CHAPTER 2

LITERATURE REVIEW

The present chapter shows an overview of the literature review regarding the development, microstructural, mechanical and tribological characterizations of copper-based composites and hybrid composites. Various authors have developed copper based composites and hybrid composites by different techniques and reported their results. This chapter is organized in the different sub-category on the basis of related work and literatures available.

2.1. Copper metal

Mallikarjuna et al. (2017) reported that the copper is an important engineering material widely used in its pure state and pure copper is the most important material for the electrical industry.

It has high corrosion resistance, electrical conductivity and is easy to fabricate. It has also reasonable soldering, joining characteristics and tensile strength. Copper based composites and hybrid composites are extensively used in different engineering applications.

2.2. Composites

When two or more constituent materials are combined on a microscopic scale it results in a composite material whose physical properties are quite different than the properties of the constituents due to their synergy. Basically two kinds of composites can be developed according to the reinforcements in the matrix. When the reinforcing phase is developed within the matrix during its fabrication is called *in-situ* composite. However, in *ex-situ* composites where the reinforcing phases are developed separately and then integrated during composite fabrication by solidification processing or powder metallurgy route.

The MMC has untapped potential for numerous applications. Several synthesis techniques have been elaborated for their development in recent times. By utilizing these techniques a huge variety of metal matrix (copper, nickel, titanium, iron and aluminum) and reinforcing particles (oxides, nitrides, carbides, borides and their mixtures) have been synthesized.

Rajmohan et al. (2014) developed ex-situ aluminium-based hybrid composites using reinforcement of nano copper oxide (CuO) and micro silicon carbide (SiC) externally. It was observed that the density, micro hardness and tensile strength increases with increasing content of fairly dispersed CuO nano-particles from 0 to 2.0 wt % with constant wt % of SiC in the aluminium matrix, owing to their good interfacial bonding. It was found that the inclusion of CuO in the metal matrix composites improve the structure and properties of the composite materials. Ahmed et al. (2004) reported the copper-based hybrid composites by utilizing the SiC and graphite as reinforcements. Liquid metallurgy route was used to develop such copper based hybrid composites. It was found that the hybrid composites have improved hardness, tensile strength and wear resistance as compared with monolithic copper materials and these properties increases with increasing reinforcing contents. However, Tu et al. (2003) synthesized TiB_2 reinforced *in-situ* Cu–based composite by reaction between copper–boron melts and pure titanium. It was observed that the wear resistance, hardness and yield strength increases with increasing content of uniformly dispersed TiB_2 nano-particles in the copper matrix from 0.5 to 2.5 wt %, owing to their good bonding between interfaces. While the developed *in-situ* composites' electrical conductivity decreases significantly due to solubility of titanium and the wear strength of the material improved which make it an appropriate candidate for application in electrical sliding contacts.

2.3. Hybrid composites

When, different kinds of reinforcements (particulates, fibers etc.) are added into a single matrix that leads to hybrid composites. In hybrid composites, matrix may be of metal, polymer, ceramic and carbon. The hybrid composite which has two or more kinds of reinforcement, the benefit of one type of reinforcement could complement with what are lacking in the other. These hybrid composites show a better performance with an optimum cost (Jacob et al., 2004; Thwe et al., 2003). The behaviors of the hybrid composite mainly depend upon the content, dimensions, orientation of reinforcements and bonding between reinforcement to matrix. The properties of the hybrid composite are also depending on the failure strain of individual reinforcements. Highest hybrid results are observed when the reinforcing phases are highly strain compatible (Sreekala et al., 2002).

The properties of the hybrid system can be determined by the following rule of mixtures.

$$PH = P_1V_1 + P_2V_2 + P_3V_3 + \dots\dots\dots \qquad (2.1)$$

$$V_1 + V_2 + V_3 + \dots\dots = 1 \qquad (2.2)$$

where, PH- Property to be investigated

P_1- Property of the first system

P_2- Property of the second system

P_3- Property of the third system, and so on.

V_1, V_2 and V_3 are the respective relative hybrid volume fractions and so on.

2.4. Classification of composite materials

2.4.1. Classification based on the matrix

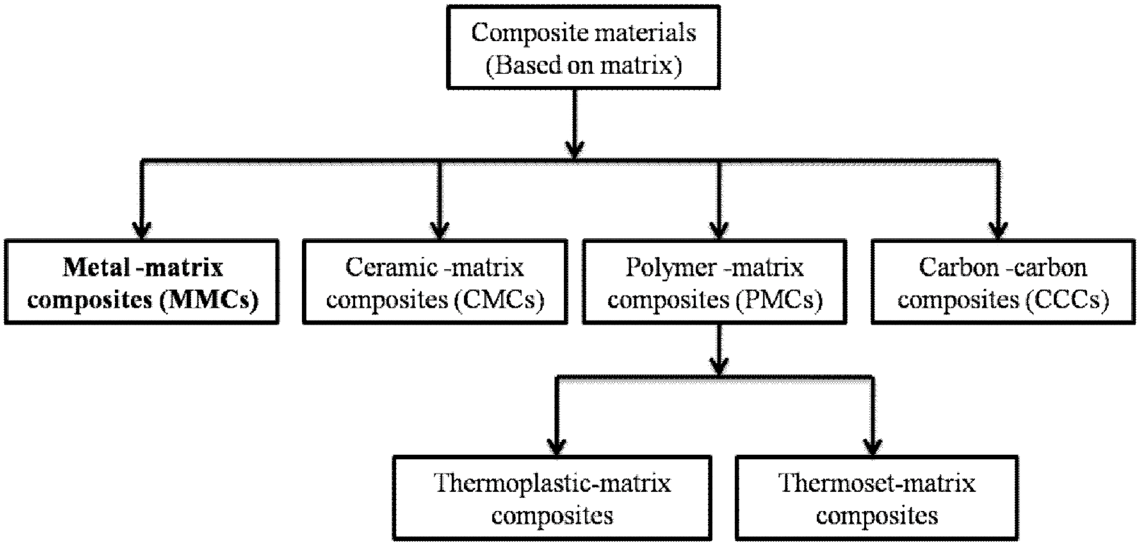

Fig.2.1. Classification of composite materials based on the matrix used

2.4.1.1. Metal matrix composites (MMCs)

Metal matrix composites (MMCs) consist of at least two components in which one must be a metal and other material may be a different metal, ceramic or organic compound as reinforcement.

2.4.1.2. Polymer matrix composites (PMCs)

PMCs possess polymer as the matrix phase and fibers as the reinforcing phase such as carbon or aramid and E-glass. The various kinds of polymer matrix composites generally used are carbon fiber-reinforced polymer (CFRP) composites, glass fiber-reinforced polymer (GFRP) composites and aramid fiber-reinforced polymer composites. Vinyl esters and polyesters are commonly used polymers as matrix.

2.4.1.3. Ceramic matrix composites (CMCs)

A ceramic matrix composite (CMCs) consists of ceramic materials as matrix phase and other as a reinforcing phases. For improving the fracture toughness of ceramics materials, its composites are primarily developed. Therefore, it can be used in extreme high temperature and stress environments. The second phase in CMCs such as reinforcement plays a vital role in obstructing the cracks propagation, where the reinforcing phase can be particles or whiskers and fibers.

2.4.1.4. Carbon-carbon composites (CCCs)

This is a new class of engineering materials which exhibit brittle to pseudo plastic behavior however, they are ceramic in nature. It is known as an inverse composite in which the carbon fibers are embedded in the matrix of carbon, it is also famous as all carbon composites. Apart from several biomedical and industrial applications the carbon-carbon composites are used in very specific applications such as aircraft brake discs, leading edges, re-entry nose-tips and rocket nozzles due to its extremely good thermo-structural properties. Design flexibility can be achieved by using the versatile multidirectional carbon-carbon product technology (Rohini, 1993).

2.4.2. Classification based on the reinforcement

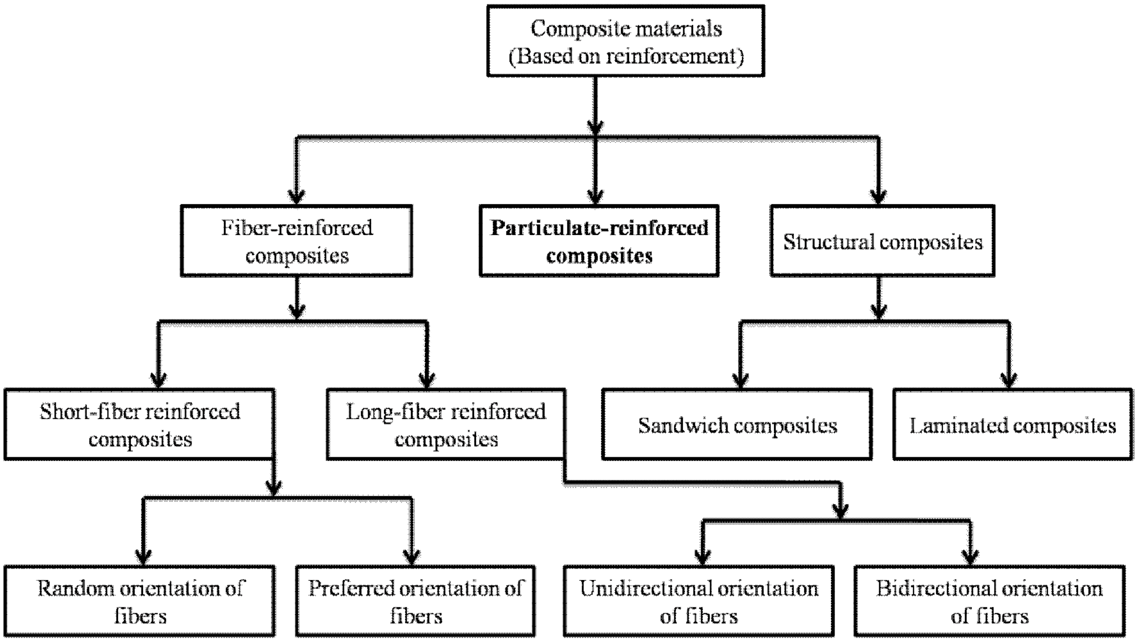

Fig.2.2 Classification of composite materials based on the reinforcement used [Schoutens et al. (1982)]

2.4.2.1. Fiber reinforced

Fiber reinforced composite includes all sorts of fibers, whiskers and filaments, continuous and non-continuous, over the entire range of concentration of the reinforcements.

