Fabrication and characterization of carbon brushes using Cu, Ag and CNT composites: Micro structural property correlation

A Dissertation submitted

In partial fulfillment of the requirements

For the degree of

Master of Engineering

In

Production Engineering

By

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July, 2017

Certificate

I hereby declare that the thesis entitled "**Fabrication and characterization of carbon brushes using Cu, Ag and CNT composites: micro structural property correlation**", is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering** in **Production Engineering** at **Thapar University, Patiala** under the supervision of **Dr. N. Harshavardhana,** Lecturer, Mechanical Engineering Department, Thapar University, Patiala & **Mr. Devender Kumar,** Assistant professor, Mechanical Engineering Department, Thapar University, Patiala during July, 2016 to July, 2017. No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

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It is certified that the above statement made by the student is correct to the best of our knowledge and belief.

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Acknowledgement

I would like to express my deep sense of gratitude and a very sincere thanks to my guide **Dr. N. Harshavardhana**, Lecturer, Mechanical Engineering Department, Thapar University, Patiala and **Mr. Devender Kumar,** Assistant professor, Mechanical Engineering Department, Thapar University, Patiala for their sincere and invaluable guidance and full support which helped me in the accomplishment of this seminar report in present form. Their dynamic and diligent enthusiasm has been highly instrumental in keeping my spirits high. Their flawless and forthright suggestions blended with an innate intelligent application have crowned my task with success.

I like to thank my parents who gave me blessings and opportunity to study at Thapar University. Finally, I like to thank my classmates especially Rahul Gupta and Hannan Gada of mechanical engineering for helping me with my work and making this journey memorable.

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Symbols

μ	=	Coefficient of friction
ρ	=	Resistivity
Å	=	Angstrom
℃	=	Degree celcius
°F	=	Degree fahrenheit
G	=	Correction factor
Θ	=	Angle

Acronyms

IACS	=	International annealed copper standard
ASTM	=	American society for testing and material
PPM	=	Parts per million
C-Cu	=	Copper graphite
C-Ag	=	Silver graphite
XRD	=	X-Ray diffraction

Abstract

Carbon brush is widely used in electrical machines such as generators, automobile parts etc which is used to transfer charges from rotating part (shaft) to stationary part (battery). The important properties of carbon brushes includes (a) good electrical conductivity (b) sufficient wear rate and low hardness as compared to rotating shaft (c) less sparking. The Graphite is the major element used in carbon brushes due to its superior properties of high wear rate and electrical conductivity (5.2% IACS). However there are other elements such as silver (105% IACS), copper (100% IACS) and CNT (142% IACS) has high conductivity than graphite.

This research work is focused on the development of carbon brushes using the graphite as the base metal and materials such as silver (105% IACS), copper (100% IACS) and CNT (142% IACS) used as composite materials. The carbon brushes were developed with variable wt. % of Cu, Ag and CNTs sintered at 800, 900 and 1000℃ in argon atmosphere.The hardness measurement were carried using Vickers micro hardness test, electrical conductivity measurement were done using four probe setup and wear test were performed using wear and friction Monitor machine. XRD (X-Ray diffraction) characterizations were done to observe the phases present in the composites.

The results shows that as percentage of silver, copper and CNT increases, conductivity of the carbon brushes increases however wear rate does not follow any trend with composite wt. %.Carbon brush with 0.75 wt. % of CNT sintered at 900℃ shows the superior electrical properties comparing from the commercially available sample. Further a comparative study on the properties (electrical and wear) of market sample with sintered pure graphitic sample were done and correlated were done using XRD data.

Keywords: C-Cu composite, C-Ag composite, C-CNT composite, resin bonded; micro hardness, conductivity, wear test.

Chapter 1

Introduction

1.1 General

Carbon brush is mainly used as a sliding contact which is used for transmit electric power between rotating shaft and static (battery) surface. The main properties of carbon brushes includes (i) high electrical conductivity (from transmitting electric charges from generator to battery) (ii) good wear rate and low hardness compared to shaft materials so that rotating shaft is not tend to wear (iii) to ensure spark free commutation. The major constituent of carbon brush is graphite, which is an allotropic form of carbon.

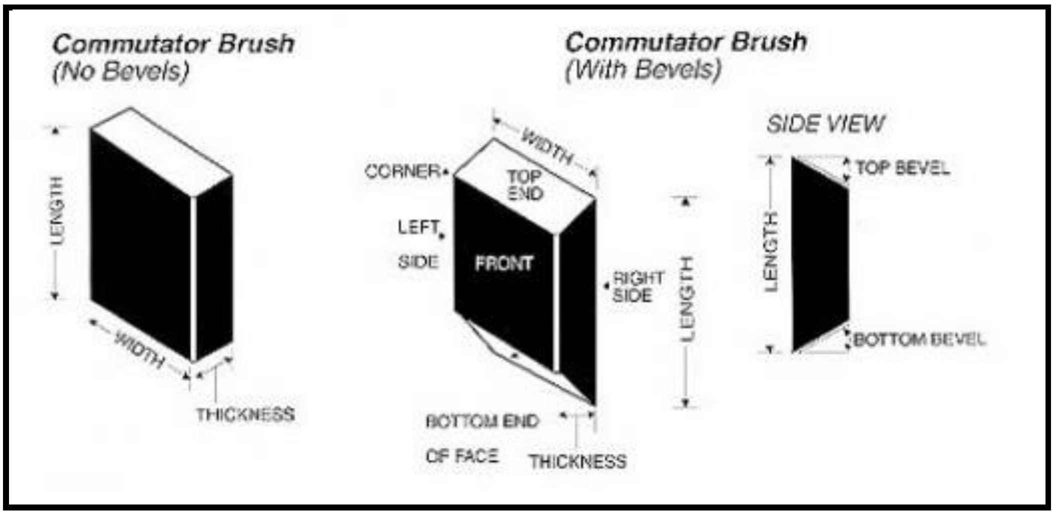

Figure 1.1: carbon brushes [W.5]

Originally, brushes were made of wire and made of standard wire brush. However it found that wire brushes tended to wear away the commutator and suffered the run time issues. Thus graphite brushes replaced wire brushes which has better an electrical conductivity, good wear and prevent sparking in commutatorv. Moreover be addition of various additives in the graphite can help lubricate the connection and the graphite is generally tailored to suit specific operational needs.

In general, carbon brushes were used widely in generator and motors. For most of the automobile, power plant application we use various different types of carbon brushes. Table -1shows the application of carbon brushes where machines are classified in coherent groups based on their operating condition i.e current density, peripheral speed and applied brush pressure.

Table 1.1: Application of carbon brushes

Machines	Current density(A/cm²)	Speed (m/sec)	Applied pressure (kPa)
Marine engines	4-8	25	18
Welding generator	0-20	<20	18
General motors	8-12	20-45	18
Marine generator	4-12	20-35	18
Reversing motor	8-20	0-15	18
Rolling mill motor	8-15	20-35	18
DC generator	10-14	40	25
Alternators (slip rings)	8-12	<50	22

On the other hand, electrical conductivity of other elements such as silver (106% IACS), copper (100% IACS) and single wall CNT (142% IACS) is found to be higher than graphite (5.2%IACS). For applications such as generator, motors etc., brush material must have high electrical conductivity, sufficiently high wear rate and low hardness so that it won't affect the life of rotating shaft.

Hence, in this thesis we have attempted to develop the composites by mixing graphite with metals such as copper, silver and CNT at various proportion for obtaining best combination of mechanical (wear and hardness) and electrical properties. We have also correlated the properties to micro structural change. Further comparison of the market sample with synthesis carbon brushes were done and reported in this thesis.

1.2 Overview of the thesis

Chapter 2 **Literature survey:** In this chapter, literature dealing with general properties of graphite, various parameters that affects carbon brushes, various synthesis route for obtaining carbon brushes are reported and finally from the literature data a detailed research plan was formulated.

Chapter 3 **Experimental procedures:** Information about the materials, synthesizing route, heat treatment condition, sample preparation technique and various characterization techniques which include (a) mechanical (wear and hardness) (b) electrical and (c) microstructure characterization (Specifically XRD) are presented in this chapter.

Chapter 4 **Results and Discussion:** In this chapter, we report on the properties (hardness, wear rate and conductivity) for various composites which is heat treatment at different temperature. We have correlated properties with microstructure (XRD). Comparison of results on market sample and synthesized sample were done which is presented in this chapter.

Chapter 5 **Summary and future work:** We summarize results from the current set of experiments and draw some conclusions about the effect of temperature and percentage composition of additives on microstructure and hence on wear rate, hardness and conductivity. Finally we propose some directions for the future investigations.

Chapter 2

Literature review

2.1 General

Our aim, in this chapter, is to study processing methods that will results in combination of high conductivity and good wear resistant in carbon brushes. This chapter presents a detailed review of literature with regards to general properties of brushes, various parameters affecting carbon brushes and fabrication technique of carbon brushes. The chapter also presents the main gaps in the existing literature with regards to processing and properties of carbon brushes.

2.2 Carbon brush

Carbon brushes are available in four main grade categories: carbon graphite, electro graphitic, graphite and metal graphite. Different types of carbon brushes were used based on the demand and operational requirement. Generally graphite is the major constituent in the carbon brush and the other constituent keeps on changing based on their uses and application. The carbon is found in nature as three allotropic form amorphous carbon, graphite and diamond. Both graphite and diamond are made only of carbon atoms only. However graphite is very soft and slippery while diamond is hard. Thermodynamically, graphite is more stable form of carbon at room temperature. Diamond is formed when graphite is subjected to high pressure and temperature above 15 bars and 1500°C [W.4].

The structure of graphite consists of a succession of layer parallel to the basal plane of hexagonally linked carbon atoms. In this stable hexagonal lattice, the inter atomic distance within a layer plane, a is 1.42Å and the interlayer distance; d between planes is 3.35Å as shown in Figure 2.3. Crystal density is 2.266 g/cm^3 as compared with 3.53g/cm^3 for diamond. In the graphite structure (sp^2 hybridization) only three of the four valence electron of the carbon form regular covalent bond (σ bond) with adjacent carbon atoms. The fourth or π electron resonates between the valence bond structures. Strong chemical bonding force exists within the layer planes however the bonding energy between planes is only about two percent of that within the plane. These weaker bonds between the planes are most often explained to be the result of Vander Waals forces.

The weak forces between layer planes account for (a) the propensity of graphitic materials to rupture the length of planes, (b) the creation of interstitial compounds and (c) the good lubricating and high compressive strength.

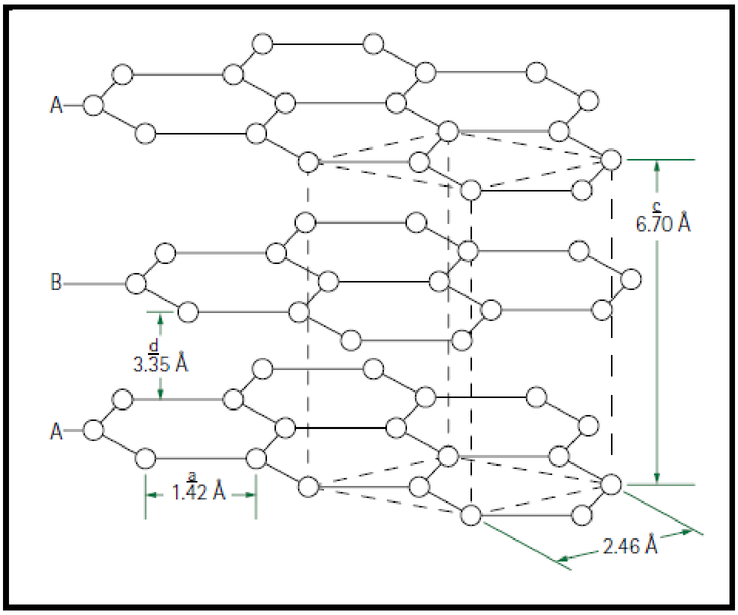

Figure 2.1: Crystal structure of graphite [W.4]

The arrangement of plane is ABAB with hexagonal structure of graphite; so that the atom is alternate planes are alike. However the natural graphite contains 17 to 22 percent of a rhombohedra structure found other than hexagonal structure.

Amorphous carbon is also referred to as non-graphitic carbon. When examined by X-ray diffraction, these material show only diffuse maxima at the normal scattering angle. This has been attributed to a random translation and rotation of the layer within the layer plane. This disorder has been called Turbo static. Some of this non graphitic carbon will become graphitic, upon heating to 1700-3000°C. Some will remain non graphitic above 3000°C.

So graphite has a very high melting point (approx 3500°C) and good conductivity compared to other metals. Table 1 shows the electrical conductivity of various elements and their corresponding conductivity. The electrical conductivity were also represented in International Annealed Copper Standard (%IACS) for easy comparison. Thus from the table, it is cleared that the elements such as copper, silver were found to be much higher conductivity than graphite. However the wear rate of these elements was found to be lower and can damage the transmitting shaft [2, 3]. In order to transfer electric charges from rotating member to non-rotation members, graphitic brushes were suggested over other brushes.

Table 2.1: Electrical conductivity of various elements

Element	Electrical conductivity (Siemens /meter)	% IACS
Silver	61.4 X 10^6	105.9
Copper	59.1 X 10^6	100
Aluminum	36.6 X 10^6	63.1
Iron	10.0 X10^6	17.1
Lead	4.7 X 10^6	8.1
Graphite	3 X10^6	5.2

2.3 Classification of carbon brushes

Classification of carbon brushes are based on the manufacturing process and the type of carbon and other additives used.

