Enhancement of Hardness Related Properties of Grey Cast Iron Powder Reinforced AA7075 Metal Matrix Composites through T6 and T8 Heat Treatments

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Abstract—In present global scenario, aluminum alloys are coining the attention of many innovators as competing structural materials for automotive and space applications. Comparing to other challenging alloys, especially, 7xxx series aluminum alloys have been studied seriously because of benefits such as moderate strength; better deforming characteristics and affordable cost. It is expected that substitution of aluminum alloys for steels will result in great improvements in energy economy, durability and recyclability. However, it is necessary to improve the strength and the formability levels at low temperatures in aluminum alloys for still better applications. Aluminum–Zinc–Magnesium with or without other wetting agent denoted as 7XXX series alloys are medium strength heat treatable alloys. In addition to Zn, Mg as major alloying additions, Cu, Mn and Si are the other solute elements which contribute for the improvement in mechanical properties by suitable heat treatment process. Subjecting to suitable treatments like age hardening or cold deformation assisted heat treatments; known as low temperature thermomechanical treatments (LTMT) the challenging properties might be incorporated. T6 is the age hardening or precipitation hardening process with artificial aging cycle whereas T8 comprises of LTMT treatment aged artificially with X% cold deformation. When the cold deformation is provided after solution treatment, there is increase in hardness related properties such as wear resistance, yield and ultimate strength, toughness with the expense of ductility. During precipitation hardening both hardness and strength of the samples are increasing. The hardness value may further improve when room temperature deformation is positively supported with age hardening known as thermomechanical treatment. It is intended to perform heat treatment and evaluate hardness, tensile strength, wear resistance and distribution pattern of reinforcement in the matrix. 2 to 2.5 and 3 to 3.5 times increase in hardness is reported in age hardening and LTMT treatments respectively as compared to as-cast composite. There was better distribution of reinforcements in the matrix, nearly two fold increase in strength levels and up to 5 times increase in wear resistance are also observed in the present study.

Keywords—Reinforcement, precipitation, thermomechanical, dislocation, strain hardening.

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I. Introduction

ALUMINIUM alloys can be rolled into sheets or sections. In the alloys mentioned above, precipitation hardening coupled with or without strain hardening is common solid solution strengthening mechanisms [1]-[3]. When cold working is combined with aging treatment, the synergetic process influenced by increase in lattice defects associated with diffusion phenomenon is responsible for the display of properties suitable for the given application [4]-[6]. In some special cases, there may be the beneficial effect of work softening due to dislocation annihilation during aging treatment which improve formability and decrease strength of alloy. On the other hand, work hardening as a result of increase in dislocation density over cold working and dislocation pinning by surrounded precipitates hinders the mobility of these dislocations during aging treatment, increases strength and hardness of material with reduction in ductility. Hence increase in degree of cold deformation decreases %elongation due to increase in dislocation density, which makes flow of material more difficult [7]-[9].

There has been a considerable industrial interest in these alloys because nearly 67% of all extruded products are made of aluminum and 90% of those are made from either 6XXX or 7XXXX series alloys. These materials can be heat treated to produce precipitation to various degrees. The T6 or T8 treatments involving solution heat treatment and subsequent artificial aging and quenching with or without cold deformation are the common methods to increase the strength of the alloy. The solution heat treatment is first performed at 500oC to obtain the supersaturated solid solution. This is followed by cold rolling for considerable degree of deformation. Artificial aging is performed by reheating the solutionized specimens at suitable temperature well below solvus temperature for various amounts of time to progress the precipitation of various solute rich phases. The hardness and strength are determined by the precipitate type, density and size. It is observed that wear rate of the alloy decreases with increase in aging temperature while increase in normal load enhances the wear rate irrespective of alloy condition [10]-[12].

