Development of Co-Cu-Sn Based Diamond Segments for Marble Cutting by Powder Metallurgy

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Development of Co-Cu-Sn Based Diamond Segments for Marble Cutting by Powder Metallurgy

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Dedication:

This research is dedicated to my father, Shah Hassan, who has always been my source of guidance and support.

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I am thankful to Allah for blessing me with the mental and physical abilities to complete this work.

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Abstract:

In this project, diamond tips were developed for the purpose of cutting marble stone. For achieving the best cutting parameters, it is necessary to optimize different factors during the development of diamond tips like composition, sintering temperature, sintering environment and sintering time etc. Therefore, different compositions, sintering temperatures and sintering environments were tested in this project and the conditions for manufacturing the best diamond tip were determined.

Firstly, different samples with copper, cobalt and diamond as the constituent materials were prepared. Copper varied from 30 vol % to 50 vol %. Cobalt varied from 30 vol % to 50 vol %. Diamond remained constant at 20 vol %. Then, samples with bronze in place of copper were prepared with the same compositions. Three sets of six samples each were prepared.

All powder samples were mixed in ball milling machine and then pressed inside a steel die. One set of samples was then sintered at 700 °C in air, the other set of samples was sintered at 900 °C in argon and the third set of samples was sintered at 1000 °C in argon.

Scanning Electron Microscopy (SEM), EDX, density measurements, hardness and wear testing of all samples were performed. It was noted that density of the samples increases with increasing copper percentage and sintering temperature while it decreases with increasing bronze percentage. Similarly, hardness and wear resistance decreases with increasing copper and bronze percentages and it increases with increasing cobalt percentage and sintering temperature.

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Chapter-1

Introduction

1.1 Background:

Before the invention of synthetic diamond in 1950s, the prices of natural diamond were very high and it was not feasible to use natural diamonds in cutting tools. After the invention of synthetic diamond in 1950s, the abrasives industry changed. Synthetic diamonds replaced conventional abrasives used in the cutting tools. With the advancement in processing and production technology, synthetic diamonds became more and more cheaper and commercialized. The production of diamond increased in the whole world as its demand increased in the market. This high production volume further dropped the prices of synthetic diamonds. Currently, the use of diamond tools is increasing at a high rate and it does not seem that the trend will change any time soon.

Powder metallurgy technology has played major role in the revolution of abrasives industry. Almost all diamond tools are manufactured by this technology. All diamond tools have a supporting part which bears load of the cutting process and a cutting part which are called diamond segments. Diamond segments perform cutting action and cut the material that comes in contact with them. Diamond segments are manufactured by combining synthetic diamonds with metallic powders through powder metallurgy technology. The diamond segments are then joined to the supporting core of the cutting tool by laser welding or brazing.

1.2 Powder Metallurgy Technology:

Powder metallurgy is the name of methods by which products are manufactured from metallic powders. It also includes different methods of additive manufacturing in which metallic powders are used.

It has many advantages over conventional manufacturing processes. The biggest advantage is that the parts produced by powder metallurgy technology do not need machining which greatly reduces the cost. Another advantage is that some parts, due to their specific design, can not be produced by other manufacturing processes and can only be produced by powder metallurgy.

1.2.1 Powder Production:

There are many methods for the production of metallic powders. Mechanical methods, chemical reactions and electrolytic deposition processes can be used for producing powders depending on the powder material and the required powder characteristics.

Sponge iron process is one of the most common methods for producing iron powder. In this process, the oxide ore of iron is reduced and the resulting product is crushed into powder.

Atomization process is used to convert molten metal into powder form. There are three types of atomization. In gas atomization process, a stream of gas is injected at high pressure along with molten metal in a small orifice. The gas spreads the molten metal into particles which cool down before reaching the bottom of the container.

In water atomization process, a stream of water at high pressure is injected over a stream of liquid metal which comes down through a small hole. The water jet converts the liquid metal into droplets and cool them down before they reach the bottom of the container. The droplets then settle down in the container as metallic powder.

In centrifugal atomization, molten metal drops on top of a rotating disc. The high speed rotating disc throws off the liquid metal into tiny droplets at the walls of the container. The drops cool down before reaching the bottom of the container and convert into metallic powder.

In electrolytic deposition process, the metal which is to be converted into powder form is deposited on the opposite electrode. The deposited powder is then collected as metallic powder.

1.2.2 Powder Mixing:

The metallic powders and the reinforcing material powders are mixed in a mixing machine to homogenize the powder composition. Mixing devices used are rotating drum, rotating double cone, screw mixer and blade mixer. Sometimes ball milling machine is also used for mixing which also reduces size of the powders. The mixing time is usually up to one hour.

1.2.3 Powder Pressing:

The powders are filled in a die and compacted under high pressures. This step gives the required shape to the powders and also increases their density. The pressures used depend upon the product shape and the die material but usually range from 100 MPa to 700 MPa. The higher the pressure, the higher the densification and vice versa. The pressure applied is usually uniaxial and vertical. Pressure can be applied from one sided called single action. Pressure can also be applied from both sides called double action.

Isostatic pressing is also used to make products with complex shape. In this type of pressing the product is put inside a flexible mould like a rubber bag and the mould is immersed in a fluid. Pressure is applied by the fluid instead of the die. Pressure is applied on the powder sample uniformly from all sides. Due to uniform pressure, the properties of the product are homogenous throughout the product.

Similarly, pressing can either be cold pressing or hot pressing. In cold pressing, the powders are pressed at room temperature. In hot pressing, the powders are pressed at high temperatures due to which both compaction and sintering are carried out simultaneously. The properties of the hot pressing process are better than the cold pressing process and is used for high strength and high temperature operated parts.

1.2.4 Powder Sintering:

To increase the density of the parts, sintering is performed. In this process, the green product is heated to high temperature close to its melting point. At high temperature, the particles deform plastically and/or diffuse and close the voids between the particles due to which the density of the product increases. The main driving force for sintering is the surface energy. The particles lower their surface energy by reducing their surface area through the movement of material to the contact points of the particles and thus filling the voids.

