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Wear Properties of Cu-CNT Nanocomposites

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1. Introduction

Currently, Carbon Nano Tubes (CNTs) are gaining wide spread applications in several high technological areas owing to its remarkable mechanical and electronic properties. Carbon nano tubes were discovered to be the fourth form of carbon by the classic experiments of Ijima in 1991. After that paper there was a flurry of activity worldwide on studies and emphasis on synthesis of CNTs (Ebbesen et al.). Worldwide the major emphasis has been on to develop quality CNTs, several routes of processing CNTs do exist which are Laser Ablation, Electric Arc Discharge and Chemical Vapor Deposition. The properties, both electrical and mechanical of the CNTs have been studied extensively all over the world by several researchers (Tans et al.).It is reported that the CNTs do processes a very high modulus of one Tera Pascal (Harris) and electrical conductivity (1013 A/cm^2). Because of these superior properties CNTs are a potential candidate as reinforcement material to produce composites. Copper and its alloys are used commercially because of its high electrical and thermal conductivity coupled with strength.

The hard and refractory ceramic reinforcements such as silicon carbide, Alumina, titanium oxide have commonly been used as reinforcements in the ductile copper matrix. Although they posses higher strength, better wear resistance they exhibit lower ductility and thermal conductivity when compared with copper. Further the enhancement in the elasticity modulus of copper based particulate composites is not significant. It is also reported that CNTs can be an ideal reinforcements to develop high-quality composites owing to their low weight and exceptional properties. Kashyap et al., have reported that use of CNT as reinforcements in Aluminum matrix has resulted in drastic improvements in strength which has been attributed to Orowan looping. It is reported that use of CNTs in Ni-matrix has resulted in lowering of Coefficient of friction and wear rates of the composites when compared with nickel matrix. However meager information is available as regards to development and study on tribological behavior of Cu/CNT composites. Dong et al., developed the composites using HIP process and reported. Copper with its low stacking fault energy enables one to observe free dislocations on a Transmission Electron Microscope (TEM) since dynamic recovery will not take place in copper during processing. This aspect has not been studied so far in the literature. In the light of the above, this research focuses on development and characterization of tribological properties of Cu/CNT (MWCNTs and SWCNTs). There is only one paper where Dong et al. studied the sliding wear behavior of

Carbon Nanotube/Copper composite. Hence, this aspect is the thrust of the present research i.e., to reinforce copper with Multi-Walled Carbon Nanotubes (MWCNTs) and Single-Walled Carbon Nanotubes (SWCNTs) to enhance its wear and friction behavior. Friction and wear tests have been conducted on both sintered pure copper and the developed composites.

2. Arc discharge chamber – production of CNTs

The Carbon arc method of synthesizing CNTs and Fullerenes consists of a stainless steel chamber, a DC power unit and inert gas supply.The arc reaction chamber fabricated is a hollow cylinder of internal of internal diameter 140 mm and wall thickness of 14 mm. Large internal diameter was provided for easy mounting, removal of electrodes and carbon soot from the inside surface of the chamber. Material selected for the reactor being stainless steel mainly due to their corrosion resistant property and it was ensured that the diameter of reactor were large enough to prevent excess heating of the wall due to arcing of electrodes (>30000 C).Water circulation through the walls of the chamber, to the electrode holders and also through the pipes surrounding the electrodes ensures proper cooling. The thickness of the chamber wall was made sufficient enough to hold a rough vacuum at high temperature. A view port is provided on the chamber to visualize the plasma generation and arcing of electrodes. Flanges are mounted at the reactor ends and to guarantee proper vacuum, o-rings were provided. The top flange of the reactor has a cooling system arrangement for the cathode (copper) to prevent the melting of electrodes due to high temperature developed during arcing process. During the early stages of the arcing process the anode is to be fed regularly to obtain a stable arc, which is being subsequently sustained by maintaining a constant gap of 1mm between the electrodes.

2.1 Power source

A saturated core reactor controlled DC power supply was used with a rating of 80V and 300A. For generation of carbon nanostructures, ripples are maintained within 5% by providing capacitor filter circuit to the power unit and an oscilloscope to monitor the arcing process of the electrodes. The voltage applied for the experiment varies depending on the inert medium used and electrode separation distance. With Helium gas at 500 torr, at a voltage of 20V and separation of 1mm or less between electrodes, gives best results.
Current does not directly influence CNT growth but rather, the heating effect of current is responsible for CNT growth. Heating to temperatures above 3000°C ensures nanotubes to remain open ended without closure there by allowing CNTs to grow. However, the same heating effect can result in the sintering of CNTs if sufficient cooling is not provided. The magnitude of current should ideally be maintained at a minimum to achieve a self-sustained stable arc.

2.2 Inert atmosphere

The inert atmosphere in the chamber is critical to the growth of CNTs. Helium is by far the most popular inert medium. However, lot of successful experiment has been conducted with other gases and even liquids. The temperature/annealing growth mechanism for CNTs by arc discharge process requires cooling of the CNT samples grown at the cathode by inert media and hence the thermal conductivity and pressure of the gas becomes an important

factor in the synthesis methodology. High thermal conductivity media provide better cooling for the CNT sample and prevent sintering.

2.3 Inert gas pressure

If the inert medium is a gas, then the pressure of the gas plays a critical role in the yield and quality of CNTs produced. At 500 torr there was a considerable concentration of CNTs. Beyond this pressure the yield of CNTs reduced. The increase in pressure of helium from 20 torr to 500 torr is beneficial to CNT growth due to better cooling of the sample by the inert medium. For generation of CNTs both SWNT and MWNT, Helium gas was vaccumised at 500 torr in the reaction chamber using a direct drive rotary vacuum pump.

2.4 Electrodes

Another very important part of the arc discharge process is electrode material and its geometry. Cooling of electrodes plays an important role in CNT synthesis. CNTs are deposited on the cathode, hence the use of copper cathodes provide better cooling than graphite, which was originally used. The anode is composed of graphite; it may include catalyst for SWNT synthesis. Both anode and cathode can be water-cooled. This reduces chances of sintering of CNT. For the preparation of single walled nanotubes or filled nanotubes, catalysts/material must be inserted into a hole drilled in the center of the graphite anode. As can be expected, Fe, Co, and Ni have been used in conjunction with lanthanide, actinide and transition metals as effective catalysts for SWCNT synthesis. The most favored configuration is a 6mm anode and a 12mm cathode.The experimental setup consisting of arc discharge chamber, inert gas, power source and cooling system is as shown in Figure 1.

Fig. 1. Arc Discharge Apparatus

2.5 Synthesis and purification of carbon nanostructures

A stainless steel arc evaporation reactor with a viewing port as discussed was used for synthesis of these Nano structures. The chamber is connected to a rotary vacuum pump and a helium supply.

The graphite (anode) and copper (cathode) electrodes are mounted on the flanges of the chamber. Cooling being the most important requirement for production of these nano structures and hence water-cooling was provided for cathode, anode and the reactor. Position of anode can be adjusted from outside the chamber so that a constant gap can be maintained during arc evaporation. A DC power supply was used and arc-discharge is usually carried out below 20V. The current depends upon the diameter of graphite rod and also on helium pressure.