The solutionized metastable structure when deformed by cold rolling is becoming further unstable due to increase in lattice defects due to increased strain hardening. Deformation also helps as forming and finishing operations for sheets and strands supported by excellent surface finish with high geometrical tolerances. Sheets are also used extensively in

building for roofing and siding, transportation vehicles, ship building. Foil applications outside packaging include electrical equipment, insulation for buildings, food processing and foil for heat exchangers. Majority of the applications mentioned above may require controlled heat treatments for better performance and durability.

For solutionizing, the general requirement for precipitation hardening of supersaturated solid solution involves the formation of finely dispersed precipitates during aging heat treatments. It may include natural aging, refrigeration aging or artificial aging. Indeed, dislocation density in the structure of material increases during cold working, which results in rise of yield strength and fracture strength of material [13]. The aging must be accomplished not only below the solvus temperature, but below metastable miscibility gap called the Guinier-Preston (GP) zone solvus line. The supersaturation of vacancies enhances diffusion rate, and thus zone formation occur in faster rate than that expected from equilibrium diffusion. In the precipitation process, the supersaturated solid solution first develops solute clusters, which then become involved in the formation of transitional (non-equilibrium) precipitates. Hardness and strength are indirectly proportional to the increase in aging temperature [14]. Increase in Mg content slows down ageing. Formation of Mg and Si co-clusters marginally contributeto the increase in hardness and yield strength.

The literature on metallographic examination of peak aged alloy at optimum aging temperature explains the precipitation of Mg3Zn3Al2 and MgZn2 stable intermetallic phases [15]. It was seen that the type, size and appearance of precipitates in specimens are depend on aging temperature and time.

II. EXPERIMENTAL DETAILS

A. Alloy Composition

The actual composition of AA7075 alloy used in this work is shown in Table I.

TABLE I
COMPOSITION OF AA7075 ALLOY USED IN THIS STUDY

Element	Si	Mg	Fe	Mn	Cr	Zn	Ti	Al
Weight %	0.4	2.25	0.4	0.26	1.96	6.12	0.2	Remainder

B. Preparation of Grey Cast Iron Powder and Casting

The grey cast iron chips produced by surface grinding are used as reinforcement. The chips are preheated to 300^0Cfor 2 hours and further ground in ball mill for 30 minutes. The resulting debris is sieved and 200-300 micron powders are collected. This powder is used as reinforcement for the AA7075 aluminium alloy. The composition of grey cast iron is shown in Table II. The two types of composites with 5 and 10 weight percentage of reinforcement (grey cast iron powder) each are prepared by two step stir casting process and compared with base alloy. These specimens are shaped into rectangular slabs to remove surface unevenness and scale. All the prepared castings are heated isothermally for 8 hours at 450^0C in the salt bath furnace to remove chemical inhomogeneity. At such high temperature the diffusion

process is accelerated and microscopic dendrites are removed. The solidified castings are cut into small pieces of 30mm x 25mm x 10mm. Totally 20 to 30 numbers of such specimens each are prepared from all the three casting groups.

TABLE II
COMPOSITION OF GREY CAST IRON POWDER

Element	C	Si	S	Mn	P	Cr	Ti	Fe
Weight %	2.67	1.93	0.11	0.56	0.71	0.12	0.02	Remainder

C. Age Hardening Treatment

Each set of specimens are heated to 450^0C in salt bath and quenched in cold water till the specimen temperature decreases to room temperature for solutionising. This solution treated samples are aged isothermally at 100^0C and 160^0C and hardness distribution graphs with aging time are plotted for all the specimens at every one hour aging intervals.

D. Cold Rolling Treatment

Specimens are subjected to cold rolling at room temperature by conventional two high rolling mill. Specimen thickness is reduced by a number of passes with one mm deformation each per pass. Any burrs formed during rolling are removed by grinding and polishing with emery papers.The specimens are subjected to cold rolling, metallurgically known as cold thermomechanical treatment with10, 20 and, 30% deformations to stain the matrix. The hardness versus aging time graphs are plotted for every one hour interval.

