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**SYNTHESIS AND CHARACTERIZATION OF  
ULTRAFINE Al-Cu POWDER PARTICLES AND  
SUBSEQUENT DISPERSION FOR HEAT  
TRANSFER APPLICATIONS**

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE  
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By

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2009



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**CERTIFICATE**

This is to certify that the thesis entitle, “SYNTHESIS AND CHARACTERIZATION OF ULTRAFINE Al-Cu POWDER PARTICLES AND SUBSEQUENT DISPERSION FOR HEAT TRANSFER APPLICATIONS” submitted by Mr. SOUMYA RANJAN OJHA in partial fulfilment of the requirements for the award of Bachelor of Technology Degree in Metallurgical and Materials Engineering at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the any Degree or Diploma.

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**Abstract**

*In recent years, fluids containing suspension of nanometer-sized particles (nano fluids) have been an active area of research due to their enhanced thermal conductivity over the base fluids. This makes them very attractive as heat transfer fluids in many applications such as coolants in the automobile and electronics industries, and manufacturing processes. Stable nano fluids are being investigated for numerous applications, including cooling, manufacturing, chemical and pharmaceutical processes, medical treatments, cosmetics, etc. In a better description, nano fluids are engineered colloidal suspensions of nano particles (<100 nm) in a base fluid. Common base fluids include de-ionized water and organic liquids.*

*In this investigation, the two step method of synthesis of ultra fine Al-Cu alloy powder particles and stable dispersion in base fluid is done. Ultrafine powders were prepared by milling elemental Al and Cu powders for 50 hours in a planetary mill. Aiming at the dispersion of nano-Al-Cu is regarded as the guide of heat transfer enhancement, the stability of Al-Cu alloy particles in de-ionized water were studied under different pH values by using nano zeta meter.*

*It is found from XRD that the crystallite size is around 7 nm and lattice strain value is around 1.4 % for Al-Cu. After 50 hours of milling, particles size has been reduced from 28  $\mu\text{m}$  to 300 nm. Transmission electron microscopy (TEM) shows that each particles consists of large number of crystallites of size around 10-15 nm. The stability of nanofluids was also studied by nano zeta meter at different pH of nanofluids for constant ultrasonication time and magnetic stirring. It has been found from Nano zeta meter that the suspension is best stable at pH value of 9.5 corresponding to zeta potential value of -90.60 for Al-Cu alloy with the presence of surfactant.*

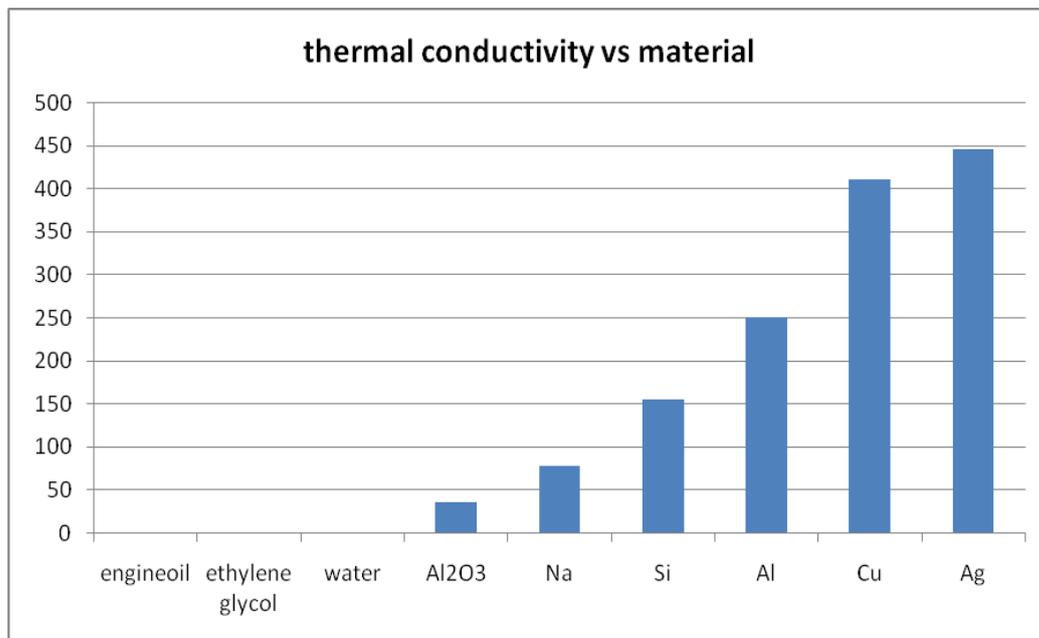
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Nanofluid is a stable colloidal suspension of low volume fraction of ultrafine solid particles in nanometric dimension dispersed in conventional heat transfer fluid [2,3]. Nano fluids may emerge as alternative heat transfer fluids. The term ‘Nanofluids’ is used to indicate a special class of heat transfer fluids that contain stabilized nanoparticles ( $< \sim 100$  nm) of metallic/non metallic substances uniformly and stably suspended in a conventional coolant. Recent studies indicate that nano-particles can favourably alter thermo physical or transport properties of the base fluid [5,6].

Since thermal conductivity of solids is orders of magnitude greater than that of liquids, dispersion of solid particles in a given fluid is bound to increase its thermal conductivity. However, dispersion of milli and micrometer-sized particles is prone to sedimentation, clogging and erosion of pipes and channels. In contrast, nano fluid is a stable colloidal suspension of low ( $< 1\%$ ) volume fraction of ultra-fine solid particles in nano metric dimension dispersed in conventional heat transfer fluid to offer a dramatic enhancement in conductivity of the fluid. It has recently been shown that a two stage approach of synthesizing nanometric powders by mechanical alloying and subsequently dispersing the same in a given fluid could be a more flexible method of producing nanofluid with greater scope of scaling up the process of synthesis. Several techniques have been developed to synthesize nanoparticles such as Laser ablation, Inert gas condensation (IGC), Mechanical attrition, Mechanical alloying etc. [7].

