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Influence of mechanical working on properties of aluminium base short steel fiber reinforced composites

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Abstract In the present investigation aluminium base short plain steel fiber, copper and nickel coated steel fiber reinforced composites were prepared by vortex method. These were subsequently given deformation upto 40% by hot rolling. Microstructure of deformed sample showed random orientation of fibers. Breakdown of fibers due to the hot rolling was also predominant. Density of composites increased with increase in % of deformation due to reduced porosity. The hardness and strength improvement observed is attributed to decrease in porosity and increase in the number of fibers due to fiber breakage. In case of copper-coated fiber reinforced composite some additional mechanism is observed to operate. After 40% rolling, porosity level of 5-wt% copper coated fiber composites was decreased from 3.9% to 0.7%. Hardness of as cast Al-5FeCu composite was 38.2 BHN, which increased to 45.8 BHN on 40% reduction. UTS (Ultimate tensile strength) of 5-wt% copper coated steel fiber composites increased from 124 MPa to 145 MPa on 40% deformation along with an improvement of percentage of elongation from 9.2 to 11.6. The simultaneous increase in UTS and percentage of elongation indicate that reduction in porosity is the main factor-giving rise to improvement of the properties. Fracture surface investigation showed that cracks are initiated at the fiber matrix interface, propagated through the interface and linked up with other cracks or fiber/matrix interface leading to failure. In case of as cast composites micro-porosity played a vital role in failure which is noted from SEM fractographs.

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Introduction

The attractive physical and mechanical properties that can be obtained with metal matrix composites (MMCs) such as high specific modulus, strength and thermal stability have been documented extensively [1–3]. MMCs combine metallic properties (ductility and toughness) with ceramic properties (high strength and modulus), leading to greater strength in shear and compression and higher temperature capability. Interest in MMCs for aerospace, automobiles and other structural applications has increased over the last few years, as a result of availability of relatively inexpensive reinforcement as well as the development of new processing routes resulting in reproducible microstructure and properties [4]. They are amenable to conventional metal working operations such as extrusion, rolling and forging of aluminium matrix composites [5, 6].

The hot working behavior of Al alloys has been extensively studied [7]. The effect of heat treatment and dynamic precipitation on the hot deformation behavior of the alloys has received attention [8]. The hot working behavior of discontinuously reinforced Al matrix composites has also been studied [9, 10]. It has been found that these composites exhibit much higher activation energy and a greater peak stress as compare to that of the unreinforced Al alloys.

However most of the discontinuously reinforced Al matrix composites studied so far have been in the as received state or equilibrium precipitated by slow cooling [11, 12] and the effect of dynamic precipitation on the hot deformation behavior of Al matrix composites has received little attention.

Hot working behavior of sand cast and squeeze cast composites of A356 aluminium alloy reinforced with 20 vol% SiC has been compared using reduction of 33, 50, 75 and 95% at 470 °C [13]. Initial porosity of 2.7% present in sand cast composites was reduced to 0.6% after 33% hot rolling and virtually eliminated after 90% reduction. The squeeze cast materials did not exhibit macro porosity, and micro porosity was completely eliminated after 33% reduction. Hot deformation processing significantly improved the ductility of this composite. At reduction levels of the order of 95% some fracturing of SiC particulates were observed [13].

Yield strength, UTS and fracture strain along the rolling direction improved as a result of increased % of cold or hot rolling but generally decreased along the extrusion direction [14]. After considering various microstructural changes, such as particulate cracking, interfacial debonding, redistribution of particulates, and disappearance of particulate free zone, the observed changes due to rolling have been attributed mainly to the redistribution of particulate [14].

Another significant finding in Lee et al. [15, 16] work relates to the resultant grain size after rolling 6061-10Al_2O_3 composites. The grain size of heavily cold rolled composites was generally smaller than as received composites. In hot rolling conditions the grain size increased with increased reduction. Ferry el al. [11, 17] found that deformation at high temperature (≥450 °C) the subgrain size and morphology were similar in both materials. This demonstrates that at high temperature the effect of the reinforcement on the deformation process is negligible.

The objective of the present work is to compare the hot deformation behavior of 5 wt% steel short fiber reinforced Al composites with that of cast composites, both made by a liquid route vortex method.

