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Investigation on mechanical and tribological properties of Boron Carbide and CNT reinforced Copper based composites

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ABSTRACT

The current work focuses on the influence and contribution of Multi-Walled Carbon Nanotube (MWCNT) and Boron Carbide (B4C) to the mechanical and corrosion properties of copper matrix composites. Different weight fractions of nano-B4C and MWCNT-reinforced copper composites were prepared using the ultrasonic-assisted stir casting methodologies. Various tests such as density, tensile, compression, hardness, and corrosion were conducted as per ASTM standards. The addition of reinforcements showed enhancements in the mechanical properties such as tensile strength, compressive strength, hardness and corrosion resistance of the composites due to the uniform dispersion of the secondary reinforcement in the copper matrix and the self-lubricating effect of the MWCNTs. Further, the weight of the composites decreased with the strength characteristics increasing leading to the enhancement in strength to weight ratios of the composite specimens. The effects of the nanoparticle distribution in the matrix and the dispersion of the composites were characterized using high-resolution scanning electron microscopy. The results of experiments highlight the use of experiential reinforcing limits of B4C on the mechanical behavior and corrosion characteristics of copper composites.

Keywords— *Copper, Boron carbide, Carbon Nanotubes (CNTs), Composites, Stir casting, Mechanical, Corrosion, Characteristics.*

1. INTRODUCTION

1.1 Copper Matrix Composites

Copper Matrix Composites are reinforced by:

- Continuous fibers of carbon (C), silicon carbon (SiC), tungsten (W), stainless steel 304 (long-fiber reinforced composites);
- Silicon carbide particles (particulate composites).
- Powder metallurgy (sintering) and infiltration technique are used for fabrication Copper Matrix Composites.

The following properties are typical for Copper Matrix Composites:

- Low coefficient of thermal expansion;
- High stiffness (modulus of elasticity);
- Good electrical conductivity;
- High thermal conductivity;

1.2 Carbon Nanotubes

Carbon Nanotubes (CNTs) are allotropes of carbon with a barrel shaped nanostructure. These round and hollow carbon atoms have unordinary properties, which are important for nano-technological innovations, nano-electromechanical systems, optics and different fields of materials science and innovation. Inferable from the material's uncommon quality and solidness, nanotubes have been developed with the length-to-width proportion of up to 132,000,000:1 [1].

Furthermore, attributable to their unprecedented thermal conductivity, mechanical, and electrical properties, carbon nanotubes have found applications as added substances to different auxiliary materials. For example, nanotubes have been reinforced in baseball bats, golf sticks, automobile, and aerospace components [2-3].

Nanotubes are individuals from the fullerene basic family. Their name is derived from their long, empty structure with the dividers shaped by one-atom-thick sheets of carbon, called graphene. These sheets are rolled at particular and discrete ("chiral") edges, and the blend of the moving edge and range choose the nanotube properties; for instance, regardless of whether the individual nanotube shell is a metal or semiconductor. Nanotubes are sorted as Single-Walled Nanotubes (SWNTs) and Multi-Walled Nanotubes (MWNTs). Singular nanotubes normally adjust themselves into "ropes" held together by van der Waals forces, particularly, pi-stacking.

Applied quantum science, particularly, orbital hybridization best depicts synthetic bonding in nanotubes. The bonding of nanotubes includes totally sp2-hybrid carbon atoms. These bonds, which are like those of graphite and more grounded than those found in alkanes and precious stone (which utilize sp3-crossover carbon iotas), furnish nanotubes with their extraordinary quality.