The major steps in sintering process are neck formation, pore size reduction and grain growth. In neck formation, the particles come in contact with each other. The material diffuses to the contact areas and thus the size of contact area increases due to which a neck is formed between the particles. In pore size reduction, as the material continues to flow to the contact points and the size of the neck increase with time. The neck slowly fills the voids between the particles thus reducing the size of the pores. In the final stage, when all the voids are filled, the material reduces its surface energy by increasing the size of its grains.

There are two main types of sintering: solid state sintering and liquid phase sintering. In solid state sintering, the sintering temperature of the material is below its melting point. In liquid phase sintering, the sintering temperature is above the melting point of one of the components of the product. This component melts and forms a liquid phase. This liquid phase fills the voids between the particles at a faster rate than the diffusion in solid state sintering. The liquid phase sintering occurs in these three stages: particles rearrangement, solution reprecipitation and final densification.

Sintering processes are also divided into pressure sintering and pressureless sintering. In pressure sintering, pressure is applied on the compact during sintering at high temperature. This process is also called hot pressing. This process is used for parts which need good mechanical properties most importantly high strength. In pressureless sintering, no pressure is applied during the sintering process. Pressing and compaction is performed before the sintering process. This process is used for parts which do not require very high strength.

Other types of sintering are spark plasma sintering (SPS), electro sinter forging and microwave sintering.

1.3 Diamond Tools:

Diamond tools are used for cutting, grinding, drilling and polishing hard materials. Diamond is the hardest naturally occurring material. It has been given a hardness measurement of 10 on Mohs scale of hardness. It is also one of the strongest material. Since the invention of synthetic diamond in 1950s, it is frequently used as an ingredient in cutting tools. It has revolutionized the abrasives industry and has enabled us to do the job faster, more accurately and at less cost. Powder metallurgy has played an important role in the evolution of abrasives industry. [1]

1.4 Advantages of Diamond Tools:

It has many advantages over other abrasive materials [2]. It is the hardest natural material. It also has high strength, good wear resistance and low coefficient of friction. Diamond is a good conductor of heat. Therefore less heat is generated in the process.

1.5 Diamond Blade:

A diamond blade is a saw blade which has diamond tips fixed on its edge for cutting hard or abrasive materials. They are used for cutting stone, bricks, concrete, asphalt, glass, ceramics, semiconductor materials and gemstones. The core of a diamond blade is made of steel. Diamond tips are joined to the outer edge of this core.

Figure 1.1: A typical diamond blade [18]

1.6 Manufacturing Methods of Diamond Blades:

1.6.1 Electroplating:

Diamond particles are spread on surface of blade tip. A metal (nickel) is electroplated on top of diamond particles. This method is used to produce extremely thin blades for precise cutting. The production of blades by this process is slow and the cost is high. [3]

1.6.2 Vacuum Brazing:

Diamond particles are brazed to the outside edge of blade in a vacuum brazing furnace. Diamonds are present on the exterior edge of the blade only. There is no diamond metal mixture. [4]

1.6.3 Sintering:

These are the most common type of blades. They consist of diamond segments which are made by combining synthetic diamond crystals with metal powder by the process of sintering and then joining them to the blade.

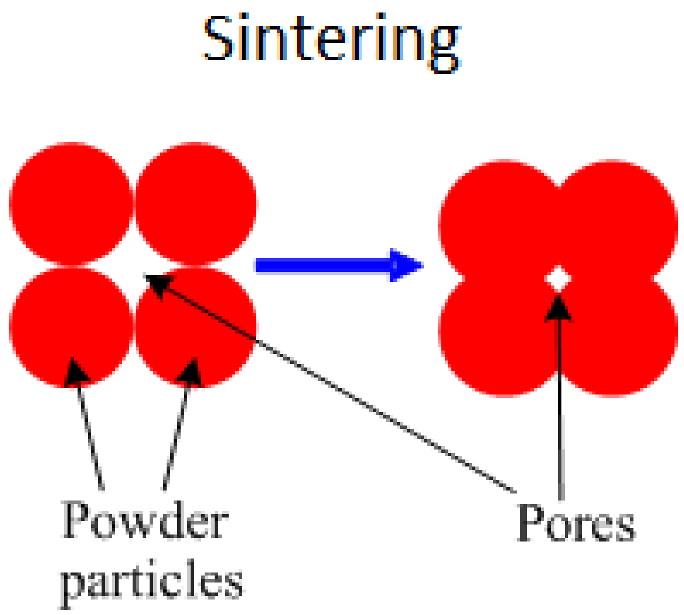

Figure 1.2: Sintering Process

They have further three types:

(1) Wholly Sintered; (2) Silver Brazed; (3) Laser Welded

1.6.3.1 Wholly Sintered:

Mixture of diamond and bond metal powder is placed on surface of outer edge of steel core and pressed and sintered simultaneously.

The steel core and mixture of diamonds and metal powder are put in a mold and sintered. Since the core is also put into mold, the diameter of these blades is small. These blades can be used for dry cutting but water coolant is used for safety. The cutting speeds are low. The process is very cheap as compared to other processes. The production rates are high.

1.6.3.2 Silver Brazed:

Diamond segments are made separately and are brazed to the steel core using a silver solder. The strength of the steel core is high as core and tips are treated separately. These blades can used for high and intensive loads but they are used for wet cuttings only as silver braze can melt. [5]

1.6.3.3 Laser Welded:

A laser melts and joins the metal of the diamond segment and steel core creating a strong weld. As the bond is stronger these blades can be used for fast cutting speed and at high temperatures. They can also be used for dry cutting. They have a longer life span. They can be used with higher horse power equipment. The diamond blades are of high quality and therefore the process is more expensive than other processes. These blades are used only for specific materials where the cutting conditions are rough. [6]

1.7 Diamond Tips:

Diamond tips are small segments made of composite of diamond and metal and joined to the steel core of the cutting blade. They consist of small synthetic diamonds and bond metal.