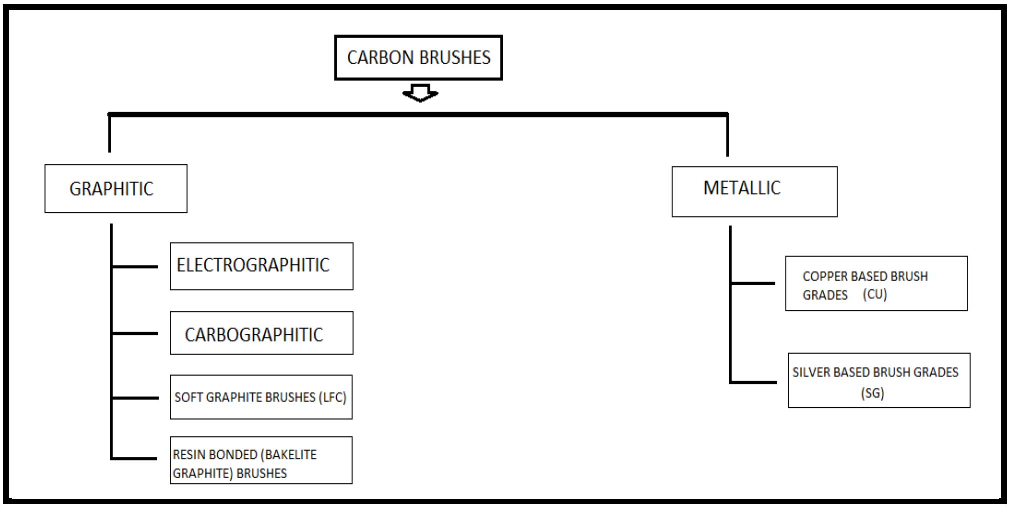

Figure 2.2: Classification of carbon brushes [W.6]

2.4 Parameters affecting carbon brushes

A carbon brush plays an important role in the functioning of the electrical devices. There are some essential parameters on which the carbon brush works.

i. Mechanical
ii. Electrical
iii. Physical and chemical

i. Mechanical parameters

- **Roughness**: Slip ring or commutator with good surface condition gives the carbon brushes a proper seating base and ensure good electrical transmission. The surface should not be too smooth or too rough for the optimal performance of the carbon brush.
- **Friction coefficient**: The coefficient of friction ‘μ’ has to be low for the best performance of the brush. Friction coefficient is having no predetermined value. It depends on many factors like carbon brush grades, speed, load, environmental conditions.
- **Vibration**: Excessive vibration should not be there. It reduces the efficiency of the brush and therefore effects the whole appliance.
- **Carbon brush pressure**: Pressure should not be too high or too low. It should be in its optimal condition. If the pressure increases the wear of carbon brush starts increasing and if the pressure decreases the conductivity of the brush decreases. So it should be optimal for the proper transmission of the electricity.

ii. Electrical parameters

- **Voltage drop or current drop**: Voltage drop supposed to be reasonable to pass up overheating and the unusual electrical losses which can harm the sliding contact. It depends on carbon brush grades, electrical contact and film.
- **Commutation**: Commutation is the phenomenon of reversing the path of the current in the armature coil over the brush of AC/DC commutator or generator. The time taken for the complete reversal is the time of commutation.
- **Current density**: The ration of current to the cross sectional is of the brush is known as current density. Current density is having foremost authority on all aspects of the brush performance.
- **Resistivity**: It depicts the resistance to the flow of the electrical current. It is denoted by Greek letter ‘ρ’. Resistivity of the carbon brushes should be low for good electrical transmission.

iii. Physical and chemical parameters

- **Humidity**: Humidity helps in developing the surface film in the brush which act as a solid lubricant and prevent the brush from wear. It is supplied by the ambient air. The film will form best in the humidity range of 8 to 15 g/m³.
- **Corrosive vapor or gases**: Corrosive vapor or gases destroy the contact film even if they are present in low quantity in the atmosphere. They spoil the commutator and even the carbon brush.
- **Dust**: The more coarse the dust the damaging it is. Dust causes grooving of commutator and slip ring. High brush wear, pollution of machine.

2.5 Properties of carbon brushes

Carbon brushes possess some properties which have a great influence on the efficiency of the carbon brush. These properties are:

i. Wear rate
ii. Conductivity
iii. Strength / hardness

i. Wear rate

Effects of the following factors on the wear rate of the brush

- **Brush spring pressure**: Wear of brush is directly relative to the brush spring pressure. As we increase the brush spring pressure wear also increases because of the increasing of the friction between the rotating shaft and the brush. But studies shows that up to a certain limit wear is directly proportional to the brush spring pressure but after a certain limit wear decreases because of the formation of surface film over the brush surface which act as a solid lubricant and prevent the brush from wear out again as load increase above the certain limit the wear increases again [7, 8, 9]. Though brush spring pressure has a considerable consequence on electrical wear rate. Higher spring pressure causes lower voltage drop and thereby lower electrical wear.
- **Friction**: Friction plays an important role in the wear of the brush. Higher the friction great higher the wear rate of the brush. So for proper efficiency of the brush friction should be in optimal rate not high not low. If friction is too low then it will reduce the conductivity of the brush and if the friction will be too high it will increase the wear rate of the brush.

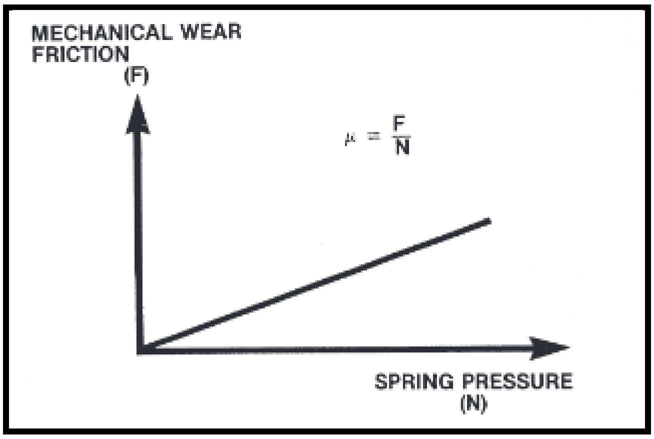

Figure 2.3: Graph between mechanical wear friction and spring pressure

- **Temperature**: When the area of current flow decreases, resistance increases. As a result joule heat and contact temperature both increases. Therefore, the current supply increases the temperature of the contact surface by electrical resistance heat, which increases wear.
- **Humidity**: Humidity also an important factor for the wear of the brush. Ambient air contains water which is the major reason for the humidity. Humidity creates a oxide film over the surface of the brush which act as a solid lubricant and prevent the brush from wear out.
- **Arcing or electrical wear:** electrical wear occurs between the contact surface and brush due to resistance at dynamic sliding boundary. Dust, oil smoke etc increases resistance to contact surface. The gap between the brush and sliding disc formed due to foreign particles is the major reason for electrical wear.

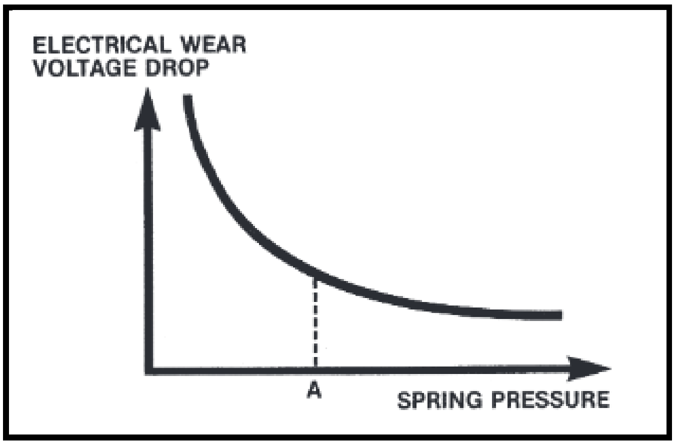

Figure 2.4: Graph between electrical wear and spring pressure

- **Brush grades**: Composition of brush is also a major cause for the wear of the brush. There are many brush grades according to the composition which have different wear rate.
- **Total brush wear**: for analyzing brush wear rate, it is said that friction is main reason for mechanical wear, while voltage is main reason for electrical wear. Because of this carbon brush wear from both mechanical and electrical way. The sum of mechanical and electrical wear rate is the total wear rate. Graphite is an allotropic form of carbon which reduces the wear rate by forming a thin film on the surface of the sample and the sliding disc. It acts as a solid lubricant [12, 21].

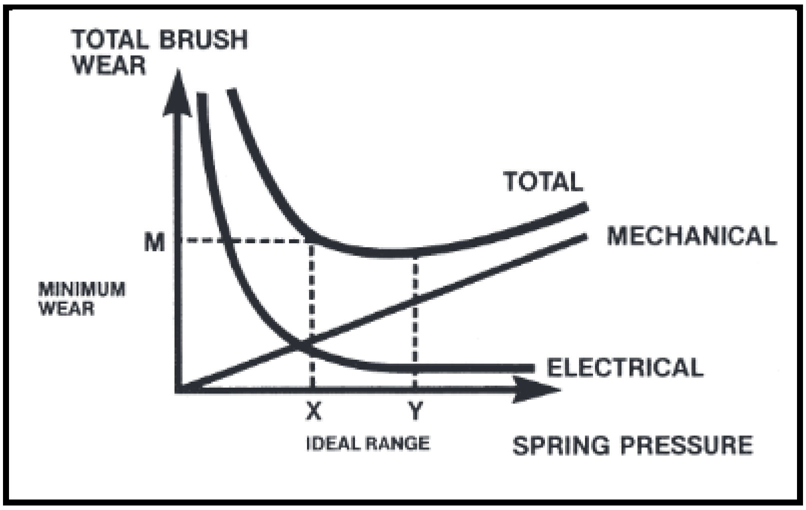

Figure 2.5: Total wear graph [W.6]

The "U" shaped curve is the total wear rate. Generally, there is less wear rate in total brush wear with high load. It suggests decreasing the spring pressure till arcing becomes visible [W.6].

ii. Conductivity

Conductivity of the carbon brush is depends upon the composition or the type of bonding between atoms of the carbon brush. To increase the conductivity of carbon brushes, highly dendrite (electrolytic) copper powder is used. Increase in metal content in the brush increases the conductivity of the brush [31]. Sintering temperature also effect the conductivity of the brush. Carbon nanotubes (CNTs) are interesting materials with high electrical conductivity and mechanical compliance (Geza et al. 2009). Performance of an electrical brush is greatly affected by the combined effects of the current flow and the sliding motion. The excessive heat due to the intense electrical and frictional heating can result in high temperatures near the electrical contact interface. This may degrade the performance of brushes, alter friction coefficient and result in severe wear. The electric conductivity and hardness of brush materials decrease as the increase of the graphite content. The conductivity of the composites increases with increase in content of reinforcement (if the reinforcement material is having high conductivity value than parent material) [22]. Conductivity of the composite material can also be increases using CNTs [26].

iii. Strength/ hardness

Hardness of carbon brushes depends on the bonding between the molecules. If the microstructure is closely packed and rigid it increases the hardness of the brush. Increasing of metal content increases the hardness of brush as the hardness of the metal is high compare to carbon. Sintering temperature also effect the hardness of the brush. Hardness increases by increasing metal content with increased particulates concentration [15, 16]. At high sintering temperature hardness of the brush increases up to a critical temperature. The bending strength and micro hardness of copper or silver composites increases with increase in content of resin which acts as a binding agent [12, 13, 17, 18]. Increasing the amount of metal content increases the hardness of the composites. This rule can be analyzed through the rule of mixture [19].

$$H_c = H_m f_m + H_r f_r$$

H_r, H_m and H_c are the hardness of reinforcement, matrix and composites. Where f_m and f_r are the volume fraction of reinforcement and matrix respectively [20].

2.6 Fabrication technique of carbon brushes

The methods used today for the fabrication of carbon do not have much in common with the methods of the early days. A lot of research into the base materials, process and process control has made this technology into a real science.

Analyzing of characteristics at each tread of the procedure assure that the ultimate product has the essential mechanical and electrical characteristics inside the narrowest promising limits.

2.6.1 Base materials

As basis for most industrial carbon applications the following products are used:

I. **Petroleum coke:** Petroleum coke is a by-product from the oil refineries and contains traces of oil and other volatile substances. Before use it is calcite at high temperature to drive out all those volatile elements. It is after that compressed and milled to flours of exact unit size.

II. **Lampblack:** Lampblack is one of the most vital constituent in carbon brushes. It is produced from oil that is burned in a special furnace under carefully controlled temperature conditions and with accurately restricted supply of air. As the flare of kerosene light, while the wick is turned moreover high, the flare in the burner of this furnace is extremely dirty. The dirt is basically unadulterated carbon which collect on the ceilings, walls and floor of vast settling chambers through which the products of combustion go by.

III. **Graphite:** Graphite used in brush materials includes a wide range of mined graphite from all over the world and artificial graphite. Artificial graphite is produced by high temperature treatment of carbon materials [30].

IV. **Pitch:** It is essential to combine the constituents with a binder that further in the procedure can be condensed to carbon. Pitch is a very good binder and will reduce to carbon at high temperatures.

2.6.2 Mixing

All the raw materials, having gone through their respective process of preparation, have to be mixed. Precise amount of lampblack, coke and graphite or probably one or two of these constituents are pulled out in amounts particular for the product to be contrived. These are put into the mixer and thoroughly mixed with the required amount of binder. This is one of the most important steps in the whole manufacturing process. To assure consistent and steady class it is of extreme importance that materials are equally combined. The carbon addition is afterward pushed in blocks. During this step in the process the pressure of the press has to be monitored carefully, as it influences the properties of the final product. For carbon brushes for some applications such as certain types of household appliances and automotive alternators the carbon mixing is directly pressed to its final shape. After all properties of the pressed material have been checked, the blocks are then baked [W.7].

2.6.3 Baking

Throughout the baking procedure the bonding material is carbonized by putting off all the volatiles to give the whole work a stiff arrangement. This process is done in specially designed furnaces at high temperatures for a period of several days. The temperature cycle, as well as the ultimate temperature, is subject to very accurate control.

2.6.4 Graphitization

Most of the carbon grades that are used in industrial direct current applications are known under the name electro-graphite. The blocks that come out of the baking process are given another heat treatment in special electric furnaces where the temperature is carried to a point far beyond that is possible to obtaining the preceding bake. At these tremendous heat (greater than 2500 º C) practically all elements other than carbon, which might have escaped earlier purifying stages and remained in the block, are volatilized and obsessed off Carbon from the novel mix up and the carbonized bond are altered from the amorphous form into

The crystalline arrangement of graphite. This gives the process its name of graphitization and the material is called electro graphite [27, 28]. Its effect on the performance characteristics of a brush material is very marked. The electrical conductivity is increased and the friction lowered. Commutating characteristics are enhanced and Abrasiveness is reduced.

2.6.5 Other types of brush material

Moreover carbon, the result from the blazing process, and electro graphite, there are some extra types of brush materials utilized in the industry, such as:

- **Resin bonded material**

The constituent such as graphite are milled and bonded with a resin as a substitute for pitch or tar. The mixed ingredients are pressed to size or in the form of blocks that are cut to the requested dimensions afterwards. The pressure and temperature for the period of the press operation are very significant factors analyzing the electrical and mechanical characteristics of the absolute grade. Resin bonded graphite is frequently utilized for smaller domestic appliances, small complicated commutating engineering machines, or A.C commutator motors [32].

- **Metal graphite**

There are two dissimilar behaviors to produce metal graphite grades, which are:

I. Metal immersed grades

Carbon is a permeable material. In autoclaves the material is immersed with molten metal, filling the small holes (pores) of the carbon composition. Material, thus obtained has lower electrical resistance than carbon and better thermal conductivity. These grades are often used for contacts or brushes for low voltage D.C motors or slip rings [29].