The discovery of Carbon Nanotubes (CNT) in 1991 opened up a new era in materials science. These incredible structures have an array of fascinating electronic, magnetic and mechanical properties. CNT are at least 100 times stronger than steel, but only one-sixth as heavy, so nanotube fibers could strengthen almost any material. Nanotubes can conduct heat and electricity far better than copper. CNT is already being used in polymers to control or enhance conductivity and are added to anti-static packaging**.**

1.3 Boron Carbide

Boron carbide (chemical formula approximately B4C) is an extremely hard boron–carbon ceramic, and covalent material used in tank armor, bulletproof vests, engine sabotage powders,[4] as well as numerous industrial applications. With a Vickers Hardness of >30 GPa, it is one of the hardest known materials, behind cubic boron nitride and diamond [5].

Boron carbide was discovered in the 19th century as a by-product of reactions involving metal borides, but its chemical formula was unknown. It was not until the 1930s that the chemical composition was estimated as B4C [6]. There remained, however, controversy as to whether or not the material had this exact 4:1 stoichiometry, as in practice the material is always slightly carbon-deficient with regard to this formula, and X-ray crystallography shows that its structure is highly complex, with a mixture of C-B-C chains and B12 icosahedra. These features argued against a very simple exact B4C empirical formula [7]. Because of the B12 structural unit, the chemical formula of "ideal" boron carbide is often written not as B4C, but as B12C3, and the carbon deficiency of boron carbide described in terms of a combination of the B12C3 and B12CBC units.

The ability of boron carbide to absorb neutrons without forming long-lived radionuclides makes it attractive as an absorbent for neutron radiation arising in nuclear power plants and from anti-personnel neutron bombs. Nuclear applications of boron carbide include shielding, control rod and shut down pellets. Within control rods, boron carbide is often powdered, to increase its surface area [5]. Boron carbide has a complex crystal structure typical of icosahedron-based borides. There, B12 icosahedra form a rhombohedral lattice unit (space group: R3m (No. 166), lattice constants: a = 0.56 nm and c = 1.212 nm) surrounding a C-B-C chain that resides at the center of the unit cell, and both carbon atoms bridge the neighboring three icosahedra. This structure is layered: the B12 icosahedra and bridging carbons form a network plane that spreads parallel to the c-plane and stacks along the c-axis. The lattice has two basic structure units – the B12 icosahedron and the B6 octahedron. Because of the small size of the B6 octahedra, they cannot interconnect. Instead, they bond to the B12 icosahedra in the neighboring layer, and this decreases bonding strength in the c-plane [8].

Because of the B12 structural unit, the chemical formula of "ideal" boron carbide is often written not as B4C, but as B12C3, and the carbon deficiency of boron carbide described in terms of a combination of the B12C3 and B12C2 units [9-10]. Some studies indicate the possibility of incorporation of one or more carbon atoms into the boron icosahedra, giving rise to formulas such as (B11C)CBC = B4C at the carbon-heavy end of the stoichiometry, but formulas such as B12(CBB) = B14C at the boron-rich end. "Boron carbide" is thus not a single compound, but a family of compounds of different compositions. A common intermediate, which approximates a commonly found ratio of elements, is B12 (CBC) = B6.5C [11]. Quantum mechanical calculations have demonstrated that configurational disorder between boron and carbon atoms on the different positions in the crystal determines several of the properties of the material - in particular, the crystal symmetry of the B4C composition [12] and the non-metallic electrical character of the B13C2 composition [13].

Boron carbide is known as a robust material having high hardness, the high cross section for absorption of neutrons (i.e. good shielding properties against neutrons), stability to ionizing radiation and most chemicals [14]. Its Vickers hardness (38 GPa), Elastic Modulus (460 GPa) [15] and fracture toughness (3.5 MPa·m1/2) approach the corresponding values for diamond (1150 GPa and 5.3 MPa·m1/2) [16].

2. METHODOLOGY OF PRESENT RESEARCH WORK

The present research work involves the need for formulation of a scientific methodology that will eventually give the basis for the development of work. The figure shows the detailed methodology of present research work in the form of a flowchart.