Figure 1.3: Different types of diamond segments

1.8 Diamond Crystals:

The diamonds' function is to cut. The diamonds used are synthetic and characteristics like shape, size, strength and hardness can be controlled depending on the requirement. Increasing the number of diamond crystals in the segment increases its cutting ability but requires high horsepower. For cutting hard materials, diamond crystals of small size are preferred and for cutting soft materials, diamond crystals of coarse size are preferred. [7]

1.9 Bond Metal:

It is a mixture of metal powders. The composition of the metal bond depends on the required wear rate and cutting speed. A good bond metal will hold the diamond for maximum time until the diamond tip is blunt and then release it and expose a new sharp diamond. [8]

The bond metal has two functions:

1) To hold the diamonds;

2) To wear along with diamonds to expose new diamonds

They have two types

1.9.1 Hard bonded:

They are used for cutting soft materials. The bond is made of a hard metal e.g cobalt. When cutting soft material, the diamonds can stay sharp for longer time, so the hard bond does not wear quickly and can hold the diamonds for longer period.

1.9.2 Soft bonded:

They are used for cutting hard materials. The bond is made of a soft metal e.g bronze. They often have a yellow color because of bronze. When cutting hard material, the diamonds become blunt, so the soft bond wears at faster rate and exposes new sharp diamonds.

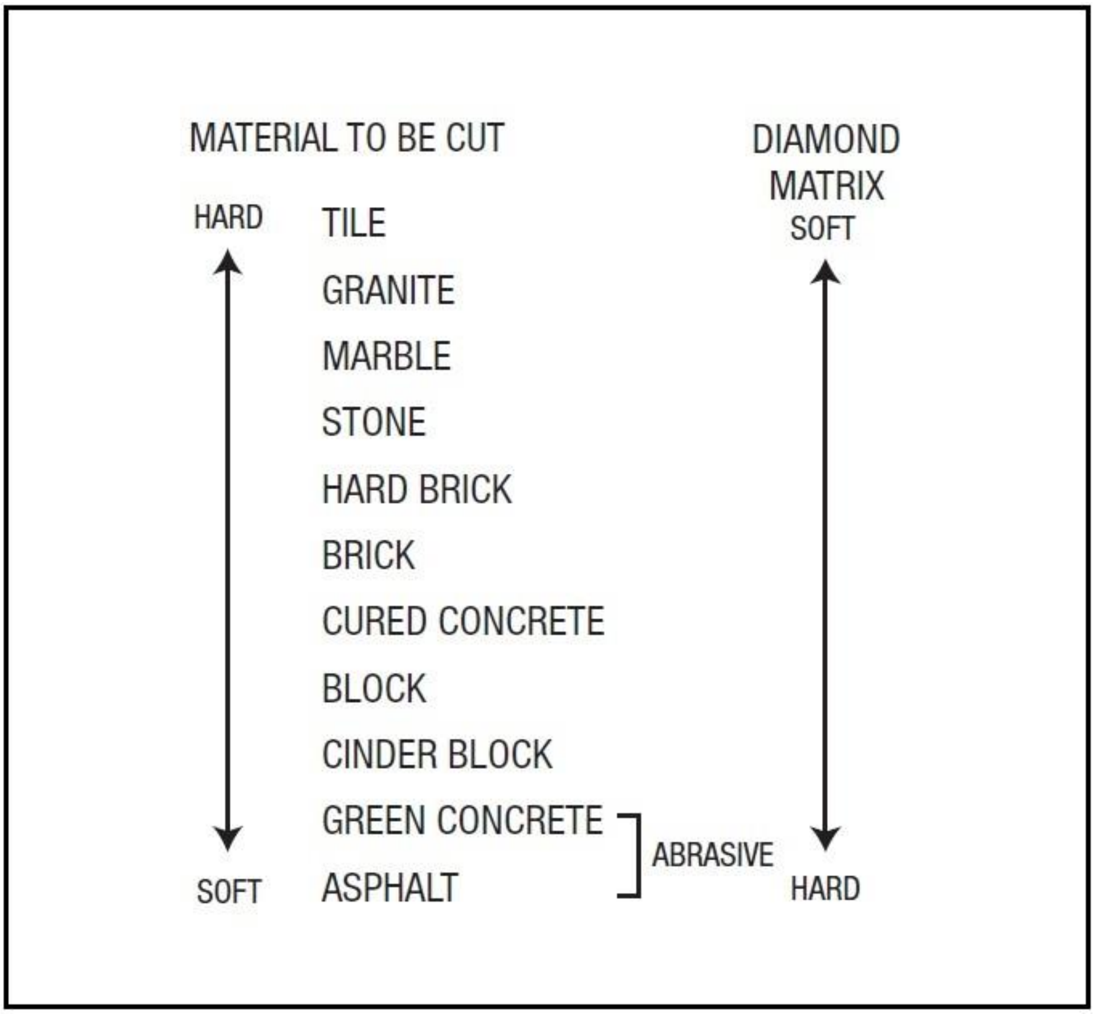

Figure 1.4: Matrix Vs Cut Material Relationship [19]

1.10 Manufacturing Diamond Tips:

There are two methods in practice for manufacturing diamond segments;

1.10.1 Hot pressed:

Mixture of diamonds and metal powders is put into a mold and pressed at a high temperature. Both pressing and sintering are performed simultaneously. The particles are rearranged and plastically deformed at contact points. As the plastic deformation of the particles is high because of the high temperature, the density achieved by this process is high and the service life is longer. [9]

1.10.2 Cold pressed:

The mixture of powders is first pressed and then sintered separately. Consequently, the density is low and porosity is high. [10]