II. Metal powder mixed grades

Graphite and metal powder are mixed and pressed under high pressure. After sintering material is created with low electrical resistance and high strength. Applications are: slip ring brushes, starter motors and alternators for automobiles, small voltage D.C motors [W.7].

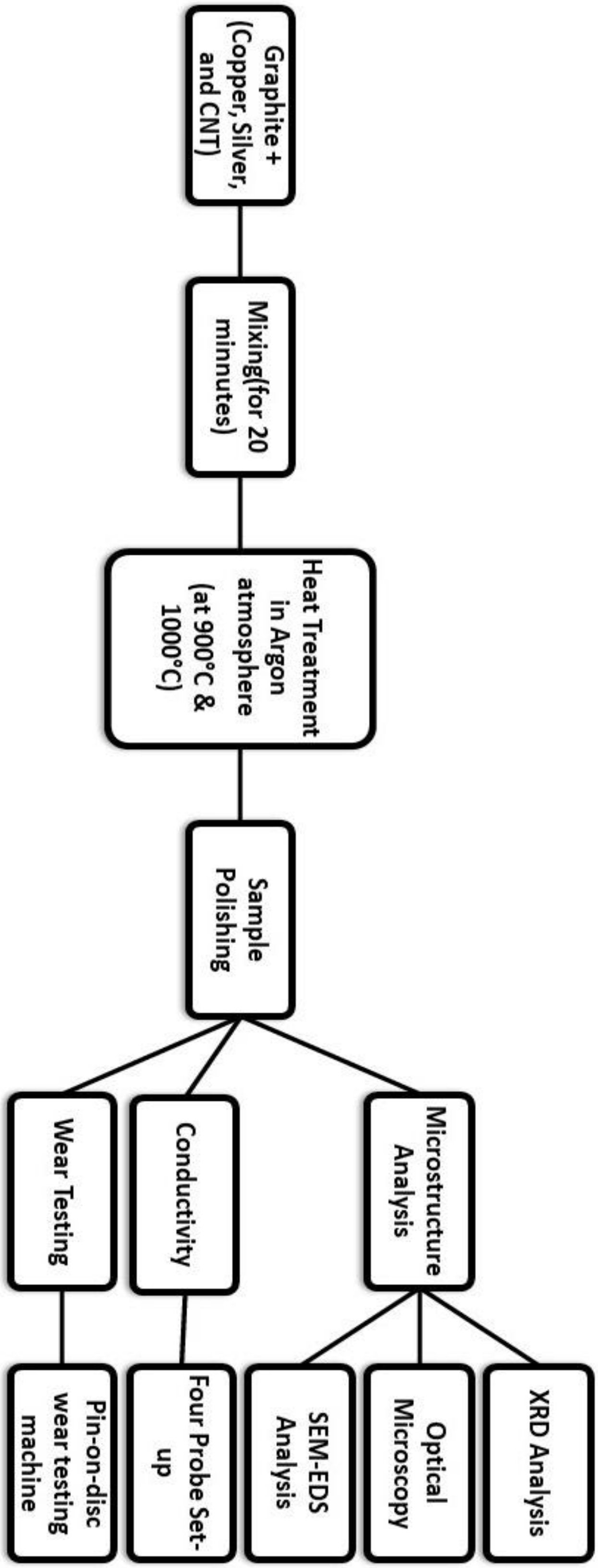

Figure 2.6: Flow chart for fabrication technique of carbon brushes [W.7]

Chapter 3

Experimental procedure

3.1 General

In this chapter, we discuss the details of the synthesis of carbon brushes using various additives, and the electrical, mechanical and micro structural characterization that we have carried out. The chapter also covers the details of sample preparation for mechanical, electrical and microstructure characterization for experimental work.

3.2 Establishing the objective function

Thus, the main objective of the present work was to fabricate and characterize the carbon brushes from powder metallurgy process for improved dry sliding wear and conductivity. To achieve this, the key issues that were addressed are as follows:

- To fabricate the carbon brushes with [i] Graphite only [ii] both graphite and copper (resin bonded) [iii] both graphite and silver (resin bonded) [iv] both graphite and CNT's. Brushes with different additives and composition were synthesized.
- The wear and conductivity test of the developed brushes were performed using dry sliding wear machine with different loads (2kg, 3kg, 4kg, 5kg) and four probe setup at room temperature.
- Micro structural information through XRD. Further optical microscopy, SEM analysis were used to understand the morphology after wear test.

3.3 Starting material

As received graphite is a carbon allotrope is being used as a major constituent in the fabrication of the carbon brushes. Graphite with particle size (<20μ) and purity 99.9% is being purchased from Sigma-Aldrich, Mumbai, India.

Copper is a metal with 2^{nd} in conductivity list. Conductivity of copper is 59.1×10^{6} S/m (101.9 %IACS). Copper with particle size (<50μ) and purity 99.9% is being purchased from Nextgen Steel & alloys, Mumbai, India.

Silver is the highly conductive metal. It is the 1st metal in the conductivity list with conductivity of 61.4×10^6 S/m (105.9% IACS). Silver with particle size (<20µ) and purity 99.9% is being purchased from Prominex Precious Mineral Resources Uttrakhand, India.

CNT (Carbon Nanotube) are the allotropic form of carbon with a cylindrical nanostructure. These cylindrical carbon molecules possess strange characteristics, which are precious for nanotechnology, electronics, optics and other fields of material science and technology. The hardness of composite increases with increasing the wt. %of MW-CNTs until a maximum value of HV=151 for 6 wt. %. Above 6 wt. % there is no further increase in hardness. This indicated that MW-CNTs are having a strengthening effect on the graphite matrix [23]. They have amazing thermal conductivity, mechanical and electrical properties. CNT also reduces wear rate by forming a carbon film, while the effect of lubrication and impedance to oxidation increases [24, 25]. Multi-walled nanotubes have been purchased from sigma Aldrich, Mumbai.

Phenolic resol resins are artificial polymers formed by the reaction of phenol with formaldehyde. Phenolic resin is used as a binder. Phenolic resins have no melting point but only a decaying point in the temperature region of 215°C (427°F) and beyond. Resin has been purchased from Chemie range Delhi, India.

Argon gas is an inert gas. It is found in group 18 in periodic table as a noble gas. It protects the sample from getting oxidized as it is not reactive at all. Argon gas cylinder has been purchased from Lalit gas service, Patiala, Punjab. The third-most plentiful gas in the Earth's environment is Argon, at 0.928% (9280 ppm). Argon is the most copious noble gas in Earth's crust, comprising 0.00017% of the crust (W.1).

3.4 Methodology

Carbon brushes of different grades using copper, silver, CNT's and phenolic resin (binder) have been fabricated using powder metallurgy process. For compaction process hydraulic press has been used with a force of 15N. Tubular furnace has been used for the sintering process with variable temperature i.e. 800°C, 900°C and 1000°C. four grades of carbon brushes have been fabricated using powder metallurgy process which are [i] Electro graphitic brushes [ii] copper graphite brushes (resin bonded) [iii] silver graphite brushes (resin bonded) [iv] CNT graphite brushes.

For the fabrication of the electro graphite brushes we used pure graphite powder (99.9% pure) and particle size of <20µ as received. The pellets of pure graphite have been fabricated using a dye with diameter 10mm. powder weighing 3g been poured into the dye and put under the hydraulic press for compaction process where force of 15N has been applied. A holding time 5 minutes of has been given for the proper binding of the particles to each other. After the fabrication of the pellets sintering process has been carried out at different temperature i.e. 800°C, 900°C, 1000°C at inert argon atmosphere.

For the fabrication of the copper-graphite and silver-graphite brushes the methodology used is same. The weight % of copper and silver used is 50%, 54%, 56%, and 58% and the rest is graphite. Phenolic resin has been used as a binding agent. First of all, the mixing has been done. Copper-graphite and silver-graphite has been taken in appropriate weight % mortar. Mortar has been used for mixing. After that very limited amount of phenolic resin has been poured into the mixture and mix it thoroughly for about 20 minutes. After mixing, the powder has been poured into the dye and compaction process is carried out using hydraulic press at 15 ton force. Again holding time was 5 minutes. After compaction, sintering has been done in different temperature at inert environment of argon gas.

For the fabrication of CNT-graphite brushes, 0.25% and 0.75% of CNT has been used (wt. %). First of all the CNTs get converted into functional CNTs using sonication process. For this process, first the acetone get mixed with surfactants i.e. triton X100 in a proper wt% in a centrifuge tube. The concentration is 0.07ml of triton X100 in 50ml of acetone. Then the CNT's got poured according to wt %.like 0.25% or 0.75% of CNT of the total weight of the pellet and shake well for mixing. After the mixing part, sonication procedure has been carried out. Sonication is the technique of using sound energy to excite particles in a sample for a variety of task.. For this process, the sonicator is filled with water up to a certain limit and the centrifuge tube with acetone, surfactants and CNT's got placed inside the sonicator. The sonication has been performed for about 10 minutes. After this process, the functional CNT's are poured into the mortar very slowly so that the mixing of rest of the wt% of graphite with CNTs can be done appropriately. The proper mixing of the graphite with functional CNT's takes around 20-25 minutes for each pellet.

After the mixing part, the powder again put into the dye with diameter of 10 mm and compaction process is carried out at force of 15ton and holding time of 10 minutes. After compaction again sintering has been done at different temperature in inert gas environment i.e. argon atmosphere.

The samples were fabricated using standard metallographic process. XRD of the pellets has been performed to analyze the different phase present in the matrix material. Further, for wear testing ASTM G99 standards have been used. The pellets were subjected to dry sliding wear testing at room temperature for different load conditions (2kg, 3kg, 4kgand

5kg). The wear test specimen i.e. wear track were subjected to optical microscopy to determine the structure property relationship. Figure 3.1 represents the flow chart of the methodology used for the processing, characterization and testing of carbon brush samples. For measuring the conductivity of the samples four probe setup is used.

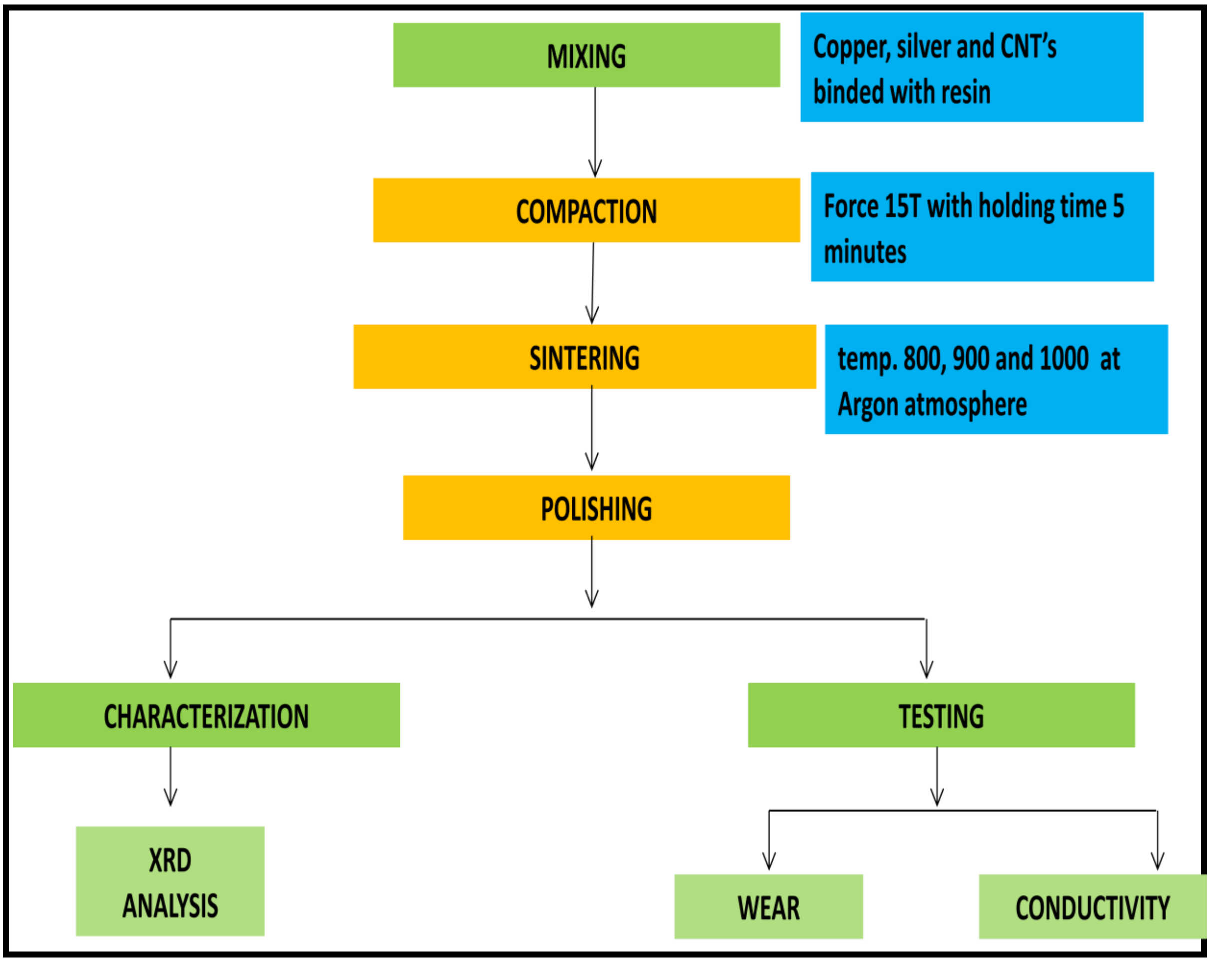

Figure 3.1: Flow chart of the methodology to be used for the proposed research.

3.5 Wear testing setup

Wear test was performed on wear testing machine (Wear and Friction Monitor TR-20 CH-400, Ducom instruments Bangalore, India) in dry sliding conditions at room temperature. ASTM G99 standards were considered for the wear test. All samples of the carbon brushes i.e. Electro graphitic, copper-graphite, silver-graphite and CNT's were tested against EN 32 steel disc having 65 HRC (832 HV) hardness. Figure 3.1 present the setup of wear testing machine.

Figure 3.2: Wear testing setup (Courtesy: Thapar University, Patiala).

3.6 Four Probe setup

Four probe setup (digital micro voltmeter Model: DMV-001, Scientific Equipment Roorkee) to analyze the conductivity of carbon brushes, Four probe setup has been Used. It is an electrical impedance analyzing method that split couple of current-carrying and voltage sensing electrode to make more precise measurement than the simpler and more usual two terminal sensing. Figure 3.2 illustrates the setup of four probe been used in the experiment.

Figure 3.3: Four probe setup (Courtesy: Thapar University, Patiala).

