Effect of FeNb on microstructure and mechanical properties of Al-Cu-Ni alloy

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Keywords: Al–5Cu–2Ni alloy, FeNb, stir casting, microstructure, mechanical properties, AMMCs

Abstract
The present research work deals with the investigation of mechanical properties and microstructure evaluation by particulate reinforcement of ferroniobium (FeNb) into Al–5Cu–2Ni alloy. The two-step stir casting method was employed for the fabrication of the material. The metallography study was carried out with optical microscopy (OM), scanning electron microscopy (SEM) with energy-dispersive x-ray spectroscopy (EDS), and x-ray diffraction (XRD). The XRD peaks revealed the presence of the Fe2Nb phase and intermetallic compound phases of Al2Cu and Al3Ni2. However, the Fe2Nb phase is in the form of short sticks uniformly distributed around the intermetallic compound phases. Tensile strength, microhardness and impact strength were evaluated according to ASTM standards. The average tensile strength and Vickers microhardness of the Al–5Cu–2Ni matrix alloy were 179 MPa and 115 HV respectively. By adding 1%, 3% and 5% of FeNb particulate reinforcement into Al–5Cu–2Ni alloy, the tensile strength could be enhanced to 185, 193 and 207 MPa respectively. The corresponding microhardness values were 130, 132 and 151 HV, respectively. Thus, the addition of 5% ferroniobium particulate reinforcement material could significantly enhance the tensile strength and microhardness of the composites. Fractography revealed that fracture mode changes from ductile to brittle with the reinforcement of FeNb particles. The FeNb particles resist the dislocation movement of the intermetallic compound phases in the composites leading to microcracks and subsequent brittle fracture.

1. Introduction
Aluminium alloys are primary materials in structural applications because of their lightweight to high-strength ratio, corrosion resistance, and easy availability. However, they suffer from shortcomings like poor tribological properties, thermal instability and low tensile strength [1]. To mitigate these shortcomings, many researchers incorporated hard ceramic particles into aluminium alloys leading to Aluminium Metal Matrix Composites (AMMCs) [2, 3]. The replacement of conventional materials with metal matrix composites (MMCs) as a structural engineering material is widespread in automobile, aerospace, military and marine sectors [4–8]. There are three significant reinforcements incorporated into aluminium matrix alloy: synthetic ceramics, industrial waste, and agro-waste [9]. The particulate-reinforcing of the aluminium matrix alloy mainly focused on the strength enhancement, reduction of weight and reducing the cost for use in advanced applications. For enhancing hardness, tensile strength, wear resistance and corrosion resistance, commonly used reinforcement materials are Al2O3, SiC, B4C, TiB2, TiC, Mg2Si, ZrB2 and ZrO2 [10–14].

Casting is one of the most economical processes to convert raw material into useful components. The preferable casting techniques for aluminium-based composites fabrication are centrifugal casting, stir casting, compo-casting, squeeze casting, and ultrasound-assisted casting [15–20]. Among these, stir casting is an easy and economical liquid state fabrication method [21]. Uniform distribution of particles in a large casting is possible by mechanical stirring. Additionally, stir casting can achieve fine microstructure due to fast cooling of
liquid metal, less porosity and good bonding between matrix alloy and reinforcement particles [22]. Aluminium, copper and magnesium alloys are widely used as matrix materials in the manufacturing of AMMCs [23]. Yuan et al. [24] carried out a compound casting process to prepare Al/Cu bimetal.

Jayalakshmi et al. [25] carried out microwave sintering followed by hot extrusion for fabrication of Al-composites reinforced with Ni60Nb40 amorphous alloy. Electrical resistivity, hardness and compressive strength of the composites increased remarkably with increasing volume fraction of particle reinforcement. Rao et al. [26] studied the effect of MoS2 on the mechanical properties of Al-4.5Cu alloy by the stir casting process. The hardness and tensile strength increased up to 4 wt% of MoS2 but decreased afterwards due to particle agglomeration. Sahu and Sahu [27] carried out computational fluid dynamics (CFD) simulations for optimizing aluminium metal matrix composite reinforced with primary and secondary particles. They demonstrated their procedure by fabricating Al7075/B4C/Fly-ash composite by stir casting process. Ravikumar et al. [28] studied the mechanical properties of aluminium/tungsten carbide composites prepared through a stir casting route. With the increase in the fraction of tungsten carbide, density, impact strength, and elongation of the composites decreased, while the hardness and tensile strength increased. Wang et al. [29] studied the microstructure, mechanical and thermal properties of Al-Cu with the addition of TiC0.5N0.5 nanoparticles. It was observed that the microhardness continuously increased with an increasing fraction of nanoparticles. Li et al. [30] studied the mechanical properties of Al-Cu matrix composites with the addition of hybrid reinforcement of SiC nanoparticles and Mg2Si particles. It was observed that the addition of these particles enhanced the yield and ultimate tensile strength of Al-Cu. Rodrigues et al. [31] studied the addition of a third component in Al-Cu binary alloy. The addition of Ni up to 2 wt% enhances the mechanical strength and improves the thermal stability and hot tearing resistance of Al-Cu alloy.