The performance of nanofluid critically depends upon the size and distribution of dispersoids and their ability to remain suspended and chemically un-reacted in the fluid. It is suggested that the uniformity and stability of suspension can be ensured by maintaining appropriate pH, using surface activators or surfactant and employing ultrasonic vibration. Though temperature dependence of thermo-physical properties of the solid particles and fluid can have significant influence on conductivity of nanofluid at elevated temperature or higher thermal gradient, studies on that aspect is beyond the scope of this study as the present nanofluid is designed for use at low temperature range and in small thermal gradient in space shuttles.



*Fig.1. Thermal conductivity of typical materials showing solid particles has a much higher thermal property than liquids.*

However, there has been no established mechanism for the heat transfer enhancement. The reason may arise from the difficulty caused by the fact that the heat-transfer between the base fluid and particles occurs while the particles are in random Brownian motion. Also,

depending on the flow condition and chemical nature of particles, dispersion state can be different. It has been suggested a mechanism by assuming that nanofluid behaves similarly to common solid suspensions in liquid. The heat transfer increases due to the combined effect of Brownian motion of nano-particles, formation of liquid-solid interface, large conductivity of particle itself and clustering of nano-particles [8].

Depending upon the above required versatile properties and applications of nanofluids, we have made an approach to synthesize Al-Cu based nanofluids which can transfer heat more effectively. Our primary objectives are to synthesize elemental ultrafine particles Al-Cu alloy & then preparation of stable dispersion of ultrafine particles in nanofluid to develop heat transfer fluids. Characterization was done by different techniques described in the thesis.

Low thermal conductivity is a primary limitation in the development of energy-efficient heat transfer fluids that are required in numerous industrial sectors. Recently submicron and high aspect ratio particles (nanoparticles and nanotubes) were introduced into the heat transfer fluids to enhance the thermal conductivity of the resulting nanofluids.

#### **METHOD OF PREPARATION OF NANOFLUIDS:**

There are two major methods for producing nanofluids;

- (i) The one-step direct evaporation method represents the direct formation of the nanoparticles inside the base fluids.
- (ii) The two-step method represents the formation of nanoparticles and subsequent dispersion of the nanoparticles in the base fluids.

In either case, the preparation of a uniformly dispersed nanofluid is essential for obtaining stable reproduction of physical properties or superior characteristics of the nanofluids. A two step approach would be adopted here to prepare nanofluids. Several techniques have been developed to synthesize nanoparticles such as Laser ablation, Inert gas condensation (IGC), Mechanical attrition, Mechanical alloying etc. Here the ultrafine particles will be prepared by mechanical alloying (MA) with the help of a Fritsch pulverisette-5 planetary ball mill. High energy ball induces high energy impact on the charged powder by collision between balls and powder causing severe plastic deformation, repeated fracturing and cold welding of charged powder leading to the formation of nanoparticles. The prepared nanoparticles will be

dispersed in de-ionized water by ultrasonic probe and magnetic stirrer to prepare desired nanofluid. Although many experimental studies on nanofluid systems have been performed, the preparation methods for stable nanofluid have not yet been systematically studied yet. In this paper, the primary objectives are to synthesize alloy of Al-Cu and preparation of stable dispersion of particles in nanofluid to develop heat transfer fluids.

## **PREPARATION OF NANOPARTICLES:**

It is done by a process called Mechanical Alloying

**Mechanical Alloying (MA)** is a solid-state powder processing technique involving repeated welding, fracturing, and rewelding of powder particles in a high-energy ball mill. The actual process of MA starts with mixing of the powders in the right proportion and loading the powder mix into the mill along with the grinding medium (generally steel balls). This mix is then milled for the desired length of time until a steady state is reached when the composition of every powder particle is the same as the proportion of the elements in the starting powder mix. The milled powder is then consolidated into a bulk shape and heat treated to obtain the desired microstructure and properties. Thus the important components of the MA process are the raw materials, the mill, and the process variables. We will now discuss the different parameters involved in the selection of raw materials, types of mills, and process variables.

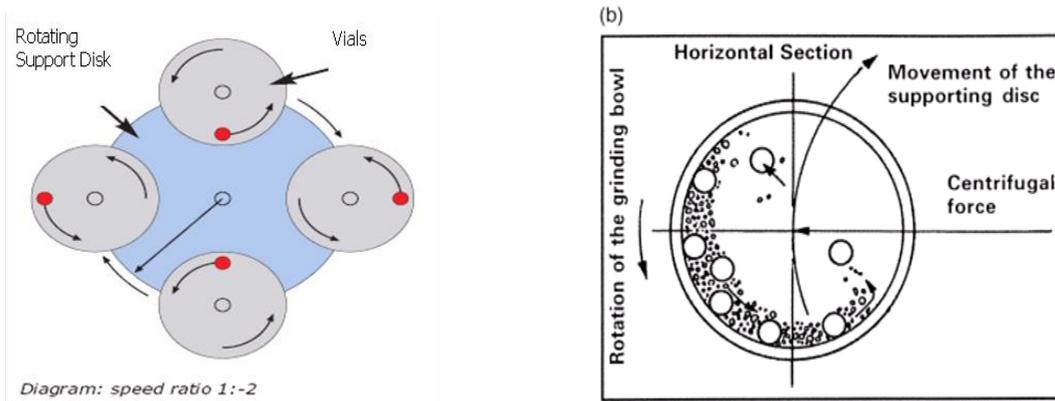
### **Raw materials:**

The raw materials used for MA are widely available commercially pure powders that have particle sizes in the range of 1–200  $\mu\text{m}$ . But, the powder particle size is not very critical, except that it should be smaller than the grinding ball size. This is because the powder particle size decreases exponentially with time and reaches a small value of a few microns only after a few minutes of milling. The raw powders fall into the broad categories of pure metals, master alloys, prealloyed powders, and refractory compounds. Dispersion strengthened materials usually contain additions of carbides, nitrides, and oxides. Oxides are the most common and these alloys are known as oxide-dispersion strengthened (ODS) materials.