For measuring the conductivity following formula has been used:

Resistivity ($\rho_{\circ}$) = $V/I \times 2\pi S$................. [W.2]

Where, V= voltage (mV)

I=current supplied

And S=spacing between the probe

Spacing between the probes measured was 1.5mm. Thickness of the sample was 3mm. so b/s ratio (correction factor 'G') has been taken 1.015 from the Figure 3.2. And conductivity is the reciprocal of resistivity. The voltage readings have taken at different current values i.e. 40mA, 80mA, 120mA, 160mA and 180mA.

For conductivity measurement, sample preparation has to be done be cutting the cylindrical sample along its length and flatten on its circumference. So that the sample can sample can rest and the conductivity measurement can be made.

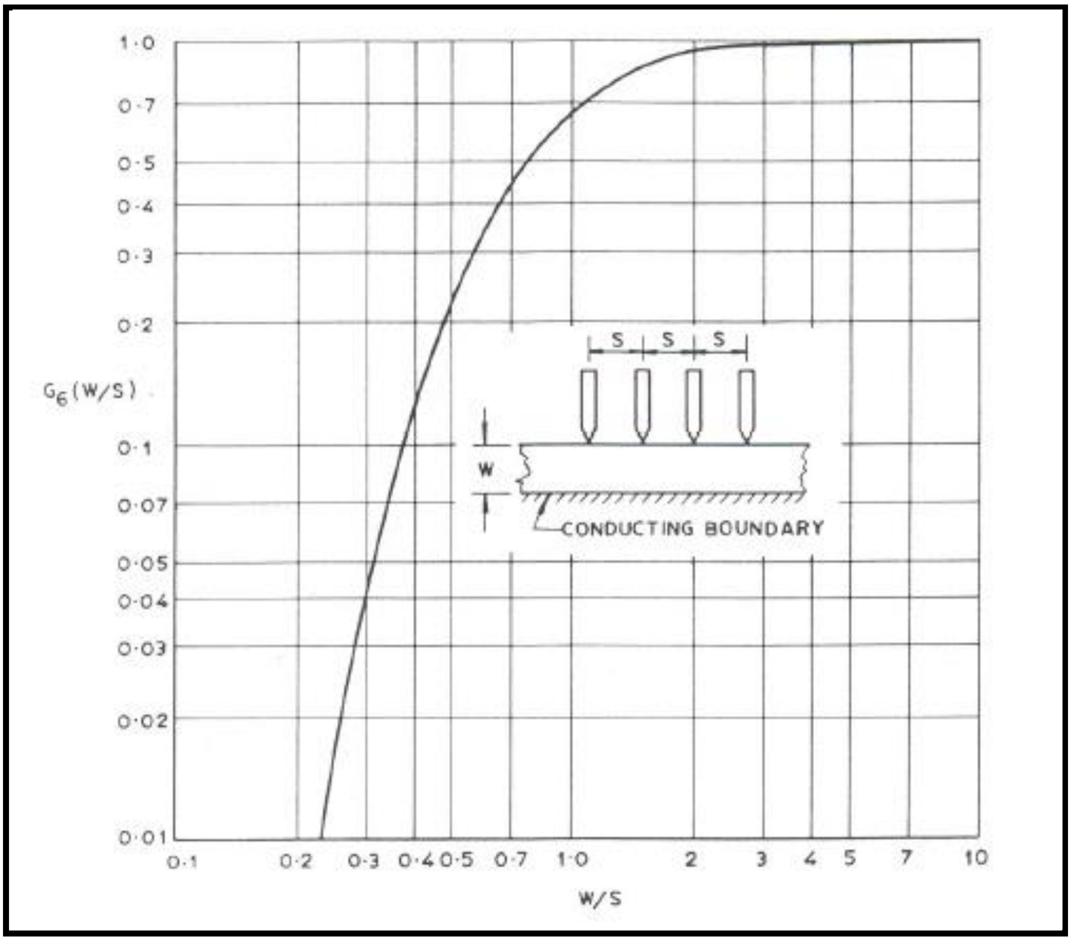

Figure 3.4 Correction factor 'G' graph for conductive body [W.5]

3.7 XRD (X-Ray Diffraction)

X-Ray Diffraction is a method where the crystalline atoms form a ray of light of X-rays to diffract into many precise directions for analyzing the atomic and molecular arrangement of a crystal, by calculating the angles and intensities of these diffracted rays, a crystallographic orientation of the sample can be found out. Figure 3.4. Presents the schematic of X-ray diffraction setup.

The 2ϴ scan was performed with the scan range: $2\theta = 20$ to 120° with Step width: 0.02°, Scan speed: 20° / min. X-ray source with Cu Kα is used for measuring crystal orientation. Silicon single crystal is used as the reference sample to comparison.

Figure 3.5: X- Ray Diffractrometer (Courtesy: Thapar University, Patiala).

Chapter 4
Results and Discussion

4.1 General

The chapter presents the characterization and testing results obtained from the fabricated carbon brushes with different additives (Cu, Ag and CNT) at various compositions. This chapter displays wear testing results (using wear and Friction monitor TR-20 CH-400), conductive property (using digital micro voltmeter model: DMV-001) and phases using XRD. The correlation of mechanical (wear testing) and electrical (Conductivity) properties with microstructure will be discussed in the next chapter.

4.2 Sintering of the C, C-Cu and C-Ag composites at 800℃

Table 4.1 shows the properties (wear and electrical conductivity) of carbon brushes which are sintered at 800°C. The sample no. S01, S02 and S03 correspond to pure graphitic, 58% copper and 42% graphite(C-58Cu) and, 58% silver and 42% graphite(C-58Ag) respectively. Wear rate is calculated be measuring the change in weight of the sample when subjected to different load such as 2kg, 3kg, 4kg and 5Kg. The conductivity of the sample is calculated using four probe method and the hardness value was measured using Vickers micro hardness test. The conductivity of the graphite carbon brushes is found to be lowest which 8.126×10^3 S/m. The conductivity and wear rate value were found to be increasing on addition of copper and silver were as the micro hardness value of were found to be increasing on addition of copper and silver as shown in Table 4.1. Our primary focus is to understand the wear and conductivity properties only and the hardness value were used to understand the strength value doing sintering process.

Table 4.1: Properties of carbon Brushes sintered at 800°C

Sample no.	Composition	Hardness (HV)	Electrical Conductivity×10³ (S/m)	Contact Load (kg)	Wear rate×10⁻⁶ (g/m)
S01	C	27.79	8.126±0.15	2	1.5
				3	2.2
				4	2.51
				5	3.75
S02	C-58Ag	24.23	26.24±1.5	2	3.85
				3	2.77
				4	4.29
				5	4.55
S03	C-58Cu	21.77	28.06±0.5	2	4.7
				3	3.77
				4	5.41
				5	6.62

Wear test has been carried on (Wear and Friction monitor TR-20 CH-400). Pin on disc setup was used under ambient room temperature. Figure 4.1 represent a graph of wear analysis of carbon brushes sintered at 800°C. Figure clearly shows that Brush S01 has less wear rate as compare to brush S02 and S03. It is observed from the graph that the wear rate is not increasing linearly with the load. For each load wear rate of brush varies. For 2kg load wear is high whereas for 3kg its low and again increases for further load i.e. 2 and 5kg. Figure 4.1 clearly shows there is an in homogeneity in the wear rate by varying the load.

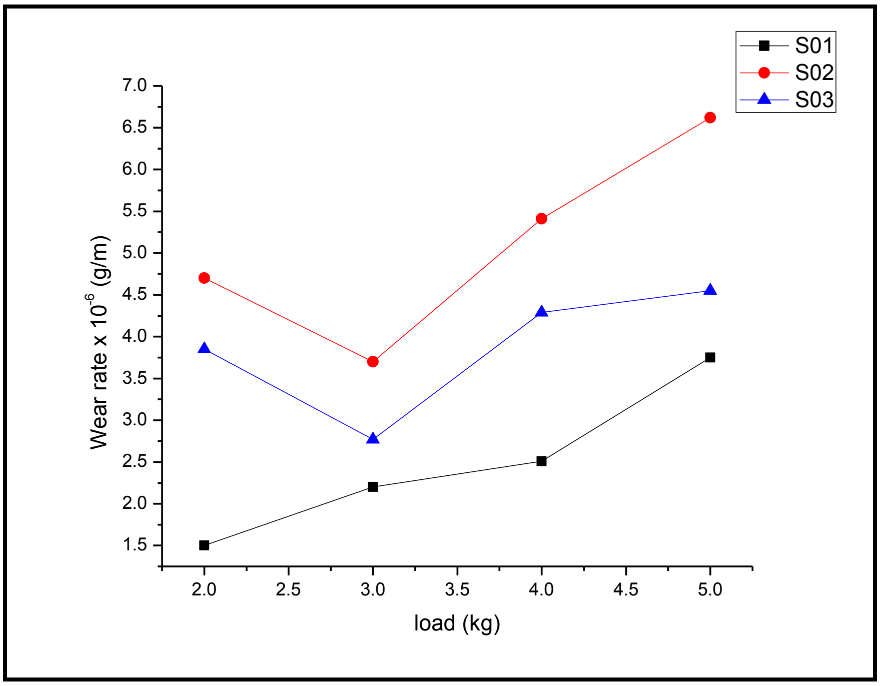

Figure 4.1: wear rate of carbon brushes sintered at 800°C

Electrical conductivity test has been performed at different current (40mA, 80mA, 120mA, 160mA and 180mA) keeping width of the sample constant i.e. 3mm. the value of correction factor (G) has been taken from the graph. For thickness 3mm and probe spacing 1.5mm, the value of correction factor has been taken 1.015. Figure 4.2 represent the conductivity graph of the brushes sintered at temperature 800°C.

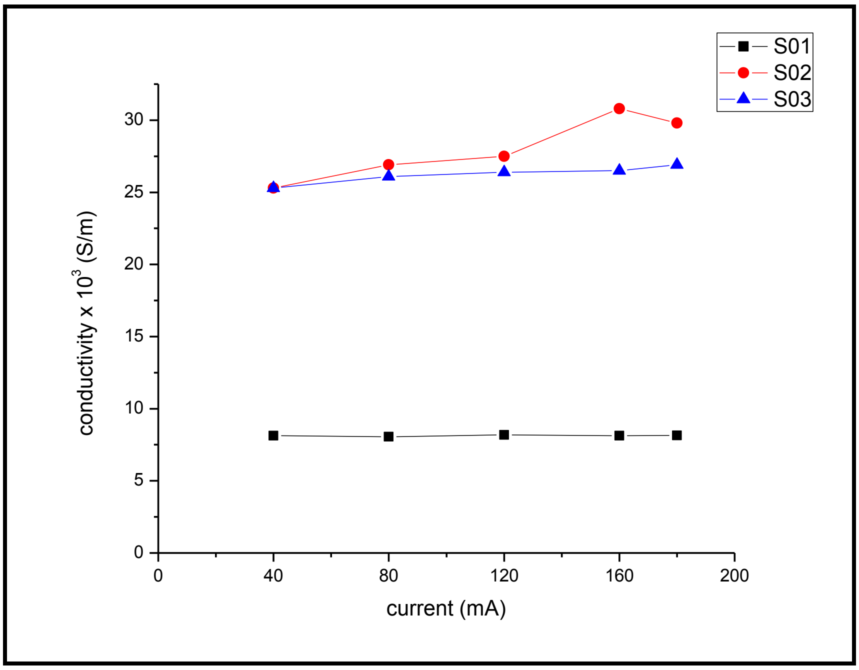

Figure 4.2 Electrical conductivity graph of brushes sintered at 800°C

The above graph represents the electrical conductivity of the brushes (S01, S02 and S03). From the graph it has been observed that the brush S01 has lower conductivity as compare to brush S02 and S03. Brush S01has conductivity 8.126×10^3 (S/m) whereas brush S02 and S03 has conductivity 26.24×10^3 (S/m) and 28.06×10^3 (S/m) respectively. Brush S03 shows high conductivity because it consist of silver and silver has high conductivity as compare to both copper and graphite. Silver has conductivity in the range of 61.4×10^6 S/m or 105.9% IACS, whereas copper and graphite has conductivity in the range of 59.1×10^6 S/m or 101.9%IACS and 3×10^6 S/m or 5.2%IACS. From figure 4.2 it is cleared that by adding metals such as copper and silver will result in increase in electrical conductivity value.

4.3 Effect of temperature on properties of carbon brushes

Another set of carbon brushes were fabricated and sintered at different temperature i.e. 900℃ and 1000℃ to understand the effect of temperature on the various properties of carbon brushes like hardness, electrical conductivity and wear rate. Table 4.2 represents various properties of brush S04 and S05 at 900℃ and 1000℃. The hardness test reveals that brush S04 has hardness 28.23HV and hardness of brush S05 is 30.21HV indicates that brush sintered at 1000℃ has high hardness value as compare to brush sintered at 900℃. Low sintering temperature 900℃ resulted in low densification compared to that brush sintered at 1000℃. However the standard deviation of the hardness value has to be measure to confirm the densification during heat treatment.

Table 4.2: Graphite brushes sintered at 900 and 1000℃

Sample no.	**Composition**	**Hardness (HV)**	**Electrical Conductivity×10^3 (S/m)**	**Contact Load (kg)**	**Wear rate ×10^{-6} (g/m)**
S04	C	28.23	23.16±1.3	2	1.69
				3	0.78
				4	1.04
				5	3.38
S05	C	30.21	25.12±1.0	2	1.22
				3	1.52
				4	1.15
				5	7.37

figure 4.3 shows the wear test results on the carbon brush S04 and S05 sintered at 900℃ and 1000℃ at different load condition (2,3,4 and 5kg) keeping sliding distance (13,576m) and time (1hr) constant. The wear rate of metal is found to be to follow no trend by varying the load value.