2.5.1 Multi-Walled Carbon Nanotubes (MWCNTs)

MWCNTs are synthesized by using Arc Discharge setup. An electric arc is struck between the graphite anode and copper cathode of 6mm and 12mm diameter respectively in a helium atmosphere of 500 torr. The current density is approximately 150 A/cm^2 DC, current and voltages are maintained at 75A and 20V respectively. Helium gas atmosphere can be static or dynamic during the processes.

Fig. 2. Cigar like structure deposited on the Copper cathode during Arc evaporation process

The soft-core material contains MWCNTs, polyhedral particles and various kinds of graphitic particles. The soft core thus obtained is dispersed in ethanol and is sonicated for 20 minutes. This solution is then decanted and the residue is sonicated again to recover any remaining nanotubes. The decanted solution is then heated to evaporate ethanol leaving behind nanotubes.

Optimum operating parameters for production of MWCNTs:

Potential drop across electrodes = 20 V
Helium pressure = 500 torr
Anode= Ø 6 mm and Cathode= Ø 12 mm
Current density = (150-200) Amp/cm^2
Inter-electrode distance during stationary period of discharge = 1mm
Average inter-electrode temperature = 4000 K
Deposit rate at cathode surface = 1mm/min
Good cooling of electrode & chamber

2.5.2 Single - Walled Carbon Nanotubes (SWCNTs)

SWCNTs are produced in the same arc evaporation chamber as shown in figure 1 by co-vaporization of graphite and bimetal catalyst in a composite anode. The graphite rod is

6mm in diameter and 150mm in length. A hole of 4mm is drilled axially and densely packed with mixture of Cobalt and Nickel in the ratio 3:1 and 96% graphite powder. The helium pressure is maintained at 500 torr. A stable arc is formed at 20V and 75A. The gap between electrodes is maintained around 2mm. SWCNTs are formed as a web like structure in the chamber and also as a collaret around the cathode. It should be noted that cylindrical deposit also grows at the cathode, consisting of a hard gray shell and a soft core. The soft core has poorly developed columnar structure and contains MWCNTs and polyhedral particles.

The product obtained can be divided in to three structural types; a spongy soft belt called collaret is formed around the cylindrical deposit while relatively a strong cloth like soot is found on the chamber walls and finally a web like structure is suspended in the chamber volume between cathode and walls. The above three type contains varying amount of SWCNTs, Fullerenes and amorphous carbon. To extract SWCNTs, the soot is heated at 450°C for 20 minutes to vaporize volatile impurities. The residue is then treated with $HN0_3$ to dissolve metal catalyst particles. The soot, free from volatile impurities and catalyst particles is filtered to separate it from $HN0_3$ and the residue thus obtained is dissolved in ethanol followed by sonication for 20 minutes. The decanted solution is finally heated to vaporize ethanol to obtain pure SWCNTs.

Optimum operating parameters for production of SWCNTs:

Potential drop across electrodes = 20 V
Helium pressure = 500 torr
Composite Anode = 7 mm outside diameter & inside diameter 4mm
Cathode = Ø 12 mm
Current density = 150 - 200 Amp/cm^2
Inter-electrode distance during stationary period of discharge = 1 mm
Average inter-electrode temperature = 4000 K
Deposit rate at cathode surface = 1.5 mm/min
Good cooling of electrode & chamber

3. Methodology / approach

The route to produce CNTs is electric arc-discharge, process parameters such as voltage, current, graphite electrode purity and the gap between electrodes and the pressure of the carrier gas (Helium) was studied. The multi-walled CNTs obtained from Arc Discharge process was sonicated in an ultrasonic sonicator. These nanostructures were purified by solvent method and their purity was confirmed by Thermal Gravimetric Analysis (TGA). CNTs were characterized by Raman spectroscopy and Electron microscopy to validate their identity and quality. Then the CNTs will be coated by Nickel. The MWCNTs will be given a electroless coating of Nickel as followed by Q Q Li et al., and also by Dong et al., for obtaining good wettability of CNTs with Copper. The coating of Nickel will be confirmed by X-ray diffraction and then Nickel coated CNTs and copper powder will be ball milled for (30 to 60) minutes and compacted in a hydraulic press of 100 ton capacity to obtain green compacts and sintered in Vacuum to increase density of the compacts .These compacts will be extruded to remove voids and tested for wear properties. Thin slices will be cut and Jet polished and the thin foil samples will be studied in a TEM. CNTs dispersion in the nano composite will be ascertained and also study of dislocations distributed with CNTs will be

carried out. These green compacts will be sintered at suitable temperature to ensure excellent bond between each grain and particle. The sintered compacts will be subjected to metallurgical studies like SEM and TEM to investigate the homogeneity of the distribution of the CNTs in the Copper Matrix. The powdered composite compacts will be subjected to hot extrusion with a suitable extrusion ratio to obtain a dense sample of nano composite. The post sintering densities of SWCNT/Cu and MWCNT/Cu composites were found to be 98% of the theoretical density. However, TEM images indicate that the distribution of CNTs in metal matrix homogeneously is the most critical issue to enhance the mechanical properties of CNT/metal nanocomposites. The volume fraction of CNTs was determined by analyzing the carbon contents using an Elemental Analyzer. SWCNTs and MWCNTs were used in varying weight percentages to reinforce commercial purity Copper matrix. Pin-on-disc machine has been used to evaluate the friction and wear behavior of the studied materials under dry sliding conditions.

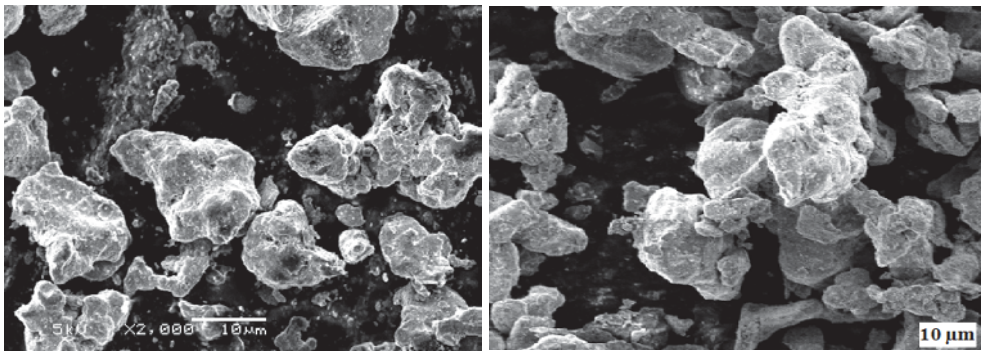

Fig. 3. SEM Images of Copper

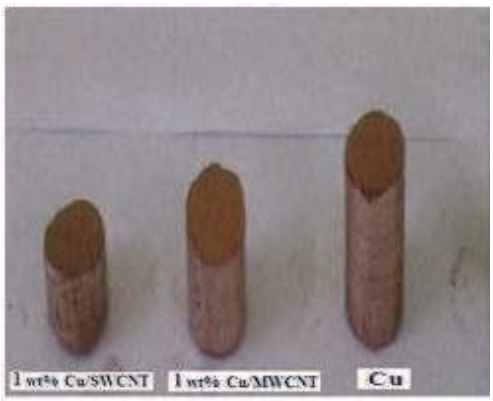

Fig. 4. Powder Compacted (Pre-sintered) Wear Test Specimens

The specimen diameter is 10mm and length is 22mm and sintering temperature is 700^0C for 1 hour. The hardness of the counter disc is 60RC. Load was varied from (20-150) N for various sliding velocities. SEM properties are compared with those of pure copper

Fig. 5. SEM Image of Wear Tested Pure Cu sample

specimens. SEM of worn surfaces has been investigated. The incorporation of carbon nanotubes and nickel-coated carbon nanotubes in the copper matrix composites improved tribological properties compared with those of pure copper specimens. The tests were conducted for CNT wt % 1, 3 & 5 and found 3 wt % (12 to 15 vol. %) to be optimum and tabulated.