Ferroniobium (FeNb), an iron-niobium alloy with a niobium content of 60%–70%, is predominantly used as a microalloying compound in high-strength low alloy (HSLA) steels. It is mainly used to increase the strength and weldability of the alloy's. The addition of FeNb refines the as-cast austenite structure of alloys. Commercial grade ferroniobium (FeNb) has a melting point of about 1370 °C, which is much higher than fabrication process temperatures (750 °C). Hence, when added to molten metal, it dissolves rather than melts, leading to the, formation of a Fe2Nb phase [32]. High-strength low alloy steel with FeNb as reinforcements finds application in automobiles, gas pipelines, tool steels, ship hulls, railroad tracks and several high-temperature systems. Santos et al. [33] studied the MgH2 + FeNb nanocomposites for hydrogen storage. It was observed that ferroniobium alloy is an effective catalyst for hydrogen sorption, mainly with ferroniobium as coarse granulates. Peilei et al. [34] studied the effect of Nb addition in Fe-Ni-B-Si amorphous and crystalline composite coatings by laser processing. It was found that ferroniobium can increase the glass-forming ability (GFA) of the coatings. Najafi et al. [35] studied the mechanical properties with the combined addition of vanadium, niobium and titanium via investment casting. The tensile strength of the micro-alloyed steel was drastically improved. However, the impact strength of the steel was decreased considerably by the addition of niobium (Nb) because of the phase transformation from ductile to brittle.

In present study, the stir casting technique was used for the fabrication of Al-5Cu-2Ni alloy by addition of FeNb reinforcement particles in 1%, 3%, and 5% (by weight). It is the first study on using ferroniobium (FeNb) particles as a reinforcement material in AMMCs. FeNb is used as a micro-alloying agent in high-strength low alloy steel. Here, effect of FeNb particulate reinforcement in Al-5Cu-2Ni alloy have been studied. The focus of the study is on mechanical strength and microstructural changes of the material. The stir casting process has been employed for the fabrication of AMMCs.

2. Experimental procedure

The process of fabrication of Al-5Cu-2Ni-xFeNb (x = 0, 1, 3, 5 wt%) and specimen preparation as per standards is discussed in this section. The procedure for studying morphology and mechanical characterization is described in subsequent sections.

2.1. Materials and methods

Al-5Cu-2Ni with 99.9% of purity was taken as a matrix alloy. Ferroniobium (FeNb) particles were taken as particulate reinforcement elements with a size of 250 μm, varying from 0% to 5% by weight. The densities of aluminum (Al), copper (Cu), nickel (Ni), and ferroniobium (FeNb) are 2.70 g cm−3, 8.96 g cm−3, 8.90 g cm−3 and 8.1 g cm−3, respectively. The sequence of the study, which is an experimental procedure and metallographic, mechanical characterization is depicted in figure 1.