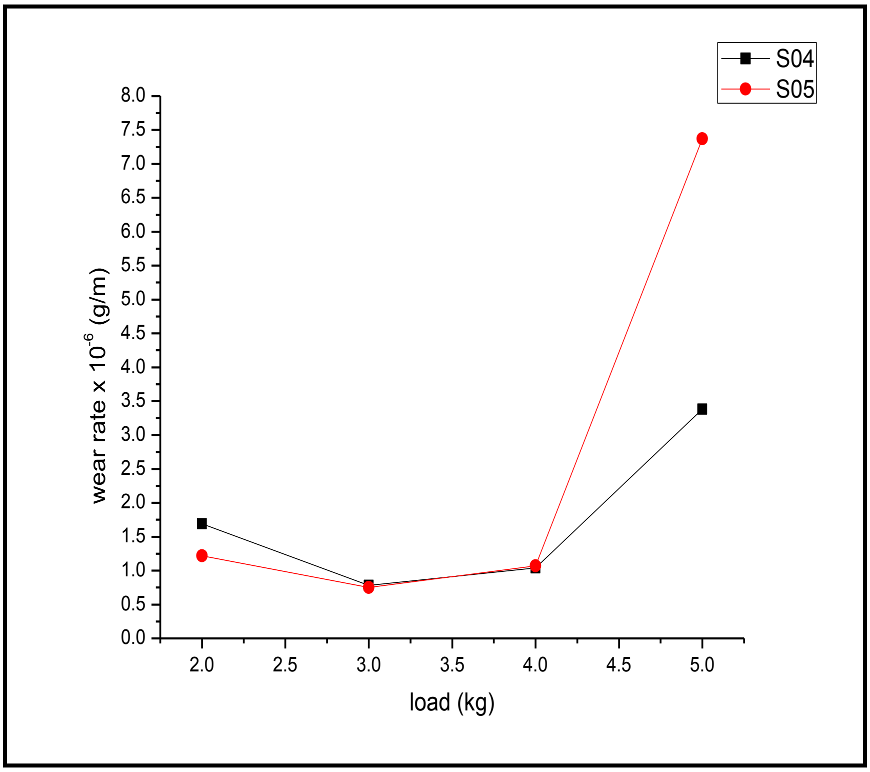

Figure 4.3: wear rate of graphitic brushes sintered at 900 and 1000℃

Figure 4.4 represents the conductivity graph of the brushes S04 and S05 sintered at 900 and 1000℃. The average of three values was taken as the measured conductivity value. It shows that the conductivity of brush S05 sintered at 1000℃ is 25.12×10^3 S/m. whereas, brush S04 sintered at temperature 900℃ having conductivity increased with increasing temperature from 900 to 1000℃.

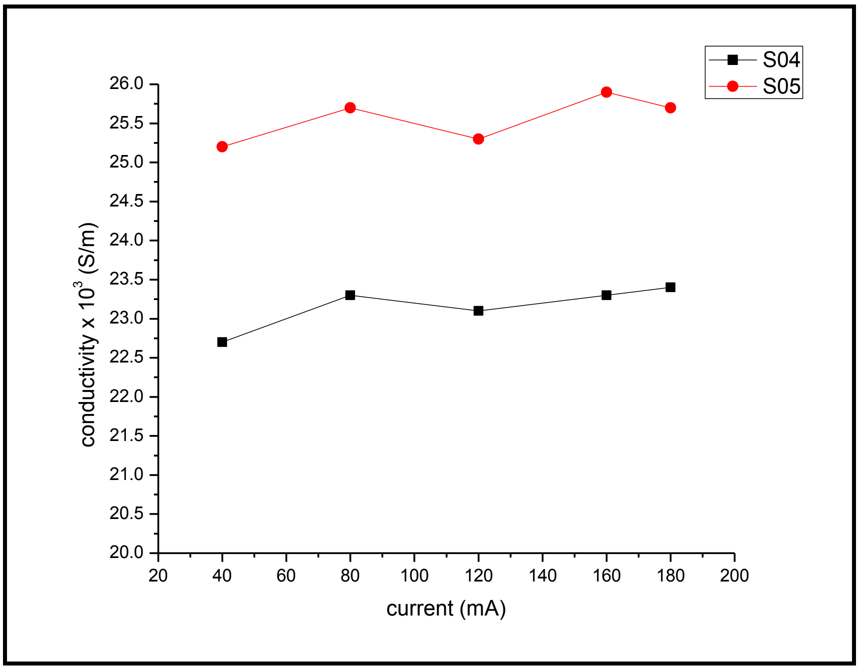

Figure 4.4 Electrical conductivity graph of brushes sintered at 900 and 1000℃

The above graph represents the conductivity of the brushes S04 and S05 sintered at 900℃ and 1000℃. It shows that the conductivity of brush S05 sintered at 1000℃ is 25.12×10^3 S/m. whereas, brush S04 sintered at temperature 900℃ having conductivity 23.16×10^3 S/m. it can be seen that electrical conductivity improved with increasing temperature from 900℃ to 1000℃.

4.4 Properties and microstructure of C-Cu composite at 900℃

Copper graphite brushes fabricated at 900℃ with different composition (C-50Cu, C-54Cu, C-56Cu and C-58Cu) in argon atmosphere to understand the change wear and electrical properties. Table 4.3 represents the characteristics values of brushes in different composition at 900℃. Hardness test reveals that S09 brush contains 58% of Cu with graphite, which makes it hard from other brushes. Hardness of S09 brush is 31.25HV whereas, hardness of S06, S07 and S08 is 26.72HV, 27.32HV and 29.27HV.

Table 4.3: Properties of C-Cu brushes sintered at 900°C

Sample no.	Composition	Hardness (HV)	Electrical Conductivity×10³ (S/m)	Contact Load (kg)	Wear rate×10⁻⁶ (g/m)
S06	C-50Cu	26.72	30.8±2.3	2	0.0039
				3	0.0026
				4	0.0043
				5	0.0052
S07	C-54Cu	27.32	47.26±1.6	2	0.0031
				3	0.0029
				4	0.003
				5	0.0037
S08	C-56Cu	29.27	27.54±1.9	2	0.0026
				3	0.0023
				4	0.0026
				5	0.0033
S09	C-58Cu	31.25	26.34±2.3	2	0.0025
				3	0.0021
				4	0.0027
				5	0.0037

Figure 4.5 represent the wear graph of brushes S06, S07, S08 and S09 sintered at 900°C. The wear rate of metal is found to be to follow no trend by varying the load value.

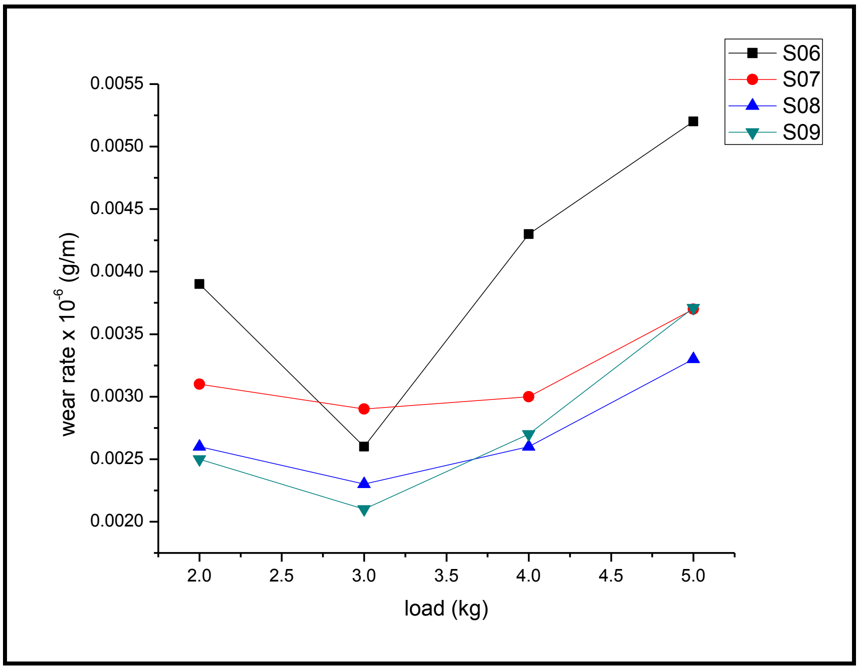

Figure 4.5: Wear rate of C-Cu brushes at different composition sintered at 900°C

Figure 4.6 represents the conductivity graph for the brush with variable composition of Cu. As observed from the graph brush S07 is showing high conductivity as compare to other brushes S06, S08 and S09.

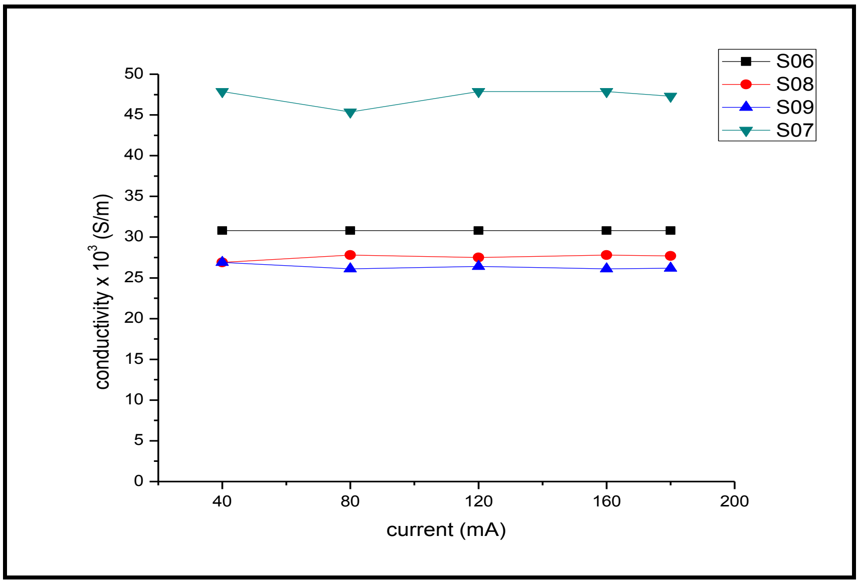

Figure 4.6: conductivity of C-Cu brushes at different composition sintered at 900℃

XRD test has been performed on the brush to analyze the phases present in it which affect the characteristics properties of the brushes. Figure 4.7 represent the XRD pattern of the brush sintered at 900℃ .The above XRD graph represents the major peaks of Cu and C. No other element has been found in the XRD pattern that shows no other foreign material had been introduced to the brush sample. There is no phase change in the microstructure of the brush.

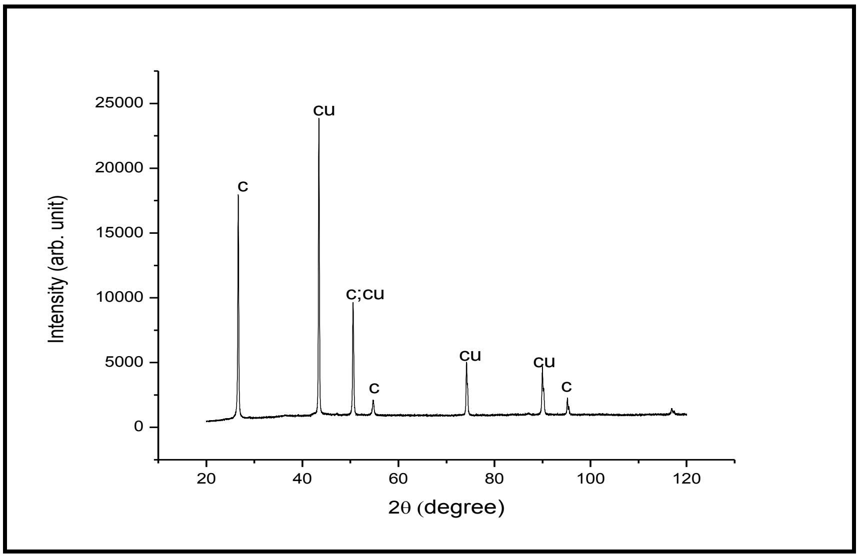

Figure 4.7: XRD graph of C-Cu brushes sintered at 900℃

4.5 Sintering of C-Cu composite at 1000℃

Carbon brush S10, S11, S12 and S13 has been fabricated and sintered at 1000℃ in argon atmosphere to analyze the affect of composition on the brushes characteristics properties when sintered at 1000℃. Table 4.4 represents the characteristics values of carbon brushes with different composition at 1000℃. From the table it is concluded that the brush S13 has the highest hardness no. i.e. 38.07 as compare to brushes S10, S11 and S12. The hardness is increased with increasing metal content in both casts.

Table 4.4: properties of C-Cu composites sintered at 1000℃

Sample no.	Composition	Hardness (HV)	Electrical Conductivity×10³ (S/m)	Contact Load (kg)	Wear rate×10⁻⁶ (g/m)
S10	C-50Cu	25.0	31.9±1.2	2	0.0002
				3	0.0004
				4	0.003
				5	0.0027
S11	C-54Cu	30.65	33.5±1.1	2	0.004
				3	0.0041
				4	0.0055
				5	0.0101
S12	C-56Cu	34.53	40.56±1.1	2	0.0088
				3	0.0062
				4	0.0075
				5	0.0192
S13	C-58Cu	38.07	53.8±1.1	2	0.0121
				3	0.0101
				4	0.0152
				5	0.0212

Wear and hardness test has been performed on the brushes S10, S11, S12 and S13 to analyze their characteristics properties when sintered at 1000℃. Figure 4.8 represent the graph of wear rate of brushes S10, S11, S12 and S13.

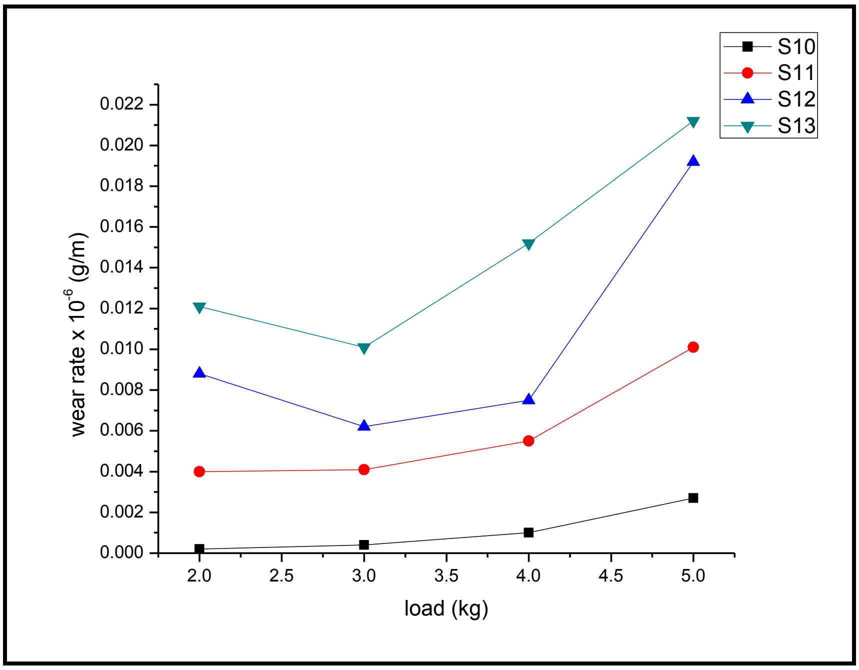

Figure 4.8: Wear rate of C-Cu brushes at different composition sintered at 1000℃

Figure 4.9 represent the conductivity graph between the 4 brushes samples (S10, S11, S12 and S13) sintered at 1000℃. As observed from the above graph brush S13 is showing high conductivity as compare to brush S10, S11 and S12. The reason for this fact is the conductivity increases as copper composition increases.

