL COMPOSITION OF AL-TI ALLOY

%Ti	Fe	Si	Mn	Cu	Zn	Ti	Mg	Pb	Sn	Al	B
0.94	0.2921	0.1736	0.0670	0.1066	0.0106	0.9435	0.0120	0.0044	0.0027	98.12	0.1563
1.15	0.3051	0.1606	0.0627	0.0356	0.0109	1.1588	0.0100	0.0037	0.0089	97.8	0.2763
1.31	0.7094	0.2130	0.0779	0.0640	0.0115	1.3098	0.0192	0.0049	0.0074	97.1	0.3024
1.69	0.9840	0.2402	0.0462	0.0584	0.0153	1.6878	0.0095	0.0035	0.0136	96.3	0.5195
2.01	0.2317	0.1665	0.0433	0.0291	0.280	2.0100	0.0077	0.0063	0.0278	96.6	0.7062
2.19	0.1276	0.1437	0.0264	0.0231	0.6072	2.1937	0.0060	0.0075	0.0293	96.4	0.8564

Samples of the alloy developed are subjected to rolling, normalizing, quenching and tempering. The rolled samples are made to pass through a two-high mill to produce fifty percent reduction. Heat treatment of the samples consist in heating at 500°C, holding for one hour and cooling in air while the other sample is quenched in water at ambient (32°C) temperature followed by tempering at 100°C for one hour. Standard tensile test samples are prepared in accordance with ASTM E8 and the actual test performed using Instron Universal Tester, model 3369. Further, hardness test is carried out using a Vickers micro-hardness tester model "Deco" 2005 with a test load of 490kN and a dwell time of 10s. A minimum of 3 indentations are made on each of the samples.

In other to determine the structural integrity of the alloys, standard microstructural test pieces are machined and their surfaces ground in succession using emery paper with grit 220 to 1200 microns. The ground surfaces of the samples are then polished using a mixture of alumina and diamond paste and then etched in a solution containing 5g of sodium hydroxide (NaOH) dissolved in 100ml of water. The etched surfaces are left for 20 seconds before they are rinsed and dried while the samples microstructures are viewed under a digital optical metallurgical microscope at X800 magnification. The photomicrographs observed are shown in Figs. 1-4.

III. RESULT AND DISCUSSION

A. Microstructure

Figs. 1-4 show the microstructures developed by both the as-cast and those subjected to deformation and heat treatment processes at varying titanium additions.

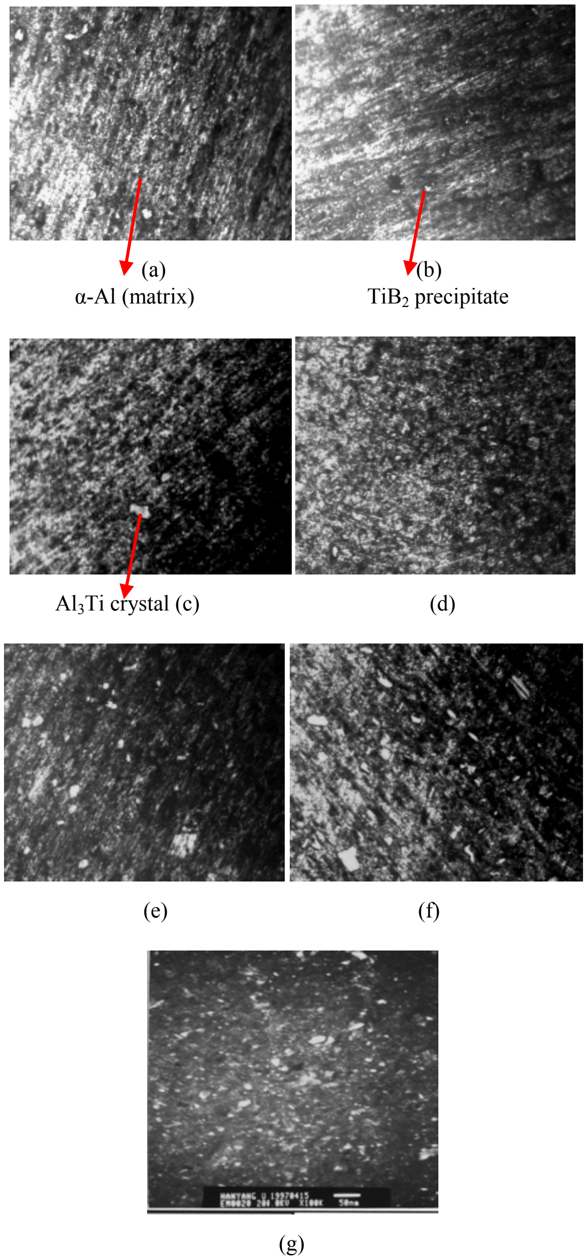
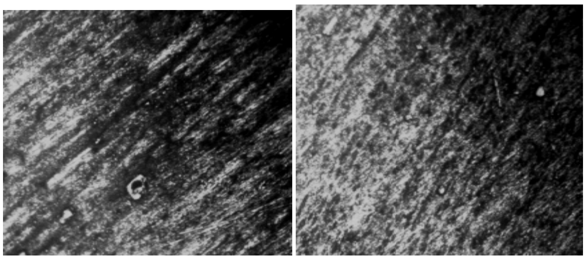