4. Wear mechanism under dry sliding condition

Compared with carbon fiber, the reinforced effect of nanotube is greater owing to the high strength and aspect ratio of the nanotubes. It is also the evidence, that the working-hardening layer of the subsurface of the worn surface become shallower and the worn chips become smaller. Owing to Carbon nanotubes and the higher toughness of the Nanotube/Cu composite, fracture cracks in the Nanotube/Cu composite have more difficulty propagation and flaking. Therefore, the nanotubes reinforced composite has better wear resistance properties.

In previous researches, when the CNT/metal or CNT/ceramic nanocomposites are fabricated by molecular level process, the chemical bonding formed between the CNTs and the matrix ions provides homogeneous distribution of CNTs as well as high interfacial strength. Therefore, it is confirmed that such remarkable enhancement of hardness by CNT reinforcement is originated from the high interfacial strength at CNT/Cu interface, the homogeneous distribution of CNTs within Cu matrix and attained high relative densities. Thus, based on this result, it can be shown that the improvement of mechanical properties of CNT reinforced nanocomposites is expected when the external load can be shared by homogeneously distributed CNTs through the load transfer from matrix to CNTs by sound interfacial strength at CNT/matrix. Under dry sliding wear condition, the wear loss of CNT/Cu nanocomposites is reduced to 1/3 compared to those of pure Cu matrix. This result means that this nanocomposite shows three times higher wear resistance by addition of CNTs.

When the surface of pure Cu flakes away during the wear process, the worn chips are formed by peeling of Cu grains near the worn surface. However, in case of CNT/Cu nanocomposite, the Cu grains are not easily peeled from the worn surface by the pinning

of homogeneously implanted CNTs across Cu grains in CNT/Cu nanocomposites. At the same time, the CNTs exposed to the worn surface during wear process can act as a lubricating carbon film owing to its low friction coefficient. Therefore, the wear loss of CNT/Cu nanocomposites is remarkably decreased with increasing volume fraction of CNTs due to the effect of homogeneous distribution of CNTs in Cu matrix and low friction coefficient of exposed CNTs on the worn surface. The remarkable enhancement of hardness is originated from the homogeneously distributed CNTs in Cu matrix, high interfacial strength at CNT/Cu interfaces and high relative density of nanocomposites. The dispersed CNTs in Cu-matrix nanocomposite provide considerably enhanced wear resistance by retarding the peeling of Cu grains during sliding wear process. Thus, the homogeneous distribution of CNTs with sound interface in Cu matrix is an important technological issue to enhance the mechanical behavior and wear resistance of CNT/Cu nanocomposite.

4.1 Wear test results of pure Cu specimen

The following are the tabulated wear test results obtained under varying load and speed conditions.

1. Copper: 99%
2. Sintering: 750 ^{0}C and 1 hour
3. Specimen: Dia. = 10mm and Length = 22mm

Load (kg)	Speed (rpm)	Time	Wear (μm)	Frictional force (N)	Temp. (^{0}C)	Weight Loss (gm)	
5	100	5 min.	14	6.6	30	Before	13.6314
		10 min.	20	8.8	32	After	13.6174
		15 min.	25	9.5	34	Diff.	00.0140
		20 min.	30	11.1	37		
5	200	5 min.	16	6.3	33	Before	13.6174
		10 min.	23	8.5	36	After	13.5879
		15 min.	29	9.2	39	Diff.	00.0295
		20 min.	34	10.8	42		
5	300	5 min.	19	6.1	37	Before	13.5879
		10 min.	25	8.2	41	After	13.5467
		15 min.	33	8.8	46	Diff.	00.0412
		20 min.	37	10.4	49		
8	100	5 min.	18	8.1	33	Before	13.6314
		10 min.	26	10.9	37	After	13.6039
		15 min.	32	12.5	40	Diff.	00.0275
		20 min.	39	13.8	44		
8	200	5 min.	19	7.7	35	Before	13.6039
		10 min.	31	10.2	39	After	13.5526

		15 min.	37	11.8	42	Diff.	00.0513
		20 min.	41	13.2	47		
8	300	5 min.	23	7.4	39	Before	13.5526
		10 min.	35	9.9	44	After	13.4712
		15 min.	41	11.2	48	Diff.	00.0814
		20 min.	47	12.1	51		
12	100	5 min.	21	8.6	38	Before	13.6314
		10 min.	34	10.9	43	After	13.6003
		15 min.	39	12.5	48	Diff.	00.0311
		20 min.	44	14.7	56		
12	200	5 min.	24	8.2	42	Before	13.6003
		10 min.	37	10.7	46	After	13.5549
		15 min.	43	12.3	53	Diff.	00.0454
		20 min.	48	13.9	59		
12	300	5 min.	26	7.7	46	Before	13.5549
		10 min.	42	10.6	49	After	13.4698
		15 min.	48	11.7	57	Diff.	00.0851
		20 min.	53	13.3	63		

4.2 Wear test results of MWCNT/Cu composite

The following are the tabulated wear test results obtained under varying load and speed conditions.

i. Cu + MWCNT: 1 Wt %
ii. Sintering: 750 ^{0}C and 1 hour
iii. Specimen: dia. = 10mm and length = 22mm

Load (kg)	**Speed (rpm)**	**Time**	**Wear (μm)**	**Frictional force (N)**	**Temp. (^{0}C)**	**Weight Loss (gm)**	
5	100	5 min.	07	3.6	28	Before	11.5401
		10 min.	09	3.7	29	After	11.5381
		15 min.	13	3.9	31	Diff.	00.0020
		20 min.	16	4.2	33		
5	200	5 min.	06	3.4	31	Before	11.5381
		10 min.	07	3.5	33	After	11.5363
		15 min.	10	3.7	34	Diff.	00.0018
		20 min.	12	4.0	36		
5	300	5 min.	05	3.2	32	Before	11.5363
		10 min.	06	3.3	35	After	11.5348
		15 min.	08	3.5	37	Diff.	00.0015
		20 min.	11	3.8	39		