E. Hardness Measurement

All the treated and untreated specimens are subjected to Rockwell hardness test and the "B" scale bulk hardness numbers are noted. Peak hardness values are noted for agehardened as well as mechanically deformed samples.

F. Tensile Test

The peak aged specimens in age hardening and aging assisted mechanical straining are subjected to tensile test on computer controlled Tensometer. Standard specimens (ASTM 8) are used for the tensile test. Test is carried out at cross head speed of 3mm/minute and load versus %elongation graphs are plotted for peak aged specimens. Yield strength is taken as 2% proof stress. The ultimate tensile strength (UTS) and ductility (% elongation) are found out.

G. Wear Test

The standard specimens are prepared and are subjected to sliding wear in unlubricated condition on wear testing machine (Pin-On-Disc). Initially a trail run of half an hour is given to all the specimens to generate a perfect smooth bearing surface. The test is conducted for 5 hours each on all specimens and the wear (weight loss) is noted for the continuous run. Specimen is mechanically glued to aluminium shank by temporary adhesion. The machine disc is run at 100 rpm, track radius 80 mm and a dead weight of 200 grams on the cantilever pin.

H. Microstructure Analysis

The specimens are systematically polished with a series of

silicon carbide embedded emery papers starting from coarser 100 microns to finer 600 microns in the steps of 100 microns. At every stage of polishing specimens are water washed and dried with acetone. Superfinishing operation known as buffing is performed on disc polisher with wet diamond paste of 50 microns. Finally, the mirror like polished specimens is etched with etchant (Keller's reagent). Microstructures of all the samples are recorded in metallurgical microscope at 300X magnification.

III. RESULTS AND DISCUSSION

A. Hardness Measurement

The hardness distribution graphs with aging time in hours are plotted for all the deformation supported and age hardened specimens during aging at 100^0C and 160^0C. Fig. 1 shows two such graphs drawn for age hardened alloy. In both graphs, two peaks each are observed at lower as well as higher temperatures. The first peak is smaller than the second one in both the cases as observed in Fig. 1. The higher peak value is recorded as peak hardness in each graph when two such peaks are observed. Similar graphs are drawn for all composites in age hardening and thermomechanical treatments and respective peak hardness values are recorded. During aging, continuous increase in hardness, reaching maximum and decreasing pattern is sited in several technical research papers as theory behind the several intermediate metastable coherent or partially coherent intermetallic phases precipitation. This transition is observed with mechanical strain due to the change in lattice structures. Peak hardness is observed for the given aging temperature where perfect coherency is maintained between the matrix and intermediate phases. The further growth of the intermetallics coarsens the particle slowly switching over from semi-coherency to incoherency. Lower the temperature slower is the diffusion coefficient, longer is the duration where coherency exists. This phenomenon explores more number of intermediate zones while aging super saturated phase. Similar positive trend in improvement of hardness is observed when aging with deformation without two peaks. As the weight percentage of reinforcement increases or the degree of deformation increases the peak hardness value increases with decrease in aging duration. This pattern is due to the complex and combined interaction effect of strain hardening coupled with increase in nucleation sites as crystal defects. As high as three fold improvements in hardness is observed when the process is tailored efficiently. The hardness versus weight percentage of reinforcement graphs for as cast and age hardened specimens are shown in Fig. 2. As the weight percentage of reinforcement in the composite increases, hardness increases. Similar increasing trend is observed for thermomechanically treated specimens as shown in Figs. 3 and 4.
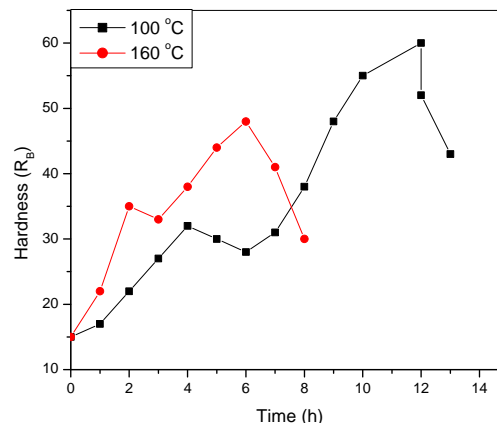