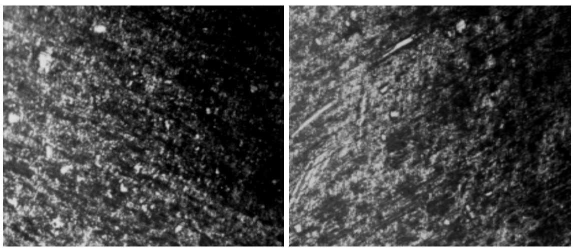
Fig. 1 Micrographs of as-cast Al alloy containing (a) 0.94%Ti (b) 1.15%Ti (c) 1.3%Ti (d) 1.7%Ti (e) 2.0%Ti (f) 2.2%Ti (g) TEM micrographs of Al-5%Ti powder ball milled for 30h

From Figs. 1 (a)-(e), the as-cast samples structures at varying amounts of titanium are dominated by alpha-aluminum while the few Al_3Ti crystals developed clustered in different colonies within the matrix. There is also evidence of formation of TiB_2 precipitate within the Al-matrix structure. Previous work has shown that TiB_2 reinforcement is both thermodynamically and microstructurally stable within the aluminide matrices [11]. Fig. 1 (f) structure contains plate-like phase with titanium which conferred some measure of directionality on the 2.2%Ti alloy.

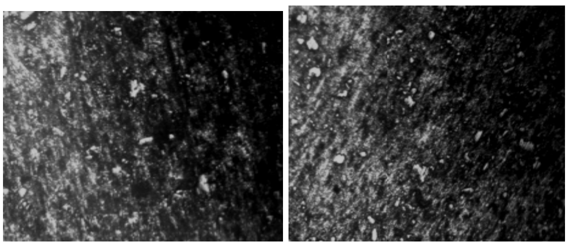
These structures developed by the as-cast samples demonstrate inhomogeneous distribution of phases coupled with subtle grain coarsening. This is often experienced with cast structures due to insufficient thermal energy which impaired grain mobility during solidification thereby preventing even distribution of phases and promoting grain growth. Fig. 1 (g) shows a typical TEM result of mechanical alloyed Al-Ti alloy [12].



(a) (b)



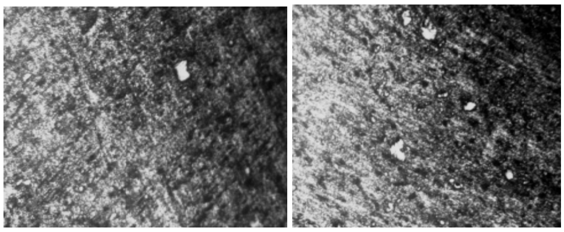
(c) (d)