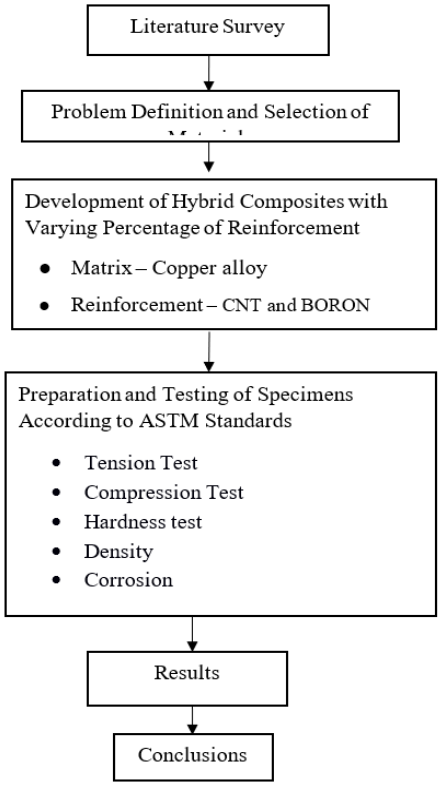

Fig. 1: Methodology

2.1 Tension test

A specimen with specified shape and size is gradually subjected to increasing uni-axial load (force) until failure occurs, simultaneous observations are made on the elongation of the specimen, and this is the typical procedure for tensile testing. The operation is accomplished by gripping opposite ends of the work piece and pulling it, which results in elongation of the test specimen in a direction parallel to the applied load. The ultimate tensile strength tests were done in accordance with ASTM E8-82 standards. The tensile specimens of diameter 12.5mm and gauge length 50mm were machined from the cast specimens with the gauge length of the specimens parallel to the longitudinal axis of the casting. Yield strength of the specimens was evaluated in terms of MPa. The test was carried out at room temperature using Universal Testing Machine shown in figure 2. The tensile specimens prepared in accordance with ASTM E8-82 were subjected to homogenous

and uniaxial tensile stresses in the Universal Testing Machine. The ultimate tensile strength of the hybrid composites specimens and of the base alloy were plotted against the CNT content and B4C. Figure 1 shows the tensile specimen before the test and figure 3 shows tensile specimens after the test.

Fig.2: Tensile Test Speciemens before the test

Fig. 3: Universal testing machine

Fig. 4: Tensile specimens after test

2.2 Compression test

Specimens were machined in according to with ASTM E9 standards, diameter=20mm and length=20mm and test were conducted using a computerized UTM. Compressive strength of the specimen was evaluated in terms of MPa. Three specimens for the composition of each composite were tested and average results are noted down.

Fig. 5: Compression specimens before the test

Fig. 6: Compression specimens after test

3. RESULTS OF TENSILE TEST

The ultimate tensile strength of the hybrid composites specimens and of the base alloy show a remarkable increase in ultimate tensile strength with the incorporation of reinforcements in the matrix phase. It follows from the graph that the specimens show an increase in UTS as the content of CNT in the composite is increased in as cast conditions.

The factors that influence in the UTS is complex and interrelated. Several variables, such as the distribution of the particles/ fibre in the matrix, the mechanical properties of the matrix and reinforcing particles/ fibre and the bonding between the matrix and reinforcement, are reported to influence the strength of discontinuously reinforcing composites strongly. Also, various strengthening mechanisms have been proposed to explain the improvement in strength in the case of discontinuously reinforced MMCs [23]. It can be observed in the result of how the UTS varied from C1 specimen to C6. The same trend is observed in some of the literature [27, 28-30]. The ultimate tensile strength varied from 245.07 MPa for unreinforced copper (C Specimen) to 370.43 for reinforced composite (C6 Specimen) thereby justifying the use of reinforcements in the matrix phase. Further, the increase in tensile strength of the composites is attributed to the strong interfacial bonding between the reinforcement and matrix phase. Furthe, the yield strength increases with the incorporation of reinforcements from 201.44 MPa to 263.65 MPa, while the percentage elongation reduces from 9.2 to 7.2, this is majorly due to the addition of boron carbide that will enhance the tensile strength and reduce the free deformation of the specimens thereby reducing its elongation.

