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A Comparative Study On Mechanical Properties Of Ultrafine-Grained Al 6061 And Al 6063 Alloys Processed By Cryorolling

Sushanta Kumar Panigrahi, D. Devanand and R. Jayaganthan
Department of Metallurgical and Materials Engineering
Indian Institute of Technology Roorkee
Roorkee-247667, India
E-mail : susant02@yahoo.co.in
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ABSTRACT

The present work has been focused to investigate the mechanical behavior and microstructural characteristics of cryorolled Al 6063 and Al 6061 alloys. Hardness and tensile tests of the cryorolled Al alloys were carried out to understand its deformation behavior. SEM/EBSD was used to characterise the microstructures of cryorolled Al alloys and observed the formation of ultrafine-grained microstructures in the materials due to severe plastic strain induced during cryorolling. XRD was used to analyse the formation of different phases during cryorolling of the Al alloys. It is evident from the present study that UFG Al alloys exhibit higher hardness and strength when compared to the bulk Al alloys due to the grain size, higher dislocation density and precipitation hardening effect. The cryorolled Al 6061 alloys exhibit higher tensile strength (346 MPa) and hardness (120 H_v) as compared to Al 6063 alloys (Tensile strength: 240MPa and Hardness: 96.5 H_v) in the present investigation. The deformation mechanisms of UFG Al alloys contributing to their enhanced strength are discussed.

1. INTRODUCTION

The selection of materials for aircraft structures, structural sectors, and automobile sector is really a challenging task, because the structural weight should be kept minimum apart from satisfying the functional requirements. Any excess structural weight would make the aircraft and automobile expensive as well as the increased cost of its operation. In view of the stringent requirements of very high strength to weight ratio (specific strength), excellent thermal and electrical conductivity, and higher oxidation and corrosion resistance, aluminium alloys are being widely used for structural components of aircraft and automobile[1-3]. The aerospace industry and various other structures rely heavily on 2XXX and 7XXX alloys, while 6XXX aluminium alloy is of particular interest in recent times due to good combination of formability, corrosion resistance, medium strength and low cost[4]. Although the members of the 6XXX alloy series are not among the strongest aluminium alloys as compared to 2XXX series and 7XXX series alloys, they represent the highest volume (90%) of the extruded aluminium products in the western world and in 1990, the share of such products of the world consumption of aluminium was 23%[5]. However, there is an ample of scope to enhance further the mechanical properties of these materials by refining the grain structure to ultrafine regime. Due to the superior properties such as higher strength and hardness, improved toughness, enhanced diffusivity, higher specific heat, enhanced thermal expansion coefficient and superior soft magnetic properties, the ultrafinegrained (UFG) materials are very promising for the structural applications[6-7].

Cryo-rolling has been established as one of the potential routes to produce nanostructured/ultrafine grained pure metals Cu, Al, Ni[8-10] and 5083 Al alloy[11] from its bulk counterpart by deforming them at cryogenic temperature. Cryorolling has been proven to be a better method to produce UFG microstructure than other severe plastic deformation (SPD) techniques due to (i) high scalability (ii) low load requirements (iii) simple processing procedure and (iv) ability to produce continuously long length products. Wang et al[8] produced UFG structure of commercial purity Cu by cryorolling at lower plastic deformation when compared to the other SPD processes at ambient temperatue.

It is well established that the solute elements such as Mg, Si, Fe and Cu in various precipitation hardenable 6xxx series alloys affect its mechanical properties and microstructure. However, the effect of solute contents in the cryorolled 6XXX series alloys is very scarce in literature. It is very important to investigate the effect of cryorolling on strength and ductility of 6XXX series alloys due to the interaction of the moving dislocations with intermetallic precipitates during plastic deformation.

The effect of cryorolling on mechanical properties and ageing characteristics of solution treated and annealed 6063 Al alloys has been investigated in our earlier work[12,13] and a large enhancement of mechanical properties with UFG structure was observed. Since 6061 alloy is a aerospace alloy and the concentration of its alloying elements are more than that of 6063, it is very essential to know whether the aforementioned properties obtained from 6063 alloy could also be found in the 6061 alloy.

In the present work, cryo-rolling was carried out on commertial purity 6063 alloy and high purity 6061 alloy. The objectives of the present study are as follows: (a) to study the influence of cryorolling strain on microstructure and mechanical properties of both the alloys; (b) to study the effect of solute content on cryorolling.

Table 1
Composition of 6061 and 6063 alloys(wt.%).