Fig. 1 Hardness versus aging time in hours for aging base alloy at 100^0C and 160^0C
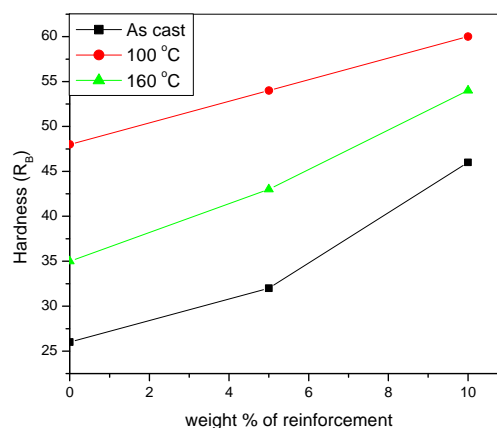

Fig. 2 Peak hardness versus weight% of reinforcement for as-cast and age hardened specimens
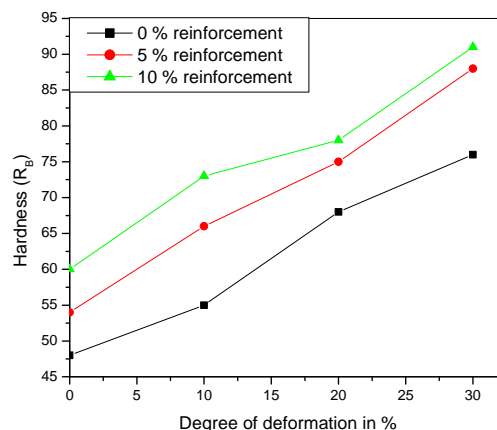

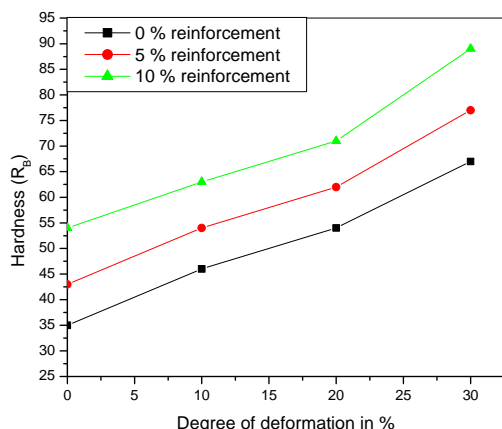Fig. 3 Peak hardness versus degree of deformation in LTMT for different weight% of reinforcement at 100^0C

Fig. 4 Peak hardness versus degree of deformation in LTMT for different weight% of reinforcement at 160^0C