Table 1: Ultimate tensile strength

Specimen Designation	Wt.% of CU	Wt.% of CNT	Wt.% of B4C	Max. load (N)	Max. Displacement (mm)	UTS (N/mm^2)
C	**100**	**0**	**0**	**1000**	**250**	**245.07**
C1	98.5	0.5	1	1000	250	256.72
C2	96.5	0.5	3	1000	250	268.15
C3	98	1.0	1	1000	250	298.55
C4	96	1.0	3	1000	250	333.52
C5	97.5	1.5	1	1000	250	351.68
C6	95.5	1.5	3	1000	250	370.43

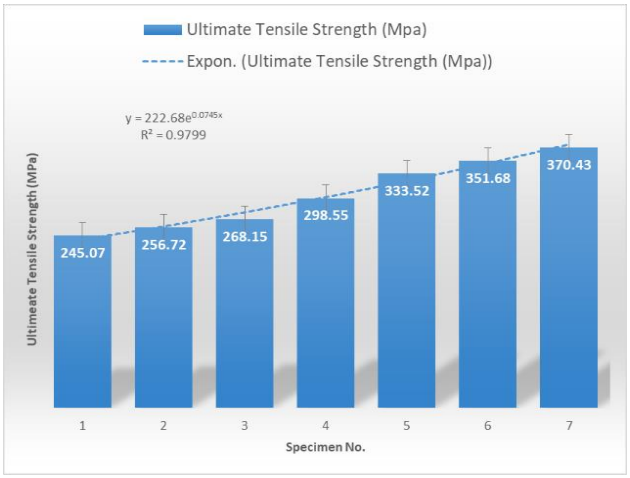

Fig. 7: Ultimate tensile strength for different specimens

Table 2: Yield Strength for different specimens

Specimen Designation	Wt.% of CU	Wt.% of CNT	Wt.% of B4C	Max. load (N)	Max. Displacement (mm)	Yield Strength (N/mm^2)
C	**100**	**0**	**0**	**1000**	**250**	**201.44**
C1	98.5	0.5	1	1000	250	216.51
C2	96.5	0.5	3	1000	250	227.25
C3	98	1.0	1	1000	250	236.72
C4	96	1.0	3	1000	250	248.97
C5	97.5	1.5	1	1000	250	255.54
C6	95.5	1.5	3	1000	250	263.65

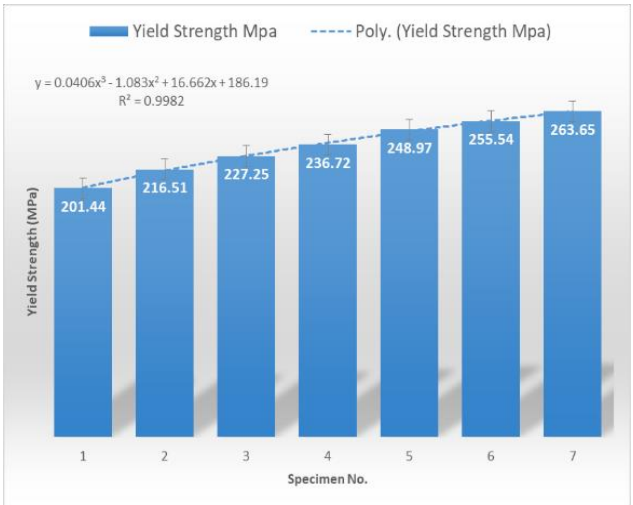

Fig. 8: Yield Strength for different specimens

Table 3: Percentage elongation for different specimens

Specimen Designation	Wt.% of CU	Wt.% of CNT	Wt.% of B4C	Max. load (N)	Max. Displacement (mm)	% Elongation
C	**100**	**0**	**0**	**1000**	**250**	**9.2**
C1	98.5	0.5	1	1000	250	8.9
C2	96.5	0.5	3	1000	250	8.5
C3	98	1.0	1	1000	250	8.3
C4	96	1.0	3	1000	250	7.6
C5	97.5	1.5	1	1000	250	7.2
C6	95.5	1.5	3	1000	250	6.8