Experimental procedure

Commercially pure aluminium, composition shown in Table 1 was used for making the composites. The composition of fibers is shown in Table 2. The length and diameter of the fibers varied from 850 to 550 μm and 80 to 120 μm respectively. The aspect ratio of fibers is 7 to 8 are calculated by taking the average of 15 readings from the SEM photograph. About 1 kg commercially pure aluminium was melted in a resistance furnace, the melt being stirred with a graphite impeller revolving at 700–750 rpm. 5 wt% of steel fiber was added slowly to the vortex in the aluminium melt at 750 °C to produce composites. After complete addition of the fibers, the melt was stirred for 2 min and subsequently poured into a 180 mm length, 65width and 8 mm thickness cast iron mould. To obtain a dense product with improved mechanical properties, hot rolling was done on the composites. A rolling mill, (Albert Mann Engineering Co. Ltd., Essex, England) was used for this purpose. Initial dimension of samples 90 [mm] × 65[mm] × 8[mm] were sectioned from the plate and hot rolled up to 4.8 ± 0.2 mm thickness (40% reduction). For hot rolling, 30 min soaking was given to the samples at 500 °C. The hot rolled specimens were examined under optical microscope. Density was measured using water displacement method. Porosity was calculated from the theoretical density and measured density value. Tensile specimen of 25-mm gauge length, 4 mm width and 3 mm thick were machined along the direction of the rolling. Tensile strength was measured using a Universal Testing (Model No-AG 5000G) machine at a cross-head velocity of 2 mm/min. Hardness was measured using Brinell hardness tester using 10 mm steel ball indenter and 500 kg load.

Results and discussion

Composites were subjected to hot rolling at 500 °C to reduce porosity as well as to improve mechanical properties. Deformation up to 40% could be given successfully.

Table 1 Composition (wt%) of commercial aluminium

Sample	Si	Fe	Cu	Mn	Ti	Al
Al	0.09	0.168	0.04	0.03	0.01	Bal

Table 2 Composition (wt%) of fibers

Sample	C	Si	Mn	Cu	Ni	S	P	Cr	Fe
Fe	0.2	0.24	0.38			0.045	0.05	0.12	bal
FeCu	0.2	0.19	0.30	25.38		0.05	0.13	0.10	bal
FeNi	0.2	0.12	0.20		12.15	0.05	0.25	0.08	bal

Microstructure

Microstructure of as cast uncoated fiber reinforced composite is shown in Fig 1a. The distribution of steel fiber was reasonably uniform with random orientation throughout the matrix in all the cases. Fiber distribution is also uniform in the rolled samples as seen from the micrographs (vide Fig 1b). During hot rolling an extensive breaking of the fibers were occurred as seen in Fig 1b. In case of nickel coated fibers the fiber breakage was more predominant. This is expected in view of the higher brittleness of the nickel coated fibers as well as greater possibility of formation of brittle intermetallic compounds at the interface. The macrostructure of cast and roll composites are shown in Fig 2a,b. The grain sized decreased and elongated after hot rolling are shown in Fig 2b as compared to cast composites (Fig 2a). The porosity decreased with increasing % of deformation is shown in Fig 2b. In case of casting samples some porosity are observed but after rolling porosity was not observed.

Density

Density variation with % deformation is shown in Fig 3. Hot rolling of the composites resulted in higher density as compared to the cast composites. The density steadily increased with increasing % of deformation due to reduction of porosity. However, even after 40 % reduction by rolling the density is still lower than the theoretical density indicating the presence of porosity. The porosity significantly decreased in the composites on hot rolling as shown

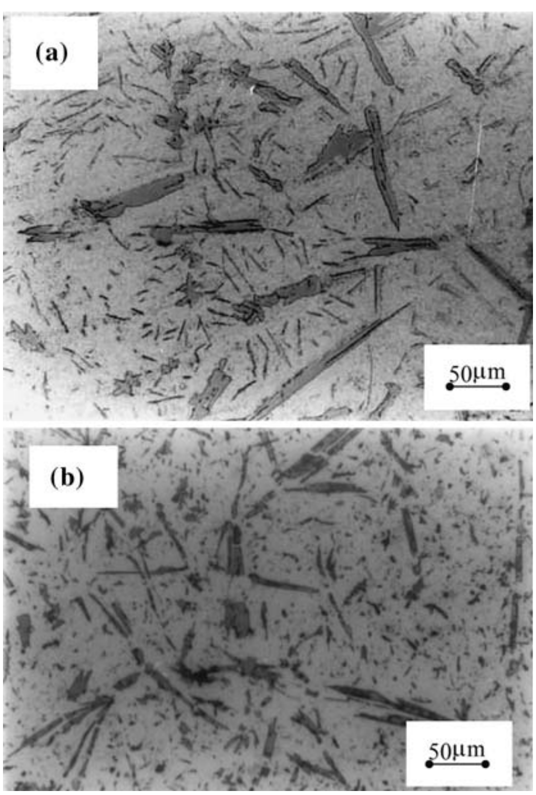


Fig. 1 Optical microstructure of composites (**a**) cast composites (**b**) rolled composites