2.4.2.2. Particle reinforced

Particle reinforced composite is almost similar to the dispersion-strengthened composite but the particles size is greater than 0.1 μm and the volume percentages can be greater than 25%.

2.4.2.3. Structural composites

In this kind of composite uniformly distributed fine hard particulates, size in the range of 0.01 to 0.1 μm and in a volume percentage from 1 to15 % are used to enhance the strength and hardness.

(a) Sandwich composites

The sandwich composites are developed by using of two thin, stiff and strong skins separated by a thick, light and weaker core (Arboui et al., 2009). To make easier the load transfer mechanisms between the components, the core materials and the faces are joined with an adhesive. The sandwich composites use to develop a structural element that has very good bending strength and stiffness to weight ratios. The applications of the sandwich composites are in automotive industries, aerospace, marine, and train (Yu et al., 2005; Wang et al., 2012; Kim et al., 2013).

(b) Laminated composites

The layers of different materials are used to develop this laminated composites in which the different layers are bonded together with adhesives, to provide additional durability, strength, and other benefit.

2.5. Type of reinforcements used in metal matrix composites

The five major categories are as follows:

- Continuous fibers
- Discontinuous fibers
- Whiskers

- Particulates
- Fabric, braid etc.

The above five major categories of reinforcement are shown in Fig.2.3. Apart from the metallic wires, the ceramics are commonly utilized as reinforcements. The ceramic reinforcements may be nitrides, oxides and carbides of metals. Due to their excellent specific strength and stiffness at both room and elevated temperature these ceramics materials are often used as reinforcements. The base metal is affected by each of the ceramic reinforcement in different ways.

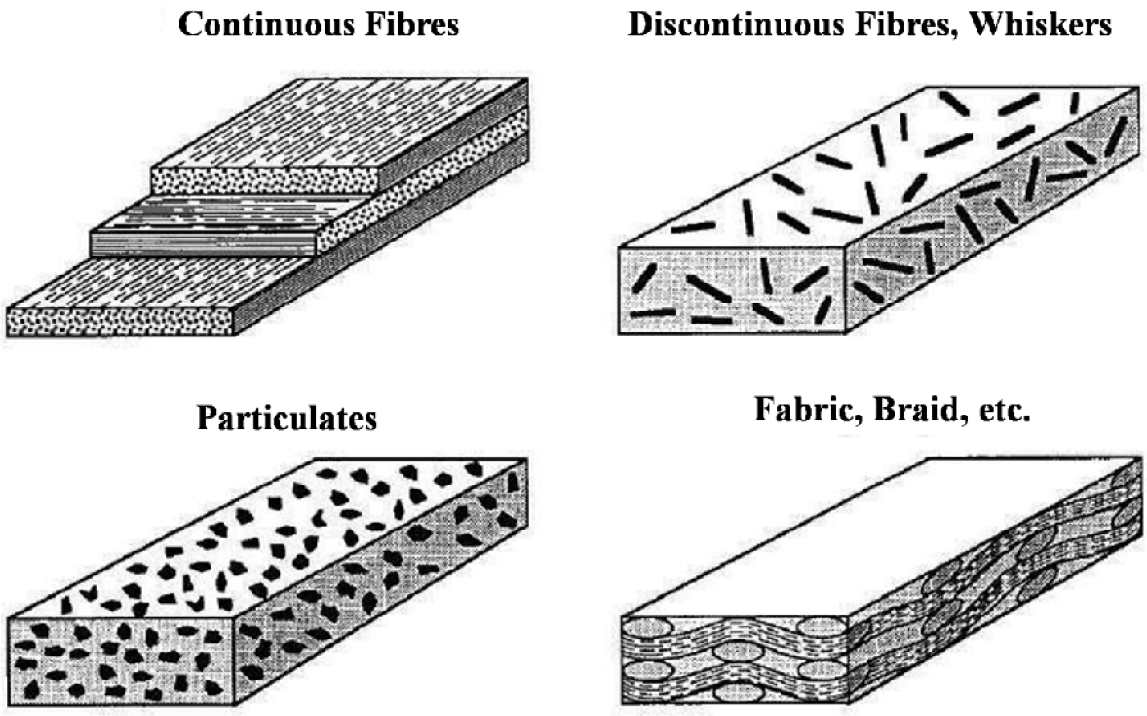

Fig.2.3. Type of reinforcements used in metal matrix composites

2.6. Advantages of metal matrix composites and hybrid composites

` There are following advantages of metal matrix composites and hybrid composites over monolithic materials:

- At elevated temperatures, it shows better properties
- It displays lower thermal expansion coefficients
- Higher specific modulus
- Wear resistance is better
- Higher specific strength

The metal matrix composites and hybrid composites are preferred in the broad field of applications due to its above mention advantages. The metal matrix composites and hybrid composites have better mechanical properties such as compressive strengths, transverse strength, stiffness, shear strength and temperature capability compared with pure materials or composites with polymer matrix. Ramesh et al. (2009), Mallikarjun et al. (2016) and Prabhu et al. (2014) have reported these advantageous properties over the monolithic materials and also suggested its various applications in starter motor, door locks, blower motors, severe arcing and welding, automotive, aerospace and electronic sectors.

2.7. Synthesis techniques to develop copper-based metal matrix composites and hybrid composites (MMCs)

The various synthesis techniques are used to produce copper matrix composites and hybrid composites (MMCs). Rosso (2006) has classified the synthesis techniques to develop the MMCs based on the processing temperature of metallic matrix. Accordingly, the five categories of processes are shown in the Fig 2.4.

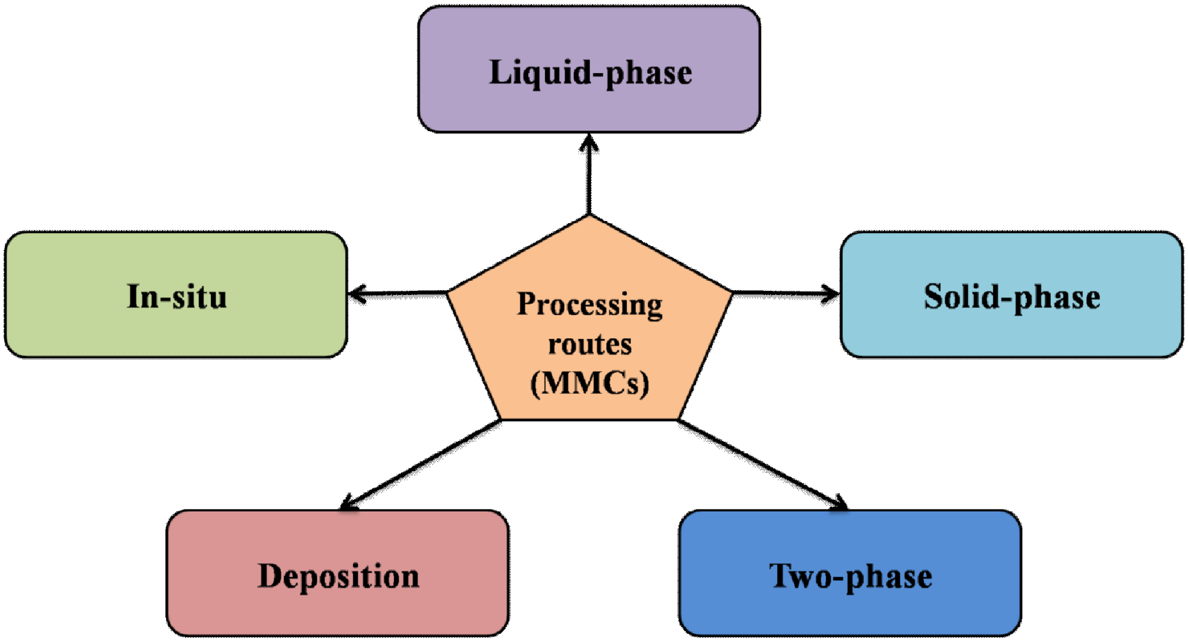

Fig.2.4. Classification of the synthesis techniques to develop MMCs

2.7.1. In-situ process

In this process, the composite materials are developed in a single step from particular starting matrix or alloy where the second phases are developed in-situ. There are several benefits of the in-situ process, in which the developed reinforcing fibers and particles are smaller than as compared to fabrication of second phases separately. Due to the smaller size of reinforcing phase better strengthening is observed in composites. Better and homogeneous distributions of the reinforcing particles are observed in in-situ process. In this technique, the choice of the reinforcing materials is confined by the ability of their precipitation thermodynamically in particular matrix; therefore it is not used for all the reinforcing phases and matrix (Aikin, 1997).