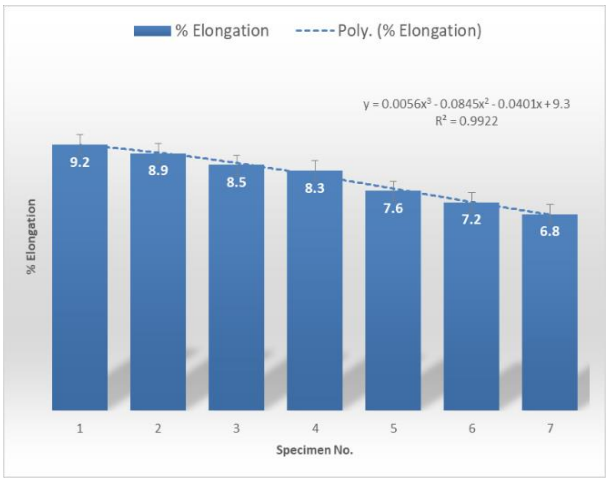

Fig. 9: Percentage elongation for different specimens

4. RESULTS OF COMPRESSIVE STRENGTH

The table shows the effect of CNT and B4C on compressive strength of copper hybrid composites. It can be seen that the compressive strength of the hybrid composites increases monotonically as the reinforcement contents are increased. The increase in compressive strength is mainly due to the decrease in the inter-particle spacing between the particles. Since B4C are much harder than copper alloys. The presence of CNT and B4C resist deforming stresses, thus enhance the compressive strength of the composite material. Figure 1 shows the load displacement curves for compressive loading of various combinations of CNT and B4C. The effect of the addition of reinforcements on UCS of the composites is presented in graphs. It is observed that the UCS of the composites monotonically increases as the particulate content is increased up to 1.5 Wt. % of CNT and it decreases beyond 1.5 Wt. %. The increase in strength can also be attributed to the addition of B4C which impart strength to the matrix alloy thereby enhancing resistance to compression. There is a reduction in the inter-special distance between particulates, which cause an increase in the dislocation pile-up as the particulate content increases [44]. This leads to restriction to plastic flow due to the random distribution of the particulate in the matrix, thereby providing enhanced strength to composites. At a lower percentage of reinforcement, the decrease in the strength may be due to poor bonding of CNT particles.

Further, the compressive strength increases from 1279.43 MPa to 1548.33 with the addition of Boron carbide and CNT reinforcements thereby validating the addition of reinforcements, also the % reduction diminishes with the addition of reinforcements, i.e., from 6.52 to 3.73, this is majorly due to the addition of Boron carbide along with the CNT that will enhance its ability to withstand the compression and give better strength capabilities, thereby reducing % compression in the specimens.

Table 4: Compressive strength for different specimens

Specimen Designation	Wt.% of CU	Wt.% of CNT	Wt.% of B4C	Peak Load (KN)	Compressive Strength (N/mm^2)
C	**100**	**0**	**0**	**600**	**1279.43**
C1	98.5	0.5	1	600	1332.28
C2	96.5	0.5	3	600	1359.43
C3	98	1.0	1	600	1385.54
C4	96	1.0	3	600	1446.12
C5	97.5	1.5	1	600	1511.7
C6	95.5	1.5	3	600	1548.33