## Milling device:

### Planetary ball mills

One popular mill for conducting MA experiments is the planetary ball mill (referred to as Pulverisette) in which a few hundred grams of the powder can be milled at a time. These are manufactured by Fritsch GmbH in Germany and marketed by Gilson Co., in the US and Canada. The planetary ball mill owes its name to the planet-like movement of its vials. These are arranged on a rotating support disk and a special drive mechanism causes them to rotate around their own axes. The centrifugal force produced by the vials rotating around their own axes and that produced by the rotating support disk both act on the vial contents, consisting of material to be ground and the grinding balls. Since the vials and the supporting disk rotate in opposite directions, the centrifugal forces alternately act in like and opposite directions. This causes the grinding balls to run down the inside wall of the vial.



*Fig: 2 first figure shows the movement of vials over the supporting disk & second shows the centrifugal force acting due to vial movement.*

### Variables of mechanical alloying:

Mechanical alloying is a complex process and hence involves optimization of a number of variables to achieve the desired product phase and/or microstructure. Some of the important parameters that have an effect on the final constitution of the powder are:

- Type of mill,
- Milling container,

- Milling speed,
- Milling time,
- Type, size, and size distribution of the grinding medium,
- Ball-to-powder weight ratio,
- Extent of filling the vial,
- Milling atmosphere,
- Process control agent, and
- Temperature of milling.

## **MECHANISMS OF HEAT FLOW IN SUSPENSIONS OF NANO-SIZED PARTICLES:**

### **1. Brownian motion**

Brownian motion, by which particles move through liquid and possibly collide, thereby enabling direct solid–solid transport of heat from one to another, can be expected to increase thermal conductivity.

Brownian motion is characterized by the particle diffusion constant  $D$ , given by the Stokes–Einstein formula

$$D = \frac{k_B T}{3\pi\eta d}$$

Where  $k_B$  is the Boltzmann constant,  $\eta$  is the fluid viscosity, and  $d$  is particle diameter.

Equivalently we can compare the time required for a particle to move by the distance equal to its size  $\tau_D$ , given by

$$\tau_D = \frac{d^2}{6D} = \frac{3\pi\eta d^3}{6k_B T}$$

with time required for heat to move in the liquid by the same distance  $\tau_H$ :

$$\tau_H = \frac{d^2}{6\chi} = \frac{d^2 c_p \rho}{6k_f}$$

## 2. Liquid layering at liquid/particle interface

A large body of literature addresses the effect of the interfacial resistance in thermal conductivity that arises from the formation of a weak interfacial contact. This could not be the origin of the discrepancy between theory and experiment in nanofluids, however, because this resistance would lead to an overestimate of  $k$  and a decrease in thermal conductivity with decreasing grain size. An interface effect that could enhance thermal conductivity is the layering of the liquid at the solid interface, by which the atomic structure of the liquid layer is significantly more ordered than that of bulk liquid. Given that crystalline solids (which are obviously ordered) display much better thermal transport than liquids, such liquid layering at the interface would be expected to lead to a higher thermal conductivity.

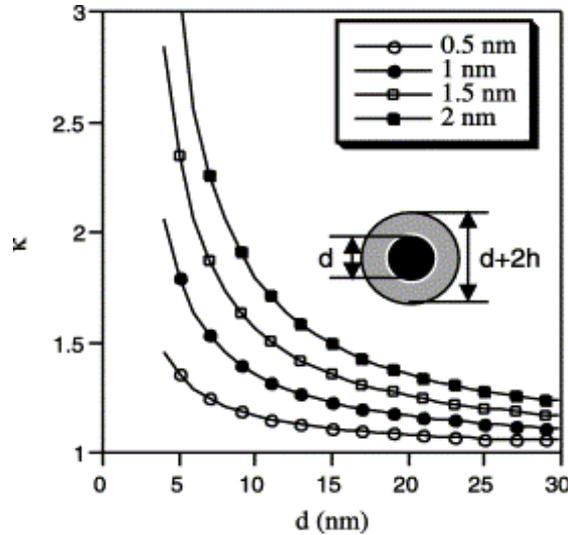


Fig.3. Excess thermal-conductivity enhancement  $\kappa$  due to formation of highly conductive layered-liquid structure at liquid/particle interface for several values of layer thickness  $h$  as a function of particle diameter  $d$ .

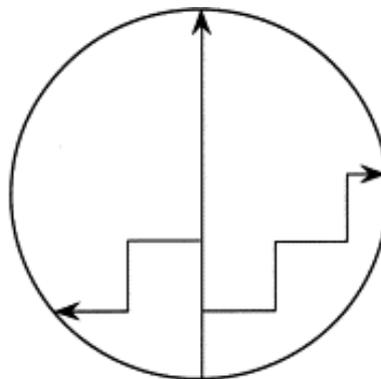
### 3. Nature of heat transport in nanoparticles

In crystalline solids, such as those used in nanofluids, heat is carried by phonons, i.e., by propagating lattice vibrations. Such phonons are created at random, propagate in random directions, are scattered by each other or by defects, and thus justify the macroscopic description of heat transport. In metals, the heat is primarily carried by electrons, which also exhibit diffusive motion at the microscopic level.