2.7.2. Deposition techniques

In this technique, the composites are developed by coating of each and every fiber on the matrix that is followed by bonding due to diffusion to develop consolidated composites of any geometry like- plate or structural shape. There are different kinds of technique for deposition such as deposition by physical vapor (PVD), immersion plating and deposition by chemical vapor (CVD), (Rosso 2006).

2.7.3. Two-phase processes

This technique is used to mix the matrix and ceramic in the phase diagram region where both liquid and solid phases of the matrix exist. This technique is further classified into two categories such as: compo-casting / rheo-casting and spray deposition.

2.7.3.1. Compo-casting/rheo-casting

Srinivasan et al. (2009) has reported that the uniform mixing can be achieved to a greater extent by allowing the melt to cool to a more viscous; two phase solid liquid state before stirring. The advantage of the process is that it is easy to mix particles more uniformly in a fluid of higher viscosity than in one of lower viscosity.

2.7.3.2. Spray deposition

In this technique molten matrix metal is break into the small particles and simultaneously sprayed with reinforcement powder on to a substrate. High production rates make the process economical (Srinivasan et al., 2009).

2.7.4. Solid phase processes

In this technique, the particulate reinforced MMCs are developed by blended mixture of particulates and matrix powders where numbers of steps are involved in this technique prior to final development of composites. This technique is classified into two categories such as:

2.7.4.1. Diffusion bonding

In this process, a fiber matrix having fibers embedded in a polymer binder is kept between two sheets of matrix foil to form a ply. This can be consolidated or cut into smaller sizes, stacked together in a required sequence and then hot pressed to form the component. It is an expensive process but shapes such as tubes and plates are made by this technique.

2.7.4.2. Powder metallurgy

The matrix and reinforcement are taken in the form of powders in proper proportion, mixed, heated and subjected to pressure causing diffusion to take place. This method is well suited for discontinuous fiber, whiskers and particulate reinforcements. One disadvantage is that there is loss of toughness when reinforcement increases over 50%. In case of powder metallurgy process the sintering can be performed by various routes like- microwave conventional and spark plasma sintering.

Microwave sintering: Microwave sintering is closely related to dielectric properties, which are seen as indicators when materials are exposed to microwave irradiation.

Conventional sintering: In this technique, preformed powder is heated at high temperatures lower than the melting temperature of powder for minutes to hours (ASM Handbook 1998).

Spark plasma sintering: In this sintering process the composites materials is heated by Joule effect and, a load applied on the material.

2.7.5. Liquid phase processes

In this technique, into a molten metallic matrix the ceramic reinforcements are added using different process which is followed by mixing and casting of the final composite solution into a component with different shaped or billets for further fabrication. Kainer et al., (2006) classified three types of liquid phase fabrication methods such as:

2.7.5.1. Melt stirring

The matrix is taken in molten form in which the reinforcement such as particulates, whiskers or discontinuous fibers are added, thoroughly mixed solidified and then cut into required shapes. This technique is simple but due to high temperature during processing can damage the reinforcements.

2.7.5.2. Gas pressure infiltration

In the process, preform is infiltrated by melt metals with the help of gas applied from outside. There is no development of pores, it’s a merit of this technique and this method can be used to produce large composite parts.

2.7.5.3. Squeeze casting

This process is used to development of MMCs by forced infiltration technique of liquid phase. In this technique, pressure is applied through a movable mold on the molten metal to enter into a performed dispersed phase which is placed into the lower fixed mold part. Small parts such as pistons of automotive engine are used to develop using this technique.

2.8. Stir-casting technique

Hashim et al. (1999) have mentioned that the stir-casting technique belongs to family of liquid-phase processes. This technique has been well known among all of the above mention techniques to develop the metal matrix composites (MMCs) and hybrid composites with excellent mechanical and tribological properties for various engineering applications. Stir-casting is most acceptable technique among the different synthesis technique available for particulate reinforced metal matrix composites. Due to the following merits of this technique, it is currently used commercially:

- Lack/absence of complications
- Pliability
- suitability to production of huge quantity
- Optimize the cost of final product

Skibo et al. (1988) have reported that the cost of developing composites using this technique of casting is approximately one-third to half of other technique, however, it goes down to one-tenth for production of higher volume. Table 2.1 displays a relative evaluation of the various techniques generally used for discontinuously reinforced metal matrix composites (DRMMCs) development.

In stir-casting technique, the development of MMCs involves producing a melt of the metal matrix which is followed by the reinforcement addition into the molten matrix and finding an appropriate dispersion. Solidification is the next step of the molten metal possesses suspended reinforcing particles under predefined conditions to achieve the expected distribution of the reinforcing phase in the matrix.

There are some parameters that need to be considered during development of metal matrix composites using the stir-casting technique, such as

- The issue of obtaining a homogeneous dispersion of the reinforcing phases;
- Wettability of the reinforcing phase with the matrix phase;
- Development of porosity in the cast composites; and
- Chemical reactions between the reinforcing phase and matrix phase.

There should be a uniform distribution and good wettability or bonding of the reinforcing phases in the matrix to obtain the optimum properties of the developed metal matrix composites. In order to achieve the optimum property of developed composites, there should be least porosity and no chemical reactions between the reinforcing phase and the metal matrix.

Table 2.1. A relative evaluation of the various techniques used for DRMMC development (Surappa, 1997)

Method	Range of shape and size	Metal yield	Range of volume fraction	Damage to reinforcement	Cost
Liquid metallurgy (stir casting)	wide range of shapes; larger size; up to 500 kg	very high, >90%	up to 0.3	no damage	least expensive
Squeeze casting	limited by preform shape; up to 2 cm height	Low	up to 0.45	severe damage	moderately expensive
Powder metallurgy	wide range; restricted size	High	-----	reinforcement fracture	Expensive
Spray casting	limited shape; large size	Medium	0.3±0.7	-----	Expensive
Lanxide technique	limited by pre-form shape; restricted size	-----	-----	-----	Expensive

2.9. Properties of copper metal matrix composites and hybrid composites

2.9.1. Microstructural and physical properties

A significant variation in the microstructural and physical properties of ex-situ metal matrix composites (MMCs) has been obtained during the last few years by improved techniques, which lead to minimizing in the level of total defects such as porosity of matrix and inhomogeneous dispersion of reinforcing phase. Gillman et al. (1991) have reported that the applications of MMCs in various fields such as automobile, energy, aeronautical and sports division due to the synergistic effect of matrix and reinforcing materials in composites. The improved behavior from these rather unique materials depends on a judicious selection of fabrication techniques, matrix, reinforcements and secondary processes. The selection of development processes is of more important due to its high impact on the dispersion of reinforcements and the interfacial bonding between the reinforcing and matrix phase. Microstructural and physical behaviors are poor if the dispersion of the reinforcing phases is inhomogeneous in the matrix.

Yuanyuan et al. (2012) have reported the microstructural and thermal conductivity of copper metal matrix composites reinforced with of SiC and diamond as hybrid particles. The microstructure of the developed diamond hybrid SiC/Cu composite shows the inferior interfacial strength between reinforcement and matrix by the particle volume fraction as 65 %, while volume mixing ratio of diamond and SiC particles as 7:3. Due to the inferior wettability of SiC in Cu matrix, almost all of the particles settle down from the interface. Further, the inferior wettability of SiC particles in Cu matrix could be improved by coating of Ti. Whereas, the results of the differential effective medium (DEM) theoretical estimation were indicated that the thermal conductivity of 500 $W \cdot m^{-1} \cdot K^{-1}$for diamond hybrid SiC/Cu composite, when the volume fraction of particle is more than 46% and the volume ratio of diamond to SiC particles is higher than 13:12. Quite variation in thermal conductivity of hybrid composite was observed when the size of particle was more than 200 µm. From the experimental results, it was observed that Ti enhances the wettability of SiC in Cu matrix and the thermal conductivity of the diamond hybrid SiC-Ti/Cu was two times higher than diamond hybrid SiC/Cu composite.

Venkatesh et al. (2018) have developed the nano alumina and graphite reinforced copper based hybrid composites using the powder metallurgy route and investigated its microstructural, physical and other properties. From the microstructural investigation, it is observed that the reinforcing particles are uniformly distribution in the metal matrix and their interfaces are clearly visible. Some clustering of reinforcing phase is also observed in the microstructure of composites but due to absence of any micro crack leads to a good interfacial bonding between reinforcement and matrix.