A two-step stir casting process of fabricating composites was accomplished [1], as shown in figure 2. Stir casting was accomplished with an electromagnetic stirrer (EMS), providing good temperature and magnetic-field-speed control. One of the significant challenges associated with casting aluminium-based composite is
inhomogeneous mixing of the reinforcement particles within the matrix alloy [4]; EMS ensures proper mixing. In the fabrication process, aluminium with 99.9% of purity was melted first; after a few minutes, 5% of copper by weight was put into the molten liquid, followed by the addition of 2% (by weight) of nickel in the form of chips and the furnace temperature was raised to 750 °C. The trace amount (0.1wt%) of magnesium (Mg) in ingot form was added to the molten metal to enhance wettability between the matrix alloy and FeNb particulate reinforcement [3, 16]. However, hexachloroethane degassing tablet 0.5% was put into the liquid metal to release impurity gases from the molten liquid [36]. The liquid metal was brought to semi-solid condition around 650 °C; it was measured by a K-type thermocouple, and the ferroniobium (FeNb) reinforcement particles were
added to the molten metal. Table 1 shows the weight percentage of FeNb particles in materials. Electromagnetic stirring was done with 500 revolutions per minute for about 5 min to avoid agglomeration and uniform dispersion of FeNb particles [2]. Then after raising the furnace temperature to 750 °C, subsequently the molten liquid metal was poured into the preheated metal mould. Specifications of the ferroniobium (FeNb) reinforcement particles is depicted in table 2. The significant parameters affecting the strength of the AMMCs in the stir casting process are particle size, stirring time, stirring speed, and preheating [26]. Sahu and Sahu [27] optimized the stir casting parameters, explaining the importance of the stir casting parameters for fabricating hybrid aluminium matrix composites. Stir casting was carried out at Vision Castings in Hyderabad, Telangana, India.

### 2.2. Density and porosity measurement

The experimental density of the composite can be calculated by the water displacement technique (Archimedes’ principle) by weighing the test specimen with a high precision electronic weighing balance with 0.1 mg of accuracy. The density was calculated by dividing the mass by the volume of water displaced [16], as per the following formula:

$$d_{ex} = \frac{m}{V}$$  \hspace{1cm} (1)

where $m$ is the mass and $V$ is the volume of the sample (amount of water displaced). The theoretical density of the specimen is given by

$$d_{th} = \frac{1}{\rho_1 \frac{x_1}{}, \rho_2 \frac{x_2}{}, \rho_3 \frac{x_3}{}, \rho_4 \frac{x_4}{}}$$  \hspace{1cm} (2)

where $x_1, x_2, x_3,$ and $x_4$ are the weight fraction of Al, Cu, Ni and FeNb, respectively and $\rho_1, \rho_2, \rho_3,$ and $\rho_4$ are the corresponding densities. The porosity of the composite can be calculated by subtracting the theoretical density from the experimental density and dividing the difference by the theoretical density, i.e.,

$$Porosity = \frac{d_{th} - d_{ex}}{d_{th}} \times 100\%$$  \hspace{1cm} (3)

### 2.3. Microstructure and XRD

Material morphology of the base alloy and composites was characterized by optical microscope and scanning electron microscope with energy-dispersive x-ray spectroscopy. The samples were sectioned as per test procedure specifications in the form of a rectangular prism of size 10 mm $\times$ 10 mm $\times$ 5 mm. The samples were polished with abrasive papers of different grit sizes ranging from rough to fine grade (up to 1500 grit size) to achieve a fine surface. Finally, velvet cloth polishing was done with 3 $\mu$m diamond paste [3]. The samples were etched with Keller’s reagent (95 ml water, 2.5 ml HNO3, 1.5 ml HCl, and 1.0 ml HF), a widely used etchant for aluminium alloys [16, 23]. The Olympus optical microscope was used to study the surface morphology of the
specimens. The average grain size of the composites was measured by the line intercept method as per ASTM E112–10 [16, 23, 29]. However, seven straight-line segments were drawn, and the number of grains intersected by each line segment was counted. The average number of grains intersected was calculated. The average line intersection was obtained by dividing the length of the line by the average number of grains intersected. The average grain diameter ($d$) was divided by magnification as the average line intersection. The XRD pattern of the fabricated composites is taken using a Bruker D8 advanced ECO x-ray diffractometer with Cu Kα-radiation and Ni filter. The XRD results were examined at a voltage of 40 kV and 25mA current intensity.

2.4. Impact, hardness and tensile test
Mechanical testing plays a vital role in evaluating the fundamental properties of engineering materials and facilitating the online development of new composite materials. The specimens for mechanical testing were prepared on a wire electric discharge machine (EDM) to maintain the accuracy of dimensions. The Charpy impact test involves the sudden and dynamic application of the load on the specimen. The amount of energy absorbed by the specimen for the rupture is measured. The test was performed on the impact tester model: IT-30 Make: FIE to measure the toughness of the specimen. The test specimens were prepared following the ASTM E23 standard with the dimensions of $10 \times 10$ mm$^2$ of cross-section, length of 55 mm; V-notch has an included angle of $45^\circ$ with 2 mm depth [28].