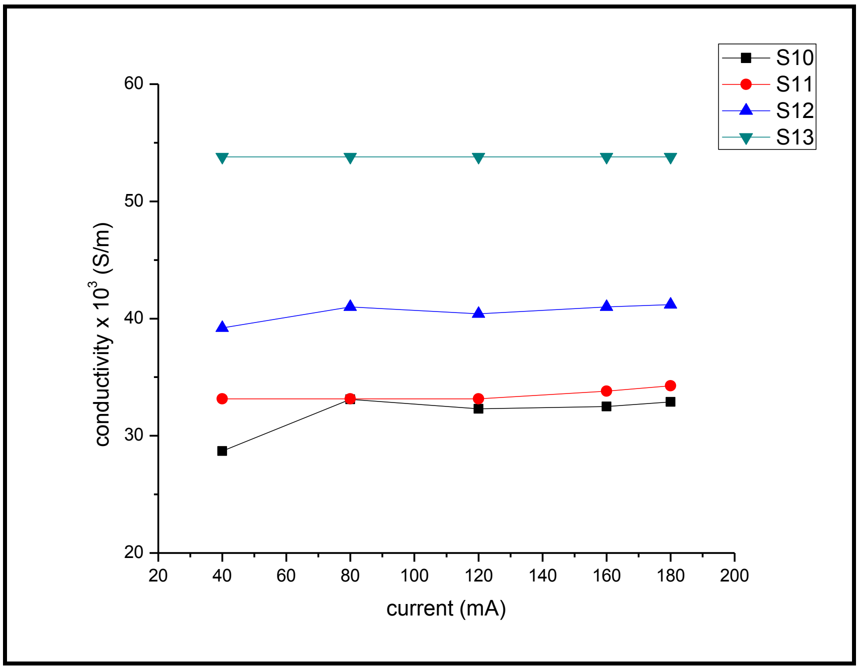

Figure 4.9: Electrical conductivity of C-Cu composite at different composition sintered at 1000℃

XRD test has been performed to analyze the phase present in the brush with major and minor elements if there is any. Figure 4.10 represent the XRD pattern for the brush sintered at 1000℃.From the above XRD pattern it is concluded that there is no phase change in the sample and all the material present in the brush are showing their actual properties. Major peaks were found for Copper and Carbon only. No other foreign element is found in the sample.

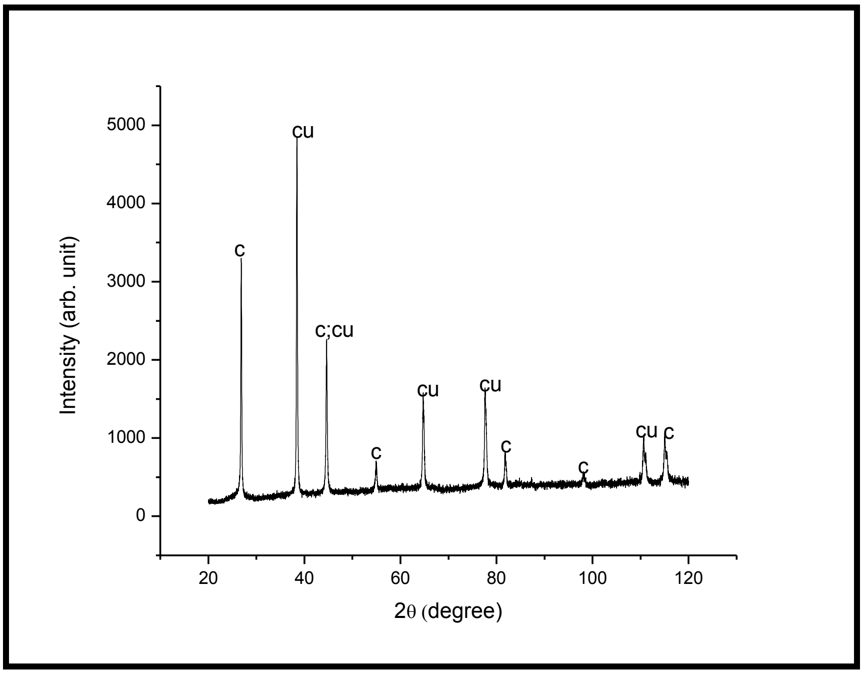

Figure 4.10: XRD graph of C-Cu brush sintered at 1000℃

4.6 Sintering of C-Ag composites in different composition at 900 ℃

Carbon brushes S14, S15, S16 and S17 has been fabricated at 900℃ in argon atmosphere using variable wt% of Ag to analyze the change in characteristics values of the brush in different composition of brushes (C-50Ag, C-54Ag, C-56Ag and C-58Ag). Table 4.5 represents the characteristics values of the brushes sintered at 900℃.

Table 4.5: Characteristics values of C-Ag brushes sintered at 900℃

Sample No	Composition	Hardness (HV)	Electrical Conductivity×10^3 (S/m)	Contact Load (kg)	Wear rate×10^{-6} (g/m)
S14	C-50Ag	22.56	34.46±0.5	2	0.0027
				3	0.0017
				4	0.0035
				5	0.0047
S15	C-54Ag	28.75	50.98±0.8	2	0.0053
				3	0.002
				4	0.0072
				5	0.0121
S16	C-56Ag	32.25	40.56±1.2	2	0.0085
				3	0.0063
				4	0.0097
				5	0.0121
S17	C-58Ag	35.6	44.26±2.5	2	0.0122
				3	0.0105
				4	0.0147
				5	0.0165

Figure 4.11 represent the wear graph of the brushes S14, S15, S16 and S17 with variable wt% of Ag at 900°C.The wear rate of metal is found to be to follow no trend by varying the load value.

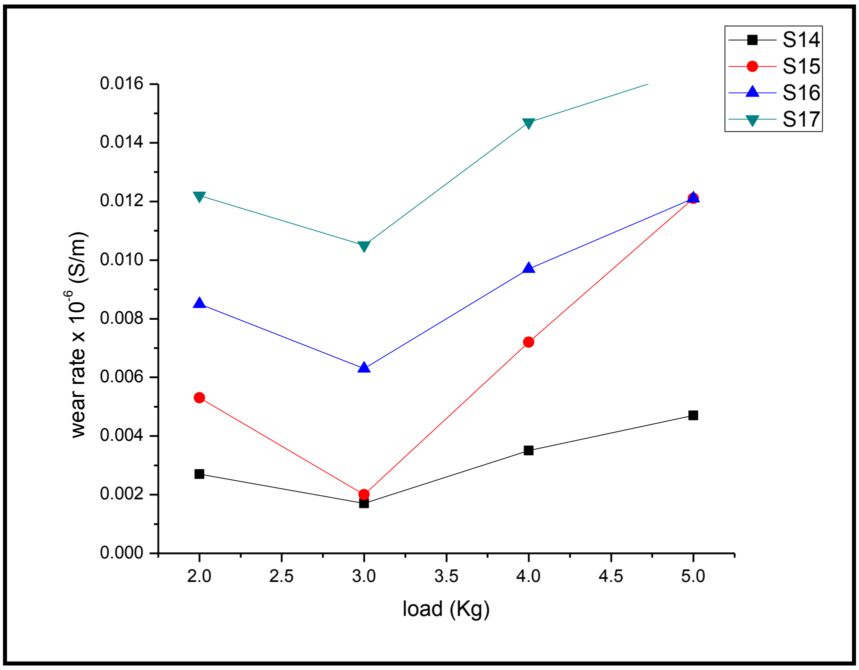

Figure 4.11: Wear rate of C-Ag brushes in different composition sintered at 900°C

Figure 4.6 represents the conductivity graph for the brush with variable composition of Ag. As observed from the graph brush S15 is showing high conductivity as compare to other brushes S14, S16 and S17.

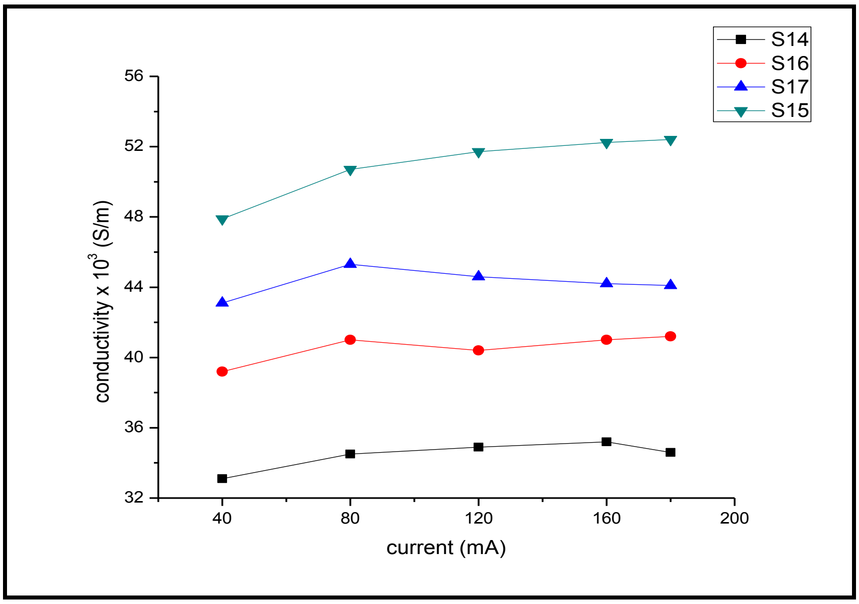

Figure 4.12: Electrical conductivity graph of C-Agr brushes sintered at 900°C

XRD test has been performed to analyze the phase present in the brush with major and minor elements if there is any. Figure 4.10 represent the XRD pattern for the brush sintered at 900℃.From the above XRD pattern it is concluded that there is no phase change in the sample and all the material present in the brush are showing their actual properties. Major peaks were found for Silver and Carbon only. No other foreign element is found in the sample.

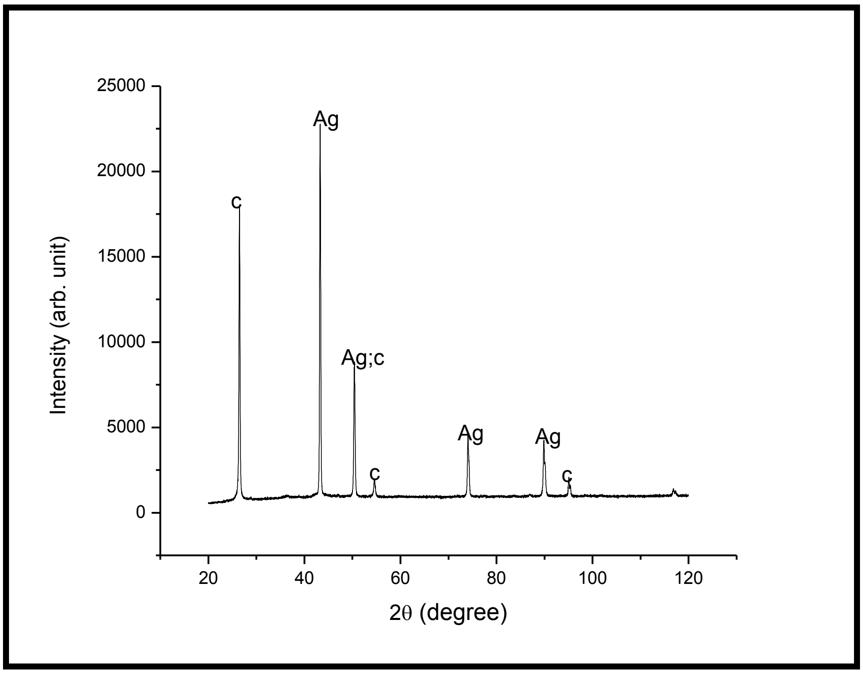

Figure 4.13: XRD graph of C-Agr brushes sintered at 900℃

4.7 Sintering of C-Ag composites of different composition sintered at 1000℃

Carbon brush S18, S19, S20 and S21 has been fabricated and sintered at 1000℃ in argon atmosphere to analyze the affect of composition on the brushes characteristics properties when sintered at 1000℃. Table 4.6 represents the characteristics values of carbon brushes with different composition at 1000℃. From the table it is concluded that the brush S21 has the highest hardness no. i.e. 35.23 as compare to brushes S18, S19 and S20. The hardness increased with increasing metal content in both cast.

Table 4.6: characteristic values of C-Ag composites of different composition at 1000°C

Sample no.	Composition	Hardness (HV)	Electrical Conductivity×10³ (S/m)	Contact Load (kg)	Wear rate ×10⁻⁶ (g/m)
S18	C-50Ag	23.25	57.2±2.2	2	1.43
				3	0.43
				4	0.68
				5	2.09
S19	C-54Ag	27.23	76.4±1.5	2	1.39
				3	1.24
				4	1.64
				5	1.75
S20	C-56Ag	32.12	65.1±1.3	2	0.3
				3	0.47
				4	1.27
				5	1.33
S21	C-58Ag	35.23	81.2±1.0	2	2.81
				3	3.2
				4	3.96
				5	5.02

Wear and hardness test has been performed on the brushes S18, S19, S20 and S21 to analyze their characteristics properties when sintered at 1000°C. Figure 4.8 represent the graph of wear rate of brushes S18, S19, S20 and S21.

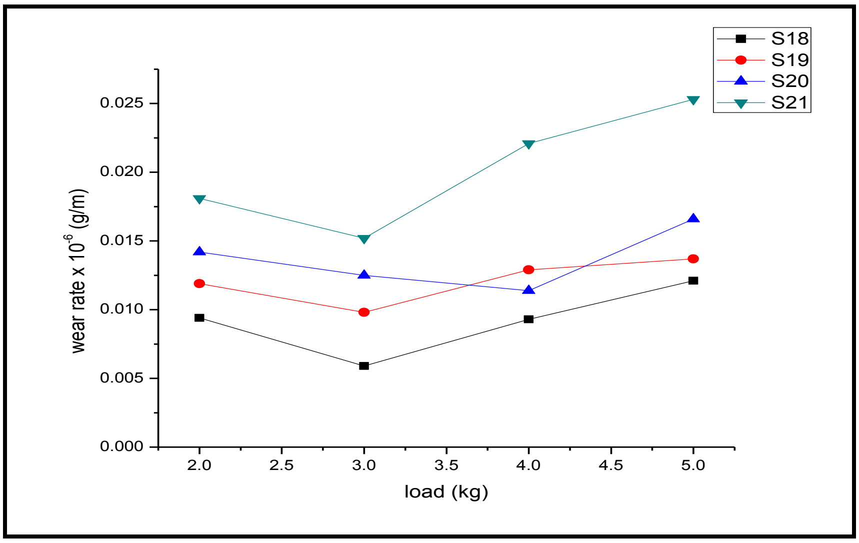

Figure 4.14: Wear graph of C-Ag brushes sintered at 1000°C at different composition

Figure 4.15 represent the conductivity graph between the 4 brushes samples (S18, S19, S20 and S21) sintered at 1000℃.As observed from the above graph brush S21 is showing high conductivity as compare to brushes S10, S11 and S12. The reason for this fact is the conductivity increases as copper composition increases.