Sl.No.	Al alloy	Mg	Si	Fe	Cu	Mn	Zn	Cr	Al
1.	6061	0.8	0.6	0.04	0.2	0.012	0.03	0.02	Bal.
2.	6063	0.3	0.45	0.058	0.015	0.013	0.022	0.02	Bal.

2. EXPERIMENTAL

The high purity 6061 Al alloy and commercially pure 6063 Al alloys were procured from HAL, Bangalore, India and Hindalco Industries Ltd, India respectively. The chemical compositions of the two alloys are shown in Table 1. The 6061 and 6063 alloys were received in ingot form with 250mm diameter and T4 treated form, respectively. These materials were machined to a thickness of 10mm and then solutionised at 530°C for 60 minutes and quenched in water. These plates were rolled at liquid nitrogen temperature to a thickness reduction of 50% and 80%. The details of cryorolling are discussed elsewhere[12,13]. The microstructural features of starting material solution treated and quenched (ST) and cryorolled (CR) sheets of the 6061 alloy and 6063 alloy were characterized using a scanning electron microscope (FEI, Quanta 200F)/EBSD analysis. TSL OIM analysis 4.6 software developed by TEXSEM Laboratories Inc. was used to analyze the EBSD maps. The influence of cryorolling strain on precipitate evolution was analyzed by using XRD analysis in a Bruker AXS D8 Advance instrument using Cu K_α radiation.

Microhardness and tensile tests were carried out to evaluate the effect of solute in strength and ductility of the 6061 and 6063 alloys subjected to various strains. Vickers micro hardness (HV) was measured on the plane parallel to longitudinal axis (rolling direction) by applying a load of 100g for 15seconds. Prior to each HV measurement, the surfaces of the specimen was polished mechanically using emery paper and diamond paste of 0.25μm to remove the surface reactions that may occur during the heat treatment. An average of at least ten readings on the surface of the specimen were taken to obtain a micro hardness value. The tensile specimens were machined as per ASTM E-8 sub-size specifications parallel to the rolling direction with gauge length of 25mm. The tensile tests were performed after polishing the samples in air at room temperature using a S-Series, H25K-S materials testing machine operated at a constant crosshead speed with an initial strain rate of $5 \times 10^{-4} s^{-1}$.

3. RESULTS AND DISCUSSION

Figure 1 shows the electron backscattered diffraction (EBSD) micrographs of the starting, solution treated (ST) 6061 and 6063 Al alloys. Both microstructures exhibit equiaxed grain morphology with average grain size of 70μm and 60μm for 6061 and 6063 Al alloys respectively. The EBSD micrographs and its grain boundary histograms of the cryorolled (CR) 6061 and 6063 alloys at a thickness reduction of 80% are shown in Fig. 2. The severely fragmented and elongated grains along the rolling direction were observed in both of the deformed materials. The parallel bands of elongated substructures with low grain boundary misorientation angles were observed. The 6063 alloy exhibits higher fraction of low angle grain boundaries as compared to 6061 alloy, however the difference is very small. It clearly indicates that the presence of higher concentration of solutes (Mg and Si) in 6061 alloy has not played a major role on grain refinement. From the EBSD micrgraphs of the cryorolled materials, it is therefore confirmed that rolling at liquid nitrogen temperature is capable of introducing very substantial grain refinement (70μm to submicron range) in each of the 6000 series alloys.

The X-ray diffraction patterns of the 6061 and 6063 alloys in the uncryorolled (ST) and cryorolled state at a thickness