For finding out Vickers microhardness, the samples were sectioned as per the specification of the test procedure and polished with abrasive papers from rough to fine grade (up to 1500 grit size). Final fine polishing was done with a velvet cloth. The Vickers microhardness test procedure followed the standard of ASTM E 384–17 [7, 11, 16]. The load of 100 g force was applied through an indenter. The indenter had a 136° diamond pyramid and a dwelling time of 15 s [1]. The tests were performed on each sample with up to five indentations, and the average was noted.

The tensile test was carried out using a digitally controlled closed-loop servo hydraulic 100 KN dynamic testing machine (Make: INSTRON, Model: 8801J4051) having a crosshead speed of 1 mm min$^{-1}$; the linear and bi-axial extensometer with a gauge length of 25 mm was used to find the elongation of the specimen [23]. The specimen dimensions were prepared as per ASTM E8 standard, as shown in figure 3(a). The tests were performed on each composite of up to three specimens, and an average was noted. The fractured tensile test specimens are shown in figure 3(b).
3. Results and discussion

Al-5Cu-2Ni-FeNb composites with the addition of FeNb (x = 1%, 3%, and 5% by weight) were fabricated successfully by a two-step stir casting method. This study describes the porosity levels, microstructure characterization, and mechanical characterization of the as-cast plates.

3.1. Density and porosity of Al-5Cu-2Ni-FeNb composites

The theoretical density, experimental density and porosity of Al-5Cu-2Ni with the addition of FeNb (up to 5% by weight) are depicted in Figure 4. The experimental density of composites is slightly less than the theoretical density, as illustrated in Figure 4(a). This is due to porosity, which increases with the fraction of FeNb (Figure 4(b)). Kumar et al. [14] also observed that the experimental density of the hybrid composite of aluminium alloy was less than the theoretical density. In the present work, a maximum porosity of 3.3% was obtained at 5% of FeNb particles. Based on literature and own findings, Kumar and Birru [16] argued that porosity of less than 4% can be considered as a benchmark for a good quality casting. Researchers have also observed that porosity increases with the increase in the fraction of reinforcements [16, 22, 26].

The porosity of the composites is due to the entrapped gases in the molten metal from the environment during the solidification process, and air bubbles present while stirring the molten metal [22, 26]. With increasing weight fraction of FeNb, pore nucleation at the surfaces of the FeNb particles resulted in the reduction of liquid metal flow. Sajjadi et al. [18] studied A356 aluminium alloy/Al2O3 composites fabricated by stir and compo-casting processes; increasing Al2O3 increased the porosity of the composite due to pore nucleation at the Al2O3 particle surfaces, causing a reduction of liquid metal flow.

3.2. Mechanical characterization of Al-5Cu-2Ni-FeNb composites

From the present study of the composites, yield strength (YS), ultimate tensile strength (UTS), and elongation are presented in Figure 5 with different wt% of FeNb particles. The YS, UTS and elongation of the Al-5Cu-2Ni-1FeNb are 173 MPa, 185 MPa and 1.5%, respectively. Similarly, for Al-5Cu-2Ni-3FeNb and Al-5Cu-2Ni-5FeNb, these are 184 MPa, 193 MPa, and 1.4%, and 188 MPa, 207 MPa and 1.2%, respectively. The YS, UTS and elongation of matrix alloy Al-5Cu-2Ni are 159 MPa, 179 MPa and 2.6%, respectively. With an increase in FeNb particulate reinforcement into Al-5Cu-2Ni-FeNb composite, the yield strength of the composite gradually increased to a value higher than that of the matrix alloy. The UTS of the composites had a monotonic increase with an increasing fraction of FeNb particulate reinforcement.

The total elongation of composites reduced to a value lower than that of matrix alloy. Nallusamy et al. [12] observed that with an increase in vol. % of ZrB2 in AA 7075, the tensile strength increased, and total elongation decreased. Li et al. [13] observed that with an increase of Mg2Si up to 5 wt% in Al-5Cu matrix alloy, the strength increased and elongation reduced.