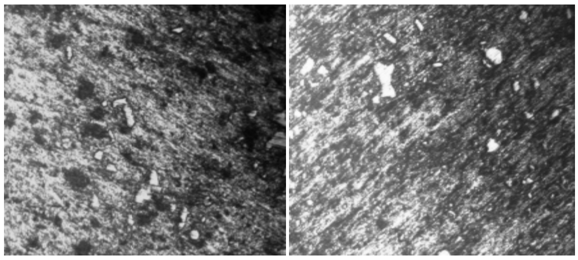
(e) (f)

Fig. 2 Micrographs of as-rolled Al alloy containing (a) 0.94%Ti (b) 1.15%Ti (c) 1.3%Ti (d) Ti (e) 2.0%Ti (f) 2.2%Ti

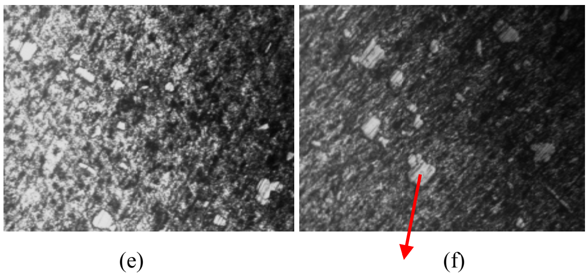
Fig. 2 (a) containing 0.94 per cent of titanium displayed a highly textured structure occasioned by cold rolling in which the titanium appears to have been completely subsumed in the α-Al matrix. However, a few Al_3Ti crystals are seen precipitated in Fig. 2 (b) while more of the crystals are induced in Fig. 2 (c). The impact of cold rolling coupled with increase in the amount of titanium gives rise to a gradual coarsening of the Al_3Ti crystals due to strain hardening of roll-stock {Figs. 2 (d)-(f)}.



(a) (b)



(c) (d)

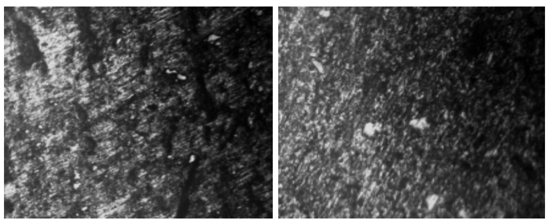


(e) (f)

Coarsened Al_3Ti crystal

Fig. 3 Micrographs of rolled and heat treated (normalised) Al alloy containing (a) 0.94%Ti (b) 1.15%Ti (c) 1.3%Ti (d) 1.7%Ti (e) 2.0%Ti (f) 2.2%Ti

The structures of normalized samples after cold rolling are shown in Figs. 3 (a)-(f). The samples exhibit increase coarseness in the reinforcing phase (Al_3Ti) as the proportion of titanium in the alloy increases. Further, clustering of phases due to indissoluble dislocation lock jam within the matrix is observed.



(a) (b)

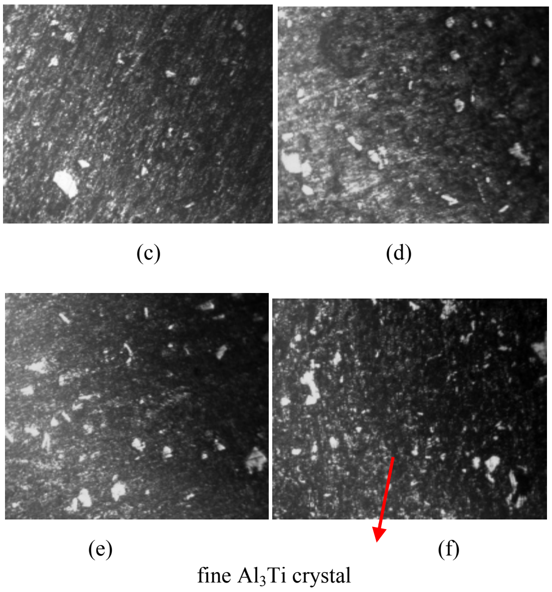


Fig. 4 Micrographs of rolled and heat treated (quench-tempered) Al alloy containing (a) 0.94%Ti (b) 1.15%Ti (c) 1.3%Ti (d) 1.7%Ti (e) 2.0%Ti (f) 2.2%Ti

On tempering of the samples after quenching in water, the Al_3Ti crystals disintegrate into fine precipitates which dispersed homogeneously within the matrix. In particular, Figs. 4 (d)-(f) display a relatively higher volume of the Al_3Ti crystals. It appears there is an increase in the volume fraction of TiB_2 precipitate in the quenched-tempered samples (Figs. 4 (a)-(f)).