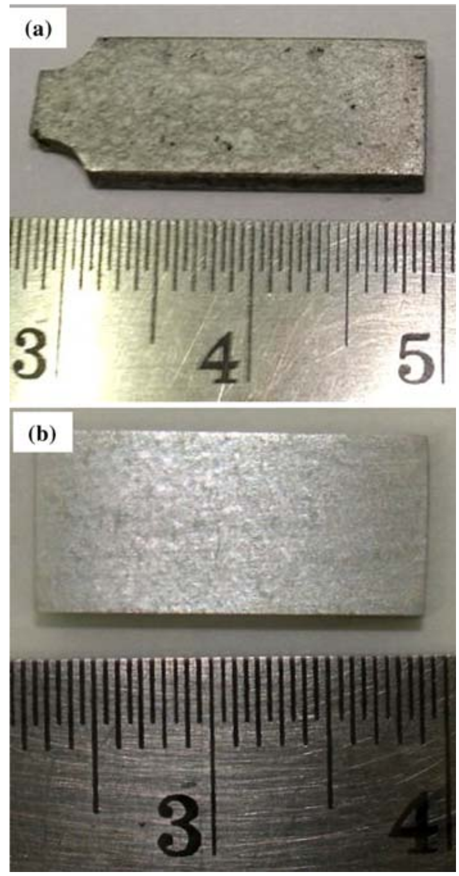


Fig. 2 Macro-structure of composites (**a**) As cast condition and (**b**) After 40% hot rolling

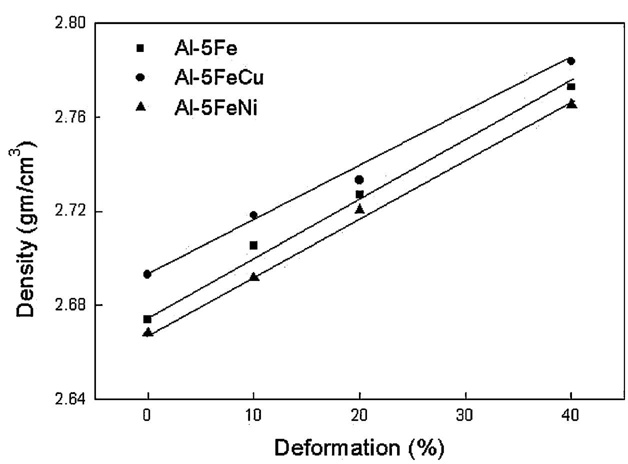


Fig. 3 Density variation with % deformation by rolling in aluminium base composite

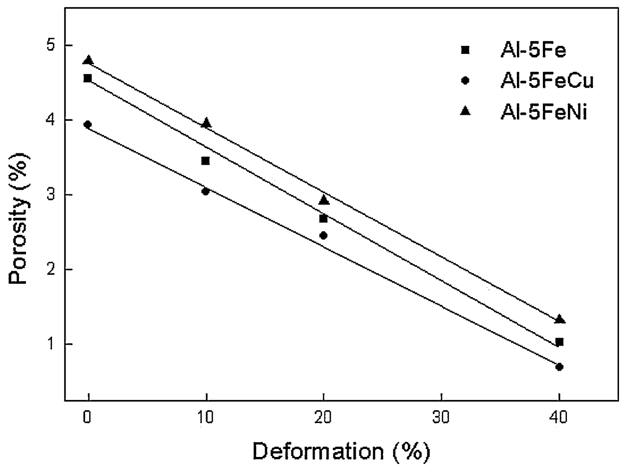


Fig. 4 Porosity variation with % deformation by rolling in aluminium base composite

in Fig 4. Initial porosity was 3.9% in cast Al-5FeCu (copper coated steel fiber reinforced) composites which decreased to 0.7 after 40% deformation, but other two composites exhibited porosity level higher than 1% even after 40% deformation.