Properties of Aluminium metal matrix composites (AMMCs) depend on the intermetallic bonding of matrix and reinforcement FeNb particles [1]; good wetting between matrix alloy and reinforcement FeNb particles enhances the strength of composites. There are four strengthening mechanisms behind the enhancement of mechanical strength of the composites—Orowan, grain refinement, load-bearing, and
thermal expansion mismatch strengthening [13, 18]. Orowan strengthening mechanism takes place from the association of distributed hard reinforcement particles and dislocations. However, the size of the Fe$_2$Nb phase in the present composites is much larger than 1 μm. Due to the larger size of FeNb particles (250 μm), this mechanism is not prominent [13]. In grain refinement strengthening, α-Al grains increase automatically with grain refinement, which results from an increase in the number of grain boundaries; it hinders the dislocation motion [12, 13]. As the grain refinement is not high, this mechanism is not dominant. Thus, load-bearing strengthening and thermal mismatch strengthening are the main contributors to composites strengthening.

According to load-bearing strengthening, the Fe$_2$Nb phase with high Young’s modulus (105 GPa) is well-bonded with matrix alloy but it undergoes shear deformation [13]. Dispersion of FeNb particles in the Al-5Cu-2Ni-xFeNb composites acts as resistance to the movement of dislocations during the loading of composites. The resistance of dislocation movement creates a loop around the fine Fe$_2$Nb phase, which results in more resistance to the movement of successive dislocations leading to an increase in the strength of composites [12]. The increase in flow stress is expressed as

\[ \Delta \sigma_{\text{Load}} = \frac{1}{2} v_p \sigma_m \]  

where $v_p$ is the volume fraction of the particles, calculated from the weight fraction and $\sigma_m$ is the YS of the Al-5Cu-2Ni matrix alloy (159 MPa).

According to thermal expansion mismatch strengthening, the Fe$_2$Nb phase has a low coefficient of thermal expansion ($8.5 \times 10^{-6} \text{K}^{-1}$), which is different from the matrix alloy ($21.96 \times 10^{-6} \text{K}^{-1}$). However, during the solidification process, a lot of geometrical dislocations are generated due to the difference in the coefficients of thermal expansion of the Fe$_2$Nb phase, and other intermetallic compound phases with matrix alloy. As a result, the strength of the composites increased. Increase in flow stress can be expressed as

\[ \Delta \sigma_{\text{CTE}} = \beta G_m b \left[ \frac{12 \Delta \alpha \Delta T v_p}{bd_p(1 - v_p)} \right] \]  

where $G_m$ is the shear modulus of the matrix alloy, $b$ is the Burgers vector of the Al matrix, which is nearer to 0.286 nm, $\beta$ is a constant close to 1.25, and $\Delta \alpha$ is the CTE difference between FeNb particles and matrix alloy, $\Delta T$ is the pouring temperature, $v_p$ and $d_p$ are the volume fraction and average particle size of the FeNb respectively. The thermal expansion mismatch strengthening occurs during the solidification process due to difference in the coefficient of thermal expansion of matrix alloy and reinforced FeNb particles. The dislocations were affected because of reinforcement FeNb particle size and different mass fractions of matrix alloy and reinforcement [12, 25] as observed from the microstructures.

The microhardness of the Al-5Cu-2Ni matrix alloy was 115 HV. By addition of 1%, 3% and 5% of FeNb, the hardness increased to 130.28, 132.26 and 150.52 HV, respectively (figure 6(a)). The percentage increase in hardness of Al-5Cu-2Ni-xFeNb for 1%, 3% and 5% of FeNb composites was 13%, 15% and 31%, respectively, concerning Al-5Cu-2Ni matrix alloy. Increasing the weight fraction of particles increases the load-bearing capacity and dislocation density of composites that tends to increase the hardness [1]. Due to the difference in coefficient of thermal expansion (CTE) between the matrix alloy and reinforcement particles during solidification, a large number of dislocations are generated around the Fe$_2$Nb phase reinforcement, leading to
the formation of heterogeneous nucleation sites for precipitates [2, 22]. The influencing factors of hardness variation in the composites are fluidity of the molten matrix, rate of solidification, density of the reinforcement particles, and distribution of reinforcement particles [14]. Ravikumar et al [28] studied the mechanical properties of aluminium/tungsten carbide composites; it was observed that with increasing weight fraction of tungsten carbide, the hardness of the aluminium composite increased. Wang et al [29] studied the microstructure, mechanical and thermal properties with the addition of TiC0.5N0.5 nanoparticles into the Al-Cu matrix; the microhardness continuously increased with an increasing fraction of nanoparticles. Similar observations were reported by other researchers [1, 18, 22].