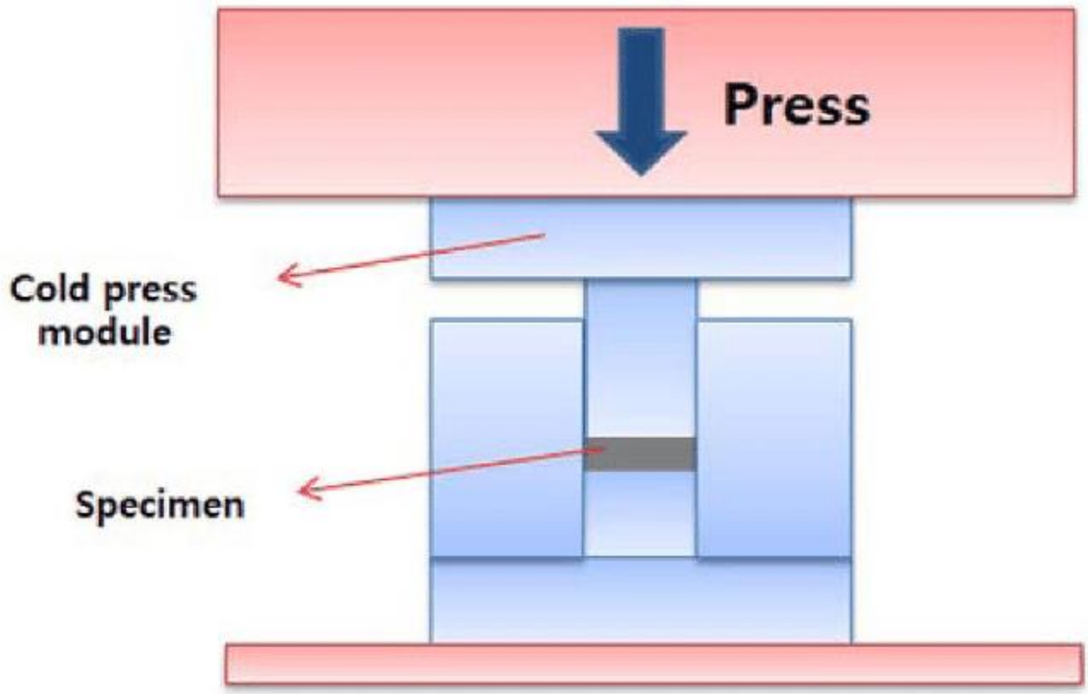

Figure 1.5: Cold Pressing Process

1.11 Oxidation and Graphitization of Diamond:

In air, diamond starts oxidizing when heated above 700 °C. [12] In the absence of oxygen, e.g in vacuum or argon gas, it can be heated up to 1700 °C without oxidizing. [13]

Similarly, diamond starts converting into graphite at temperatures above 800 °C. [14]

Chapter-2

Literature Review

Rahmi Unal and E. Alper Gurcay in their study titled "Matrix Composition Effect on the Wear Behavior of Diamond Segments" [10] have used cobalt, bronze, tungsten carbide and synthetic diamond as the composing materials. The diamond grit used was of 60/70 mesh (SDA-70). Average particle sizes of cobalt powder and bronze powder were 1.8 µm and 100 µm respectively. Proportions of diamond and tungsten carbide were kept constant at 20 vol% and 2wt% respectively. Proportions of cobalt and bronze were varied from 19 to 79 wt%. They mixed the powders by using V-type powder mixing machine with paraffin.

They found out that with increasing percentage of cobalt, the hardness of the samples increased and the wear rate decreased. They concluded that for the optimum wear rate, the percentage of cobalt should not be more than 60wt%.

S. Islak and H. Celik in their study titled "Effect of Sintering Temperature and Boron Carbide Content on the Wear Behavior of Hot Pressed Diamond Cutting Segments" [9] have used bronze, boron carbide and synthetic diamond as the composing materials. The diamond grit used was of 40/50 US mesh. Average particles sizes of bronze powder and boron carbide powder were 45 µm and 20 µm respectively. Proportion of diamond was 30 vol% in all samples. The proportion of boron carbide was 2, 5 and 10 wt%. The powders were then mixed by adding paraffin wax.

The powder mixtures were then hot pressed in graphite moulds for 3 minutes at 600, 650 and 700 °C under a pressure of 35 MPa.

With increasing boron carbide content, the hardness increased and transverse rupture strength also increased. The wear rate was high in 2 and 10 wt% boron carbide samples and minimum in 5 wt% boron carbide sample.

They found out that with increasing sintering temperature, the density, hardness, transverse rupture strength and wear resistance of the samples increased.

LI Wensheng et al in their study titled "Characterizations and mechanical properties of impregnated diamond segment using Cu-Fe-Co metal matrix" [7] have used copper, iron, nickel, cobalt-chromium alloy, tin and synthetic diamond as the composing materials. Size of the diamonds is varied from 270 to 380 µm. Average particle sizes of copper, iron and nickel vary from 75 to 100 µm. Size of the cobalt varies from 80 to 125 µm. Proportions of copper, iron, nickel, cobalt-chromium alloy and tin are 50, 36, 8, 7 and 2 wt% respectively.

They have mixed the powders in a three dimensional vortex mixer for 1 hour at a speed of 24 rpm. They have added 0.7 wt% ethanol as a forming agent which avoids the segregation of diamond crystals and metal powders because of differences of size and density.

They have hot pressed the powder samples in graphite moulds at 740, 780 and 820 °C for 3 min under a pressure of 13 MPa. The heating rate is 100-150 °C/min and the cooling rate is 180 °C/min.

With increasing sintering temperature, the density, hardness and tensile strength of the samples increased.

The properties of the samples were good enough to cut marble. Therefore it is proved that decreasing the content of cobalt and using iron instead will reduce the costs.

I Ucun et al in their study titled "An Investigation on the effect of diamond concentration and matrix material composition in the circular sawing process of granites" [20] have used cobalt, bronze, tungsten, iron and nickel as the composing mateirals. The diamond crystals were of sizes 40-50 US mesh. Proportion of tungsten-cobalt powder is varied from 45 to 95 wt%. Proportion of bronze-iron powder is varied from 5 to 50 wt%.

Hardness and wear resistance of the segments increased as the percentage of tungsten-cobalt powder increased.