Ravindran et al. (2013) studied the microstructural and density behaviours of aluminium-based hybrid nano-composites with the addition of solid lubricants. The analysis of microstructure reveals the existence of graphite and SiC in all the hybrid nano-composites. It was observed that the good chemical bonding among the Al particles and bonded to each other in such a way which construct a solid structure. The flake graphite and cube like structure of SiC were observed in the microstructure of hybrid composite and found uniform distribution of SiC particles in Al 2024 matrix. The micrograph also displayed the absence of cracks. However, the density of hybrid nano composites was evaluated using the Archimedes' principle and found lower compared with its matrix. It was also observed that the decrease in density of hybrid nano composites with increase in graphite content due to reinforcement of lower density of graphite.

Mai et al. (2018) have developed the copper-based composites reinforced with the nickel nanoparticles anchored graphene nano sheets and investigated its various properties. From the microstructural observation it is found that the nickel nano particles anchored graphene nano sheet with some wrinkles dispersed along with the grain boundary of the copper matrix and observed a homogeneous distribution of the graphene nano sheet. The hybrid composites do not reveal any kind of impurity, voids or gap between the interfaces of matrix and nano graphene sheet which results a strong bonding between the interfaces of matrix and reinforcements.

Hu et al. (2016) developed B_4C and Al_3Ti reinforced aluminium hybrid composites by two-step stir-casting technique and studied its mechanical and microstructural behaviors. The SEM microstructures of prepared materials exhibited the B_4C and blocky Al_3Ti dispersed particles uniformly in the metal matrix with average size of 5 µm. The microstructure also revealed some of reaction compounds with fine plate-like geometry. The intermetallics compound such as fine Al_3BC, narrow strips and blocky AlB_2 phase were also observed in the microstructure. In addition to this the microstructure displayed the gray colored phase around the B_4C reinforcement which indicates severe reactions between interfaces. So, it could be say that the B_4C reinforcing phases were not stable in Al melts.

Chen et al. (2018) have investigated the behavior of copper hybrid composites reinforced with carbon nanotubes-graphene. From the microstructural observation using SEM, it is found that the homogeneously distributed of the reinforcements in the copper matrix without formation of interconnected structures. The absence of gaps or voids is also observed in the microstructure of hybrid composites.

Akbarpour et al. (2013) fabricated and characterized the nano SiC and carbon nanotubes reinforced copper-based hybrid composites. Where, the Archimedes' principle evaluated the experimental density of developed hybrid nano composites with low standard deviation. The theoretical density of the nano hybrid composites was also calculated and found higher than experimental density. The experimental density was lower due to the existence of porosity. It was also observed that the density of materials decreases with increasing content of reinforcements. However, in the microstructural study, it was observed that the uniform dispersion of the CNTs in the copper matrix but as the content of CNTs reinforcement increases the clusters of CNTs were observed. The grain refinement in the hybrid nano composites was observed, it might be attributed to the pinning effect of SiC nanoparticles during solidification. It suggested that the movement of the grain boundaries was obstructed by the reinforcement of small insoluble phases that goes preferentially at the interfaces of grain boundary.

Zhou et al. (2014) have reported that the laser induction hybrid rapid cladding was used to develop a copper metal matrix composites reinforced with carbon nanotubes and Fe_p. In this investigation, microstructures of fine dendrites were observed. Microstructural study of the composite materials revealed that several particles of spherical geometry were unevenly distributed in the copper matrix and connected to each other. The EDS investigation of the composite materials showed that the spherical particle possesses 22.8, 4.2, 73.1 wt% of Cu, Ni and Fe however, the matrix possesses 84.5, 9.7, 5.9 wt% of of Cu, Ni and Fe, respectively. The EDS analysis indicated that Fe was the major constituent of spherical particles, while Cu is major constituent of the matrix. The Fe rich composite materials displayed the relative density of approximately 97.2%. However, the relative density increased to 96.5% from 93.7% when the content of CNT increased to 2.6 wt% from 1, and due to this addition of CNT in the copper rich matrix the spherical Fe particles size became smaller and more uniformly distributed. However, on further increase in content of CNT up to 4.0 wt%, Fe-rich particles become larger of 20 μm in diameter with inhomogeneous distribution in the copper-rich matrix. It was also displayed the lowering in the relative density to 92.3%. The thermal conductivity of the Fe-rich copper based composites was evaluated and found 76 Wm^{-1} K^{-1} that was very low as compared with its matrix. However, it was also observed that the thermal conductivity of the composites first increases and then decreases on the increasing content of CNTs.

Mallikarjuna et al. (2016) studied the effect of CNT and SiC on the microstructural behaviour of copper hybrid nanocomposites. In this study, the HRSEM micrograph of hybrid nanocomposites revealed that the CNTs were dispersed homogeneously in the matrix and no harm to CNTs were seen. The good interfacial bonding was also observed because of no intermetallics compounds were developed at the interfaces that can be due to coating of copper on MWCNTs and SiC. The EDS analysis was done at interfaces of all the composites which revealed only intensity peak of Si, C and Cu elements that denying any possibilities of reaction at interfaces. The theoretical and experimentally densities were measured by using rule of mixture and Archimedes principle, respectively. The hybrid nanocomposites showed the decreasing tendency of both experimental and theoretical density with increasing content of MWCNTs with constant SiC content. It may be due to the addition of low densities materials (MWCNTs and SiC) in matrix. However, the relative density of the nanocomposites decreased minutely on increasing wt% of MWCNTs.

Sorkhe et al. (2014) determined the electrical conductivity of TiO_2 (0, 1, 3, 5 and 7 wt%) reinforced copper composite by using four probe technique. It was observed that electrical conductivity of the developed composites decreases as the content of TiO_2 particles increases. It was also suggested that the low electrical conductivity of the composites was not due to addition of low conducting reinforcing phase. It may also attribute to the presence of the porosity and scattering of the conduction electrons due to the numbers of dislocations developed during the process of milling.

Chandrakanth et al. (2010) developed graphite and TiC reinforced copper based hybrid using microwave sintering. In this investigation electrolytic copper powder (99.5%, 12 μm) were taken as matrix material whereas graphite (99.8%, 50 μm) and TiC (99.2, 11 μm) were taken as reinforcements. The content of graphite was 5 and 10 vol. % and TiC was 5, 10, and 15 vol. %. The sintering of the specimens was performed at 700, 800 and 850°C. TGA investigation of Cu–15TiC-10graphite mixture displayed that there were no weight loss at the ramp rate of 12°C/min and 800°C for sintering. The relative density of the composite materials increased with increasing in temperature of sintering and isothermal holding time. Sintered density of the composites did not show a significant change with increase in temperature of sintering to 850°C from 800°C. The Microstructural investigation of the composites displayed the homogeneous dispersion of the TiC and graphite particles in the matrix. EDS analysis of the composites depicted the presence of C, Ti, and Cu. It was also observed that the porosity in composites increases with increasing content of the graphite due to the agglomerates formation. However, the TiC reinforcement improved the hardness of the hybrid composites by sharing the most of the externally applied load.

2.9.2. Mechanical properties

To attain an effective load bearing potential of the reinforcing particles there must be a homogeneous dispersion of the reinforcing phase in the MMCs. The MMCs display lower toughness, ductility and strength if the dispersion of the reinforcing phase is inhomogeneous in the matrix phase. Conventional development of MMCs demands the incorporation of ceramic particles into the matrices via PM route and casting technique but the ceramic particles frequently agglomerates due to the differences in the density with matrix and surface tension of the melts. Tjong et al, (1999) have explained about the fact of the fine ceramic particles which have a greater tendency to settle down into clusters during the mixing of the reinforcing and matrix powders with variable sizes. Therefore, stir-casting technique is used in which stirring process prevent the agglomeration of ceramic particles and distributed more homogeneously in the matrices which significantly improved the stiffness, yield strength, creep and wear resistance of the metal matrix composites.

Slipenyuk et al, (2004) and Prasad et al. (2007) have suggested that the MMCs reinforced with different reinforcements such as ceramic particles, whiskers or fibers are of great interest for industrial applications because of its good mechanical properties like-modulus of elasticity, fatigue and tensile strength, fatigue including good resistance of wear as compared with its matrices. Generally, the MMCs reinforced with particles show the better physical and mechanical properties. The MMCs which are developed by the powder metallurgy technique exhibit the best results when the particle size ratio (PSR) of matrix to reinforcement is close or less than 1. The agglomeration of the reinforcing particles take place when the particle size of matrix is significantly high as compared to particle size of reinforcements which leads to the lowering of the mechanical properties of the MMCs.

Hu et al. (2016) have investigated the mechanical behaviors of the (B_4C+Al_3Ti)/Al hybrid composites developed by the two-step stir-casting technique. In this study, it was observed that the elongation, tensile strength and hardness of the hybrid composites improved by 21.6, 41.8 and 13.6 respectively as compared with composites free from Al_3Ti particles. Such results suggested that Al_3Ti particles not only act as reinforcement but also motivated the continuous development of the TiB_2 layer at the interfaces of the matrix and reinforcements. This developed layer stops the further reaction of B_4C with liquid Al and leads to the better bonding between the interfaces of Al matrix and B_4C reinforcements.

Ravindran et al. (2013) investigated the mechanical behavior of aluminium nano hybrid composites with the addition of solid lubricants. In this investigation, a ball indenter with diameter of 2.5 mm and a load of 30 kg at Brinell scale was used to measure the hardness of sintered products. The hybrid composites displayed a poor hardness with increasing content of the solid lubricant i.e. graphite. Such decrement in hardness of the hybrid composites may be attributed to the mainly three reasons: first, the poor hardness of the graphite particles, second, the homogeneous dispersion of the graphite particles in the hybrid nanocomposites and third, the lower density of the hybrid composites which leads to the lowering in hardness.