The density and % of porosity values were plotted against % deformation. A liner equation of the type $Y = A + B * X$ was fitted. The slope B and constant A of the equations are given in Table 3 and Table 4 respectively.

As seen from the Table 3 and Table 4 the rate of increase/decrease of density/porosity is lowest in case of copper coated fiber composite. This is expected as the as cast porosity level in copper coated fiber reinforced composites is the lowest and quality of the interface is the best. Nickel coatings on the fibers however appears to deteriorate the quality of surface, decrease the density and increase the porosity. This is explained by the possibility of interfacial reaction between Al and Ni leading to formation intermetallic in addition to the intermetallic between Al and Fe.

Table 3 Coefficient of the equation for density

Sample	Density (gm/cc)	A_D	B_D	R_D
Al-5Fe	2.664	2.677	0.0024	0.997
Al-5FeCu	2.684	2.692	0.0022	0.996
Al-5FeNi	2.652	2.664	0.0024	0.998

Table 4 Coefficient of the equation for porosity

Sample	A_P	B_P	R_P
Al-5Fe	4.439	–0.0864	0.997
Al-5FeCu	3.927	–0.0798	0.997
Al-5FeNi	4.775	–0.0872	0.998

Hardness

Hardness of all the composites gradually increased with increasing deformation by hot rolling as shown in Fig 5. This results from significant reduction of porosity as well as atomic rearrangement in composites. This is evident from the increased density, strain hardening and consequent increase in dislocation density on rolled samples. There is breakdown of fibers and reduction in the fiber diameter, further the difference in the thermal expansion behavior of the fiber and matrix leads to increase in the dislocation density. All these contribute to the improvement of hardness in composites. The improvement in hardness during hot rolling is significant in all the composites. It is much more prominent in case of copper coated fiber reinforced composites. Whereas, the reduction of porosity is operative in all the composites during hot rolling, in case of copper coated fiber reinforced composites dissolution of copper and ageing take place during the hot rolling giving rise to further improvement in hardness.

A linear equation ($Y = A + B * X$) was fitted to the hardness data with % deformation as shown in Fig 5. There is good agreement as seen from the Fig 5. The slope B_H and constant A_H are given in Table 5. There is a qualitative similarity with the variation in the porosity (Fig 4). The slopes of the hardness variation and porosity variation lines were compared to see if the hardness is directly related to porosity. The hardness slopes were divided with porosity slopes. The values obtained are given in Table 5. It is seen that the values are more or less same. It is expected for

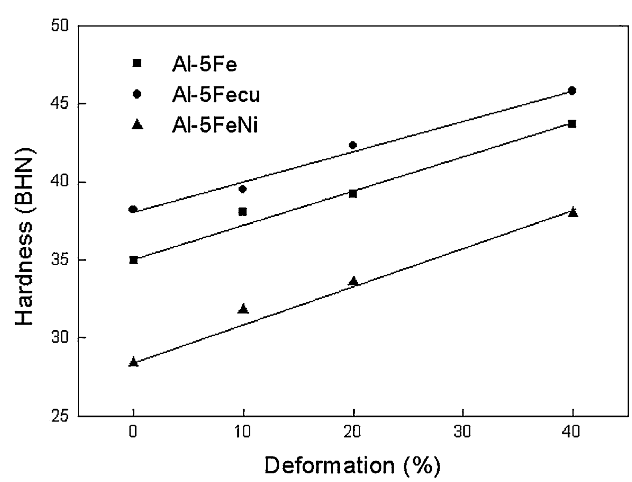


Fig. 5 Hardness variation with % deformation by rolling aluminium base composites

Table 5 Coefficient of the equation for hardness

Sample	A_H	B_H	R_H	B_H/B_P
Al-5Fe	35.28	0.21	0.992	2.40
Al-5FeCu	38.02	0.196	0.994	2.46
Al-5FeNi	28.86	0.232	0.993	2.66

nickel coated fiber reinforced case which showed slightly higher value. This indicates that the increase in hardness can be primarily attributed to the decrease in porosity. In case of nickel coated fibers the fragmentation of fibers is much more pronounced which could be the reason for a greater degree of increase in hardness.