R. Kh. Atabiev et al in their study titled "Composition Dependence of Mechanical Properties of Diamond Segments" [21] have used tungsten carbide, cobalt, copper, nickel and synthetic diamond as the composing materials. The diamond grit used was of 30/40 mesh (425-600 µm). The diamond concentration in the samples was 9 vol %.

They have cold pressed the powder samples under a pressure of 80 MPa. The cold pressed samples were then sintered at 1100-1150 °C for 15 minutes in hydrogen atmosphere.

They found out that the hardness of the matrix increases with the addition of diamonds. Similarly, the hardness and wear resistance of the samples increases with the addition of Nickel.

I. S. Buyuksagis in his study titled "The effects of circular saw blade diamond segment characteristics on marble processing performance" [11] has used iron, cobalt, copper, tin and synthetic diamond as the composing materials. The diamond crystals size varied from 200 to 600 µm. Proportions of all the constituents are varied in different ranges. It was found out that the sample with 15 % iron, 14 % cobalt, 68 % copper, 4 % tin and 15 % diamonds had the best cutting properties.

Y. Q. Yu and X. P. Xu in their study titled "Improvement on the Performance of Diamond Segments for Rock Sawing, Part 1: Effects of Segment Components" [23] have used cobalt, copper, tin, iron, tungsten carbide and synthetic diamonds as the composing materials. Diamond grit size was 40/50 US mesh. Diamond concentration varies from 28 to 42 %.

They have mixed the powders in an infinity shape rotary mixer for 40 minutes. Then they hot pressed the powders in graphite molds for 10 minutes at sintering temperatures from 740 to 830 °C.

They found out that high percentage of diamond crystals with microfractures requires low power for cutting and has good wear resistance.

Shenghui Guo et al in their study titled "Fabrication of Cu Based Metallic Binder for Diamond Tools by Microwave Pressureless Sintering" [25] have used copper, iron, cobalt, tin, nickel, titanium and synthetic diamond crystals as the composing materials.

They have mixed the powders in a three dimensional vortex mixer for 1 hour. They then cold pressed the powder mixtures at pressures 150 to 450 MPa in a singleaxis semi-automatic hydraulic press. They have sintered the green samples at 820, 860 and 920 °C for 15, 30 and 45 minutes each.

They found out that 375 MPa pressure is the most suitable pressure for better properties. They determined that 880 °C sintering temperature with 35 minutes holding time are most suitable for best properties. With increasing sintering temperature and time, the density, hardness and flexural strength of the samples increased.

He Dai et al in their study titled "Iron based partially pre-alloyed powders as matrix materials for diamond tools" [26] have used iron, copper, tin, nickel, zinc and synthetic diamond crystal as the composing materials. The proportion of diamond grit was 20 %.

They have cold pressed the powder samples at a pressure of 350 MPa. They have sintered the green samples at 850-930 °C for 60 minutes in ammonia-hydrogen atmosphere.

With increasing sintering temperature, the hardness of the samples increased but the bending strength decreased.

Janusz Stefan Konstanty et al in their study titled "Wear-resistant iron-based Mn–Cu–Sn matrix for sintered diamond tools" [27] have used iron, manganese, copper, tin and diamond crystals as the composing materials. The diamond grit was of 35/40 US mesh (420-500 µm) and 5 vol %.

They have mixed the powders in a chaotic motion turbula type mixer for 10 minutes and then ball milled the powders for 8, 30 and 120 hours. They have hot pressed the powder mixtures in graphite moulds for 3 minutes at 900 °C under a pressure of 35 MPa.

Dorota Tyrala et al in their study titled "The Effects of Powder Composition on Microstructure and Properties of Hot-Pressed Matrix Materials for Sintered Diamond Tools" [28] have used iron, nickel, bronze, graphite, aluminum oxide and aluminum carbide powders as the composing materials.

They have mixed the powders in a turbula type mixer for 10 minutes and then milled the powders for 120 hours. They have hot pressed the powder samples in graphite moulds for 3 minutes at 900 °C under a pressure of 25 MPa.

They found out that the addition of alumina and aluminum carbide increased the bending strength but slightly decreased the hardness of the samples.

L. J. de Oliveira et al in their study titled "Processing and characterization of impregnated diamond cutting tools using a ferrous metal matrix" [29] have used iron, copper, silicon carbide and diamond crystals as the composing materials. The size of diamond powder was 40/50 mesh (300-425 µm).

They have cold pressed the powder samples under a pressure of 350 MPa. They have sintered the green (cold-pressed) samples at 1050 and 1150 °C for 25 minutes.

With increasing sintering temperature, the hardness and wear resistance of the samples increased.

Ming Hou et al in their study titled "Fabrication of Fe–Cu matrix diamond composite by microwave hot pressing sintering" [33] have fabricated diamond segments using two different routes i-e conventional hot press sintering (CHPS) and microwave hot press sintering (MHPS).

They achieved high densification and hardness of the segments by using MHPS instead of CHPS.

Berrak Bulut et al in their study titled "Effect of aluminium and silver addition on the wear characteristics of circular diamond saw blades for cutting Ankara andesite rocks" [34] have fabricated diamond segments by adding aluminum and silver to the segment materials of cobalt, nickel, tin and tungsten.

They determined that the mechanical properties (hardness and wear resistance) of the segments increased with the addition of aluminum and silver due to the formation of intermetallic compounds of aluminum and cobalt.

Z. Nitkiewicz and M. Swierzy in their study titled "Tin influence on diamond–metal matrix hot pressed tools for stone cutting" [35] have evaluated the effect of adding tin to the matrix of diamond segment. They added tin to segments made of different combinations of nickel, copper, iron, cobalt and chromium.

They found out that density and hardness of the segments increased with the addition of tin.

Joanna Borowiecka-Jamrozek and Jan Lachowski in their study titled "Modelling of retention of a diamond particle in matrices based on Fe and Cu" [36] used simulation softwares to study different factors of the matrix that are responsible for holding diamond grains in place.

They determined that two parameters are responsible for holding diamond grains: the elastic energy of matrix and the radius of plastic zone around particle.