The mechanical behaviors of copper-based hybrid composites reinforced with SiC and CNTs nanoparticles have been studied by Akbarpour et al. (2013). A significant improvement in the hardness of the nano hybrid composites was observed on the addition of

CNTs and SiC nano particles in the copper matrix. This improvement in hardness of hybrid composites may be attributed to the uniform distributions of the harder SiC and CNTs reinforcement in the matrix which offers a strong resistance to any kind of indentation. In addition to this, the reinforcement of nano particulates in the matrix reduces the grain size by the pinning effect during the solidification which also helps the improvement in the hardness of the nano composites which follow the Hall-Petch equation. As the content of the CNTs reinforcement increases the improvement in the micro hardness of the composites was observed insignificant it may be attributed to the formation of the CNTs clusters. The modulus of elasticity for the composites was estimated by the slope of the engineering stress-strain curve developed during compression test. The highest modulus of elasticity of 140.23 GPa was observed in Cu/(2vol % SiC+6 vol % CNT) composite whereas lowest modulus of elasticity of 105.69 GPa in HPed Cu

Show et al. (2013) developed a novel 6351 Al hybrid composite reinforced with (Al_4SiC_4+SiC) with improved mechanical behaviors. It was observed that the better elongation and tensile strength of the hybrid composites as compared with its matrix. The improved percentage elongation and ultimate tensile strength of hybrid composites were 13% and 174 Mpa respectively, on the reinforcement of 4 vol% SiC in the matrix. Moreover, the high hardness of the SiC coupled with predominant presence of equiaxed α-grains enhanced the ductility and strength of the hybrid composites.

Slipenyuk et al. (2004) have reported that the relative change of the tensile deformation feature of composites due to agglomeration of reinforcing phase was a linear function of damage parameter and was not depended on the elongation/ductility of the matrix materials. Hence, a quantitative evaluation of the deteriorating behaviors of the composites having agglomeration of reinforcing phase was possible when the modulus of elasticity and consequently, the damage parameter of the material were known.

Rajmohan et al. (2013) studied the mechanical behaviors of aluminium hybrid composites. The highest tensile strength of 150 MPa was observed for the composites materials reinforced with 3% mica and 10% SiC particles. However, the composites reinforced with 6% mica and 10% SiC particles displayed the tensile strength of 148 Mpa. Here, it was observed that the tensile strength of composite materials increases up to a definite value and then decreases with increasing in content of mica. The composite reinforced with 3% mica exhibited the higher tensile strength and hardness as compared with 6% mica reinforcement. The Lower values of strength and hardness were the demanding parameter for good machinability. The hardness of the MMCs varied almost linearly with the content of reinforcing particles in the matrix because of increased ceramic phase in the matrix.

Alaneme et al. (2016) investigated the mechanical properties of the copper matrix reinforced by steel machining chips and its hardness at different compositions of composites was reported. It was observed that when steel machining chips content increases the hardness of the composites increases. However, it was also explored that composites reinforced with steel chips has higher hardness than the composites reinforced with alumina. It can be attributed to the higher porosity in alumina reinforced composites compared with steel chips reinforced composites. Whereas, the optimum mechanical properties of the steel chips reinforced composites was observed at 5 wt% steel chips among all the materials. Such enhancement in strength of the steel chips reinforced composites was attributed to the good bonding between the interfaces of matrix and reinforcements which offer the resistance to externally applied load.

Slipenyuk et al. (2006) have suggested that lowering the particle size of reinforcements offers better yield and tensile strength. It can be achieved by making homogeneous dispersion of reinforcement in the matrix with the help of better mechanical arrangements. It was also reported regarding the limiting contents of the reinforcements in any matrix and that would be sufficient for its uniform distribution in that matrix.

Mechanical behaviors of copper-based composites reinforced with high volume TiC were investigated by Akhtar et al. (2009). It was observed that the strength and hardness of the composites increases with increase in content of the TiC reinforcements. It can be attribute to the higher content and higher modulus of elasticity of TiC reinforcements in matrix phases which carry the most of the load which externally applied. Therefore, it can be infer that the strength and hardness of the composites were mainly dependent on the content of the TiC reinforcements.

2.9.2.1. Strengthening mechanisms in composites and hybrid composites

In the specific context of particle reinforced composites, the extent of strengthening by the particles depends on the following factors:

- Size of the reinforcement phase (Particulates)
- Characteristics of the reinforcements phase
- Inter-particle distance/gap
- Appearance and content of the reinforcing phase
- State at the interfaces between reinforcement and matrix

The strength of the materials also depends on characteristics of the matrix for example- strain hardening coefficient, effect of heat, constituents and microstructure.

Haubold et al. (1992) has given an explanation regarding the effect of grain size on strength of the materials. The strength of the materials improved when the grain size reduced because a reduced grain size hindered the nucleation of crack and enhances the ductility of materials by decreasing the length of slip. Hall-Petch has given a relation between the size of the grain and flow stress of the composite materials as:

$$\sigma = \sigma_0 + k\,d^{-1/2} \qquad (2.3)$$

where, σ - Flow stress,

σ_0 - Friction stress and

k - Coefficient of Hall-Petch

In the relation of Hall-Petch, the yield strength of materials is inversely proportional to square root of the grain size i.e. as the grain size decreases the strength of the materials increases.

Improved yield stress in a particle reinforced composite may be also contributed by mechanisms other than a simple transfer of stress from the matrix to the reinforcements as explained in the circumstances of modulus of elasticity. To estimate the composite longitudinal strength utilizing the rule of mixture as:

$$\sigma_c = \sigma_f V_f + \sigma_m V_m \qquad (2.4)$$

where, σ_c - Strength of the composite

σ_f - Strength of the reinforcement

σ_m - Strength of the matrix

V_f - Volume fractions of the reinforcement

V_m - Volume fractions of the matrix

Kelly (1966) has reported about the continuum-mechanics models of composite strengthening deals primarily with a situation where load is transferred from the matrix to reinforcement deforming non-plastically during loading of the composite. One such preliminary model is shear-lag theory, which supposes that the load transfer occurs between the matrix and reinforcing phase, generally having a high aspect ratio, by means of shear stresses developing at the interface of reinforcements-matrix. The following assumptions have been made in the shear-lag model:

- The matrix is continuous and contains randomly distributed reinforcing particles
- Particle-matrix interface is strong enough to affect load transfer.
- Poisson's effect is negligible and
- Both the matrix and the embedded particles have equal shear modulus

Aikin Jr. et al. (1991), Nardone and Prewo, (1986) and Nardone, (1987) have proposed that modified shear-lag theory which evaluate the load transfer to the particles, the yield stress of the composite σ_{yc} can be calculated by the following equation:

$$\sigma_{yc} = \sigma_{ym} [1+ (L+t)A /4L] V_f + \sigma_{ym} (1-V_f) \qquad (2.5)$$

where, σ_{ym} is the yield stress of matrix, L is the particle length perpendicular to the imposed stress, t is the particle length parallel to the imposed stress, A is the aspect ratio of particles and V_f is the volume fraction of particles. Since most of the in-situ composites contain equiaxed particles so take $L=t$ and $A=1$ and eq. 2.5 become:

$$\sigma_{yc} = \sigma_{ym} (1+ \tfrac{1}{2} V_f) \qquad (2.6)$$

From the Eq. 2.6, it is very clear that the yield strength of composites increases with increasing volume fraction of reinforcements and there is no dependency of particle size. The strength of composite reinforced with spherical particle due to load transfer by shear lag theory, but obtained an expression for strength lower than that of the matrix, (Prasad et al. 1985). When attempts to explain the observed strengthening of DMMCs by rule of mixture (ROM) models have failed. This expression modified by deviating from spherical shape and also by including dispersion strengthening effect by Ashby-Orwan mechanism (Nath et al. 2002). However, Manoharan et al. (1989) have suggested an expected mechanism of strain hardening by geometrically necessary defects that are incorporated to keep only differences in deformation characteristics between the soft matrix, and hard reinforcements, may also contribute significantly.

The increase in yield strength of composites reinforced with homogeneous discontinuous particles in the diameter range of 0.5-5 μm studied by Aikin Jr et al. (1991) and Taya (1991). It was also highlighted that the dislocations developed by the variation in thermal expansion coefficients (ΔCTE) of reinforcements and the matrix or ΔCTE effect may contribute to strengthening. The strengthening mechanisms in composites had summarized by Arsenault (1991) all as given below:

- Strengthening of composites by load transfer (Classical mechanism of strengthening),
- Dispersion Strengthening,
- Residual elastic stresses,
- Difference in texture,

- The strengthening of composites due to high densities of dislocation attribute to dislocation formation due to variation in thermal expansion coefficient
- Small sub-grain size as a result of the development of huge density of dislocation.