Within the simplest theory due to Debye, the mean free path  $l$  of a phonon is given by

$$l = \frac{10aT_m}{\gamma T},$$

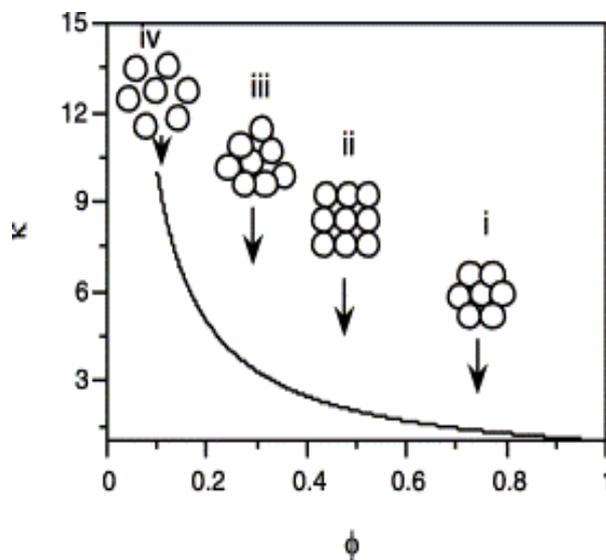
Where  $T_m$  is the melting point,  $a$  is the lattice constant ( $\approx 0.5$  nm), and  $\gamma$  is the Gruneisen parameter.



*Fig.4. Schematic diagram of ballistic and diffusive phonon transport mechanisms in a solid particle.*

#### 4. Effects of nanoparticle clustering

By creating paths of lower thermal resistance, clustering of particles into percolating patterns would have a major effect on the effective thermal conductivity. However, clustering to the extent that solid agglomerates span large distances are unlikely; moreover any such large clusters would most likely settle out of the fluid. Indeed, although the percolation threshold for random dispersions is  $\approx 15\%$  volume fraction in three dimensions, the unusual enhancement of thermal conductivity is already observed at very low volume fractions of  $\approx 1\%$  and less.



*Fig. 5. Excess thermal conductivity enhancement  $\kappa$  due to increased effective volume  $\phi$  of highly conducting clusters. Schematic diagrams indicate (from right to left) (i) closely packed fcc arrangement of particles, (ii) simple cubic arrangement, (iii) loosely packed irregular structure of particles in physical contact, and (iv) clusters of particles separated by liquid layers thin enough to allow for rapid heat flow among particles.*

### 3.1 SYNTHESIS OF ULTRAFINE PARTICLES

Milling was carried out in Pulverisette-5 planetary ball mill with steel vials and steel balls. Starting material used for milling Al-Cu alloy powder of equal % by weight. The ball to powder weight ratio (BPR) was 10:1. Milling was conducted at 300 rpm in wet medium (about 50 ml of toluene) to prevent undue oxidation and agglomeration of powder. Powder particles were milled for 50h in two vials- each containing 35g powder and 350g steel balls. Steel balls of diameter 10mm were used for milling. Powder sample was picked up from the vials after selected interval of milling time to see the change in shape and size reduction of powder sample.

### 3.2 DISPERSION OF POWDER:

In the two-step method, nanoparticles were first separately produced, and then the prepared nanoparticles were dispersed in the base fluid with the assistance of various physical treatment techniques, including the stirrer, the ultrasonic bath, the ultrasonic disruptor, and the high-pressure homogenizer. These two-step methods were aimed at dispersion of these submicron solid particles in ethylene glycol to produce nanofluids with different levels of solid dispersion. Solid particles were de agglomerated and homogenized by adding an appropriate surfactant (1 vol. % oleic acid) and intensive ultrasonic vibration and magnetic stirring, respectively. The particle and grain sizes of Al-Cu alloy powders were varied by milling for different numbers of hours. The milling was carried out in wet conditions in toluene to prevent undue oxidation, cold welding and agglomeration. The identity and grain size of phases were determined by X-ray diffraction (XRD). The average crystallite size and

lattice strain were measured by separating the X-ray peak broadening contributions due to the Gaussian and Cauchian factors after subtracting the broadening due to strain and instrumental errors. Bright field transmission electron microscopy (TEM) studies were carried out to ascertain the size, morphology and distribution of the powder particles.

#### **A. X-RAY DIFFRACTION (XRD):**

X-ray diffraction of the milled powders was performed using the diffractometer (ISO Debyeflex-2002, supplier: Rich Seifert & Co., Germany). The radiations used were  $\text{CuK}\alpha$  ( $\lambda=1.542 \text{ \AA}$ ). X-ray diffraction was carried out with a scan speed of  $3^\circ/\text{minute}$ .

#### **B. SCANNING ELECTRON MICROSCOPY (SEM):**

The SEM micrographs of the milled powders were obtained using the scanning electron microscope (JEOL). The images were taken in secondary electron (SE) mode.

#### **C. TRANSMISSION ELECTRON MICROSCOPY (TEM)**

The sample for TEM was prepared by adding a pinch of milled elemental metallic powder particles in the beaker containing acetone and kept in an ultrasonic bath for about 15 minute to get uniform dispersion of powder particles in the liquid. After that 2 drops of fluid containing dispersed particles were added in carbon coated Cu-grid and then dried. The desired sample was fixed in the sample holder of TEM for analyzing the internal structure of mechanically alloyed powder.

### **3.3 STABILITY OF NANOFUIDS:**

The stability of Nanofluid was determined by measuring zeta potential values of elemental metallic powder dispersed in deionised water. However, for measurement of zeta potential, dilute fraction of metallic nano-suspension was selected here. The values of zeta potential  $\zeta$  can be calculated by the Helmholtz-Smoluchowski equation.

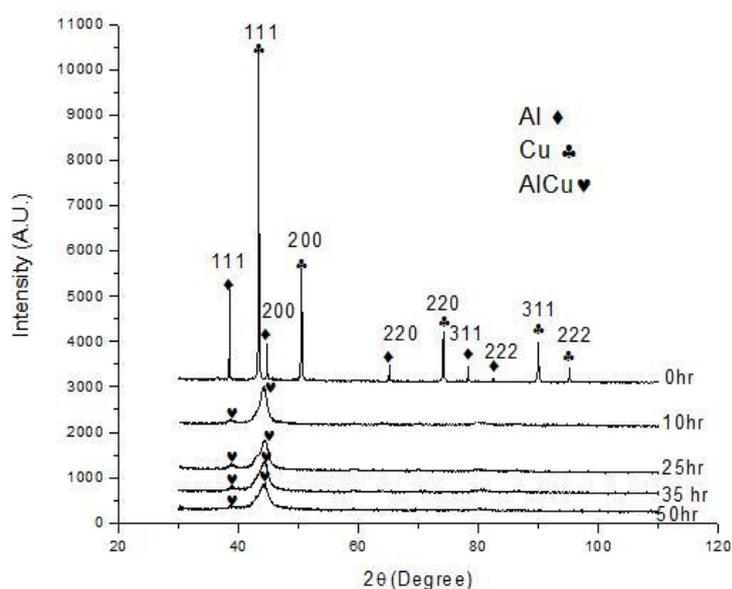
$$\zeta = \mu U / \varepsilon$$

Where  $U$  is the electrophoretic mobility, and  $\mu$ ,  $\varepsilon$  are the viscosity and the dielectric constant of the liquid in the boundary respectively.