Xiuyu Chen et al in their study titled "Model Establishment of a Co-Based Metal Matrix with Additives of WC and Ni by Discrete Element Method" [37] simulated different compositions of matrixes for diamond segments. They added different elements to the matrix and studied their effects and compared the simulation data with literature.

Their results were in agreement with the literature data hence they demonstrated that discrete element method can be used to save costs for designing a matrix of the required mechanical properties for a diamond segment.

Y.S. Liao and S.Y. Luo in their study titled "Effects of matrix characteristics on diamond composites" [38] fabricated diamond segments composed of cobalt with other elements using the hot pressing route.

They found that the addition of tin to cobalt made the segments less ductile due to the formation of tin rich brittle phase. They also found that diamond segments with less porosity and high hardness had good wear resistance during the sawing process.

N.I. Polushin et al in their study titled "Influence of the matrix composition, structure, and properties on the service life of a diamond drilling tool" [39] studied four different matrices of diamond segments containing copper and tin along with other elements at 1000 and 1100 °C sintering temperatures.

They found out that the segments containing bronze instead of copper had high hardness and good abrasive ability.

Hedayat Mohammad Soltani and Morteza Tayebi in their study titled “Determination of wear parameters and mechanisms of diamond/copper tools in marble stones cutting” [40] have fabricated soft bonded diamond segments from cheaper metals to reduce the prices of diamond segments. The diamond segments were composed of 78 % brass, 16 % bronze and 6 % cobalt.

They found out that the hardness and wear resistance were very low and could not hold the diamond grains in place for a long time but the cutting speed of the segments was very high.

Xiaojun Zhao et al in their study titled “Effect of Fe-based pre-alloyed powder on the microstructure and holding strength of impregnated diamond bit matrix” [41] have fabricated diamond segments composed mainly of iron along with other powders.

They found out that density, bending strength and plasticity of the samples increased with increasing sintering temperature and pre-alloying degree. Matrixes composed of iron have a corrosive effect on diamond particles at high sintering temperature. Above 900, the rate of graphitization rapidly increases and the holding strength of the matrix decreases. A certain degree of pre-alloying increases the bending strength and reduces the amount of graphitization.

Rahmi Unal in his study titled “Effect of Cobalt to Bronze Ratio on Transverse Rupture Strength of Diamond Segments” [42] has fabricated diamond segments mainly composed of cobalt along with other powders by cold pressing, then sintering under pressure at 750 °C.

He determined that the hardness and wear resistance of the matrix increases with the increase in cobalt ratio. But when the wear resistance is so high that the matrix holds the diamond grains even after they become blunt, it will negatively impact the cutting ability of the segments. He determined that the cobalt ratio in these segments should not be greater than 60 wt %.

Liang Xu et al in their study titled "Segment Matrix Design and Drilling Test of Diamond Bit for Sapphire" [43] have analyzed different combinations of metallic powders and characteristics of diamond particles in order to manufacture diamond segments for the purpose of drilling sapphire stone. They prepared samples with different compositions of metallic powders and diamond particles of different sizes.

They found out that diamond particles of fine size exhibited good mechanical and cutting properties in the final drilling bits. They also found out that diamond concentration should be between 30 and 60 % for optimum mechanical properties. Moreover, the addition of tin to the matrix made the final segment more brittle and sharper. Similarly, the addition of nickel, silver and copper to the matrix made the enhanced the tensile strength and toughness of the segments. The addition of tungsten and cobalt to the matrix enhanced the wear resistance of the segments. The drill bits prepared with the above stated materials and processes exhibited improved efficiency, greater service life and low defect rate during drilling of the sapphire crystal.

W. Tillmann et al in their study titled "Tribological investigation of impregnated diamond tools" [44] have ANSYS software to simulate the performance of diamond tools of different compositions. They designed diamond segments with 10 vol % diamonds of size approximately 250 µm. They also used alumina of the same size in the samples. The matrix materials were either bronze or cobalt. They performed simulations at temperatures ranging from 293 K to 793 K.

They concluded that alumina can be added to diamond cutting tools for machining without any coolant. They also found out that at the start of cutting process, the temperature distribution is the same throughout the segment i-e diamonds and matrix material. After about 200 ms, the temperature distribution changes. The temperature is now lower deep inside the segment and higher on the outside surface.

Bing Cui et al in their study titled "Microstructure and mechanical properties of vacuum brazed diamond abrasive segments with zirconium carbide reinforced Cu-based active filler metals" [45] studied the brazing bond between diamond segment and solder. They used filler alloy made of Cu-Sn-Ti and added ZrC to this filler alloy in different proportions and tested the resulting bonds between diamonds and steel base.

They found out that the addition of ZrC to the filler alloy made the bonding of diamonds and steel base stronger. The bond is the strongest at adding 15 wt % ZrC. The addition of ZrC above 15 wt % made the welding joints weaker. Furthermore, at high brazing temperature of 950 °C, the elements in the filler material react with each other and form different compounds. The most important compound among them is TiC which results from the reaction of Titanium of filler alloy with the carbon on the surface of diamonds. Due to the formation of TiC, a strong bond is formed between the diamonds and filler alloy.

Moreover, they concluded that 980 °C brazing temperature with 15 minutes holding time results in the best possible joint between diamond segments and steel base. The wear rate is the lowest, the service life is longer and large quantity of marble is cut in smaller time.

Shuai Li et al in their study titled "Formation characteristics of nickel-based diamond abrasive segment by selective laser melting" [46] prepared abrasive diamond segments mainly composed of nickel as matrix material through the process of selective laser melting (SLS).

They found out that the surface is rough due to balling of the bond components. The porosity also increases with increased balling and bridging. The hardness of the matrix material increases with precipitates formation, eutectic formation and fine dendritic structures formation. Through selective laser melting, a good bond was formed between matrix material and diamond grains.