The Strengthening of composites reinforced with particulates may also involve Orowan mechanism where a dislocations gliding may bend or mold between small particles which are impenetrable and bypass them, leaving behind a loop around the reinforcing phase that is known as Orowan loop. The Orowan has given a relation between effects of this mechanism on the yield stress of the composites as:

$$\sigma_{yc} = \frac{0.83MGb}{2\pi\sqrt{1-\nu}} \frac{\ell n(2r_s / r_0)}{\lambda} \tag{2.7}$$

where, M – Factor of Taylor

G – Modulus of Shear of the matrix

b – Burgers vector of the matrix

v – Poisson's ratio

r_s - Effective radius of the particles

r_o - Cut-off radius

λ - Mean inter-particle separation on the slip plane

Taya and Arsenault (1991) have developed an analytical model based on shape of the SiC particles which is ellipsoidal in an aluminium matrix that takes into account tensile stress which is thermally residue that sets in during cooling after high temperature processing the composites having whisker with a length-to-diameter ratio of 1.8. The model successfully predicted that the variation in the compressive and tensile yield stress attribute to the thermal residual stresses observed in whisker reinforced composites where $\sigma_{yc}^{C} > \sigma_{yc}^{T}$. It was inferred that the transverse residual stress should be lower than the longitudinal residual stress and the yield stress in tension should be equal to the yield stress compression if the SiC particles were spherical.

If increases in density of dislocations were contributing factors for enhancing the strength of the composites and this dislocations density was homogeneously distributed in the matrix then the following equation set a relation between the enhanced strength of composites and density of dislocations.

$$\Delta\sigma = \beta\mu b\rho^{1/2} \tag{2.8}$$

where, $\Delta\sigma$ - Increase in yield strength

μ – Grain size number

b – Burger vector of the matrix

ρ - Increase in dislocation density

β - Geometric constant

Extensive research were carried out on aluminum and its alloys based ex-situ composites reinforced with plates, particles and whiskers of SiC. In majority of the composites, due to a variations in thermal expansion coefficient (CTE) between the SiC reinforcement and matrix developed huge dislocations matrix during heat treating process. Since as explained above the developed dislocation density improved the strength of the composites or alloy. The development of the dislocation density and it extent in the materials depends on the several parameters such as strength of the matrix, CTE, particle size and particle-volume fraction.

At small strains the work-hardening behavior may be affected by the dislocations in the materials. The tensile behavior of equiaxed alumina particles reinforced 2014 and 2024 aluminum alloys investigated and suggested that dislocation tangles form around reinforcing particles at small strains due to the plastic incompatibility. These developed dislocations, geometrically necessary connected to form dislocation cells and the diameter of these cells is directly proportional to the inter particle spacing $\lambda_{s,}$ this is extensively studied by Kamat et al. (1989) and suggested that these cells should lead to improved flow stress and expressed by the relation:

$$\sigma = \alpha_0 \frac{\mu b}{\lambda_s} \tag{2.9}$$

where, α_0 - Proportionality constant

b – Burger vector of the matrix

Thus, Aikin Jr. et al. (1991) have also suggested that it is expected that the reinforcement in matrix may not notably change the inception of plastic deformation in some composites. Instead, at low strains an enhancement in the strain-hardening rate can increase in the 0.2% offset yield stress, the 0.2% offset yield stress which depend on λ^{-1} observed in such alloys.

Chawla and Metzger (1972) have studied of a single crystal copper matrix containing large-diameter tungsten fibers and suggested that the improved density of dislocation in matrix close to the fiber arises due to the plastic deformation attribute to thermal mismatch between matrix and fiber which develop thermal stress. The inter-fiber spacing was a deciding factor of the magnitude of the gradient in dislocation density; it decreases with decreasing inter-fiber spacing. TEM was used to assure the presence of the plastically deformed zone with huge dislocation density in the matrix close to the reinforcing phase.

2.9.3. Dry sliding friction and wear behaviors of metal matrix composites and hybrid composites

Tribology (study of friction, wear and lubrication) deals with contact mechanics of surfaces moving against each other which involves energy dissipation. It deals with the science of friction, wear, lubrication and adhesion. The father of modern Tribology Leonardo da Vinci credited with pioneering studies on the various subtopics of the tribology such as bearing materials, friction, plain bearings, wear, lubrication systems, screw-jacks, rolling-element bearings and gears.

Wear is the main reason of material loss and deteriorating the mechanical behaviors and any decrease in wear may result in significant savings. Wear and dissipation of energy are mainly caused by friction and any kind of improvement in friction control lead to the significant saving of energy and materials. It has been evaluated that one third of the current world's energy resources utilized to overcome friction.

Based on the nature of movement or the media involved in an interaction under load, different type of wear have been classified on the basis of action involved as follows :

- Wear due to adhesion (Adhesive wear)
- Wear due to abrasion (Abrasive wear)
- Wear due to erosion (Erosive wear)
- Wear due to impact (Impact wear)
- Wear due to fatigue (Fatigue wear)
- Wear due to corrosion (Corrosive wear)

Adhesive wear is associated with low sliding velocity, small load and smooth surfaces. This is a universal type of wear that is hard to eliminate totally. Adhesion process involves the contact of asperities on two mating surfaces in relative movement. The asperity contact may join together or developing a bond at the junction when the asperities come into contact and which has higher rupture strength than the yield strength of one of the contacting materials. In such a situation, the fracture may take place through the low strength material of the contact which leads to the transferring of material from one contacting surface to other.

Abrasive wear occurs when two surfaces, one of which is harder and rougher than the other, are in sliding contact. Abrasive wear is the process of removing or displacing of materials by ploughing or micro-cutting from one surface by the harder asperities of another surface or by loose harder particles. This type of wear is dangerous because it can occur suddenly with introduction of a contaminant and may lead to high wear rates and extensive damage to the surface.

Erosive wear is the combined processes of repeated deformation and cutting. When a solid surface is gradually worn away by the action of fluids and particles, it is called erosion. Erosion of material can take place under four different conditions:

- Impingent of solid particles against a solid surface
- Impingent of liquid droplets against a solid surface
- Flow of hot gases over a solid surface and
- Cavitation at a solid surface in liquid media.

The most important form of erosion is that caused by solid particle impingement.

Impact wear arises from repetitive impact of two surfaces, which differ from impact of solid particles on surface causing erosive wear.

Fatigue wear refers to the repeated imposition of cyclic loading or stress on the surface of materials, developing a low degree of mechanical damage to the surface and subsurface region with imposition of each cyclic loading or stress. Finally, the compilation of damage results in breakdown by fracture and/or deformation at the surface.

Corrosive wear occurs due to the combined effects of the chemical reaction at surface in presence of any of the mechanical wear mechanisms. In a corrosive environment sliding surfaces experience corrosive wear. However, in some cases the reaction layer may protect the surface or even act as a lubricant.

A simple theoretical analysis involving two contacting surfaces sliding over each other under a load normal to the sliding surfaces has carried out by Archard (1953). It was suggested that the communication between the two surfaces is suppose to happen at the asperities and true area of contact is equivalent to the summation of the individual asperity areas of contact. Therefore, from the above definition, the hardness of the softer materials, the real contact area, A_r which is the indentation area under the asperities of the harder materials are related by the following expression,

$$A_r = \frac{W}{H} \tag{2.10}$$

where, W - Applied normal load

H - Softer surface's hardness

The volume of material wearing out for a unit distance of sliding, Q, is directly proportional to real contact area, A_r and the Eq. 2.10 can be written as,

$$Q = KA_r = \frac{KW}{H} \tag{2.11}$$

The constant K is usually termed as the wear coefficient or the coefficient of wear, which is dimensionless and is always less than unity i.e. in range of 10^{-5} to 10^{-3}. The dimensionless wear coefficient K is considered by many as an important way of comparing wear processes in various systems. Eyre, (1976) has reported that the coefficient of wear represents the characteristics of the friction couple and only has actual meaning provided the no change in wear mechanism, i.e. no change to severe wear from mild wear. However, the coefficient of wear, which is essentially wear rate per unit real contact area, is not a judicious parameter representing wear resistance explained by Rohatgi et al. (1995). If wear rate decreases the real area of contact decreases more due to increased hardness and the wear coefficient will increase which may be interpreted by non-discerning observed as lowering of wear resistance.

The resistance offered by any materials may be known as friction force while moving over each other. So, on the basis of this definition of force of friction the relative motion can be classified into two important classes i.e. sliding and rolling. In both these motions, ideal rolling and sliding, a tangential force F is required to travel the upper body over the immobile counter face. Therefore, the coefficient of friction can be defined as the ratio of this tangential force of friction and the applied normal load W, generally denoted by character μ:

$$\mu = F/W \tag{2.12}$$

The value of the friction coefficient conventionally defines the degree of the frictional force. For the majority of materials which slides over another surface in the presence of air, the values of μ typically varies in the range of 0.1 to 1.

The basic laws of friction (Bowden and Tabor, 1964) may be defined as follow:

- The force of friction force is directly related to the applied normal load;
- The force of friction does not depend on the apparent contact areas.
- The force of friction force does not depend on the velocity of sliding.

These three laws of friction are not so much reliable, but apart from few important cases they do offer useful summary of pragmatic observations.

Bowden and Tabor (1954, 1964) had proposed a model for sliding friction, in its simplest form, suppose that the force of friction overcome for sliding, arises from two sources, an force of adhesion generated at the real contact area between the mating surfaces (the asperity junctions), and a deformation force required to plough the asperities of the harder surface over the soft surface. Although, in later part of the theory, it has been clear that these two contributions cannot be independent strictly. However, it is suitable and enlightening to consider them individually. This frictional force F is the sum of the two forces, F_{adh} due to adhesion and F_{def} due to deformation. The condition of the surface has a deciding effect on friction level if a friction-adhesion junction is poor and shearing occur at the interface and not through subsurface material.