Fig. 5 Ultimate tensile strength (UTS) of as- cast and age hardened specimens

B. Tensile Test

The load versus percentage elongation graphs as recorded by the computer during the tensile test are analysed and ultimate tensile strength and percentage peak elongation (ductility) for all the heat treatment conditions are noted. Figs. 5-7 show the variation of tensile strength of the alloys or composites in different conditions. As the weight percentage of reinforcement in the composite increases the ultimate tensile strength increases. Strength and hardness distribution pattern is almost similar with respect to the trend. Nearly 1.5 to 2.2 times improvement in strength is observed when the best heat treated alloy or composite is compared with that of as cast one. The ductility of the specimen decreases with the increase in the weight percentage of the reinforcement. Figs. 8-10 show the variation in the peak ductility of alloy or composites in peak aged condition. The reinforced particles act as secondary hard phases to pin down the percentage elongation by providing more number of obstacles for dislocation movement to improve the strength and reduce ductility. As the aging temperature decreases ductility decreases. Age hardened specimens show similar trend where the ductility increases with the increase in reinforcement, reaching a maximum for 5% reinforced composite then decreases. Peak aging at 160^0C shows better ductility in the group. As cast specimen shows continuous decrease in ductility with the increase in weight percentage of reinforcement. In all the composites or alloys degree of deformation is very sensitive to ductility. Up to 10% deformation the decrease in ductility is of smaller order compared to higher percentage deformation. The ductility of 10% reinforced, heavily deformed peak aged specimens are insensitive to aging temperature. 5% reinforced and heavily deformed one shows excellent tensile strength when aged at lower temperature and very poor ductility at lower and higher aging temperatures. This indicates the requirement of an optimum percentage of reinforcement to obtain the combined property.
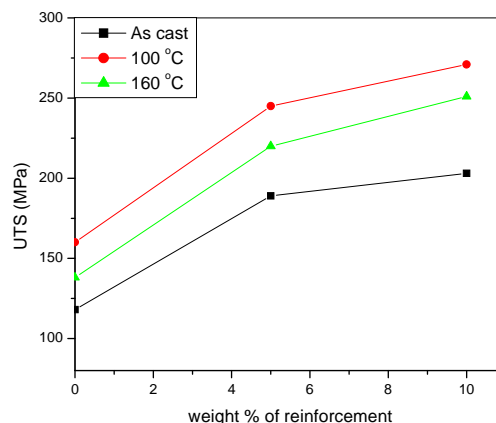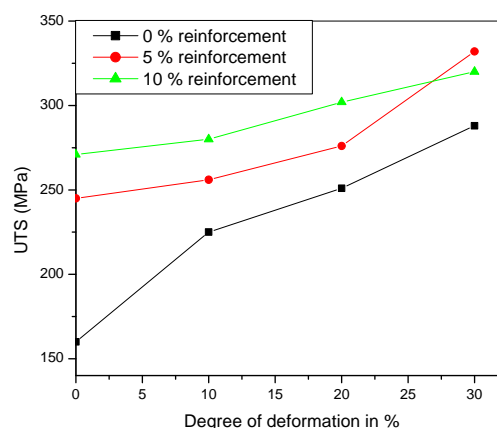

Fig. 6 Ultimate tensile strength (UTS) of LTMT specimens at 100^0C for different degree of deformations
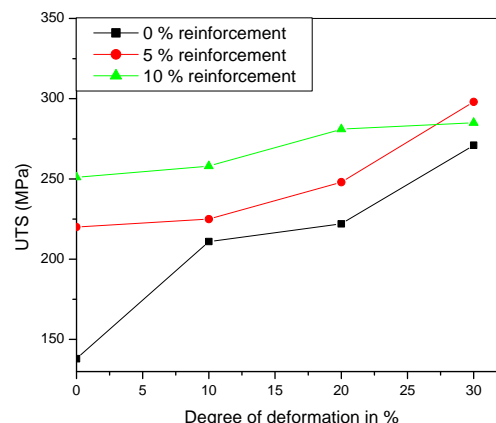

Fig. 7 Ultimate tensile strength (UTS) of LTMT specimens at 160^0C for different degree of deformations
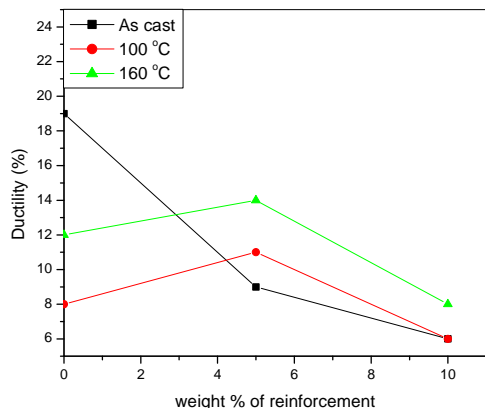
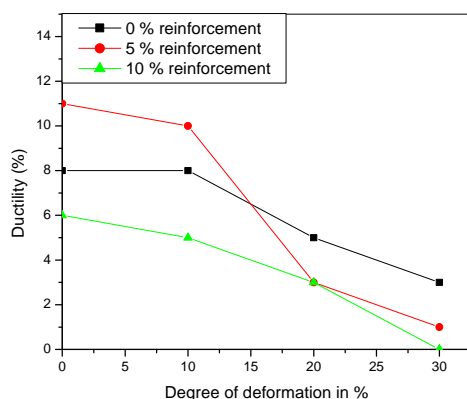Fig. 8 Ductility (% Elongation) of as cast and age hardened specimens