8	100	5 min.	12	4.1	28	Before	11.5401
		10 min.	16	4.4	29	After	11.5374
		15 min.	19	4.9	31	Diff.	00.0027
		20 min.	21	5.4	33		
8	200	5 min.	07	3.6	30	Before	11.5374
		10 min.	09	3.7	31	After	11.5352
		15 min.	13	4.5	33	Diff.	00.0022
		20 min.	16	4.9	34		
8	300	5 min.	05	3.2	32	Before	11.5352
		10 min.	06	3.3	35	After	11.5333
		15 min.	08	3.9	37	Diff.	00.0019
		20 min.	11	4.4	39		
12	100	5 min.	17	4.4	28	Before	11.5401
		10 min.	22	4.7	29	After	11.5374
		15 min.	25	4.9	31	Diff.	00.0032
		20 min.	28	5.4	33		
12	200	5 min.	12	4.2	30	Before	11.5346
		10 min.	16	4.4	31	After	11.5331
		15 min.	19	4.6	33	Diff.	00.0028
		20 min.	21	5.1	34		
12	300	5 min.	07	3.8	32	Before	11.5352
		10 min.	09	4.1	35	After	11.5333
		15 min.	13	4.3	37	Diff.	00.0025
		20 min.	16	4.8	39		

Cu + MWCNT: 3 Wt %; Sintering: 750 ^{0}C and 1 hour;
Specimen: dia. = 10mm and length = 22mm

Load (kg)	**Speed (rpm)**	**Time**	**Wear (μm)**	**Frictional force (N)**	**Temp. (^{0}C)**	**Weight Loss (gm)**	
5	100	5 min.	04	2.9	26	Before	11.5401
		10 min.	05	3.1	28	After	11.5386
		15 min.	09	3.3	30	Diff.	00.0015
		20 min.	11	3.7	33		
5	200	5 min.	03	2.8	29	Before	11.5386
		10 min.	05	3.1	30	After	11.5373
		15 min.	09	3.2	33	Diff.	00.0013
		20 min.	10	3.6	37		
5	300	5 min.	2	2.7	30	Before	11.5373
		10 min.	4	3.0	31	After	11.5361

		15 min.	8	3.1	33	Diff.	00.0012
		20 min.	9	3.2	36		
8	100	5 min.	11	4.0	27	Before	11.5401
		10 min.	13	4.2	29	After	11.5379
		15 min.	17	4.7	30	Diff.	00.0022
		20 min.	19	5.1	31		
8	200	5 min.	06	3.3	30	Before	11.5379
		10 min.	08	3.5	31	After	11.5360
		15 min.	11	4.2	32	Diff.	00.0019
		20 min.	17	4.6	34		
8	300	5 min.	04	3.1	31	Before	11.5360
		10 min.	05	3.2	34	After	11.5343
		15 min.	07	3.7	36	Diff.	00.0017
		20 min.	14	4.2	37		
12	100	5 min.	15	4.2	27	Before	11.5401
		10 min.	20	4.5	29	After	11.5373
		15 min.	23	4.7	31	Diff.	00.0028
		20 min.	25	5.1	32		
12	200	5 min.	10	4.0	31	Before	11.5373
		10 min.	14	4.1	32	After	11.5349
		15 min.	17	4.3	34	Diff.	00.0024
		20 min.	19	4.9	35		
12	300	5 min.	06	3.7	32	Before	11.5349
		10 min.	07	3.9	33	After	11.5327
		15 min.	11	4.1	35	Diff.	00.0022
		20 min.	14	4.5	37		

Cu + MWCNT: 5 Wt %; Sintering: 750 ^{0}C and 1 hour;
Specimen: dia. = 10mm and length = 22mm

Load (kg)	**Speed (rpm)**	**Time**	**Wear (μm)**	**Frictional force (N)**	**Temp. (^{0}C)**	**Weight Loss (gm)**	
5	100	5 min.	02	2.7	25	Before	11.5401
		10 min.	04	2.8	27	After	11.5387
		15 min.	07	3.0	30	Diff.	00.0014
		20 min.	09	3.3	32		
5	200	5 min.	02	2.6	28	Before	11.5387
		10 min.	03	2.9	29	After	11.5375
		15 min.	07	3.0	31	Diff.	00.0012
		20 min.	08	3.2	35		

5	300	5 min.	02	2.5	30	Before	11.5375
		10 min.	03	2.7	32	After	11.5364
		15 min.	06	2.9	33	Diff.	00.0011
		20 min.	07	3.1	35		
8	100	5 min.	09	3.9	29	Before	11.5401
		10 min.	11	4.0	30	After	11.5381
		15 min.	14	4.4	32	Diff.	00.0020
		20 min.	16	4.9	33		
8	200	5 min.	05	3.1	31	Before	11.5381
		10 min.	07	3.3	32	After	11.5363
		15 min.	09	3.9	34	Diff.	00.0018
		20 min.	11	4.2	35		
8	300	5 min.	03	3.0	32	Before	11.5363
		10 min.	04	3.1	35	After	11.5348
		15 min.	06	3.5	37	Diff.	00.0015
		20 min.	09	4.1	39		
12	100	5 min.	13	3.9	29	Before	11.5401
		10 min.	17	4.0	31	After	11.5375
		15 min.	20	4.2	33	Diff.	00.0026
		20 min.	22	4.8	34		
12	200	5 min.	08	3.8	32	Before	11.5375
		10 min.	12	4.0	34	After	11.5352
		15 min.	15	4.1	37	Diff.	00.0023
		20 min.	16	4.7	39		
12	300	5 min.	05	3.4	34	Before	11.5352
		10 min.	06	3.6	35	After	11.5333
		15 min.	09	3.8	37	Diff.	00.0019
		20 min.	12	4.3	40		

4.3 Wear test results of SWCNT/Cu composite

The following are the tabulated wear test results obtained under varying load and speed conditions.

i. Cu + SWCNT: 1 Wt%
ii. Sintering: 750 ^{0}C and 1 hour
iii. Specimen: dia. = 10mm and length = 22mm

Load (kg)	**Speed (rpm)**	**Time**	**Wear (μm)**	**Frictional force (N)**	**Temp. (^{0}C)**	**Weight Loss (gm)**	
5	100	5 min.	07	4.2	30	Before	10.5401
		10 min.	10	4.5	32	After	10.5378

