# PREFACE

Recently, there has been more effort in developing discontinuously reinforced metal matrix hybrid composites due to relatively low cost of processing and their isotropic nature of properties with acceptable performance. Metal matrix hybrid composites are being increasingly used for structural, automobile and aerospace industry, sporting goods and general engineering industries. On account of having a very high electrical and thermal conductivity, ductility and ease of forming, copper lends itself to countless applications, such as automobile radiators, heat sink materials, rocket nozzle, electrodes for resistance welding, electric switches, etc. However, the application scope of copper and its alloys gets restricted due to its inferior mechanical properties. To achieve better mechanical strength, wear resistance, creep and fatigue, ceramic particles reinforced copper based metal matrix hybrid composites are developed.

Metal matrix hybrid composites can be synthesized by various processes, such as powder metallurgy, squeeze casting, compo casting, stir casting, etc. Among these, stir-casting technique is considered to be the most viable due to certain advantages, such as, easy to perform and very economical. The developed hybrid composites by stir-casting technique have better properties, provided the reinforcement particulates are dispersed homogeneously in the matrix and good interface bonding between reinforcement and matrix. If the reinforcement is not properly distributed, the agglomeration of the reinforced particles occurs and that decreases the mechanical properties of the developed hybrid composites. To avoid the agglomeration of the reinforcement particles in the matrix, particularly when the reinforcement particulates are smaller in size, stirring with graphite stirrer is utilized to achieve homogeneous distribution of the reinforcement particles. Despite having high hardness, high chemical stability, high modulus, grain refining effect, better corrosion and wear resistance, WC, $Al_2O_3$, $ZrO_2$, BN and $B_4C$ particles, as reinforcement in copper metal matrix have attracted a little attention from the research community. WC, $Al_2O_3$, $ZrO_2$, BN and $B_4C$ reinforced copper hybrid composites can be used for various engineering applications such as resistance welding electrodes, electrical contacts, shipping hulls, etc. However, its potential as a mechanical applications and tribological material has not yet been fully investigated. Hence, the present investigation is focused at analyzing the microstructures, density, hardness, ultimate tensile strength, compressive strength, dry sliding friction and wear behaviors of the WC, $Al_2O_3$, $ZrO_2$, BN and $B_4C$ reinforced copper-based hybrid composites.

The thesis has the following six chapters.

**Chapter-1:** This chapter comprises the introduction of the composite and hybrid composites with its classification based on matrix and reinforcement. Mechanical, physical and dry sliding friction and wear behaviors of materials are also discussed and followed by the application of the developed materials in the present study.

**Chapter-2**: The literature review as reported in this chapter of the thesis describes the detailed knowledge regarding the development of cast copper-based composites and hybrid composites with particular emphasis on solidification processing and powder metallurgy route where the reinforcements are added externally within the copper metal matrix. The present understanding of physical properties (like density, electrical conductivity), mechanical and tribological properties of copper composites and hybrid composites have been reviewed but there is lack of studies involving copper-based hybrid composites reinforced by two or more ceramic particles. Formulation of the work is also introduced in this chapter followed by objective of the works.

**Chapter-3:** This chapter of the thesis contains the details of experimental procedures followed in the current investigation. In the present study, commercial copper has been selected as the base material and chromium with various ceramic materials as reinforcements to develop the binary and tertiary reinforced copper-based hybrid composites using stir-casting technique. The chemical composition of the as received copper ingots was determined by energy dispersive analysis of X-ray (EDAX). The hard ceramic powders such as WC, $Al_2O_3$, $ZrO_2$, BN and $B_4C$ have been selected as reinforcements for developing binary and tertiary reinforced copper-based hybrid composites. The hard ceramic particles may impart strength, wear resistance and the developed copper-based hybrid composites may still have acceptable electrical property. There are broadly two different kind of copper-based hybrid composites known as binary reinforcement and tertiary reinforcement system developed depending on the number of reinforcement into the copper metal matrix. The binary reinforced hybrid composites have been designated on the basis of their composition as Cu-2Cr-1WC-1$ZrO_2$ (Hybrid composite-1 (HC-1)), Cu-2Cr-1WC-1$Al_2O_3$ (HC-2), Cu-2Cr-1WC-2$ZrO_2$ (HC-3) and Cu-2Cr-1WC-2$Al_2O_3$ (HC-4). Whereas, tertiary reinforced hybrid composites are designated as Cu-2Cr-1.5WC-1BN-0$B_4C$ (HC-5), Cu-2Cr-1.5WC-1BN-0.5$B_4C$ (HC-6), Cu-2Cr-1.5WC-1BN-1$B_4C$ (HC-7) and Cu-2Cr-1.5WC-1BN-1.5$B_4C$ (HC-8). The developed copper-based hybrid composites have been examined for characterization and distribution of phases by X-ray diffraction (XRD), high-resolution X-ray diffraction (HRXRD), optical, scanning electron microscopy (SEM), energy dispersive analysis of X-ray (EDAX) and high-resolution scanning electron microscope (HR-SEM). The hardness, compressive strength and the tensile properties of developed hybrid composites have been measured. The electrical property has also been measured by four-probe technique. Friction and wear tests were conducted according to ASTM G99-05 standard using a pin-on-disc tribometer (Magnum Engineers, Bangalore, India) with a counter face of EN31 steel hardened to 60-62 HRC at ambient temperature. The worn surfaces of all the materials studied in the present investigation were examined under SEM and EDAX to explore the operative mechanisms of wear.