The impact strength of the material can be calculated by the energy absorbed while its fracture takes place. The impact strength of Al-5Cu-2Ni matrix alloy with the addition of FeNb particles is shown in figure 6 (b). As an experimental outcome, the impact strength of matrix alloy was 2.6 Joules. By the addition of 1%, 3%, and 5% of FeNb into matrix alloy, the impact strengths became 2.3, 2.2 and 2 Joules, respectively. With increasing weight fraction of FeNb particles, the impact strength is reduced. The impact strength is the highest for the matrix alloy and the lowest for the composite with 5 wt% of FeNb particles. However, a reduction in impact strength in composites may be due to the thermal mismatch between the matrix and FeNb particles, leading to the formation of brittle behaviour. Al-5Cu-2Ni alloy hardness got increased due to FeNb addition enhancing the brittleness. Consequently, the amount of plastic deformation energy in the composites decreased. By increasing the deformation energy, there is a greater likelihood of debonding during the fracture, thus lowering the impact strength. However, the material lost its ductility, and the stress concentration area increased. As a result, it favours the crack formation and its propagation. These cracks create the debonding between matrix alloy and particles, thus decreasing its impact strength. It was also observed that the solid solubility of the alloy is greater than the composite [37]. Ravikumar et al [28] observed that impact strength reduces with an increasing fraction of tungsten carbide reinforcements in AA6082 alloy. Similar outcomes were reported by other researchers [38, 39]. The impact strength of the composites may be enhanced by a secondary process of fabrication such as hot forging [37].

3.3. Metallographic characterization of Al-5Cu-2Ni-xFeNb composites

The microstructure study was accomplished using an optical microscope. The microstructures of the composites revealed after fine polishing with silicon carbide papers up to 1500 grit size. For obtaining the mirror surface; finally, velvet cloth polishing was done with 3 μm diamond paste and then cleaned with distilled water [3]. The samples were etched with Keller’s reagent to reveal the structure of the composites [16, 23], as shown in figure 7. It was observed that α -Al dendrites were present in the structure; it is due to supercooling of molten metal in the casting process [13]. The primary α -Al dendrites were comprised of the Al-5Cu-2Ni matrix alloy. It was observed from the microstructures that the grain size of α-Al dendrites significantly changed with different FeNb content. Fine α-Al dendrites were observed with increasing wt% of FeNb content as shown in figures 7(c) and (d). The average grain size was calculated by the line intercept method [23, 29]. The grain size of the composite changed with varying FeNb, as shown in figure 8. Initially, it was 59μm at 1wt% of FeNb, and then gradually decreased to 46μm and 44μm with increasing wt% of FeNb (3wt% and 5wt%) as shown in figure 8. There were not many voids found in the composites; it shows the negligible porosity present in the composites by a stir casting process. Figure 9 shows the high resolution microstructures of Al-5Cu-2Ni matrix alloy and

![Figure 6. Mechanical properties of Al-5Cu-2Ni-xFeNb composites with weight fractions of FeNb content: (a) Microhardness; (b) Impact strength.](image-url)
Al-5Cu-2Ni-5FeNb composite, which clearly depicts the intermetallic compound phases of Al$_2$Cu and Al$_3$Ni$_2$ along with Fe$_2$Nb Phase.

The SEM micrographs with EDS images for matrix alloy and composites are shown in figures 10 (a)–(d). The micro-pores were found in composite; there were negligible pores in the matrix alloy. It is evident that the composite has significant porosity of 3.3% compared with the matrix alloy. The FeNb particles settled at the intermetallic compound grain boundaries of the Al$_2$Cu phase, Al$_3$Ni$_2$ as seen in figure 10(c). The elements present in the matrix alloy and composites were confirmed with the EDS spectrum; the peaks of the elements are
clearly visible in figures 10(b) and (d). It is also confirmed with EDS elements mapping, as shown in figures 11 and 12.