		15 min.	11	5.2	34	Diff.	00.0023
		20 min.	13	5.5	36		
5	200	5 min.	06	4.1	29	Before	10.5378
		10 min.	09	4.4	31	After	10.5356
		15 min.	10	5.1	33	Diff.	00.0022
		20 min.	12	5.4	35		
5	300	5 min.	05	4.0	28	Before	10.5356
		10 min.	08	4.3	30	After	10.5336
		15 min.	09	5.0	32	Diff.	00.0020
		20 min.	11	5.3	33		
8	100	5 min.	14	5.3	30	Before	10.5401
		10 min.	19	5.8	31	After	10.5381
		15 min.	23	6.3	32	Diff.	00.0020
		20 min.	31	6.9	33		
8	200	5 min.	16	5.2	40	Before	10.5381
		10 min.	22	5.5	43	After	10.5352
		15 min.	26	6.1	46	Diff.	00.0029
		20 min.	29	6.4	48		
8	300	5 min.	18	5.0	42	Before	10.5352
		10 min.	23	5.3	44	After	10.5319
		15 min.	27	5.9	48	Diff.	00.0035
		20 min.	31	6.2	50		
12	100	5 min.	18	5.8	48	Before	10.5401
		10 min.	23	6.1	52	After	10.5378
		15 min.	30	6.5	55	Diff.	00.0023
		20 min.	34	6.8	58		
12	200	5 min.	20	5.5	51	Before	10.5378
		10 min.	27	5.9	55	After	10.5353
		15 min.	33	6.2	58	Diff.	00.0025
		20 min.	36	6.6	61		
12	300	5 min.	22	5.3	53	Before	10.5353
		10 min.	30	5.5	57	After	10.5326
		15 min.	35	6.0	60	Diff.	00.0027
		20 min.	39	6.3	63		

Cu + SWCNT: 3 Wt %; Sintering: 750 ^{0}C and 1 hour;
Specimen: dia. = 10mm and length = 22mm

Load (kg)	Speed (rpm)	Time	Wear (μm)	Frictional force (N)	Temp. (^{0}C)	Weight Loss (gm)	
5	100	5 min.	06	4.0	29	Before	9.3312
		10 min.	08	4.3	31	After	9.3292
		15 min.	10	4.9	33	Diff.	0.0020
		20 min.	12	5.1	35		
5	200	5 min.	08	3.9	30	Before	9.3292
		10 min.	10	4.1	32	After	9.3274
		15 min.	11	4.7	35	Diff.	0.0018
		20 min.	14	4.9	37		
5	300	5 min.	09	3.6	31	Before	9.3274
		10 min.	11	3.9	34	After	9.3257
		15 min.	13	4.3	37	Diff.	0.0017
		20 min.	16	4.7	39		
8	100	5 min.	10	5.1	30	Before	9.5332
		10 min.	15	5.6	32	After	9.4952
		15 min.	20	5.9	34	Diff.	0.0380
		20 min.	28	6.5	35		
8	200	5 min.	14	4.9	32	Before	9.4952
		10 min.	19	5.4	34	After	9.4587
		15 min.	23	5.7	35	Diff.	0.0365
		20 min.	25	6.1	37		
8	300	5 min.	15	4.8	33	Before	9.4587
		10 min.	21	5.2	34	After	9.4235
		15 min.	25	5.3	36	Diff.	0.0352
		20 min.	28	5.8	38		
12	100	5 min.	14	5.9	53	Before	9.5332
		10 min.	20	7.2	58	After	9.4852
		15 min.	27	8.6	61	Diff.	0.0480
		20 min.	30	9.0	63		
12	200	5 min.	12	5.6	54	Before	9.4852
		10 min.	17	6.8	60	After	9.4392
		15 min.	24	8.2	62	Diff.	0.0460
		20 min.	27	8.9	65		
12	300	5 min.	11	5.4	56	Before	9.4392
		10 min.	15	6.3	62	After	9.3947
		15 min.	23	7.8	63	Diff.	0.0445
		20 min.	25	8.5	66		

Cu + SWCNT: 5 Wt %; Sintering: 750 ^{0}C and 1 hour;
Specimen: dia. = 10mm and length = 22mm

Load (kg)	Speed (rpm)	Time	Wear (μm)	Frictional force (N)	Temp. (^{0}C)	Weight Loss (gm)	
5	100	5 min.	04	3.8	30	Before	9.3220
		10 min.	06	4.0	32	After	9.3201
		15 min.	07	4.5	34	Diff.	0.0019
		20 min.	09	4.9	36		
5	200	5 min.	07	3.6	31	Before	9.3201
		10 min.	08	3.8	33	After	9.3184
		15 min.	10	4.1	36	Diff.	0.0017
		20 min.	12	4.7	39		
5	300	5 min.	05	3.4	33	Before	9.3184
		10 min.	06	3.6	35	After	9.3169
		15 min.	08	3.9	37	Diff.	0.0015
		20 min.	10	4.4	40		
8	100	5 min.	08	4.8	32	Before	9.3220
		10 min.	13	5.2	33	After	9.2950
		15 min.	17	5.5	36	Diff.	0.0270
		20 min.	24	6.0	38		
8	200	5 min.	12	4.6	33	Before	9.2950
		10 min.	17	4.9	35	After	9.2730
		15 min.	19	5.1	37	Diff.	0.0220
		20 min.	22	5.8	40		
8	300	5 min.	10	4.4	35	Before	9.2730
		10 min.	15	4.6	36	After	9.2535
		15 min.	16	4.9	39	Diff.	0.0195
		20 min.	19	5.4	42		
12	100	5 min.	17	5.4	55	Before	9.3220
		10 min.	23	6.8	59	After	9.2885
		15 min.	30	8.2	64	Diff.	0.0365
		20 min.	33	8.7	68		
12	200	5 min.	14	5.2	56	Before	9.2885
		10 min.	21	6.5	61	After	9.2543
		15 min.	26	7.9	65	Diff.	0.0342
		20 min.	29	8.4	70		
12	300	5 min.	12	4.9	58	Before	9.2543
		10 min.	19	6.2	61	After	9.2211
		15 min.	23	7.4	67	Diff.	0.0332
		20 min.	26	8.0	72		

SEM observations (Figure 6) show that there are some crates and flake-like wear scars on the worn surface of the Cu/CNT nanocomposites, which appears to be a typical characteristic of adhesive wear, and many carbon chips also can be seen.