In case of Al-Cu alloy powder particles, the zeta potential is zero at isoelectric point. Therefore the force of electrostatic repulsion between particles is not sufficient to overcome the attraction force between particles and hence the dispersion is least stable. As pH increases or decreases by adding reacting reagent oleic acid, then the particles tend to acquire more charge, so the electrostatic repulsion force between particles becomes sufficient to prevent attraction and collision between particles caused by Brownian motion. Greater electrostatic force can also lead to more free particles by increasing particle-particle distance so that the distance exceeds the hydrogen bonding range between particles and further reduces the probability of particle coagulation and settling and hence improving the dispersion stability of Al-Cu alloy.

#### 4.1 X-RAY DIFFRACTION (XRD)

For structural studies, the prepared samples were characterized using laboratory setup of X-ray diffraction with Cu-K $\alpha$  radiation ( $\lambda=1.54\text{\AA}$ ). The XRD patterns of Al-Cu alloy powder particles at different intervals of milling time are shown in Fig.6. XRD pattern of as received powder shows the peaks of Cu and Al, whereas the final milling product is a single phase nanocrystalline Al-Cu alloy which is clear from the graph. It is evident from the figure that after 10 hours of milling, Al-Cu has started to form. It is also clear from the figure that Bragg peaks for milled product (after 50h of milling) are broad, suggesting accumulation of lattice strain and reduction in crystallite size.



*Fig.6. XRD pattern of milled powder of Al-Cu alloy.*

## Crystal size and lattice strain

To find the crystallite size, the milled powder was analyzed under X ray diffraction (XRD) with CuK $\alpha$  radiation. The XRD peak broadening was used to measure the crystallite size and internal strain. The decrease of the grain size and lattice strain to characterize the activation process has been determined from the X-ray diffraction patterns. The crystallite size and the lattice strain of the powder measured from the XRD peak broadening is shown as a function of milling time in table 1.

**Table a: variation of crystallite size and lattice strain as a function of milling time**

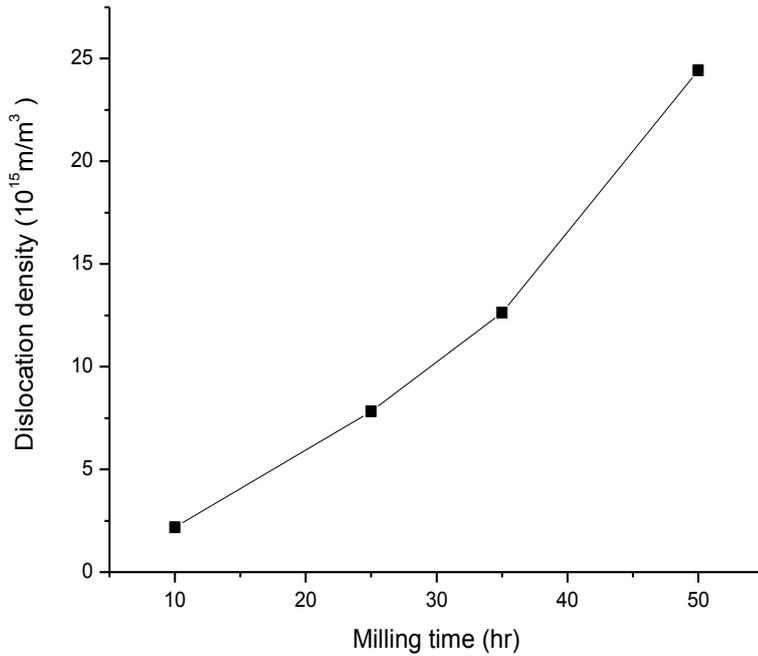
Milling time	Crystallite size (nm)	Lattice strain (%)
10 hr	21	0.435
25 hr	11	0.815
35 hr	9	1.028
50 hr	6	1.434

## 4.2 Dislocation density

During high energy milling (HEM), the milling energy leads to flattened surfaces. Flattening is also accompanied by an increase in the dislocation density. Dislocation density was assumed to be at least one dislocation per crystallite. Hence dislocation density (N) becomes the inverse square of the crystallite size.

$$N = (Lc)^{-2}$$

The dislocation density increases continuously with milling time as shown in fig. 7. The dislocation density increases due to heavy plastic deformation during HEM.



*Fig. 7. Dislocation density of milled powder at different milling time.*

### **4.3 PARTICLE SIZE ANALYSIS**

To study the size reduction of powder during milling, particle size was measured after different milling periods. Firstly, the liquid dispersant containing 500ml of distilled water and 25 ml of sodium hexa metaphosphate was kept in the sample holder. Then the instrument was run keeping ultrasonic displacement at 10.00 micron and pump speed 1800 rpm.

Fig. 8 (a) shows the particle size analysis of powder milled for different periods. It is clear from the graph that particle size reduces during milling. It is noted that 80% of the particles are finer than 10  $\mu\text{m}$  after 50 hours of milling. Fig 8(b) shows median size plot of powder milled for different periods. It is observed that median size has been reduced from 22 to 3  $\mu\text{m}$  after 50 hours of milling. In the initial milling period, size reduction rate is very high, whereas as milling progresses size reduction rate decreases and tend to remain constant.