Bing Cui et al in their study titled "The abrasion resistance of brazed diamond using Cu–Sn–Ti composite alloys reinforced with boron carbide" [47] studied the brazing bond between diamond segment and solder. They used filler alloy made of Cu-Sn-Ti and added B_4C to this filler alloy in different proportions and tested the resulting bonds between diamonds and steel base.

They found out that the addition of B_4C to the filler alloy made the bonding of diamonds and steel base stronger. The bond is the strongest at adding 2 wt % B_4C. The addition of B_4C above 2 wt % made the welding joints weaker. Furthermore, at high brazing temperature of 950 °C, the elements in the filler material react with each other and form different compounds. The most important compound among them is TiC which results from the reaction of Titanium of filler alloy with the carbon on the surface of diamonds. Due to the formation of TiC, a strong bond is formed between the diamonds and filler alloy. The amount of TiC increases as the proportion of B_4C increases.

Moreover, they concluded that 2 wt % B_4C is the optimum proportion to add in filler alloy. It results in the best possible joint between diamond segments and steel base. The hardness value of the filler layer is the highest, wear rate is the lowest and the service life is longer.

Depeng Sun et al in their study titled "Wear behavior and morphologic characterization of diamond segments induced by crystal plane characteristics of diamond grits in sawing hard materials" [48] have studied the wear phenomenon of diamond grains during the sawing process of granite stones taking into account the crystal plane factors. They performed sawing of the granite stones and analyzed the wear of diamond grains in scanning electron microscope (SEM). They divided the wear of diamond grains into seven different categories. The wear at the surface of diamond grains displaced from the matrix occurred on {100} planes. While wear at the ends of diamond segment mostly occurred at {111} planes.

They concluded that there are two main types of wear during sawing of granite stone: abrasive wear and surface fatigue wear. Furthermore, river pattern, cleavage, fracture steps and cracks are the most common morphological features on the diamond segments. The wear characteristics of {100} planes are different than {111} planes during the sawing of granite stones. The cracks on the {111] planes are greater in number than those on {100} planes. The flush type of fracture happened mostly at the two ends of the diamond grains. The type of cutting, cutting speed, impact force, strain mechanism and crystal plane features are the major factors affecting the wear behavior.

S. Spriano et al in their study titled "Low content and free cobalt matrixes for diamond tools" [49] used titanium, nickel and cobalt in different combinations as matrix material for making diamond tools. They also checked the effect of aluminum addition to these matrixes. They cold pressed the samples under a pressure of 35

MPa. They used pressure-less sintering at temperature of 930 °C for making green compacts. The sintering time was about 1 hour.

They found out that the relative density and hardness increased with increasing sintering time. Furthermore, due to formation of TiC between titanium of matrix and carbon of diamond, the diamond retention ability of the matrix is stronger. The titanium nickel alloy with 13 % nickel and 87 % titanium showed the least erosion rate. The addition of aluminum to this alloy further decreased the erosion rate of the diamond segments. It is concluded that titanium is a better candidate for diamond segments as matrix material compared to other materials due to its good diamond retention ability and other mechanical properties.

Berrak Bulut et al in their study titled "Determination of matrix composition for diamond cutting tools according to the hardness and abrasivity properties of rocks to be cut" [50] studied different compositions of diamond matrix to cut different types of rocks depending upon the hardness, abrasiveness and cutting properties of the different rocks. The most important parameter in this respect is that wear rate of the diamond grains and the matrix material should be as close as possible. It is so because if their wear rates are different then one of them will wear out before completing its service life, which will be waste of material and will increase costs.

For this purpose they investigated two types of matrices, one cobalt based and the other iron based. Scanning electron microscopy and other mechanical tests were performed to compare the different matrices.

The results showed that the mechanical properties of cobalt based matrices were better than iron based matrices. Furthermore, the iron based matrices showed good performance during the cutting of marble while the cobalt based matrices showed good performance during the cutting of granite.

The sample with 30 % iron, 10 % nickel and 50 % copper exhibited the lowest wear resistance while the sample with 80 % cobalt, 10 % nickel and 10 % copper exhibited the highest wear resistance. The wear resistance increased as the iron and cobalt percentages in the segments increased. Similarly, the hardness of the samples with cobalt was greater than the samples with iron as matrix material. The hardness of the samples decreased as the copper percentage increased.

Serkan Islak et al in their study titled “The effects of the CNF ratio on the microstructure, corrosion, and mechanical properties of CNF-reinforced diamond cutting tool” [51] added carbon nano fibres (CNF) in different proportions to the different matrix materials and studied their effects. They first added CNF to bronze based matrix from 0 % to 1 % in steps of 0.25. Different mechanical and corrosion tests were performed on the samples to study the effects of these additions. They hot pressed all the samples at 680 °C under a pressure of 35 MPa for 4 minutes.

The results showed that the transverse rupture strength was maximum at 0.25 % CNF. Above this value, the TRS decreased. The corrosion resistance decreased as CNF percentage increased. Similarly, the mechanical properties like hardness, wear resistance etc improved as the CNF percentage increased. The hardness value increased from 175 HV to 210 HV as the percentage of CNF increased from 0 % to 1 %. The density of the samples decreased as the CNF percentage increased. The wear rate decreased as the percentage of CNF increased.

I. S. Buyuksagis and R. M. Goktan in their study titled “Investigation of marble machining performance using an instrumented block-cutter” [57] performed different on field tests to find out the optimum conditions for sawing of different types of marble rocks. They used seven different types of marble rocks and cut them with circular diamond blades. The two main sawing conditions which were studied were the cutting depth and the travel speed of the workpiece i-e the marble rock. These two were varied in order to optimize them.

They found out that the cutting efficiency increases as the cutting depth increases and it also increases with increasing workpiece travelling speed. But there is a limit to both these two beyond which there is no increase in cutting efficiency. They also concluded that it is possible to predict the optimum sawing conditions for untested rocks from the statistics of the previously studied rocks as there are strong correlations between them.