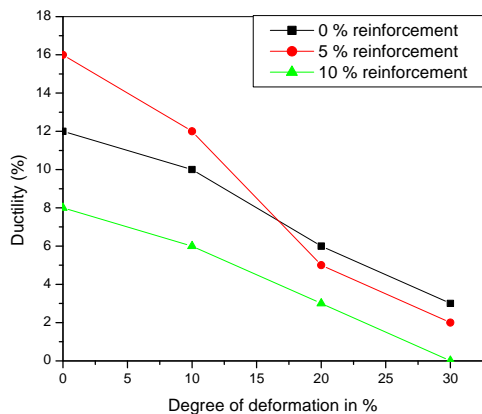Fig. 9 Ductility (% Elongation) of LTMT specimens at 100^0C for different degree of deformations

Fig. 10 Ductility (% Elongation) of LTMT specimens at 160^0C for different degree of deformations

C. Wear Test

Figs. 11-13 show the variation in weight loss in grams for different compositions for as cast, age hardened and thermomechanically treated specimens. Wear is generally the function of resistance to indentation and presence of lubricating element in the wear surface. Grey cast iron powder itself contains carbon in combined form as cementite and free

form as graphite. The cold rolled and aged specimens show better wear resistance as compared to conventionally aged one. Even in the cold rolled and lower temperature aged specimen show higher wear resistance compared to age hardened at the same temperature. Cold rolling easily exposes carbon flakes present in the cast iron reinforcement to the wear surface. Higher the intensity of deformation more is the flake formation and lesser is the wear because graphite or carbon is the solid lubricant. In the as cast condition, wear increases when the weight percentage of reinforcement increases beyond 5%. This may be due to chipping off of the surface as larger debris. The wear resistance is better in age hardened or thermomechanically treated condition as the weight percentage of reinforcements in the composite increases. The wear pattern trend remains almost same for the heat treated specimens. Lower temperature aged one shows better wear resistance. Composites exhibit better wear resistance compared to alloy. Wear resistance is sensitive to higher weight percentage of reinforcements and heavy intensity of deformation. Increase in wear resistance may be due to the synergetic complex effect of increased crystal imperfections due to deformation, intermetallic precipitation and lubrication.
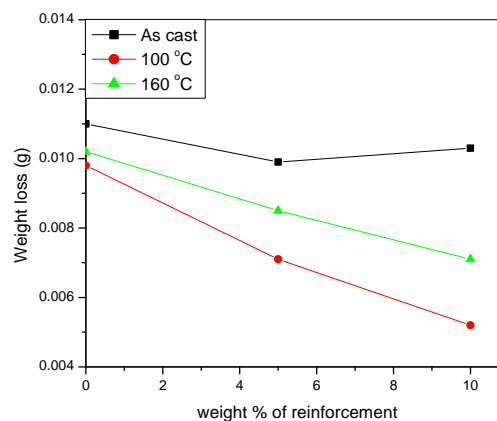

Fig. 11 Weight loss in grams for 5 hours of continuous run for as-cast and age hardened specimens
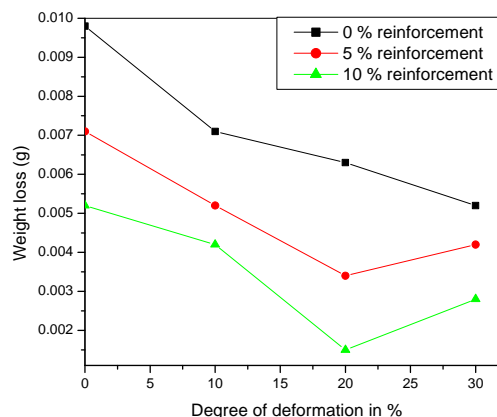