**Chapter-4:** This chapter describes the reinforcing particles (WC, $Al_2O_3$, $ZrO_2$, BN and $B_4C$) morphology and its compositional details. It also explains the effect of content on the microstructural, physical and mechanical properties of hybrid composites. Effect of reinforcement on the microstructural behavior of the developed hybrid composites has been investigated by using SEM, EDS, XRD and optical microscope. This microstructural study reveals that the uniform distribution of second phase (reinforcing particles) rather than its amount which plays a vital role in attaining the desired properties in such developed hybrid composites. Density of the developed hybrid composites is found lower as compared to its matrix due to addition of low density of reinforcing particles in matrix. However, Hardness, compressive strength and ultimate tensile strength of the both binary and tertiary reinforced hybrid composites were evaluated and found higher as compared with its metal matrix and these properties increase with increase in reinforcement content also. To explore the fracture mechanics involved in hybrid composites during tensile test, the fracture surfaces are analyzed using SEM equipped with EDAX. The deeper and larger dimples conferred that the ductile fracture of metal matrix and smaller and shallow dimples exhibit the brittle fracture of hybrid composites. The electrical conductivity of the both binary and tertiary reinforced hybrid composites is measured using the four probe technique and achieved deteriorated electrical properties as compared to the metal matrix. It may be attributed to the addition of non conducting nature of reinforcements.

In the current investigation, it is observed that the hybrid composites display better mechanical properties as compared with its matrix. Among all the materials, the tertiary reinforced hybrid composites exhibit best mechanical properties.

**Chapter-5:** This chapter presents the results and discussion on the dry sliding friction and wear behavior of CC and binary and tertiary reinforced copper-based hybrid composites. Friction and wear behavior has been determined at four different normal loads of 9.81, 19.62, 29.43, and 39.24 N and constant sliding speed of 2.43 $m.s^{-1}$ by sliding against a hardened counter-face made of EN31 steel (60-62 HRC) under ambient conditions, using a pin-on-disc test rig. The worn surfaces of all the specimens under different loads of 9.81, 39.24 N and constant sliding speed of 2.43 $m.s^{-1}$ have been examined under SEM equipped with EDAX to reveal the involved operative mechanisms of wear. SEM studies have also been carried out to understand the nature of wear debris at load of 39.24 N. The coefficient of friction of CC and both binary and tertiary hybrid composites showed a fluctuating behavior with respect to sliding distance and no certain trend is observed. However, coefficient of friction shown by the CC is always less than the binary hybrid composites and higher than the tertiary hybrid composites. Average coefficient of friction has been observed to decrease with increasing normal load. However, binary hybrid composites have revealed the higher values of coefficient of friction and tertiary hybrid composites displayed the lower value of coefficient of friction as compared to CC. The cumulative volume loss of CC and hybrid composites investigated in the current study increased almost linearly with increasing sliding distance. It is observed that cumulative volume loss for both the hybrid composites is much lower than the matrix alloy. The wear rate, described as volume loss per unit of sliding distance has been estimated from the slope of the variation of cumulative volume loss vs. sliding distance it has been found to increase linearly with increasing normal load for all the materials investigated, following Archard's law. However, both the hybrid composites have shown a lower wear rate compared to CC which has been correlated with the estimated hardness also. A better wear performance of both hybrid composites is attributed to its relatively higher hardness and ability to hold a transfer layer of relatively larger in comparison to CC. The best wear performance among all the materials investigated is shown by the HC-7. The examination of the worn surface of CC as well binary and tertiary hybrid composites under SEM showed that wear mechanism for is a mix of adhesive and oxidative wear whereas it is primarily abrasive for the both the hybrid composites. EDAX analysis displayed the presence of Fe in the spectra confirming thus the metal transfer from the counter face to the pin's surface in the binary reinforced hybrid composites. The presence of oxygen peak in the spectra pointed toward the possibility of occurrence of oxidation during the sliding wear for both the hybrid composites.

**Chapter-6:** This chapter lists the salient conclusions on the microstructure, mechanical, density, electrical properties and dry sliding friction and wear behaviors of the developed binary and tertiary reinforced copper-based hybrid composites using the stir-casting technique in the present investigation.