Figure 13 shows the XRD patterns of matrix alloy and various contents of FeNb of the Al-5Cu-2Ni-xFeNb composites. The main constituent phases are primary $\alpha$-Al, intermetallic compounds of $\text{Al}_2\text{Cu}$, $\text{Al}_3\text{Ni}_2$, and $\text{Fe}_2\text{Nb}$ phase. It was observed that the $\alpha$-Al has higher intensity with EDS peaks, as shown in figure 10. With increasing weight fraction of FeNb content in the matrix alloy, the phase $\text{Fe}_2\text{Nb}$ gradually increased and $\alpha$-Al phase intensity reduced. It is evident that the Al-5Cu-2Ni-xFeNb composites have enhanced hardness and tensile strength as compared to matrix alloy. It was observed that for composites with increasing weight fraction of FeNb, there is a slight shift in the position of the $\text{Fe}_2\text{Nb}$ peak towards the right side. The same trend was reported by Jayalakshmi et al [25], who studied the structural and mechanical properties of Ni$_{60}$Nb$_{40}$ particles reinforced Al-based composites.

For the failure analysis of the fractured specimens, a broken portion of the tensile test samples was examined with the FESEM. Figure 14 shows the tensile fracture images of the Al-5Cu-2Ni alloy with various fractions of FeNb. The main cause of fracture is the presence of voids, causing tearing of the matrix [40]. Uniformly distributed large-sized dimples were found in the Al-5Cu-2Ni alloy (figure 14(a)), indicating ductile fracture. In figures 14(b)–(d), the transparent interface of the Fe$_2$Nb phase with matrix alloy is seen. The micro-cracks were found in the composites, which indicate a brittle fracture. The dimple size was reduced with the addition of FeNb due to fine $\alpha$-Al dendrites formation. The addition of hard FeNb particles in matrix alloy leads to a plastic flow localization at the particle-matrix interface, and micro-cracks were noticed. Hence, the failure starts at the metal-particles interface. The fracture growth in high quantity FeNb composites is very much localized. The failure path in these composites is through the matrix due to the matrix cracking and decohesion, and rupture of interfaces. The tensile strength of the Al-5Cu-2Ni-5FeNb composite is the highest among all investigated samples. The fractography of the Al-5Cu-2Ni-5FeNb composite, shown in figure 14(d), shows smaller dimples indicating grain refinement. However, the Al-5Cu-2Ni-5FeNb composite reveals a noticeable fracture surface after tensile tests in macroscopic images and deep dimples spread over the fracture surface. Dimples enclose the greater area with considerable dimple depth and intermetallic segregation due to the reinforced agent present in the matrix [41].
When the FeNb content is further increased to 5 wt%, the fracture surface of the composites is mainly dominated by the coarse eutectic Fe$_2$Nb phase [13]. It is also a typical brittle fracture, and the crack is mainly generated at the corner of the coarse Chinese character eutectic Fe$_2$Nb phase, as shown in figure 14(d). The current results align with Samal et al [37] and Kumar et al [39].
4. Conclusions

The effect of FeNb particles on mechanical properties and metallography was studied. The following conclusions are drawn:

1. Successful manufacturing of Al-5Cu-2Ni matrix alloy with addition of 1wt%, 3wt%, and 5wt% of FeNb could be accomplished by the stir casting route. The porosity of the composite was 3.3% for the Al-5Cu-2Ni-5FeNb composite, which is less than 4%. Thus, the casting is acceptable.
2. The average tensile strength of the matrix was 179 MPa, and Vickers microhardness was 115. With the addition of 1%, 3% and 5% FeNb particles, the tensile strength increased to 185, 193 and 207 MPa, respectively. The corresponding microhardness values were 130, 132 and 151. Thus, 5% ferroniobium as reinforce material could significantly enhance tensile strength and hardness.

3. Increasing micro-hardness decreases the impact strength of the composites. The average Charpy impact strength of Al-5Cu-2Ni matrix alloy was 2.6 Joules. By the addition of 1%, 3% and 5% FeNb particles, Charpy impact strength was reduced 2.3, 2.2 and 2 Joules, respectively.

4. Optical microstructures reveal that the α-Al grains first increased and then reduced with the addition of FeNb particles. The SEM micrographs show precipitation Al₃Cu phase, at the grain boundaries. Results of SEM were correlated with XRD, which confirmed the presence of FeNb particles and the precipitation of matrix phases.

5. From tensile fracture images, a good interface of FeNb with matrix alloy and micro-cracks was observed in composites; much elongation was not found at the grain boundary. Thus, it is a brittle fracture.

Acknowledgments

The authors would like to express their gratitude to the NPIU-New Delhi, TEQIP-III and Indian Institute of Technology Guwahati for providing facilities. Kumara Swamy Pulisheru, wishes to thank the Ministry of Tribal Affairs Government of India for providing fellowship for pursuing PhD.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.
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