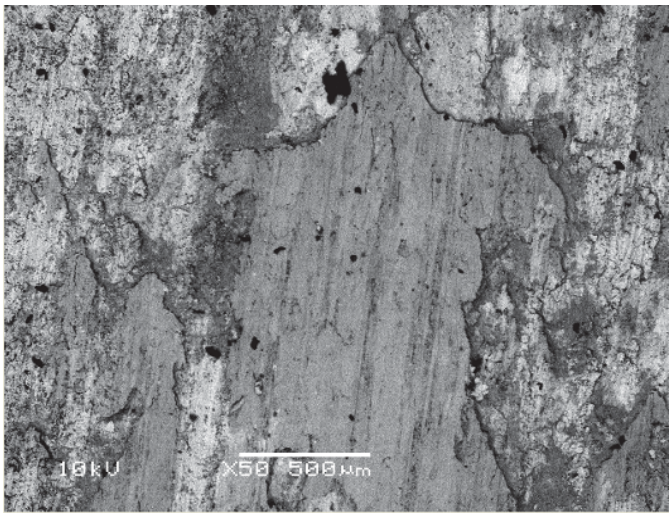

Fig. 6. SEM Images of Wear Tested MWCNT/Cu composite sample

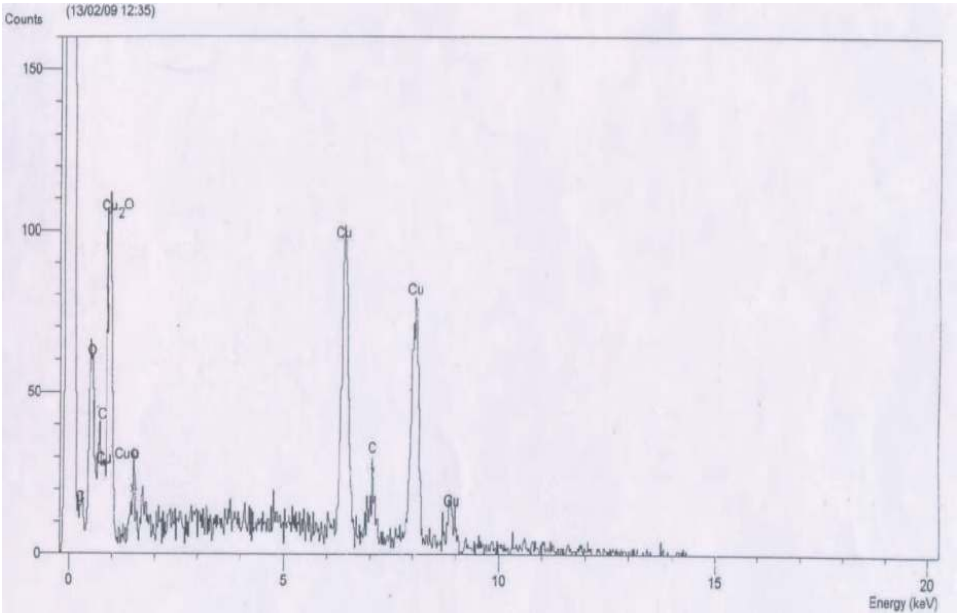

Fig. 7. XRD result of the worn chips of the Cu/MWCNT composite showing formation of Carbon and Oxides of Copper(Cu2O and CuO)

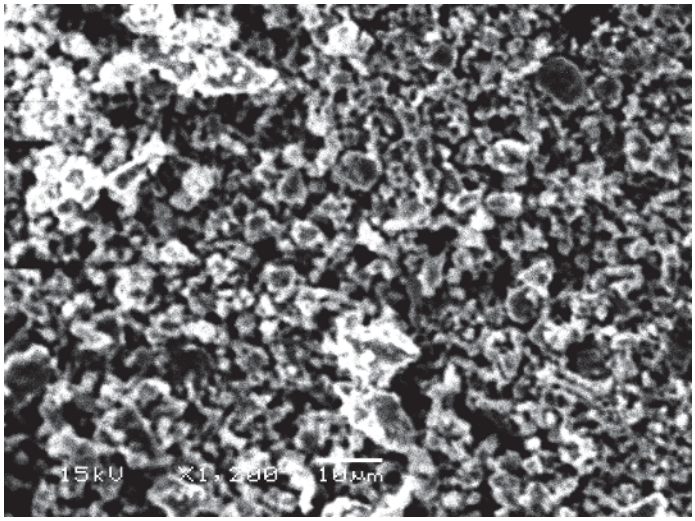

Fig. 8. SEM Image of worn chips of the Cu/MWCNT composite

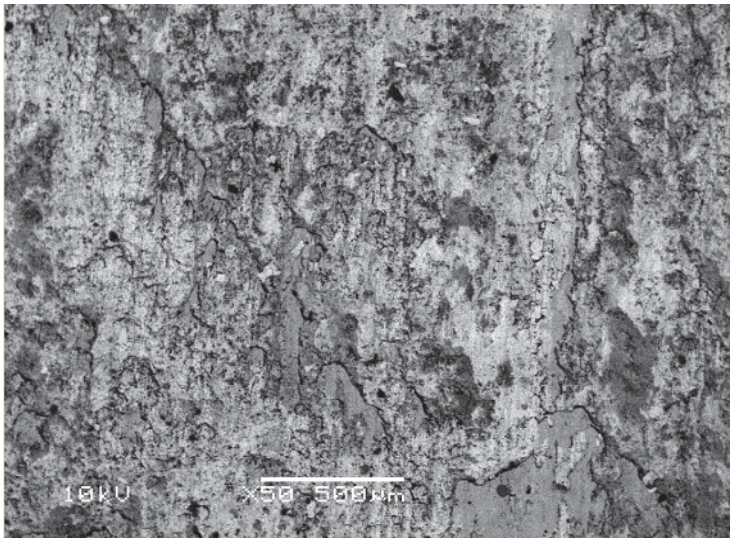

Fig. 9. SEM Images of Wear Tested SWCNT/Cu composite sample

XRD results (Figure 7) show that there exist some oxides of copper (Cu_2O and CuO) in the worn chips of the composite (Figure 8), suggesting that oxidation wear appears to be the main wear mechanism of the composite. The coefficient of friction and the weight loss for the Cu/CNTs composite is less than the pure copper specimen made by the same method. As the Cu-matrix got worn out gradually, carbon nanotubes in the matrix near the surface were exposed and became the working film on the worn surface. Now the worn

contacting surfaces changed from the original metal surfaces into metals with a lubricating carbon film.
Based on oxidation theory, the carbon film not only provides lubrication in the wearing process and reduces the wear surface exposed in the air, but also prevents the copper from oxidizing. Therefore, the weight loss of the composite is reduced, which also been supported by the experimental results that both the coefficient of friction and weight loss for the Cu/CNT composite are much lower than those of the pure copper specimen made by PM.

4.4 Effect of the nanotubes volume fraction

Increasing the carbon volume fraction significantly decreases the coefficient of friction and weight loss for both the Cu/CNT composite. When carbon content exceed 8%, the graph of the weight loss for the Cu/CNT composite becomes flat and when carbon content is beyond 12%, the weight loss raises. This phenomenon is contributed to the increase of porosity of the composite when the nanotube content is beyond 12%.When nanotube content is low (< 8%), a carbon film can not cover wear surface. When the nanotubes volume fraction increases, the carbon film become larger and cover the wear surface, while the effect of lubrication and impedance to oxidization increases. The optimum nanotubes content is between 12 and 15%.

4.5 Effect of load

The effects of the applied load on the weight loss for Cu/CNT composite are shown below. It is found that the increasing the load had a minimal effect on Cu/CNT composites as compared to pure copper specimen. In another observation, the temperature of the pure copper specimen increase linearly as the load increases, whereas in case of Cu/CNT composite it increases marginally as the volume fraction of CNTs increase, providing the indirect evidence of good thermal conductivity of nanotubes.