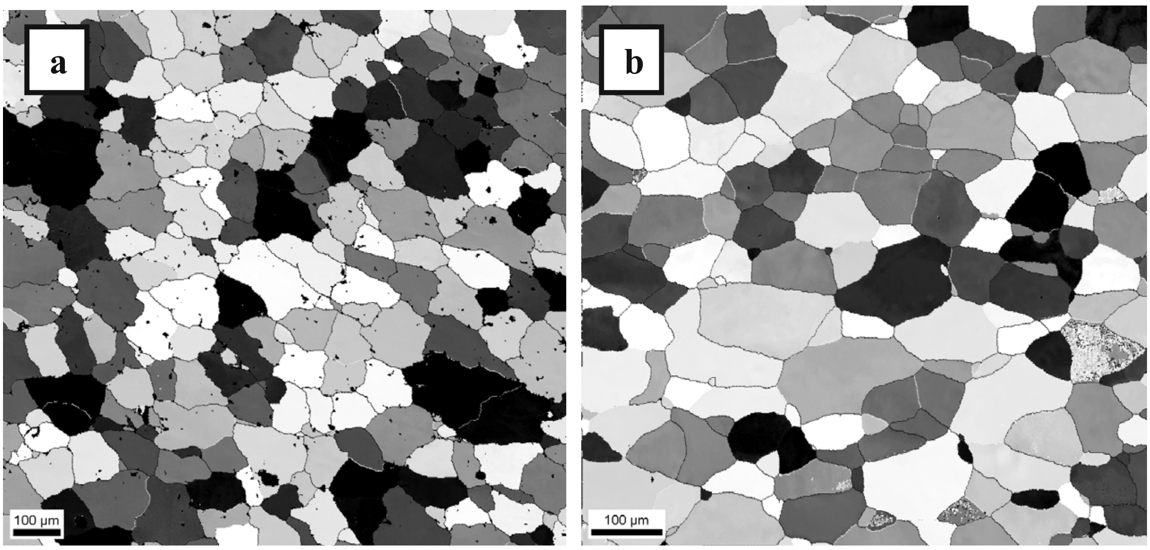

Fig. 1 : EBSD micrographs of the solution treated material (ST) before cryo-rolling (a) Al 6061 alloy (b) Al 6063 alloy.