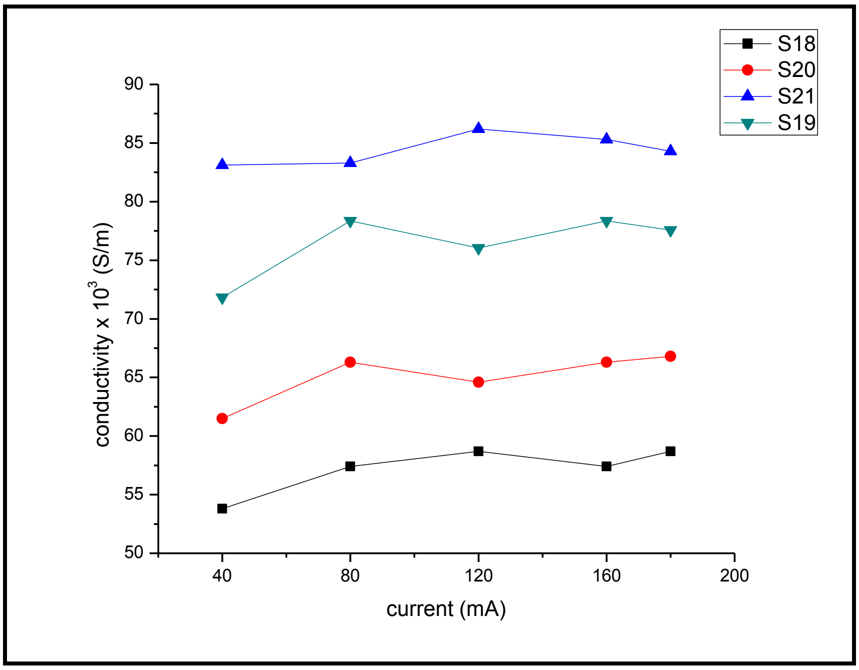

Figure 4.15: Electrical conductivity graph of Silver-Graphite composites sintered at 1000℃

XRD test has been performed to analyze the phase present in the brush with major and minor elements if there is any. Figure 4.10 represent the XRD pattern for the brush sintered at 1000℃.From the above XRD pattern it is concluded that there is no phase change in the sample and all the material present in the brush are showing their actual properties. Major peaks were found for Silver and Carbon only. No other foreign element is found in the sample.

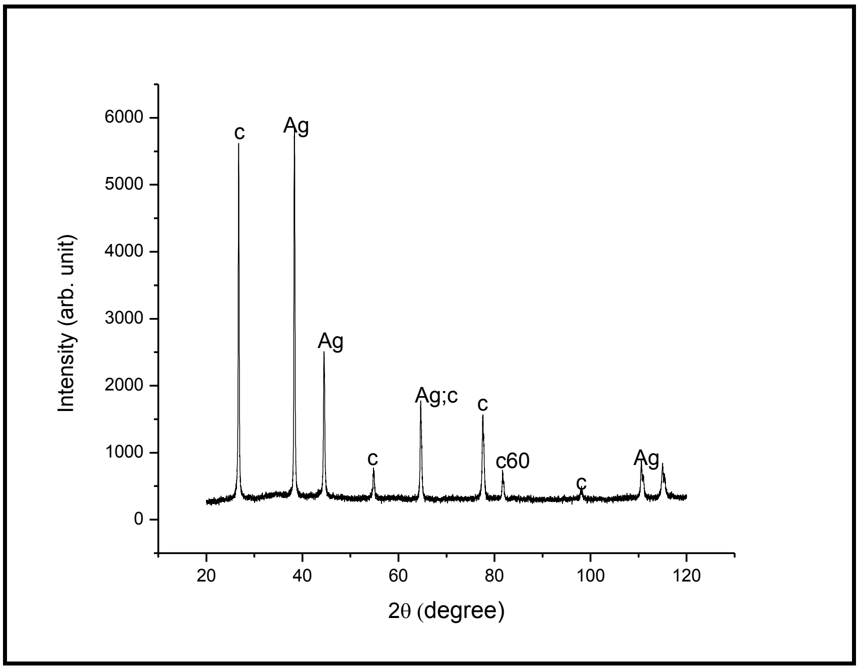

Figure 4.16: XRD graph of C-Ag brushes sintered at 1000℃

4.8 Sintering of CNT dispersed Graphite brushes of different composition at 900℃

Carbon brushes dispersed with CNT has been fabricated at 900℃ to analyze the effect of wt% of CNT being used on hardness wear and electrical conductivity of the brushes. 0.25wt% and 0.75wt% of CNT has been used with graphite to fabricate the brush and analyze the effect of it in brushes characteristics properties. Table 4.7 represents the properties of CNT dispersed brushes at 900℃.

Table 4.7: characteristics values of CNT brushes of different composition sintered at 900℃

Sample no.	Composition	Hardness (HV)	Electrical Conductivity×10^3 (S/m)	Contact Load (kg)	Wear rate×10^{-6} (g/m)
S22	C-0.25CNT	37.66	42.6±0.3	2	1.64
				3	2.29
				4	2.73
				5	3.01
S23	C-0.75CNT	43.25	58.36±0.5	2	0.49
				3	0.23
				4	0.67
				5	0.86

Figure 4.17 represent the wear graph of brushes S22 and S23 sintered at 900℃.The wear rate of metal is found to be to follow no trend by varying the load value.

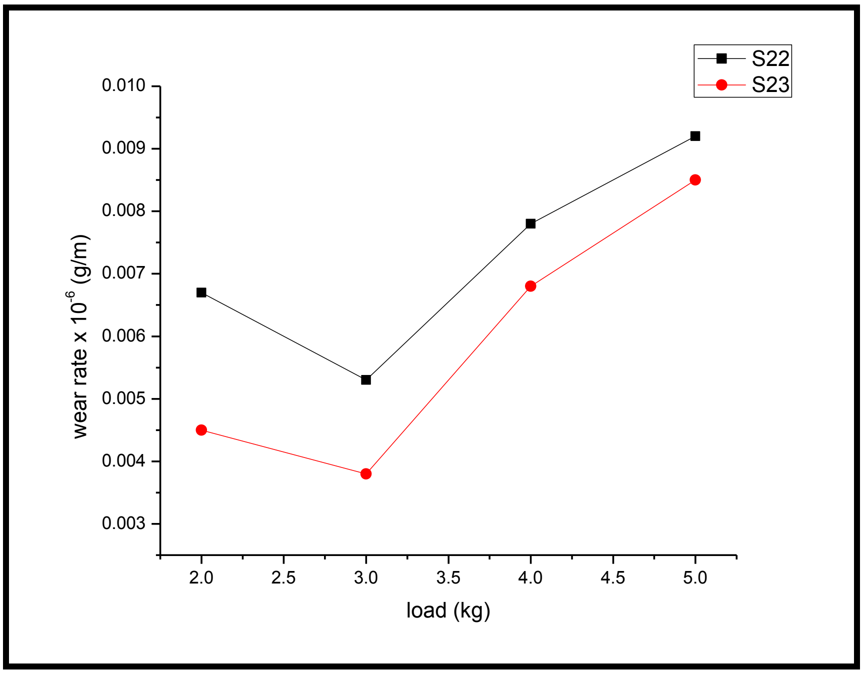

Figure 4.17: Wear graph of CNT brushes sintered at 900℃

Figure 4.18 represents the conductivity graph for the brush with variable composition of CNT.As observed from the graph brush S23 is showing high conductivity as compare to brush S22.

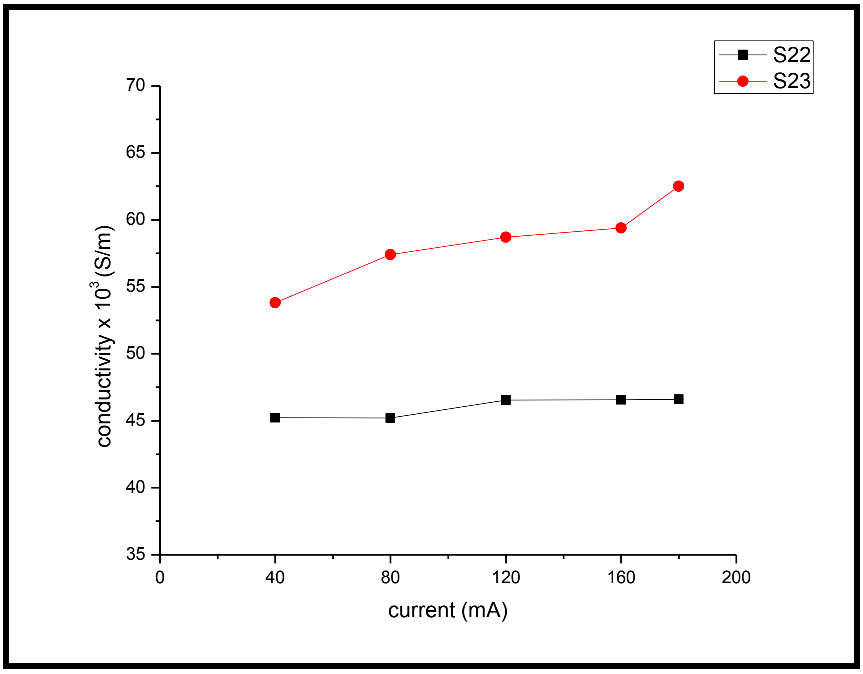

Figure 4.18: Conductivity graph of CNT brushes of 0.25 wt% and 0.75 wt% compositions sintered at 900℃

XRD test has been performed to analyze the phase present in the brush with major and minor elements if there is any. Figure 4.19 represent the XRD pattern for the brush sintered at 900℃.From the above XRD pattern it is concluded that there is no phase change in the sample and all the material present in the brush are showing their actual properties. Major peaks were found for Carbon and C60 (an allotropic form of carbon) only. No other foreign element is found in the sample.

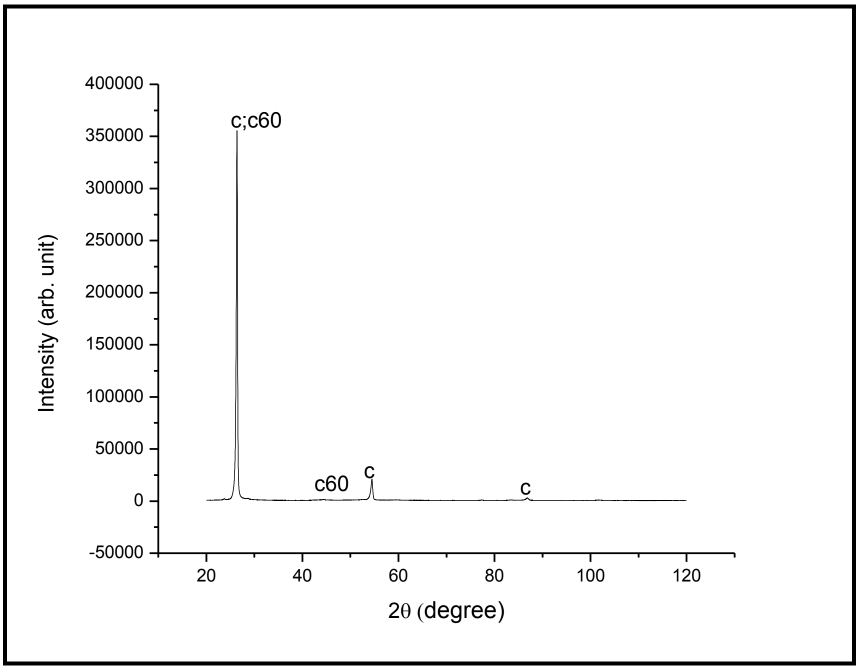

Figure 4.19: XRD graph of CNT dispersed brushes sintered at 900℃

4.9 Sintering of 0.25 and 0.75 wt. % CNT dispersed brushes sintered at 1000℃

Carbon brushes dispersed with CNT has been fabricated at 1000℃ to analyze the effect of wt% of CNT being used on hardness wear and electrical conductivity of the brushes. 0.25wt% and 0.75wt% of CNT has been used with graphite to fabricate the brush and analyze the effect of it in brushes characteristics properties. Table 4.8 represents the characteristics values of CNT dispersed brushes at 1000℃.

Table 4.8: characteristics values of CNT composites 0.25 and 0.75 wt. % at 1000°C

Sample no.	Composition	Hardness (HV)	Electrical Conductivity×10³ (S/m)	Contact Load (kg)	Wear rate ×10⁻⁶ (g/m)
S24	C-0.25CNT	32.25	29.02±1.1	2	1.19
				3	1.14
				4	1.28
				5	1.42
S25	C-0.75CNT	33.12	111.0±1.7	2	0.89
				3	1.01
				4	1.12
				5	1.26

Figure 4.17 represent the wear graph of brushes S25 and S24 sintered at 1000°C. The wear rate of metal is found to be to follow no trend by varying the load value.

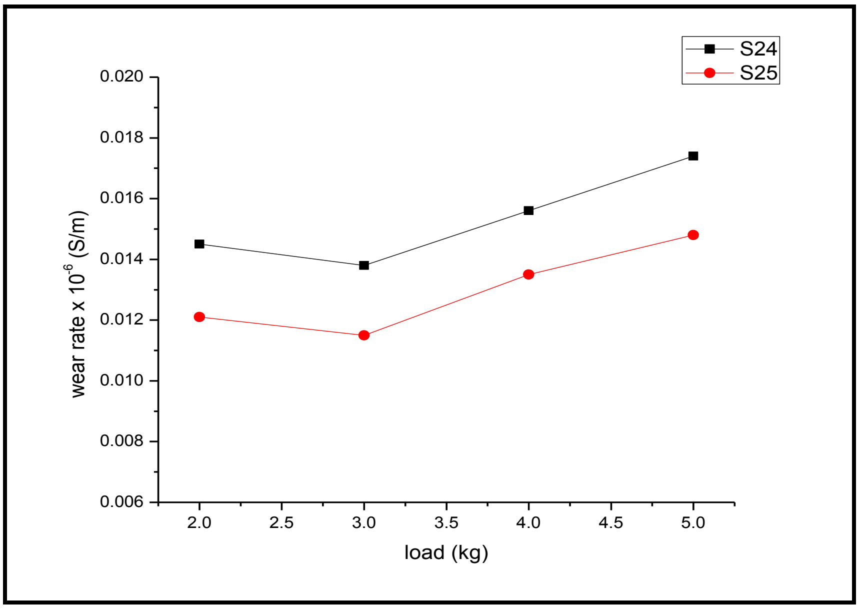

Figure 4.20: Wear rate of CNT brushes sintered at temperature 1000°C

Figure 4.21 represent the conductivity graph between the 2 brushes samples (S24 and S25) sintered at 1000°C. As observed from the above graph brush S25 is showing high conductivity as compare to brushesS25. The reason for this fact is the conductivity increases as CNT composition increases.