Constants: Load=5Kgs, Speed=200 rpm, Duration=20 min			
Composition of CNT (Wt%)	**Coefficient of Friction**		
	Pure Copper (Cu)	Cu + MWCNT	Cu + SWCNT
0	0.22	0.22	0.22
1	NA	0.082	0.11
3	NA	0.073	0.099
5	NA	0.065	0.096

Table 1. Values of Coeff. Of friction for different Wt% of CNTs

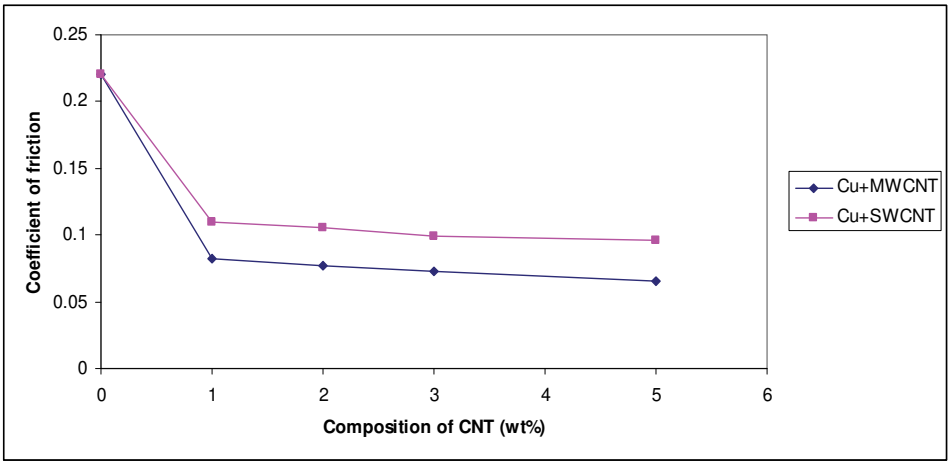

Fig. 10. CNT Composition Vs Coefficient of Friction of Cu, Cu/MWCNT & Cu/SWCNT

Constants: Load=5Kgs, Speed=200 rpm, Duration=20min			
Composition of CNT (Wt%)	Wear Rate (mm^3/Nm)		
	Pure Copper (Cu)	Cu+MWCNT	Cu + SWCNT
0	11.24	11.24	11.24
1	NA	0.0065	0.0092
3	NA	0.002	0.0031
5	NA	0.0030	0.0042

Table 2. Values of Wear rate for different Wt% of CNTs

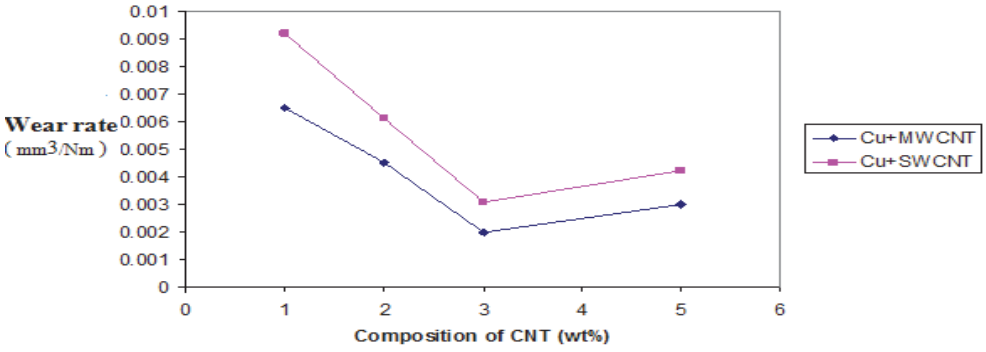

Fig. 11. CNT Composition Vs Wear rate

Constant: Composition of CNT = 1 wt%, Speed = 200 rpm		
Load (N)	Weight Loss (gms)	
	Cu + MWCNT	Cu + SWCNT
50	0.0018	0.0022
80	0.0022	0.0029
120	0.0028	0.0035

Table 3. Load Vs Weight Loss at 1 Wt% of MWCNT & SWCNT

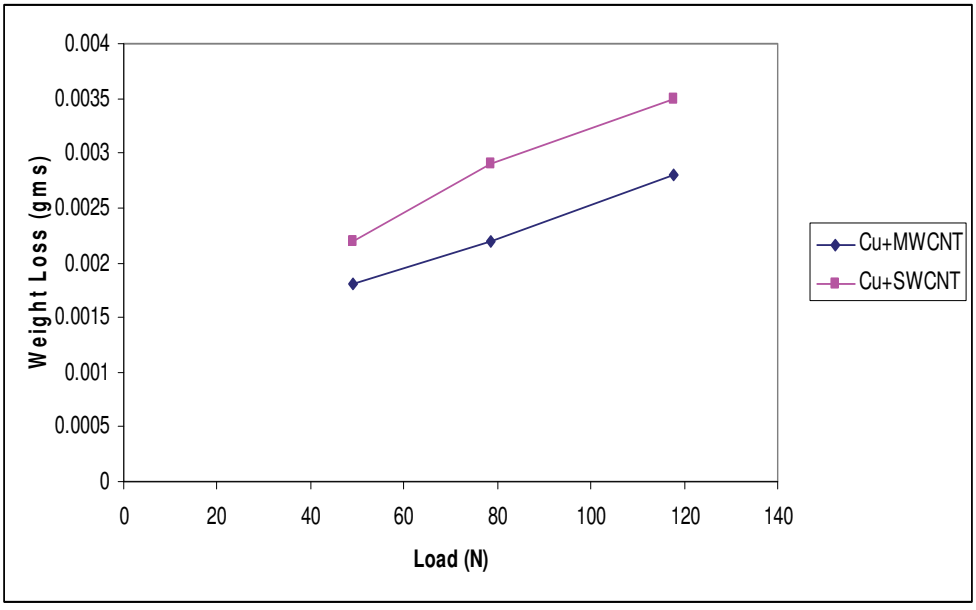

Fig. 12. Load Vs Weight loss

Constant: Composition of CNT = 3 wt%, Speed = 200 rpm		
Load (N)	Weight Loss (gms)	
	Cu + MWCNT	Cu + SWCNT
50	0.0013	0.0018
80	0.0019	0.0037
120	0.0024	0.0046

Table 4. Load Vs Weight Loss at 3 Wt% of MWCNT & SWCNT

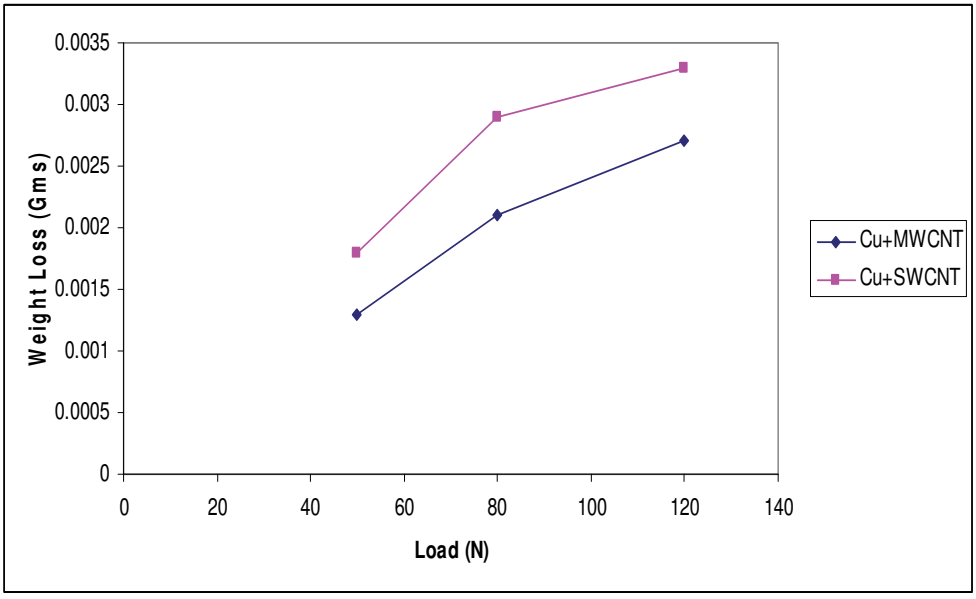

Fig. 13. Load Vs Weight loss

Constant: Composition of CNT = 5 wt%, Speed = 200 rpm		
Load (N)	Weight Loss (gms)	
	Cu + MWCNT	Cu + SWCNT
50	0.0012	0.0017
80	0.0018	0.0022
120	0.0023	0.0034