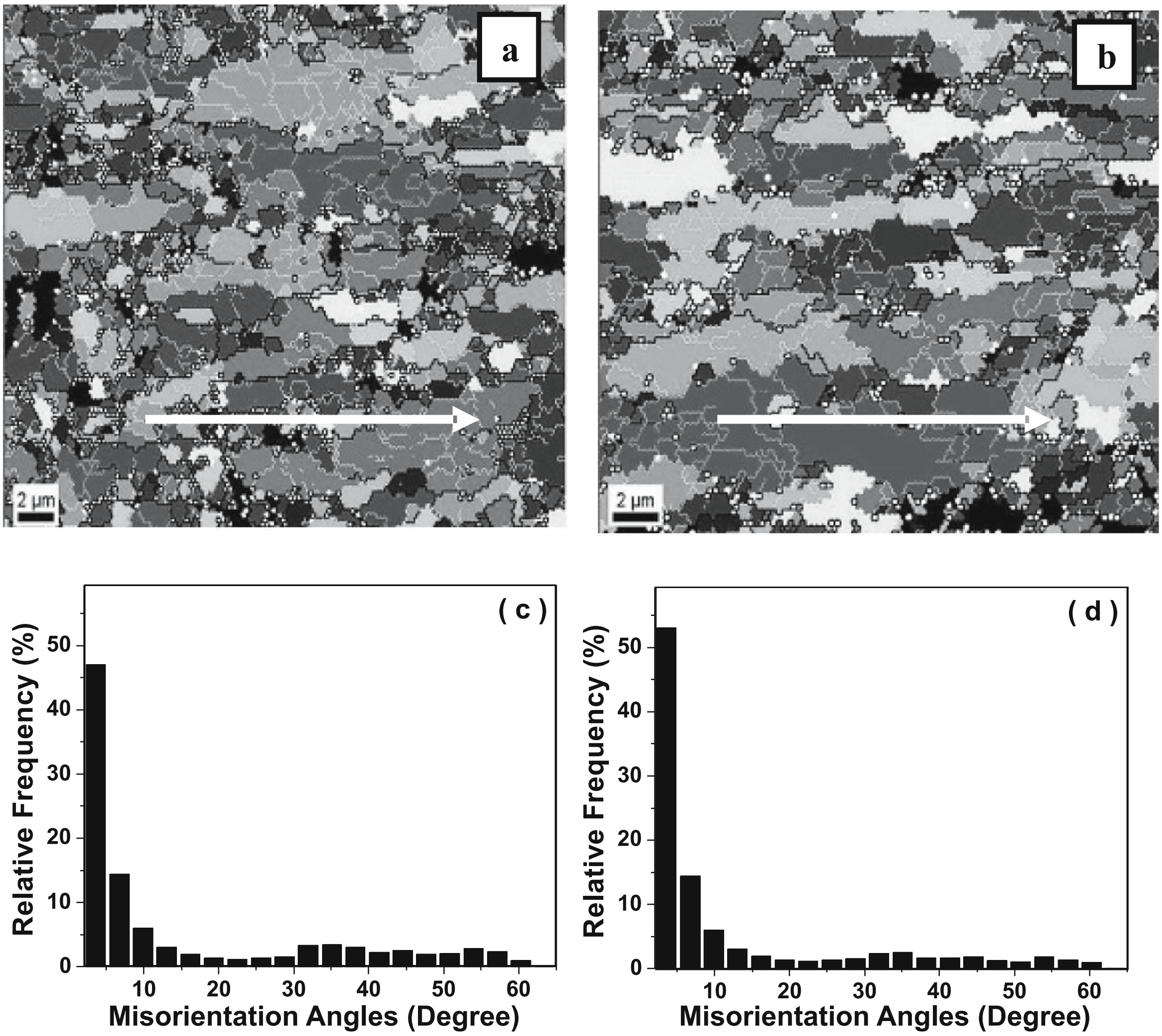

Fig. 2 : EBSD micrographs and misorientation angle histograms of 6061 alloy and 6063 alloy at 80% of thickness reduction: EBSD micrographs of (a) 6061 alloy; (b) 6063 alloy (arrow indicates rolling direction); Frequency histograms of misorientation angles of (c) 6061 alloy; (d) 6063 alloy.

reduction of 80% is shown in Fig. 3. The undissolved Fe-rich (Al-Fe-Si) and Cu-rich precipitate particles are observed in both the solution treated materials prior to cryorolling (Fig. 3(a)) due to the low solubility of Fe in Al. Whereas, the peak for Mg_2Si precipitate was not observed in both of the solution treated materials. When these materials are cryorolled to a thickness reduction of 80%, the Cu rich particles are dissolved in the Al matrix (Fig. 3(b)) due to severe strain. However, a new peak of Mg_2Si with low intensity has emerged out from both the materials upon cryorolling with 80% thickness reduction. The accumulation of dislocations may act as a short-circuit path for solutes and atomic migration[14] facilitating the precipitation. Because of higher concentration of alloying elements in the 6061 alloy, the intensity of Mg_2Si peak in 6061 alloy is more as compared to that of 6063 alloy (Fig. 3(c)).

Figure 4 shows the hardness values of 6061 and 6063 alloys versus the amount of deformation at cryogenic temperature. The hardness of both the alloys increased rapidly upto 50% thickness reduction (ε = 0.7) and then increased gradually. An enhancement of hardness for the cryorolled 6061 and 6063 alloys could be directly attributed to the considerable substructure refinement, which occurs during cryorolling.

The ultrafine-grained microstructures formed due to cryorolling with 80% reduction of 6061 and 6063 alloys obeys the Hall-Petch effect[15-16] to substantiate the improved hardness observed in the present work. Due to the formation of ultrafine grains in the cryorolled 6061 and 6063 alloys with 80% reduction, the dislocation density is restricted by grain boundaries as well as misorientation of the grains, resulting in the enhancement of hardness. It is observed that the hardness of the CR 6061 alloys is higher than that of CR 6063 alloys at different strains.

The tensile properties of 6061 and 6063 alloys cryorolled at different percentage of thickness reduction are shown in Fig. 5. The tensile strength (UTS) of the CR 6061 alloy with a thickness reduction of 80% has increased from 140 to 346 MPa (nearly 147% increase). However, a relatively lower increase in tensile strength (nearly 118% increase) was observed in case of CR 6063 alloy with the same thickness reduction. This is because of the presence of higher concentration of solute contents (Mg and Si) in the 6061