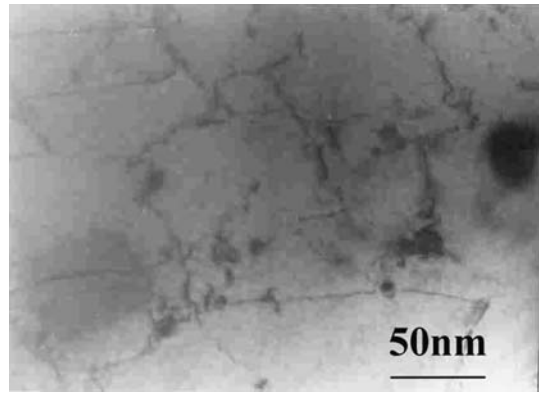


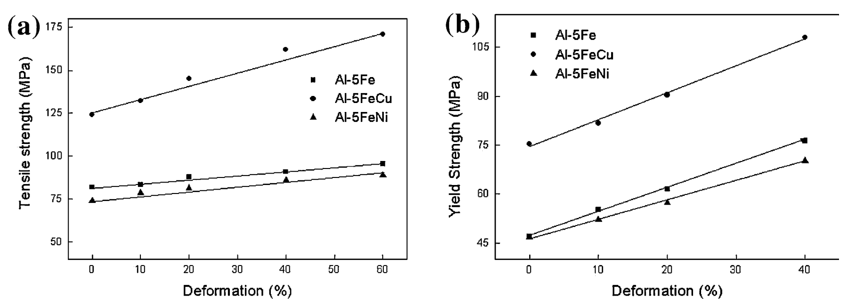
Fig. 7 TEM photograph of dislocation distribution on composites

Mechanical properties

Variations of tensile strength properties on hot rolled samples are shown in Fig 6a,c. UTS (Ultimate tensile strength) and YS (Yield strength) of all the composites increased with increasing % of rolling. As is well known properties of composites depend strongly on interface bonding between matrix and reinforcement and distribution of reinforcement. Coating on the fibers is expected to have an influence on both these parameters.

It is observed that strength of aluminium-base composites significantly increases with increasing % deformation. There is slight increase in % of elongation. Simultaneous increase in strength and % elongation shows that this is the result of a decrease in the porosity and grain refinement in the samples due to the hot deformation.

The improvement in the strength is primarily due to the reduction of porosity, grain refinement and solid solution strengthening. Presence of porosity in cast composites specially surrounding the fibers, results in a lower UTS and elongation. Hot working eliminates the porosity to a great extent, fragments the fibers and increases the dislocation density. Figure 7 shows TEM photograph of Al-5FeCu composite deformed by 40%. A high dislocation density is seen in this increase strength. Causes for higher dislocation density are the differential thermal expansion behavior of matrix and fibers and higher rates of work hardening. The increase in tensile strength can be attributed to the solid solution hardening and possible ageing during hot working in case of copper coated fiber reinforced composite. Fragmentation of fibers also influences the mechanical properties of composites. It has been observed from a previous study [18] that finer particles are more effective in increasing strength of the composite.



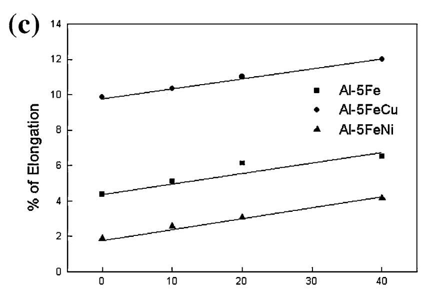


Fig. 6 Mechanical properties with % of deformation (**a**) UTS, (**b**) Y.S and (**c**) % El of aluminium bases composite

Table 6 Coefficient of equation for tensile strength (UTS)

Sample	A_T	B_T	R_T	B_T/B_P
Al-5Fe	82.023	0.227	0.988	2.63
Al-5FeCu	125.95	0.805	0.986	10.10
Al-5FeNi	75.54	0.241	.979	2.30

A linear equation ($Y = A + B * X$) was fitted to the UTS with % deformation data. The slope B_T and the constant A_T values are given in Table 6. The slope for the copper coated fiber reinforced composites shows the highest. The nickel coated fiber reinforced and uncoated fiber reinforced case the slopes are more or less same. These slopes were compared to the slopes of porosity line. The ratio of the slopes are given in Table 6. The ratio (B_T/B_P) for the copper coated fibers is much higher. Further the rise in % elongation is more significant in this case. This indicated that a different mechanism is effective in case of copper coated fibers.

For example in case of Al-5FeCu composites the strength is increased from 123 MPa to 145 MPa and elongation increase from 9.2 to 11.6 % after 40% deformation. It is observed that the UTS, Y.S and % of elongation increase linearly with increasing % of rolling.