Suh (1973 & 1977) has proposed that the basic mechanism which is responsible for the origin of friction as:

- Asperity deformation,
- Ploughing
- Adhesion

The static friction coefficient is determined by asperity deformation and it also affects the dynamic friction coefficient. Due to generation of wear particles by delamination, new asperities are developed, and the process needs a huge number of repeated loading by the asperities of the opposite surfaces. The role of asperity deformation to the dynamic coefficient of friction is not huge as compared with ploughing or adhesion action.

Sin et al. (1979) has reported that the penetration of hard asperities / penetration of wear particles into the softer material develop a ploughing element of frictional force. The particle can plough or penetrate both the surfaces if the hardness of the both surfaces is equal. No ploughing happen if hardness of one of the surfaces is very high, the wear particle will only slide along the harder surface. However, the ploughing of soft surfaces occurs when the roughness of the hard surface is very high due to this wear particle may anchor and start ploughing.

Alidokht et al. (2013) have studied the deformation of surfaces of hybrid composites under variable applied normal loads of 10, 25, 40 N and dry sliding condition using the pin-on disk machine against hardened steel. The weight loss data for all the specimen was plotted with sliding distance at all the loads and found that as the sliding distance increases the weight loss increases. For the entire specimen, it was also found that the weight loss increases with increasing applied load. Here, for all specimens the trend of the weight loss with sliding distance was divided into two stages. During the initial stage weight loss per sliding distance for all specimens was increased and in the second stage it decreased. The composite materials displayed low wear rate and a steady state of weight loss for a longer sliding distance.

Alpas et al. (1994) have presented the ideal wear scenario of the composite having good bonding between matrix and reinforcement during dry condition of sliding. They observed that the aluminium matrix near to the particles worn away and established a contact between the counter surface and reinforcement particles which developed a contact shear stress at the particle-matrix interface and leads to a de-cohesion of the particle. For the wear mechanism, temperature rise and wear rate, a wear map was suggested by Wilson and Alpas (1997). The wear maps clearly explored that all the facts are consequences of interaction of sliding speed and load. It was also observed that the temperature of the surface increases and transition load decreases on increasing the speed of sliding.

Monikandan et al. (2016) studied the wear behaviour of aluminium based hybrid composites produced by the stir-casting technique under dry sliding condition. In the present investigations, the effect of concentration of MoS_2 and sliding speed on the coefficient of friction and rate of wear are mentioned. It was observed that the rate of wear decreases on increasing sliding speed up to 2 $m.s^{-1}$ for all the composite materials investigated due to the generation of lubricating tribo-layer of MoS_2 between the mating surfaces. In addition to this, as the sliding speed increases the strain rate increases which improve the hardness, improved hardness reduce the real contact area and lead to low wear rate. The wear rate of the composites was found inversely proportional to the MoS_2 content.

2.9.4. Dry sliding friction and wear behavior of copper composites and hybrid composites

Due to involvement of various factors such as materials properties, sliding parameters, lubricating conditions, abrasive effects and etc. the phenomenon of wear behavior of materials become so complicated.

Mallikarjuna et al. (2016) have investigated the effect of SiC and CNTs on dry sliding wear response of copper-based hybrid nanocomposites. The nanocomposites and copper displayed the decreasing friction coefficient with increasing load. The high friction coefficient was observed at low load due to higher force of adhesion occur between the surfaces. However, lower friction coefficient was observed at higher load due to the asperity of the sliding surfaces gets sheared. It was also observed that the more formation of oxide layer at the contacting surfaces at higher loads which provide a lubricating effect due to its low shearing strength. Overall, the nanocomposites show lower coefficient of friction at higher CNTs content as compared to its copper matrix at all the applied loads.

Tjong et al (2000) examined that the higher delamination of copper's surface layer resulting high wear loss and it increases with increasing distance of sliding. A significant improvement in hardness of the composites was observed on the reinforcement of 20 vol. % SiC particles to copper which drops the degree of plastic deformation of the matrix. The composites also displayed the very good wear resistance. Work-hardening due to plastic strain localization in the subsurface region of pure copper was also observed on sliding against a hardened disc. Therefore, the subsurface region of pure copper has higher micro hardness than underlying bulk material. However, the micro-hardness of copper matrix of the composite near the subsurface region is significantly lower on reinforcement of SiC. It may be attribute to the addition of SiC particles to copper was extremely helpful in reducing the degree of strain localization in the sub surface region. Tjong and Lau (1999) also observed a better wear resistance in TiB_2 reinforced copper-based composites compared with its copper matrix. Moustafa et al, (2002) also reported that the composites made by Cu-coated and uncoated graphite displayed better wear resistance and low coefficients of friction compared to pure copper.

Rohatgi et al. (1990) have also reported that the composites materials reinforced with graphite generally develop the film of graphite on the sliding surface and reduce the metal to metal contact during dry sliding. Thus, the bearing composites reinforced with graphite displayed significant reduction in wear loss and transition to severe wear was pushed to higher contact pressure than its matrix.

Tu et al. (2003) have studied the dry sliding wear behavior of in situ Cu–TiB_2 nano-composites developed by reaction of pure Ti and Cu–B melts. The wear behavior of the composites was investigated using pin-on-disc machine against disc made up of medium carbon steel at sliding speeds and normal load ranging between 0.089 to 0.445 $m.s^{-1}$ and 20 to 140 *N* respectively. The in-situ composites displayed increasing wear resistance with increasing content of TiB_2 from 0.5 to 2.5 wt% into matrix. No transition from mild wear to severe wear was observed due to the superior bonding between homogeneously distributed reinforcing particle and matrix at all the applied loads.

The wear resistance of the Cu–Ag–Cr alloy, as compared to that in Cu–Ag alloy contact wire was studied by Jia et al., (2007) and observed the remarkable increase in resistance to wear in Cu-Ag-Cr alloy has been attributed to precipitation of fine and coherent particles of size 6-7 nm, on ageing. Crack nucleation, crack propagation and subsurface deformation were the major process of wear of the precipitation-hardened alloys. Cu–Ag–Cr alloy exhibited the rate of wear increases with distance of sliding under various tribological parameters. The similar results were also reported by Moustafa et al., (2002) where, the improved sliding wear was observed of copper–graphite composites containing 8, 15 and 20 wt% of graphite developed by P/M technique. Cu-coated graphite composites showed the least friction coefficient, followed by copper matrix composites having uncoated graphite in equal content, whereas the pure copper displayed the highest friction coefficient.

Chen et al. (1996) have investigated that the sliding wear behavior of copper-20 wt% Nb and copper-15 wt% Cr composites and reported that the rate of wear increases with increasing normal load and decreases with increasing speed of sliding. Cu-20 wt% Nb composite revealed the higher resistance of wear and lower coefficient of friction compared to Cu-15 wt% Cr composite. Both the composites displayed the decreasing average friction coefficient with increasing speed of sliding. It was also observed that the both the composites exhibit increasing average bulk temperature with increasing normal load and sliding velocity. However, Cu-20 wt% Nb composite shows the lower average bulk temperature than Cu-15 wt% Cr composite under the same condition due to this low wear is possible reinforcing of 20 wt% Nb. Due to this reason Cu-20 wt% Nb composite displayed smaller thickness of subsurface damage than Cu-15 wt% Cr composite. The plastic damage of the subsurface of both the composites occurred at an early stage.

Saka et al. (1992) have thoroughly studied the wear response of metal and polymer matrix composites reinforced with graphite or carbon fiber. The composites exhibited very low wear and friction coefficient due to the lubricating nature of graphite. Initially, both the composites revealed the higher value of friction due to the higher adhesion between the mating surfaces until the formation of tribo-layer of graphite which reduces the direct contact of surfaces and reduces the friction between sliding surfaces.

Liu et al. (1992) have suggested that the coefficient of friction of various composites containing hard particles indicated higher coefficient of friction which may be attributed to higher deformation during asperity-asperity interaction despite reduced contribution of adhesion.

The Tribological behavior of copper composites reinforced CNTs was investigated by Lin et al. (2011) and suggested that the composite with addition of 5vol. % CNTs revealed the maximum rate of wear and it decreases significantly as the CNTs content increases. This is due to the lubricating action of the CNTs which offer a carbonaceous layer between the sliding surfaces. Gautam et al. (2008) have investigated the dry sliding friction and wear behavior of SiCp reinforced into Cu-Cr alloy *in-situ* composites using pin-on-disc machine at variable loads of 10, 20, 30 and 40 N and constant speed of sliding of 0.786 $m.s^{-1}$. Author reported the variation of the cumulative volume loss with respect to the distance of sliding for all the materials. The cumulative volume loss increases almost linearly with sliding distance at all the normal load. The composite showed the significantly low cumulative volume loss as compared with copper matrix at lower loads of 10-30 N. However, the cumulative volume loss in composite increases with sliding distance but still lower than its matrix at higher load of 40 N. The composite reinforced with SiC had higher hardness which reduces the true contact area due to this the cumulative volume loss decrease in the composite.