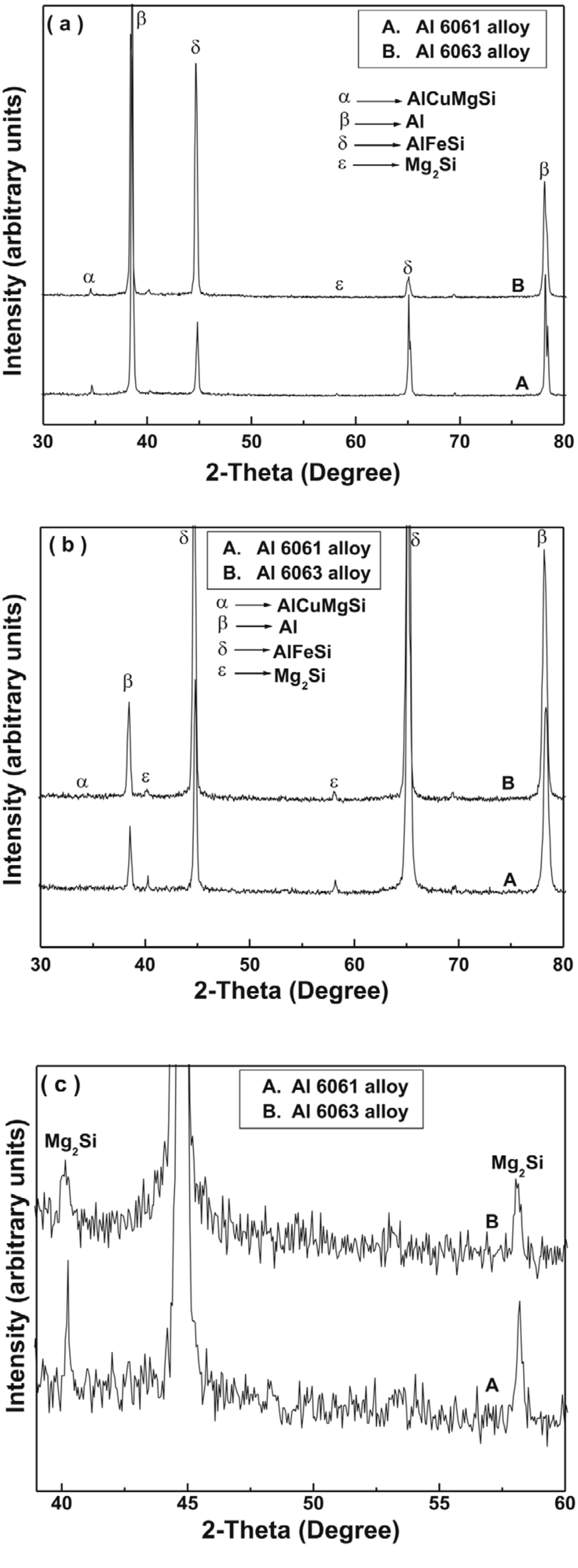

Fig. 3 : XRD patterns of 6061 and 6063 alloys at (a) ST; (b) cryorolled (CR) with 80% reduction; (c) enlarged intensity peak of Mg_2Si precicipitate at 80% reduction.

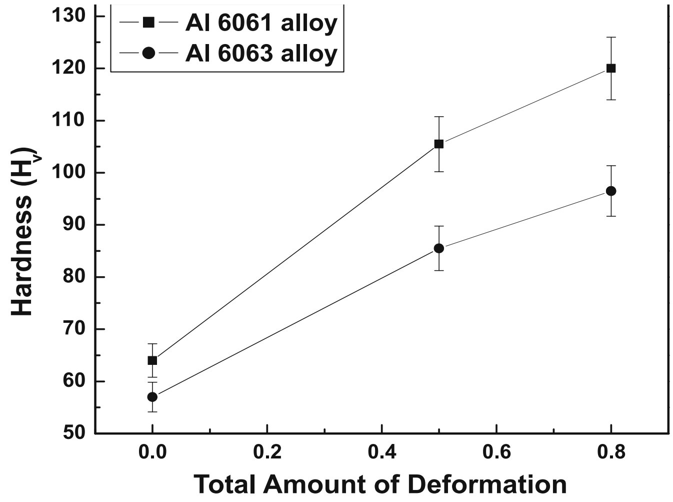

Fig. 4 : Hardness of 6061 and 6063 alloys with the amount of deformation at cryogenic temperature.

alloy increases the strength by either partially pinning the dislocations and impeding their motion or by retarding the dislocation annihilation during deformation, resulting in enhanced dislocation density and dislocation-dislocation interactions [17,18]. The observed trend in strength of both of these alloys is similar to that of hardness values (Fig. 4). As compared to the tensile strength, the cryorolling strain is more pronounced in yield strength (YS) in both of these alloys due to effective grain refinement. However, an uniform elongation of both of the alloys decreases with cryorolling deformation as shown in Fig. 2(b).