Table 5. Load Vs Weight Loss at 5 Wt% of MWCNT & SWCNT

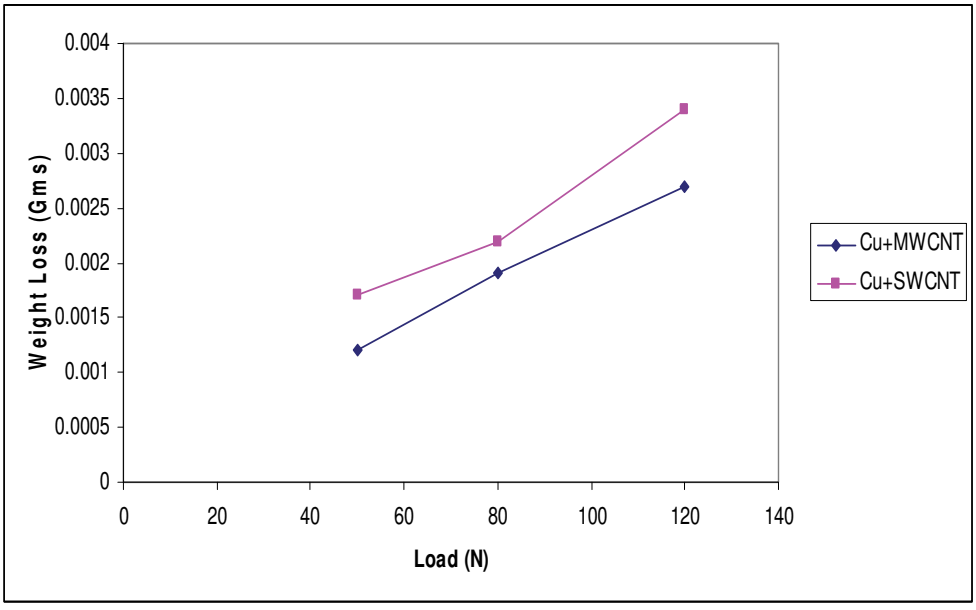

Fig. 14. Load Vs Weight loss

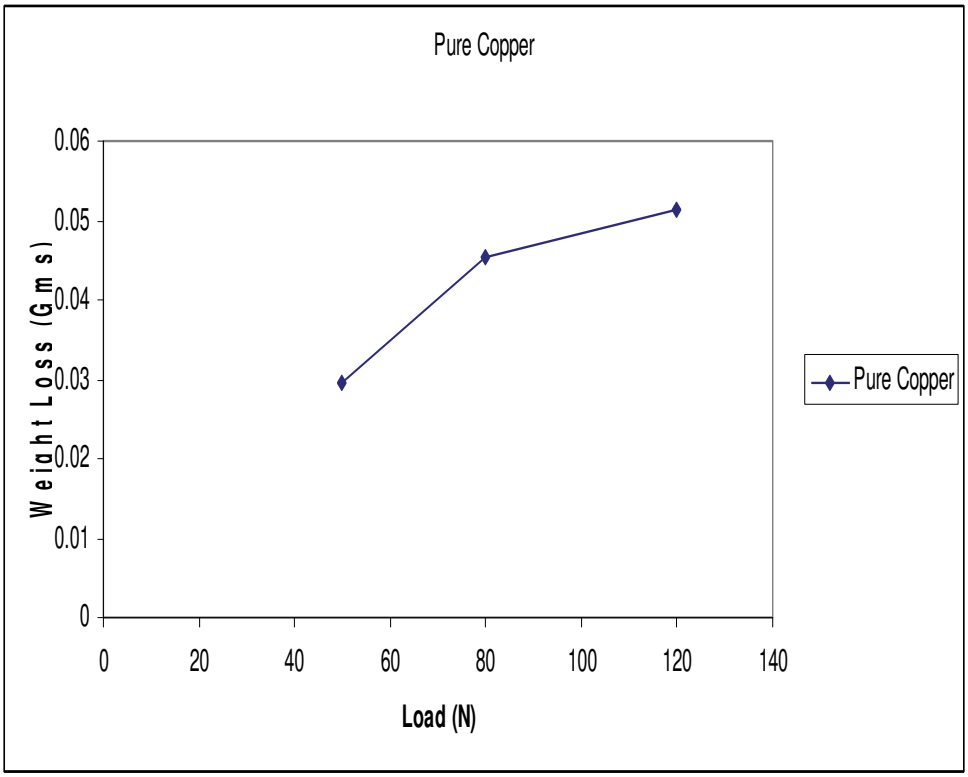

Fig. 15. Load Vs Weight loss

Load (N)	Weight Loss (gms)
50	0.0295
80	0.0454
120	0.0513

Table 6. Load Vs Weight Loss for Pure Copper at 200 rpm

5. Conclusion

CNTs both Multi-walled and Single-walled were synthesized by Arc Discharge method. This method was adopted for its simplicity and cost effectiveness. Arc discharge setup was successfully fabricated to generate good quality CNTs. The yield of MWCNTs was optimum for a helium pressure of 500 torr and a DC current of 75 amps at 20 volts. Adequate cooling of the chamber and graphite electrodes is a pre-requisite for their synthesis.

It is concluded that the homogeneous distribution of CNTs with sound interface in Cu matrix is an important technological issue to enhance the mechanical behavior and wear resistance of CNT/Cu nano composite. Oxidation wear is the main wear mechanism for the CNT/Cu composite under dry sliding conditions. The formation of carbon film can reduce the friction and wear rate. Compared with pure Cu composite, the CNT/Cu nanocomposite has a lower coefficient of friction and reduced weight loss. Increasing the nanotube volume fraction can significantly decrease both the coefficient of friction and wear rate of the composite. The optimum nanotubes content is 3 wt % i.e., between (12 and 15) Volume %.

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Since their discovery in 1991, carbon nanotubes have been considered as one of the most promising materials for a wide range of applications, in virtue of their outstanding properties. During the last two decades, both single-walled and multi-walled CNTs probably represented the hottest research topic concerning materials science, equally from a fundamental and from an applicative point of view. There is a prevailing opinion among the research community that CNTs are now ready for application in everyday world. This book provides an (obviously not exhaustive) overview on some of the amazing possible applications of CNT-based materials in the near future.

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