B. Tensile Strength

Fig. 5 illustrates samples response on subjection to uniaxial force. The samples demonstrate increase ultimate tensile strength (UTS) as the proportion of titanium added increases. The presence of solute titanium in aluminum causes a significant change in the growth kinetics. The crystallization behavior of the Al-Ti alloy indicates the possible formation of Al_3Ti phase responsible for the nucleation of aluminum grains [13].

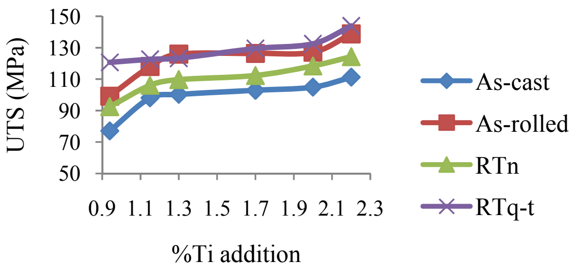


Fig. 5 Ultimate tensile strength of Al-0.94-2.2%Ti

The above behavior of samples developed as more titanium is added coupled with a combined effect of deformation (rolling) and heat treatment resulting in volume increase of second phase (Al_3Ti) precipitates {Figs. 4 (d)-(f)}. Thus, the UTS exhibits by the rolled-quench-tempered sample is superior, 138.7 MPa to both the as-rolled, 132.5MPa and normalized, 124.3MPa while that of as-cast is the least, 111.2MPa. Given that Al_3Ti is the reinforcing phase, the disparity in the UTS values appears to be dependent on the volume of stable Al_3Ti crystals within the samples matrices, and promote additional dispersion hardening [14].

The implication of this result is that with about 2.2 percent titanium in aluminum and subjected to four hours of solution heat treatment, quench in water and tempered, an increase of 39.8 per cent in *UTS* would be achieved. This represents a significant improvement capable of enhancing reliability in service as strength is a major consideration in material selection. The improved tensile strength with corresponding increase in titanium strength is by precipitation hardening [4]

C. Yield Strength

The test samples demonstrate varied responses under elastic deformation as depicted in Fig. 6. The as-cast sample exhibits the least yield strength regime of 72.5MPa against 83.3MPa, 88.7MPa and 92.9MPa for normalized, as-rolled and quench-tempered samples respectively. This is due to the type of microstructure developed at various titanium additions {Figs. 1 (a)-(f)}.

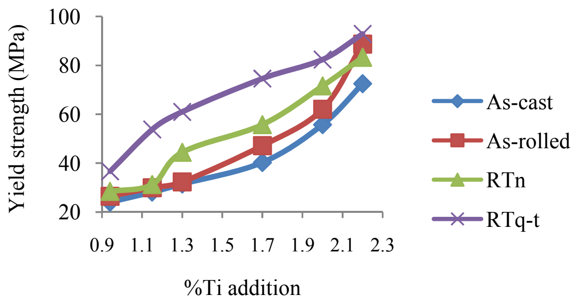


Fig. 6 Yield strength of Al-0.94-2.2%Ti

The yield strength of the as-rolled sample is significantly compromised due to work hardening which is attributed to solute atoms (titanium) forming an environment that could be likened to Cotrell atmosphere around aluminum exhibiting myriads of dislocation tangles. Further, the amount of residual stress in the sample is a major contributing factor that impaired the as-rolled sample's yield strength. However, a modest increase in yield strength by 22 per cent is demonstrated by the quench-tempered sample. Quenching followed by tempering enabled relief of stress caused by cold rolling in the sample and the transformation of the stress free phases into fine crystals which gives rise to improve yield strength.