It was observed that rate of strengthening during hot working is higher in case of copper coated fiber composites. Copper dissolved at interface and diffused to aluminium matrix during hot working and formed a solid solution with aluminium that improved strengthening rate. In composites interface strength plays a vital roll for improving material strength. In case of plain steel fiber and nickel coated fiber composite brittle compounds formed at the interface and solid solution strengthening is not operative. The brittle intermetallic formed cause earlier failure of composites.

Fracture surface

Fracture surfaces of cast and hot rolled composites are shown in Fig 8 (a and b). Micro mechanism of fracture as seen is by dimple formation, fiber breakage and pullout of fibers. The micrographs in Fig 8a show that the failure in the uncoated steel fiber reinforced composites occurred adjacent to the fiber/matrix interface, within the reaction phase. In previous study [19] of steel reinforced aluminium composites, it was observed that the failure occur at the fiber/matrix interface. In case of composites with uncoated fibers the high volume fraction of reaction products allowed the crack to propagate readily, link up with other cracks, and microporosity along the fiber/matrix interface caused failure. In case of the rolled samples (Fig 8b) fracture mechanism dominated by the crack initiation at the interface, propagation through the interface and link up with other cracks or fiber/matrix interface caused failure. It was observed that size of dimple was smaller in case of rolled samples due to fiber breakage and reduced microporosity. It is observed that ductile fracture occurs at the Cu coated fiber composites, which indicate a good bonding at interface resulting in higher strength. Copper at interface diffuse into the matrix during hot rolling caused solid solution strengthening of matrix. Tensile strength of uncoated and nickel coated fiber composites increased due to reduce porosity in the matrix.

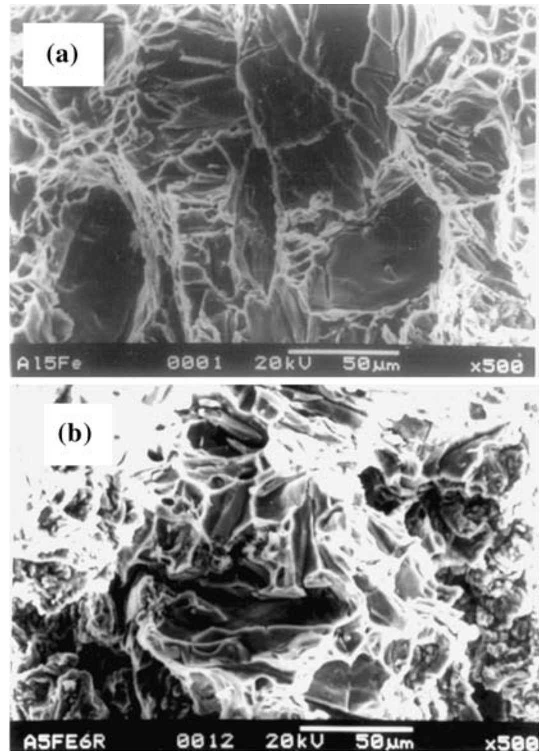


Fig. 8 Fracture surface of tensile specimen (**a**) Cast Composite and (**b**) Rolled Com

Conclusions

1. Hot rolling reduced porosity of cast composites and increased density and hardness value. There is linear relationship between % porosity and deformation %. Initial porosity of 3.9 in as cast Al-5FeCu composite is reduced to 0.7 after 40% hot rolling.
2. A linear relationship can be fitted to the hardness, UTS, Y.S and % elongation with % deformation.
3. Hardness increased by 20–33% after 40% hot rolling. Initial hardness of Al-5Fecu composite was 38.2

BHN which increased to 45.8 BHN after 40 % rolling.
4. Mechanical properties of composites increased due to reduced porosity, better fiber destitution and solid solution strengthening during hot rolling. In case of Al-5FeCu composites the strength is increased from 123 MPa to 145 MPa after 40% hot rolling.
5. Coating has a string influence on the porosity level and the influence of deformation on porosity.
6. Improvement in mechanical properties on deformation is also influenced by the coating. Copper coating on fibers give rise to the maximum improvement in strength.
7. There is a simultaneous increase in percentage of elongation with increase in % deformation.
8. Strengthening rate was higher in case of copper coated fiber composites compared to plain steel and nickel coated fiber composites due to solid solution strengthening.
9. Micromechanism of fracture revealed that crack initiate at interface and link up with other cracks cause failure of hot rolled composites. Porosity accelerate fracture in case of as cast composites.

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