Fig. 12 Weight loss in grams for 5 hours of continuous run for LTMT specimen's at 100^0C for different degree of deformations
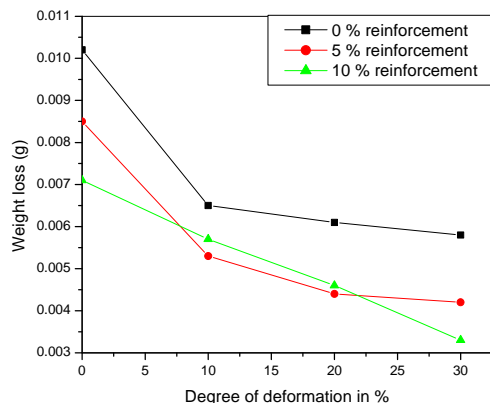
Fig. 13 Weight loss in grams for 5 hours of continuous run for LTMT specimen's at160^{0}C for different degree of deformations

D. Microstructure Analysis

Fig. 14 shows the microstructure of heat treated composites at 300X as recorded by ImageAnalyzer. Homogenised specimens show better dispersion of reinforcement without clustering.
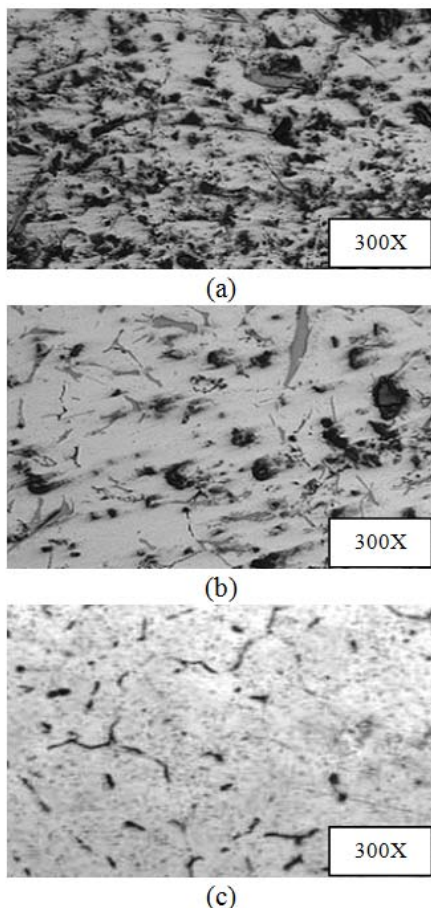

Fig. 14 Microstructure of homogenized (a) AA7075 composite with 10% Grey cast iron powder (b) AA7075composite with 5% Grey cast iron powder (c) AA7075alloy

Microstructure of as cast and homogenized specimen show equi-axial grains.

IV. CONCLUSIONS

Composite is successfully heat treated by age hardening and deformation supported heat treatment. There is remarkable improvement in the hardness of the alloy and composites especially by deformation supported age hardening. The following conclusions are drawn during the characteristic study.

- Lower the aging temperature better is the peak hardness values in age hardening.
- Deformation supported aging shows higher peak hardness values compared to simple age hardening.
- Higher the intensity of deformation higher is the hardness, shorter is the cycle time.
- Deformation supported aging improves UTS and hardness to higher values compared to age hardening.
- As the weight percentage of grey cast iron powder increases, the hardness, UTS, wear resistance increase with the reduction in ductility.
- All the composites contribute higher wear resistance when deformed and aged.
- Wear resistance is higher in the deformation backed heat treatment process.
- Higher the intensity of deformation better is the wear resistance.
- The microstructure shows good dispersion of reinforcement in the matrix without clustering.

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