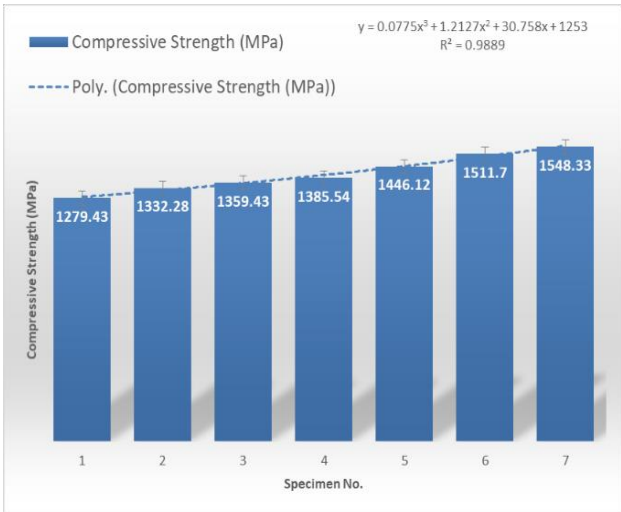

Fig. 10: Compressive strength for different specimens

Table 5: % Reduction for different specimens

Specimen Designation	Wt.% of CU	Wt.% of CNT	Wt.% of B4C	Peak Load (KN)	% Reduction
C	**100**	**0**	**0**	**600**	**6.52**
C1	98.5	0.5	1	600	5.58
C2	96.5	0.5	3	600	5.13
C3	98	1.0	1	600	4.88
C4	96	1.0	3	600	4.27
C5	97.5	1.5	1	600	3.94
C6	95.5	1.5	3	600	3.73

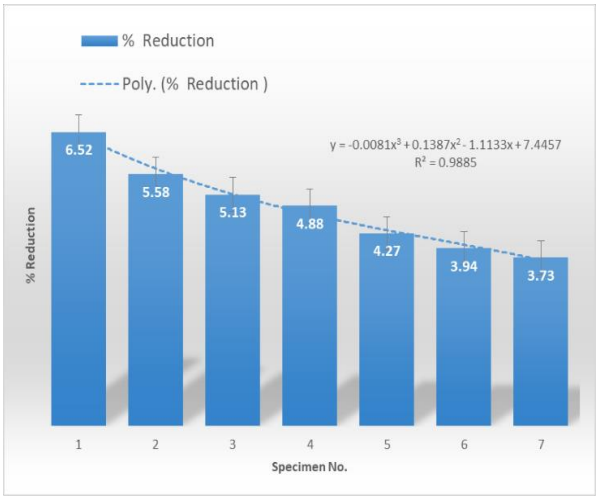

Fig. 11: Percentage reduction for different specimens

6. CONCLUSIONS

The present work on the preparation of CNT and B4C reinforced Copper metal matrix composite by stir casting and evaluation of mechanical characteristics has led to the following conclusions.

CU/CNT/B4C composites have been successfully developed and fabricated with a fairly uniform distribution of reinforcements using stir casting technique.

The Ultimate tensile strength (UTS) increased from 245.07 MPa to 370.43 MPa, while the yield strength increased from 201.44 MPa to 263.65 MPa, % elongation reduced from 9.2 to 6.8. The increase in UTS is attributed to the presence of hard B4C reinforcement particles which imparts strength to the matrix alloy, thereby providing enhanced tensile strength. There is a substantial increase in tensile strength of C6 composites when compared with 'C' Specimen. Ductility of the composites was low probably because of high porosity content, early void formation at low strains during tensile elongation and heterogeneous particle distribution. The percentage elongation of the MMC's decreased with increase in B4C and CNT content, which confirmed that B4C addition increased brittleness. The reduction in ductility can be attributed to the presence of a hard ceramic phase that is prone to localized crack initiation and increased embrittlement effect due to local stress concentration sites at the reinforcement matrix interface.

The compressive strength increased from 1279.43 MPa to 1548.33 MPa, while % reduction dropped down from 6.52 to 3.73, this is majorly due to the bonding of reinforcements with the matrix phase that will ultimately enhance its ability to resist compression.

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