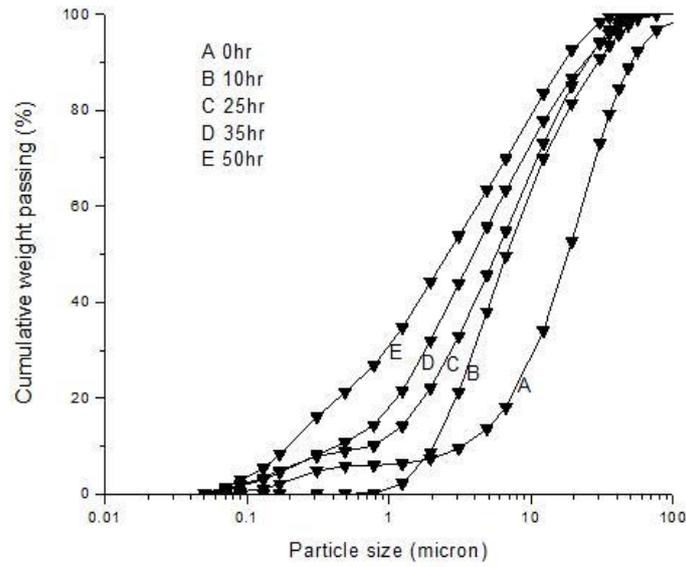


Fig.8(a) shows the particle size distribution of powder at different intervals of milling time.

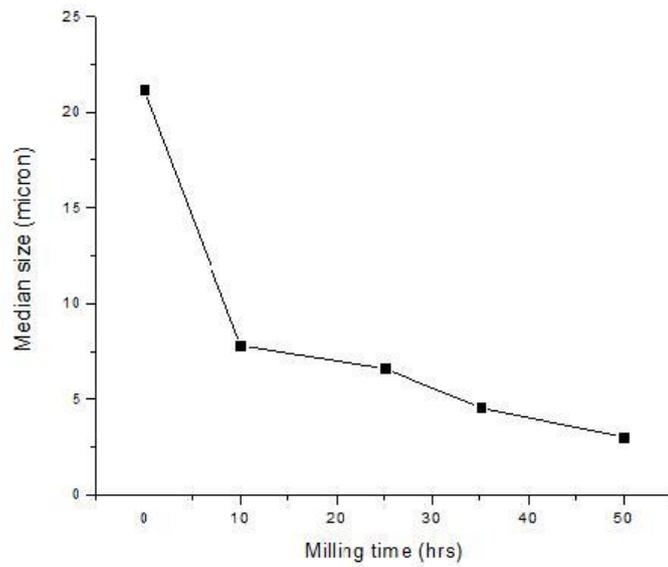
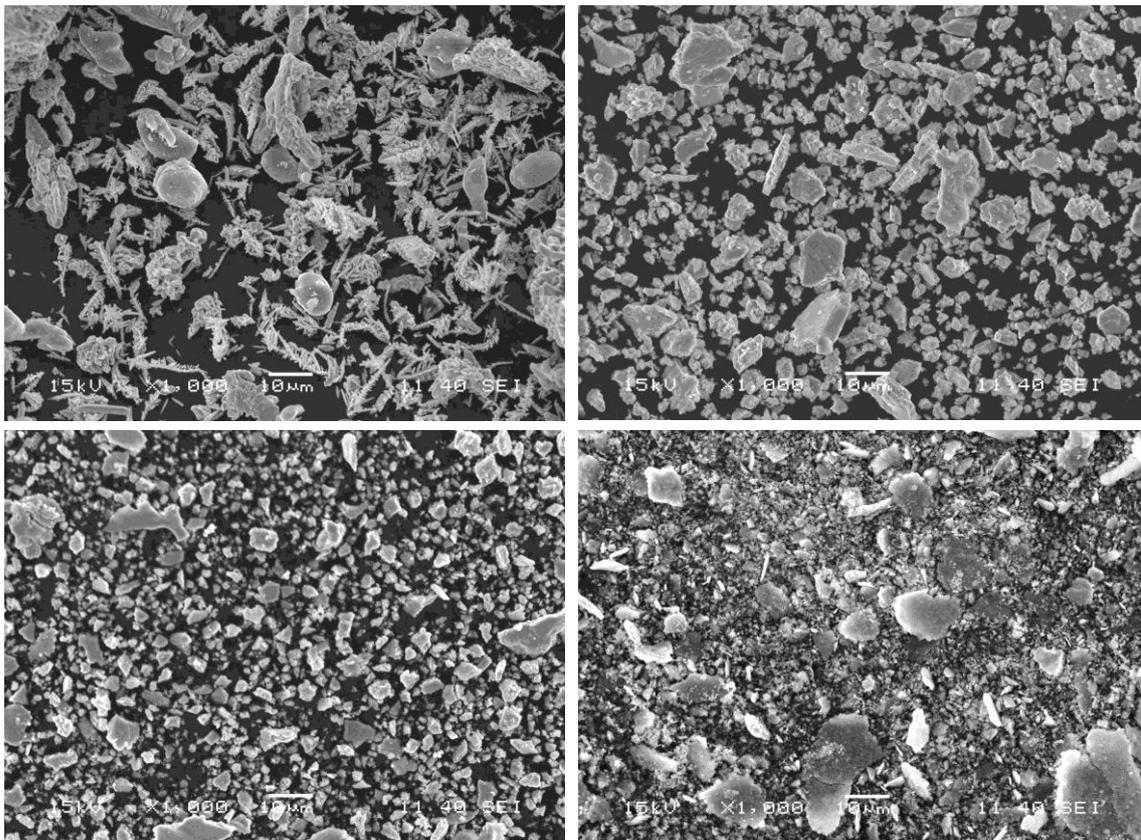


Fig.8(b) median size of Al-Cu powder particles at different milling time.