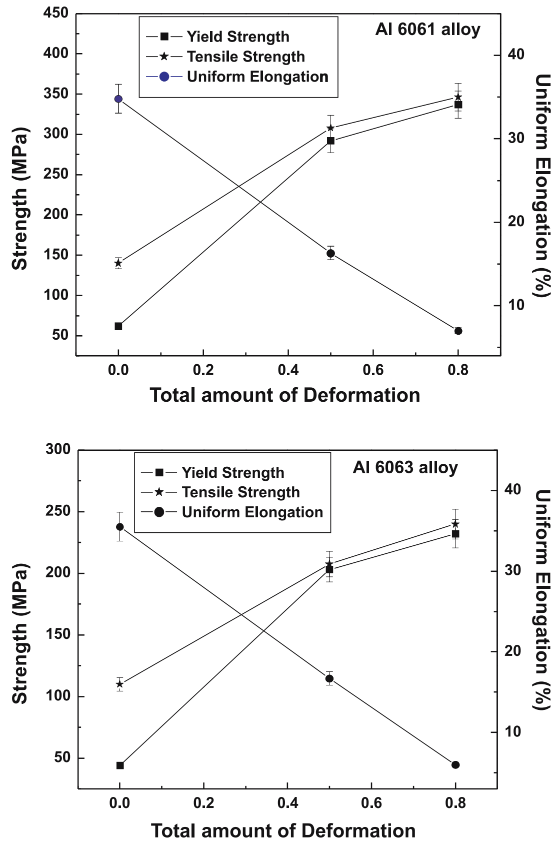

Fig. 5 : Tensile properties of 6061 ald 6063 alloys as a function of total amount of deformation at cryogenic temperature.

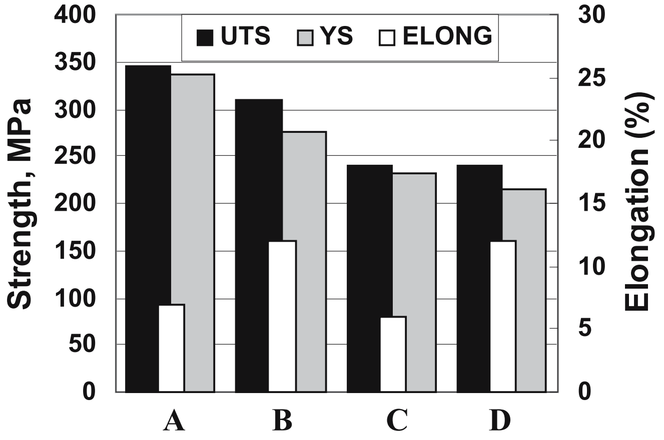

Fig. 6 : Tensile properties of CR (80% reduction) and T6 treated 6061 and 6063 alloy: (A) CR 6061 alloy at 80% reduction; (B) 6061 alloy at T6 condition[19]; (C) CR 6063 alloy at 80% reduction; (D) 6063 alloy at T6 condition[19].

Figure 6 shows a comparative tensile properties of CR 6061 alloy with 80% thickness reduction, T6 treated bulk 6061 alloy[19], CR 6063 alloy with 80% thickness reduction, and T6 treated bulk 6063 alloy[19]. The YS and UTS of the CR 6061 alloy with 80% have increased from 276 to 337MPa and 310 to 346MPa respectively with decrease in ductility as compared to its T6 treated condition [19]. However, a considerable increase in YS and UTS of CR 6063 alloy with same deformation as compared to its T6 treated condition [19] was not observed. The enhanced strength of 6061 and 6063 alloys after cryorolling with 80% reduction may be due to the combined effect of grain refinement, solid solution strengthening and partially precipitation hardening. It is reported in our previous investigation[12] that, ageing at 175^0C and 150^0C of the cryorolled 6063 alloys resulted in the decrease of hardness. To improve both the strength and ductility further, both of these alloys should be aged at low temperature for a prolonged period till to obtain the optimum properties. The pre-cryorolled (pre-CR) solid solution treatment combined with the post cryorolled (post-CR) ageing (100^{o}C for 48h) treatment of the 6063 alloy at higher strain has improved its tensile strength (277MPa) and good tensile ductility (11%) as reported in our earlier work [12]. Hence the mechanical properties in both of the present materials may be improved further by proper ageing treatment.

4. CONCLUSIONS

The mechanical properties and microstructural characteristics of 6061 and 6063 Al alloys subjected to cryorolling were investigated in the present work. It is observed that the cryorolled Al alloys (6061 and 6063) exhibits an improved strength and hardness as compared to their bulk Al alloys. The tensile strength (UTS) of the CR 6061 alloy with a thickness reduction of 80% has increased from 140 to 346 MPa (nearly 147% increase) as compared to a lower increase in tensile strength (nearly 118% increase) in the case of CR 6063 alloy with the same thickness reduction. This is because of the presence of higher concentration of solute contents (Mg and Si) in the 6061 alloy increases the strength by either partially pinning the dislocations and impeding their motion or by retarding the dislocation annihilation during deformation, resulting in enhanced dislocation density and dislocation-dislocation interactions. The hardness values of cryorolled 6061 Al alloys exhibited a similar trend and it is higher than that of the 6063 Al alloys.

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