Bagheri et al. (2016) have studied the friction and wear behaviors of the copper composites reinforced with variable content of TiC reinforcements. In this study, the author mentioned that the typical behavior of wear rate of composites with varying TiC reinforcement. The composites revealed the enhanced anti-wear property with increasing TIC content. As discussed above by Gautam et al., (2008) that the harder reinforcement improved the hardness of the composites which reduces the real area of contact leads to the low wear of composites. Apart from this reason, another reason may be that uniformly dispersed particles in composite can tolerate the applied load and offer good resistance against plastic deformation.

2.10. Worn surface characterizations and analysis

Surfaces of solids correspond to a very intricate form of matter, more complex compared with simple plane. Any real surface always has a variety of defects and distortions.

These surface textures, ranging from bulk distortions to local microscopic irregularities on surface, exercise a strong influence on wear and friction.

Thomas et al. (1982) and Majumdar et al. (1991) have explained about the roughness of a surface were not flat but form either a valley or a peak. The amplitude between the valleys and peaks for any engineering surfaces was the order of 1 μm. The profile of an uneven surface was almost always arbitrary unless some regular features have been intentionally introduced. Other distinctive feature of surface roughness was that, if continually exaggerated, increasing information of surface features was observed down to the nano-scales.

Song et al. (1992) have suggested that there were number of techniques and parameters developed to characterize the surface topography. Successful surface profile evaluations were carried out with the help of renowned statistical descriptors of height like the average roughness, R_a, rms roughness, R_q.

Jahanmir et al. (1977) have described about the two most important surface features which influenced the wear behavior of machined surfaces were surface integrity and topography. To give details the deviations of a surface from the nominal geometric shape there were two morphological aspects such as 1-surface roughness, 2-surface waviness. The parameter which was used to characterize the quality of the surface and the subsurface material in terms of cracks, plastic deformation, structural unevenness through second phase and residual stresses was generally known as surface integrity. The effects of surface roughness and its integrity on the tribological response were studied in the context of delamination theory of wear.

Suh et al. (1976) have also investigated that the effects of surface roughness in terms of waviness on the dry sliding wear behavior of the materials which may cause the seizing of the geometrically constrained mating surfaces. The predicted analysis inferred that due to waviness on the sliding surfaces the large wear particle stuck between them and cause seizure.

Huang et al. (2017) have investigated the worn surfaces of aligned CNTs reinforced copper composites. In this investigation, the worn surface of copper was observed by SEM and found seriously worn due to the higher adhesion. This adhesion intensified as the time passes which produces the chips of copper that leads to the severe plastic deformation and damage. However, the worn surfaces of the nanocomposites displayed a good worn surface morphology due to the formation of tribo-layer of carbon by CNTs and protect the further damage.

Sapate et al. (2009) have studied the worn surfaces of pre-coated SiCp reinforced copper composites under dry sliding condition. The worn surface of the copper composites at low load and sliding speed was characterized by SEM and observed very smooth and no de-bonding or pullout of reinforcements. However, the worn surface at higher loads and sliding speeds, copper matrix smeared off and the reinforcing particles pull out by shearing action.

Maji et al. (2009) made the exhaustive analysis of worn surfaces by SEM-EDS of copper composites and its matrix to reveal the governing mechanisms at variable normal loads. At normal load of 2 N, tribo-chemical layer fully cover the worn surface and appearing in different contrasts compared to unworn surrounding surfaces. The EDS analysis of wear debris observed the O, Fe and Cu similar intensity peaks. It indicated the development of oxide tribo-layers and transfer of steel debris to specimen. At normal load of 10 N, almost similar characteristics were found; including the sign of abrasion.

2.11. Electrical properties of metal matrix composites

Zuhailawati et al. (2009) have explored the electrical behavior of NbC reinforced copper composites and observed the low electrical conductivity in composite due to electron dispersion by fine NbC reinforcement and copper grain.

Electrical property of CNTs reinforced copper-based composites developed by electro-less deposition technique was studied by Daoush et al. (2009). In this study, the copper nano composites revealed the low value of electrical conductivity in term of %IACS and it decreases on increasing CNTs contents. Since the electrical resistivity of copper is order of 10^{-6} Ωcm however, CNTs has electrical resistivity of order of 10^{-3} Ωcm due to this reason the electrical conductivity of copper nanocomposites decreases linearly up to 15 vol.% CNTs but in case of 20 vol.% CNTs conductivity was suddenly dropped because of the following reasons:

- Due to the clustering of few CNTs at the grain boundaries of copper, which develop a grain boundary phase lead to increase the dispersion of the charge carrier at the boundary.
- Due to the higher porosity value of 20 vol.% CNTs reinforced nanocomposites than the other nanocomposites.
- Due to the tin content those come from the sensitization process of CNTs which incorporated in the nanocomposites. This tin may react with copper and form a non-conducting intermetallics compound.

Wood et al. (1997) have explored the effects of microstructural changes on the electrical resistivity and strength of copper composites. In the investigation, the copper gains dislocations when it strain harden which offer only resistivity of 10^{-25} Ωm^3 per unit length thus the heavily deformed copper displayed the decreased conductivity by 1.2% of annealed copper without any dispersion mechanisms.

Vettivel et al. (2014) measured the electrical resistivity of W reinforced copper composite of 2.02×10^{-8} Ωm at 850 ºC and it increases with increasing W content. It was observed that the measured resistivity of composites is quite higher than the reference value of 1.7241×10^{-8} Ωm. It is primarily attributed to the clustering and pore development in the composite which form the insulation sites that reduce the conductivity.

Tokutomi et al. (2015) reported the electrical conductivity of hot extruded aluminium composite reinforced with CNTs. In this study, the hot extruded sample of monolithic aluminium powder displayed the increasing electrical conductivity as compressive stress increases. the electrical conductivity of the hot-extruded specimens of pure Al powder increased with increasing compressive stress. It was found close to 61.77 %IACS at 561 Mpa compressive stress but it was not higher than the specimen developed by casting. However, the electrical conductivity of a hot-extruded CNTs reinforced aluminium composites of 64.21 %IACS was observed at compressive stress of 561 Mpa, it was 5% more as compared to pure Al powder specimen.

Akhtar et al. (2009) have explored that the electrical conductivity decreases with increasing of TiC content due to its non-conducting nature. The predictive three point upper bound model was utilized to predict the electrical conductivities copper composite reinforced with TiC and compared with experimental value. It was observed that the three point upper bound model has huge variations in electrical conductivities compared to the experimental values. The variations were attributed to the reinforcement of TiC in the copper composite and presence of porosity in case of monolithic copper.

2.12. Formulation of the problem

This chapter of the thesis describes the detailed knowledge extracted from the literature review as reported regarding the development of cast composites and its properties. The present understanding of electrical and mechanical properties, have been reviewed but there is lack of studies involving copper-based composites reinforced with ceramic particles. The dry sliding friction and wear behaviour is important for many of the application of copper-based materials and the current knowledge in this regard has been reviewed. Studies are available on TiC, SiO_2, WC, SiC, Al_2O_3, TiB_2, cBN and hBN in copper matrix. But only limited investigation of friction and wear behavior of copper-based hybrid composites is available including the effects of true deformation strain on wear rate and coefficient of friction. It appears that the composite approach to develop properties beyond that of its matrix is expected to open up new corridors of development of new copper-based hybrid materials. The choice of particles of WC, ZrO_2, Al_2O_3, BN, B_4C and Cr to synthesize copper-based hybrid composites is based on their ability to easily wetting with copper in presence of Cr. Such ceramic reinforcement may contribute to improved mechanical and tribological properties of the matrix. Thus, the present investigation has been carried out to develop copper-based hybrid composites on reinforcement of different ceramic particles in the copper matrix by stir-casting technique and study its physical, mechanical and dry sliding friction and wear behavior with the following objectives:

- To develop broadly two different kind of copper-based hybrid composites known as binary reinforcement and tertiary reinforcement system depending on the number of reinforcement into the copper metal matrix. These binary reinforced hybrid composites have been designated on the basis of their composition as Cu-2Cr-1WC-1ZrO_2 (Hybrid composite-1 (HC-1)), Cu-2Cr-1WC-1Al_2O_3 (HC-2), Cu-2Cr-1WC-2ZrO_2 (HC-3) and Cu-2Cr-1WC-2Al_2O_3 (HC-4). Whereas, tertiary reinforced hybrid composites are designated as Cu-2Cr-1.5WC-1BN-0B_4C (HC-5), Cu-2Cr-1.5WC-1BN-0.5B_4C (HC-6), Cu-2Cr-1.5WC-1BN-1B_4C (HC-7) and Cu-2Cr-1.5WC-1BN-1.5B_4C (HC-8).

- To determine the effect of particle content on the microstructure, physical and mechanical properties like hardness, compressive and tensile properties of developed hybrid composites. These properties have also been evaluated in cast copper for comparative study.

- To determine the influence of particle content on dry sliding friction and wear behaviour of developed copper based hybrid composites and compare them with those observed in cast copper following the similar route of synthesis as that of cast hybrid composites.
- To analysis the worn surface of copper based hybrid composites and cast copper, their surface roughness is evaluated in terms of average value.
- To determine the electrical behaviours of cast copper and copper-based hybrid composites.