#### 4.4 SCANNING ELECTRON MICROSCOPY (SEM):

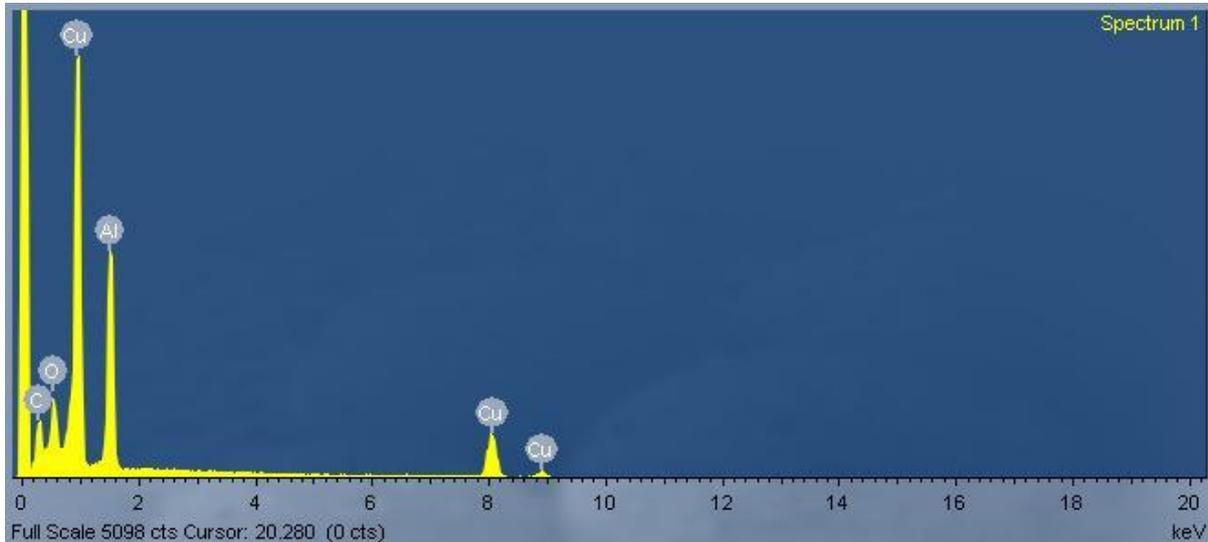
By 50 hours of milling in planetary ball mill it is possible to prepare very ultra fine powder particles of Al-Cu alloy. This microscopic study helps to analyze particle size, morphology, types of other materials present in the structure. SEM study was done for powder different milling time at different magnifications. At the initial stage of milling, the powders of Al and Cu are bulky, with random shape and size. As the milling progresses the powders become more homogeneous and compact.



*Fig.9. SEM micrographs of Al-Cu alloy at different milling times: 0 hrs, 10 hrs, 25 hrs, 50 hrs.*

From above pictures it can be seen that with increasing milling time the grain size decreases and particles become flat because of straining.

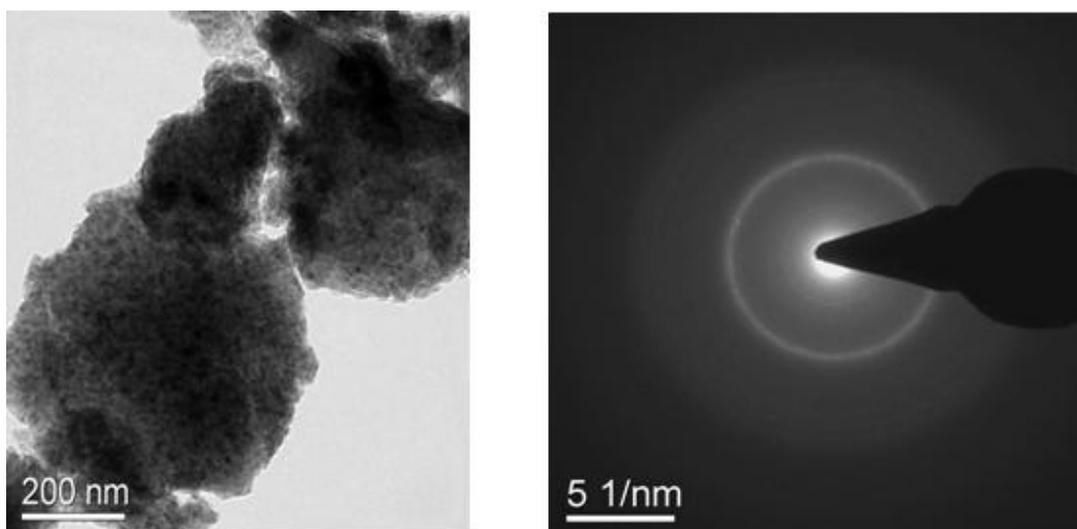
Fig. 10 shows the EDAX analysis of 50 hours milled product. The EDAX spectrum shows the presence of O and C peaks along with Al and Cu. The reason is that milling was performed in open atmosphere and so some oxidation has occurred during milling.



*Fig.10. EDAX spectra of 50 hours milled powder.*

#### **4.5 TRANSMISSION ELECTRON MICROSCOPY (TEM):**

The sample for TEM was prepared by adding a pinch of milled elemental metallic powder particles in the beaker containing acetone and kept in an ultrasonic bath for about 15 minute to get uniform dispersion of powder particles in the liquid. After that 2 drops of fluid containing dispersed particles were added in carbon coated Cu-grid and then dried. The desired sample was fixed in the sample holder of TEM for analyzing the internal structure of mechanically alloyed powder. Fig.11 shows the bright field TEM micrograph and corresponding SAD pattern of 50 hours milled powders. It is evident from the figure that the particle size is around 300nm and contains large number of crystallites (size around 15-20 nm) with difference in contrast due to the variation of orientation. It is evident from the figure that the particle size is around 300nm and contains large number of crystallites (size around 15-20 nm) with difference in contrast due to the variation of orientation.