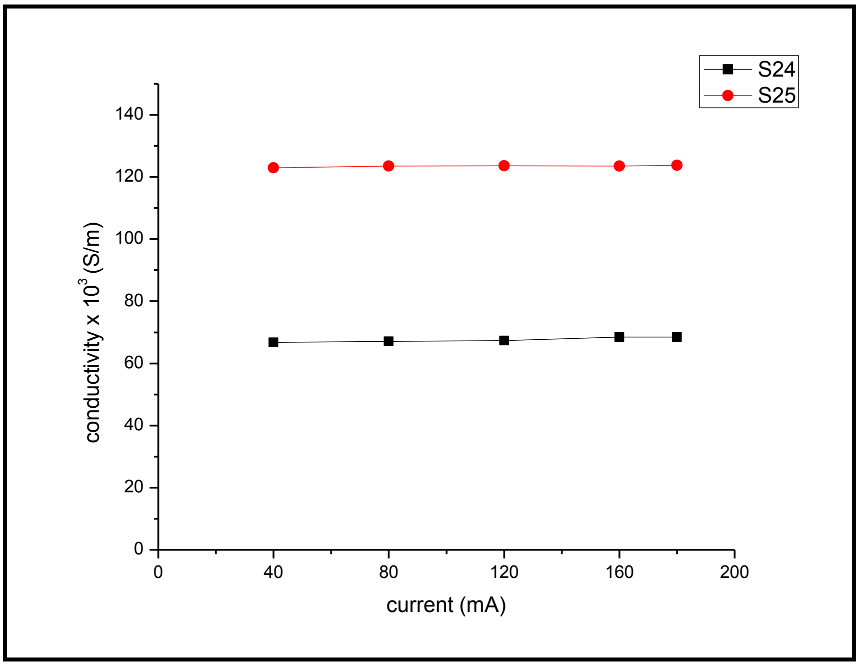

Figure 4.21: Electrical conductivity graph CNT brushes at temperature 1000°C

XRD test has been performed to analyze the phase present in the brush with major and minor elements if there is any. Figure 4.22 represent the XRD pattern for the brush sintered at 1000°C.From the above XRD pattern it is concluded that there is no phase change in the sample and all the material present in the brush are showing their actual properties. Major peaks were found for Carbon and C60 (an allotropic form of carbon) only. No other foreign element is found in the sample.

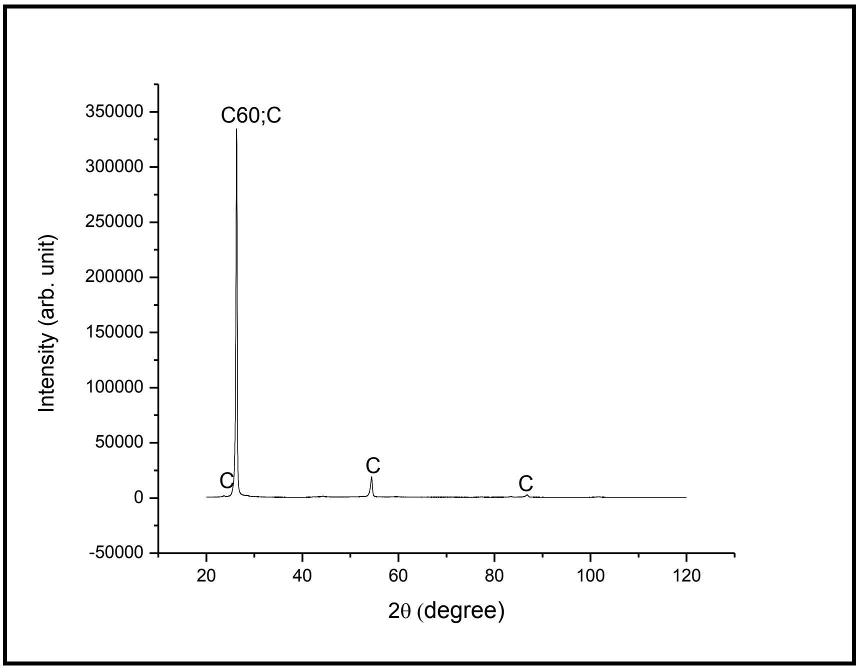

Figure 4.22: XRD graph of CNT brush sintered at temperature 1000℃

4.10 Comparison between fabricated composites with commercial sample

Comparison of graphite brushes sintered at 800℃ with market brushes (TOSHIBA) has been done to analyze the brush with better wear and conductive property. Table 4.9 shows the properties of both market brush (S26) and graphitic brush (S01).

Table 4.9: properties of S26 and S01 sample

Sample no.	**composition**	**Hardness (HV)**	**Electrical Conductivity×10^3 (S/m)**	**Contact load (kg)**	**Wear rate $\times 10^{-6}$ (g/m)**
S01	C	27.79	8.126±0.15	2	1.64
				3	2.29
				4	2.73
				5	3.01
S26	C-[Ni, Fe]-ZnS	31.26	0.09026±0.0022	2	1.12
				3	0.79
				4	1.08
				5	1.69

From the above table it is observed that brush sintered at 800℃ has low hardness value i.e. 27.79HV as compare to market brush having hardness values of 31.26HV.

Wear and conductivity test has been performed to analyze the wear and conductive properties of the brush S01 and S26. Figure 4.23 shows the wear graph of the brush S01 and S26.

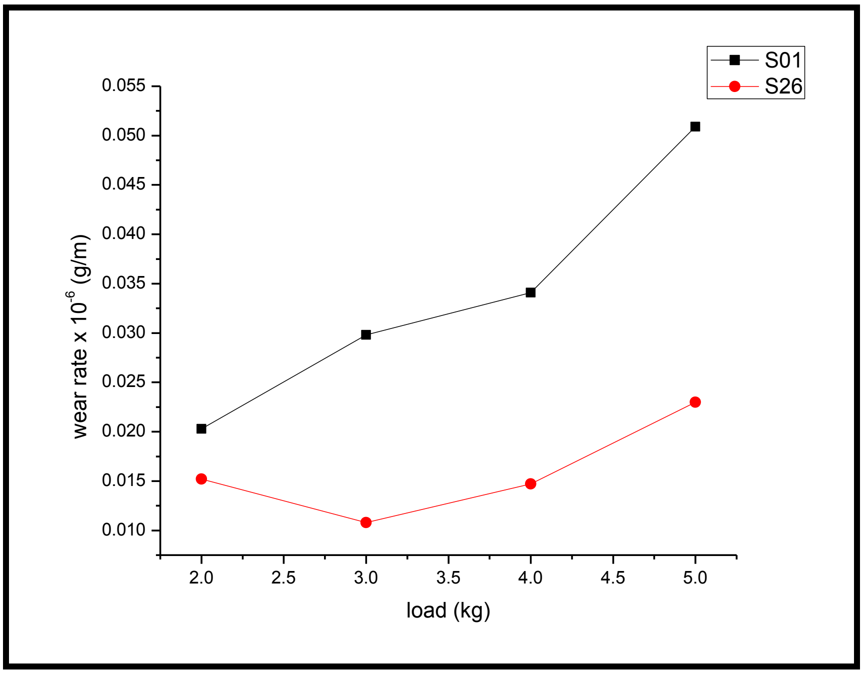

Figure 4.23 wear rate of brush sample S01 and S26

It has been clearly observed from the above graph that brush S01 has high wear rate as compare to S26. The reason for this is the high hardness value of S26 i.e. 31.26HV as compare to S01. From XRD it has been cleared that S26 consist of taenite and zinc sulphide with graphite. Taenite is mineral found naturally on earth mostly in iron meteorites. It is an alloy of iron and nickel with hardness of 5-5.5 mohrs harness no. due to which hardness of S26 is high comparative to S01 which resembles with the wear of the brush. That's the reason of less wear rate of S26 in comparison with S01.

Conductivity test has been performed on the brushes S01 and S26. Figure 4.24 shows conductivity graph between brushes S01 and S26.

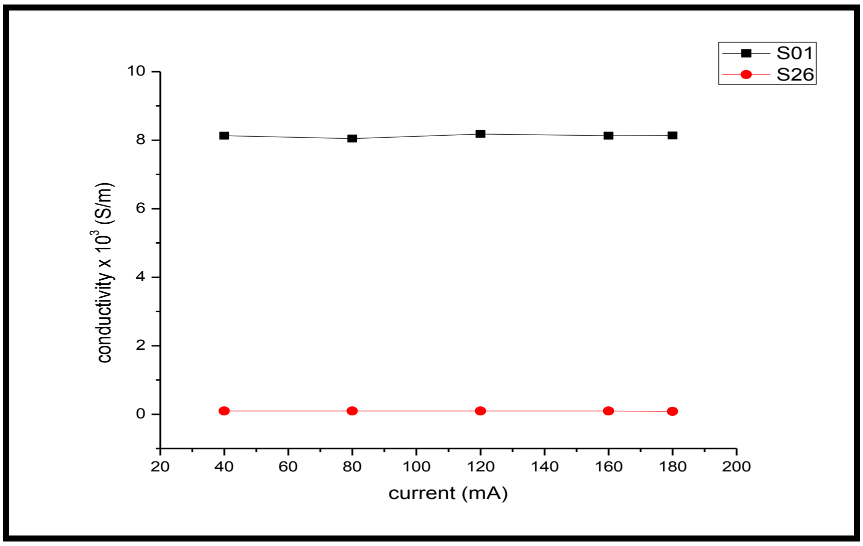

Figure 4.24: conductivity graph of brushes S01 and S26

Conductivity graph reveals that brush S01 has high conductivity as compare to brush S26. Conductivity of brush S01 is 8.126×10^3 (S/m), while conductivity of S26 is 0.09026×10^3 (S/m). Conductivity of brush S26 is decreases because taenite and zinc sulphide are less conductive elements as compare to graphite. Their presence in the brush reduces the conductivity of the brush sample S26.

XRD of the market sample has been performed to analyze the phases and elements present in it. Figure 4.24 shows the XRD pattern of the market sample. XRD test reveals that not only graphite but taenite (alloy of nickel and iron) and zinc sulphite also present in the sample in effective amount, which affect the properties of the brush S26. Taenite increases the hardness which results in less wear rate of the sample whereas; it also decreases the conductivity of the sample. So, taenite affect the brush in both ways as revealed from XRD graph.

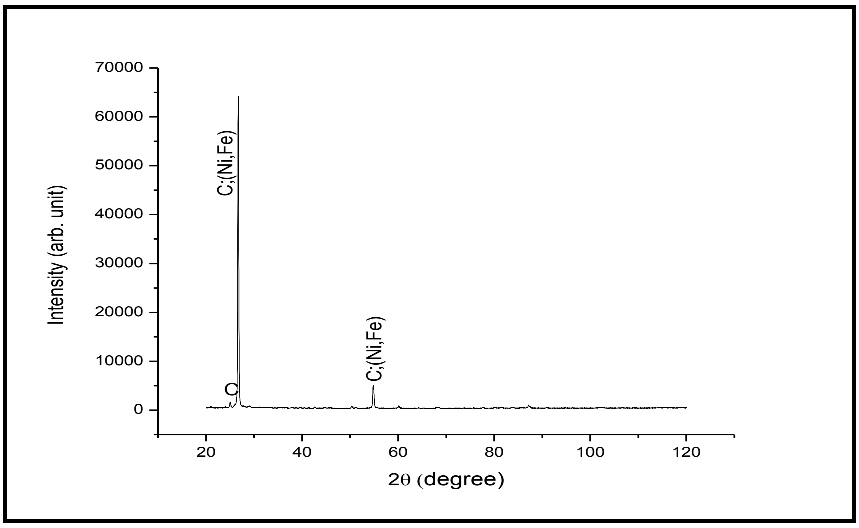

Figure 4.25: XRD pattern of market sample

Chapter 5

Conclusions and future work

5.1 General

Carbon brushes are having wide applications in generator and motors. The important properties required for carbon brushes includes (i) high electrical conductivity (ii) sufficient wear rate and low hardness compared to rotating shaft (iii) spark free commutation. The major constituent of carbon brush is graphite, which is an allotropic form of carbon which has low conductivity (5.2% IACS) compared to other metals such as silver (105% IACS), copper (100% IACS) and CNT (142% IACS)

5.2 Conclusions

In this work we have developed a composite material mixing graphite with metals such as copper, silver and CNT at various proportion for obtaining best combination of mechanical (wear and hardness) and electrical properties. Microstructure study on brush is done using XRD. The result shows that there is not clear tread in case of wear testing process. We are not able to correlate heat treatment temperature and % composition with the wear rate. The wear rate was found to be in the range of 1.5 to 8 X 10^{-6}g/m. However the conductivity of sample were found to be increasing on addition of copper, silver and reaches maximum on addition of CNT sample (120 X 10^{3} S/m) [4,5]. The XRD also shows that the major peaks for carbon and the additional element only and No other foreign element or oxides is found in the sample.

Finally we have also compared the conductivity and wear rate of sintered graphitic sample with the market sample. The main finding of our results is listed below.

The main findings from this work are:

- Composites C-0.75CNT (refer S23 sample) sintered at 900℃ shows high conductivity and less wear rate compared to other sample. XRD results show the intensity of graphite particle increases on addition on CNT in graphite. CNT can fill the interstitial voids which can results in increase in electrical conductivity and wear rate.
- On increasing the wt% of Cu and Ag, the conductivity of the composites increases. The conductivity of Ag composites found to be higher compared to conductivity of copper composites (refer S21 and S13).

- The comparison of electrical and wear properties from market sample and graphitic sample were done (refer S01 and S26 sample). The market sample shows very low conductivity compared to sintered graphitic sample. The XRD results of the market samples show the presence of foreign elements other than graphite. These impurities results in the drastic loss in electrical conductivity.

5.3 Future scope

The work done in present investigation has led to some conclusions which have been described in this chapter. However, the possibilities of further investigation of these developed composites based on above work can be explored. These are as below:

- Wear behavior of carbon brushes and its correlation with microstructure has to be understood in detail.
- Effect of heat treatment which results in percolated structure has to be studied and its effect on electrical conductivity and wear has to be understood.
- Effect of percentage impurities on electrical conductivity of the sample has to be understood.

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