D. Stiffness

The Young Modulus expresses the amount of stress necessary to produce unit elastic strain. This value is directly related to the materials stiffness which is a primary design consideration in structural computations. Hence, there should be a positive correlation between a material's yield strength and its elastic modulus.

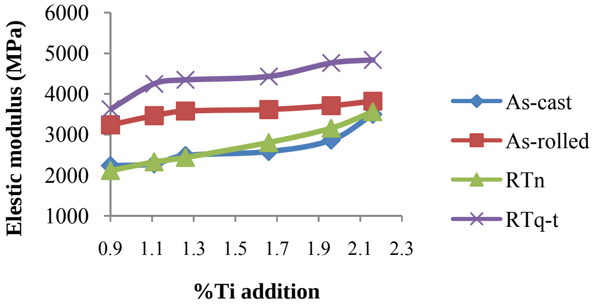


Fig. 7 Elastic modulus of Al-0.94-2.2%Ti

The as-cast samples demonstrate very low levels of stiffness at all titanium additions as shown in Fig. 7. Similar low elastic modulus values are exhibited by the normalized samples. This must have been occasioned by the dominance of clustered crystals of Al_3Ti (Fig. 1 (c)) and coarsening of same in the normalized samples (Fig. 3 (f)). However, both the as-rolled and quench-tempered samples exhibit a relatively higher elastic modulus. This can be attributed to the presence of a plethora of dislocation network nodes in the cold rolled samples and fine crystals of Al_3Ti dispersed homogeneously in quench-tempered samples.

E. Micro Hardness

Fig. 8 shows the extent of micro-hardness developed in the samples consequent upon the various treatments carried out on them.

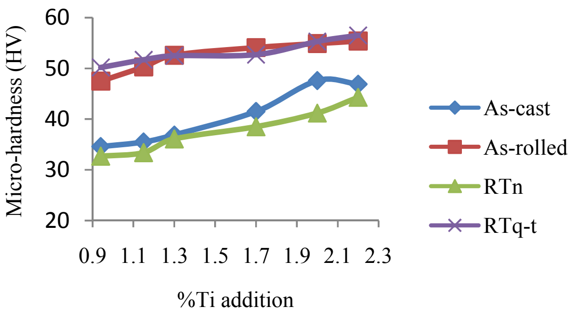


Fig. 8 Micro-hardness of Al-0.94-2.2%Ti

Generally, hardness values are observed to increase with increase in Ti addition. However, both the as-rolled and quench-tempered samples demonstrate higher micro-hardness values in the range of 47-56HV compared with as-cast and normalized samples, 32-47HV. Specifically, the as-cast exhibits 34.1-46.9HV compared with 32.7-44.3HV of normalized sample due to subtle coalescence of crystals which conferred a softening effect on the samples. Work hardening of the material must have been responsible for relatively high micro-hardness values (47.5-55.4HV) exhibited by the cold rolled samples. In the case of quench-tempered samples, increase micro-hardness (50.2-56.5HV) with increase proportion of titanium results to more precipitation of TiB_2 precipitate which further hinders dislocations motion. TiB_2 is particularly attractive reinforcing phase because it possesses many desirable properties, such as high hardness, low density, high melting temperature, high modulus, and high corrosion resistance [15]-[17].

IV. Conclusion

From the results obtained in this study, it can be concluded that the combined effect of rolling, heat treatment with varying addition of alloying element impact significantly on the mechanical properties of Al-Ti alloy. Given that aluminum on its own is highly limited in engineering applications, scientifically proven alloying scheme is imperative for enhanced performance. In this study, the addition of titanium in the range of 1.7-2.2 per cent with subsequent deformation (rolling) and heat treatment (quenching and tempering) significantly enhanced the alloy mechanical properties such that UTS, yield, elastic strain and micro-hardness increase by 24.7, 28, 38.3 and 20.5 per cent respectively.

However, the normalized samples mechanical characteristics are impaired due to coarsening of the main reinforcing phase, Al_3Ti coupled with a rather superfluous ductility which is above 47 per cent. High elongation characteristic in an engineering material meant for structural application is not desirable.

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