*Fig.11. Bright Field TEM micrograph and corresponding SAD pattern: (Al-Cu)*

#### **4.6 STABILITY STUDY:**

In case of Al-Cu alloy powder particles, the zeta potential is zero at pH= 9.7(fig. 13), which is isoelectric point. Therefore the force of electrostatic repulsion between particles is not sufficient to overcome the attraction force between particles and hence the dispersion is least stable. As pH increases or decreases by adding reacting reagent ammonium hydroxide (NH<sub>4</sub>OH) or acetic acid respectively, the particles tend to acquire more charge so the electrostatic repulsion force between particles becomes sufficient to prevent attraction and collision between particles caused by Brownian motion. Greater electrostatic force can also lead to more free particles by increasing particle-particle distance so that the distance exceeds the hydrogen bonding range between particles and further reduces the probability of particle coagulation and settling and hence improving the dispersion stability of Al-Cu alloy.

At pH = 10.3 and 4.96, the zeta potential becomes higher; the electrostatic repulsion force between particles is stronger, and the coagulated particles can re disperse through mechanical force. Therefore the dispersion stability of Al-Cu alloy is best at pH=10.3 and 4.96 (fig. 12). If pH-value is more than 10.3 or less than 4.96, then the zeta potential of particle surface and

electrostatic repulsion force decreases due to compression of electrical double layer. Therefore, the suspension exhibits a poorer dispersion.

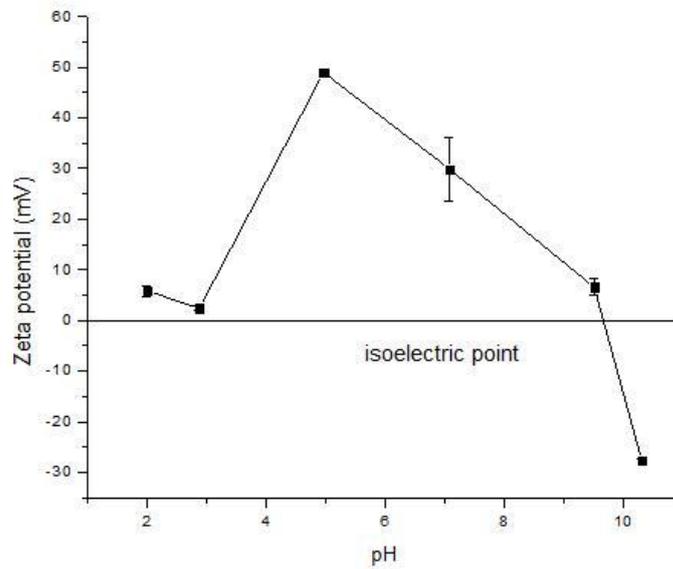


Fig.12. The evolution of zeta potentials of the deionised water-based elemental metallic powder nanofluids as a function of PH without surfactants. (Al-Cu)

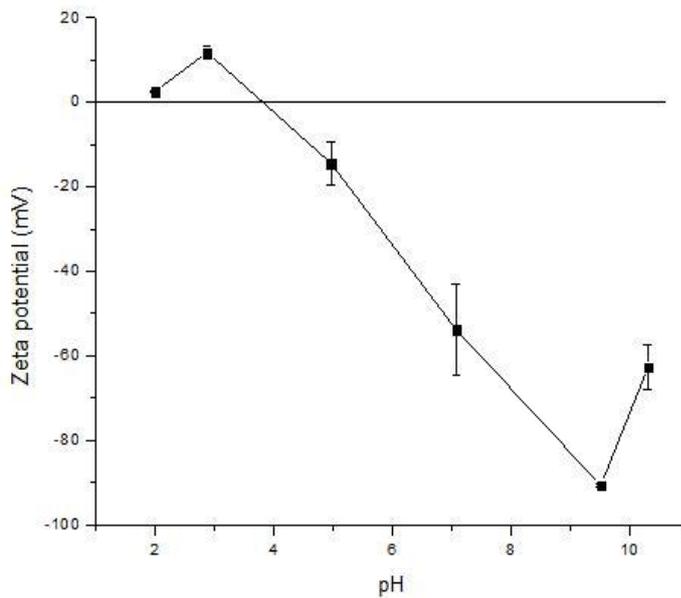


Fig.13. The evolution of zeta potentials of the deionised water-based elemental metallic powder nanofluids as a function of pH with surfactants (Al-Cu)

For Al-Cu alloy powder with the presence of surfactants, the zeta potential is zero at pH = 3.8 which is isoelectric point as shown in *Fig 13*. Isoelectric point is the point at which zeta potential crosses the zero line. At pH = 2.87 and 9.5, the zeta potential becomes higher; the electrostatic repulsion force between particles is stronger, and the coagulated particles can redisperse through mechanical force. Therefore the dispersion stability of Al is best at pH=2.87 and 9.5. If pH-value is more than 9.5 or less than 2.87, then the zeta potential of particle surface and electrostatic repulsion force decreases. Therefore, the suspension exhibits a poorer dispersion.

The following conclusions can be drawn from the present investigation:

1. It is possible to prepare ultrafine Al-Cu particles through mechanical alloying process by 50 hours of planetary ball milling.
2. The crystallite size decreases and internal strain increases rapidly with milling time up to about 25 hours. With further milling, the crystallite size remains almost constant but the lattice strain appears to increase. It is found from XRD that the crystallite size is around 31nm after 50 hours of milling.
3. The dispersion stability of Al-Cu nanoparticles in nanofluids is best at pH value of 4.96, 10.3 corresponding to zeta potential value 49, -27.7 without presence of surfactants respectively. While in the presence of surfactants, the dispersion stability of Al-Cu nanoparticles in nanofluids is best at pH value of 2.87, 9.5 corresponding to zeta potential value 11.8, -90.6 respectively.

- Thermal conductivity of nanofluids can be measured by varying the volume fraction of solid particles.
- Development of computer based models of nanofluid phenomena including physical and chemical interactions between nanoparticles and base-fluid molecules.

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