Shuo Wang et al in their study titled “Comparison of wear characteristics of diamond segments under different sawing modes in sawing hard stone” [58] prepared two different types of diamond segments based on their matrix composition and tested them under two different sawing modes. Scanning electron microscopy was performed and the wear tests were conducted for the diamond segments. After that the two sawing modes were tested to find out the best among them according to costs, saw length and sawing time.

They concluded that the rocking reciprocating sawing mode is better than the horizontal reciprocating sawing mode as it requires small saw length and saves time, thereby increasing the cutting efficiency. Furthermore, in the segments composed of the cobalt based matrix, the bonding strength of the matrix and diamond grains is higher as compared to iron based matrix. They also found out that the main reason for wear out of diamond grains is the heavy loads caused by the rocks. This wear mechanism can slowed down in significantly by using the rocking reciprocating sawing mode.

Janusz Stefan Konstanty and Dorota Tyrala in their study titled "Wear mechanism of iron-base diamond-impregnated tool composites" [59] studied the effects of martensitic transformation that is induced by the abrasive loads inside the matrix of the diamond tools. They prepared two main types of diamond segments, one iron based and the other cobalt based. They designed a new wear test to measure the wear rate of diamond segments.

They concluded that the austenite phase present in these alloys transforms into martensite under heavy abrasion loads. This martensitic transformation occurs more commonly and in greater amount in iron based matrixes due to which they are more resistant to wear.

Qin Sun et al in their study titled "Segment wear characteristics of diamond frame saw when cutting different granite types" [60] analyzed different types of rocks of granites by cutting them with diamond segments by studying their wear properties. They cut ten different types of granite rocks.

They concluded that there are two main types of the diamond grains wear, whole fractured grains and micro fractured grains of diamonds. The two main wear mechanisms of the diamond grains and the matrix material were impact abrasion and flushing abrasive erosion. The major parameters of the stones of granite responsible for the wear of the diamond segments were compression strength, bend strength and amount of quartz. They also concluded that the wear rates of the rocks can be predicted from the statistical models due to great correlation between the data.

Fatih Bayram and Seyfi Kulaksiz in their study titled “Evaluation of rock cutting performance of diamond segmented frame saw in terms of diamond segment wear” [61] analyzed the wear behavior of diamond segments by cutting different types of marble rocks with different mechanical and physical properties.

They concluded that the rock properties which played a major role in the wear of diamond segments were shore hardness, tensile strength, modulus of elasticity and impact strength. They designed a statistical model from which unit wear (UW) of the diamond segments can be predicted using the advance rate (AR) parameter in cutting. They determined that advance rate (AR) is the major parameter in the cutting process that affects the unit wear (UW). The advance rate (AR) is directly proportional to unit wear (UW). Similarly, the stone characteristics shore hardness (H_{shore}) and tensile strength (TS) are directly proportional to unit wear (UW) and elastic modulus (EM) and impact strength (IS) are inversely proportional to UW.

Chapter-3

Methodology

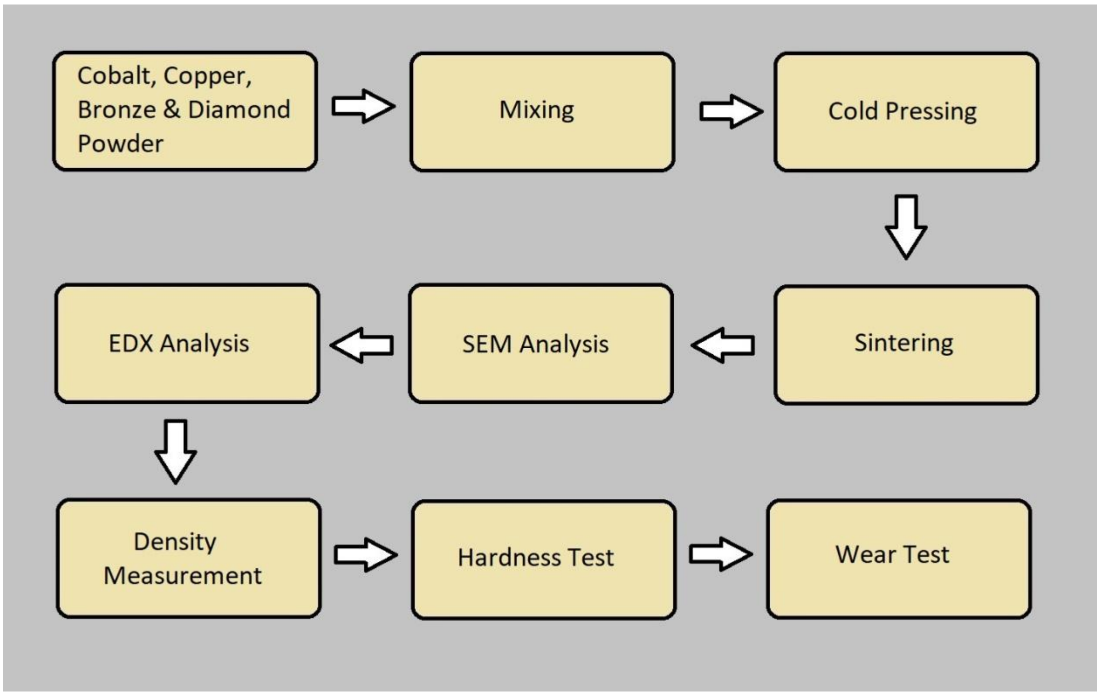

Figure 3.1: Project Methodology Chart

3.1 Powders:

Copper, Bronze, Cobalt and synthetic diamond were used as composing materials. The diamond crystals were of sizes 111-232 US mesh. Average particle sizes of copper, bronze and cobalt vary from 5 to 50 µm. Size of the cobalt varies from 80 to 125 µm. Copper powder was in fine spherical shape. Cobalt powder was in the form of irregular shaped agglomerates. Bronze powder was in the form of fine shiny powder. Diamond powder was in the form of small single particles with sharp edges.

Table 3.1: Powders characteristics

S. No	Size (µm)	Avg Size (µm)	Shape
Copper	5-30	15	Spherical
Bronze	5-45	20	Spherical
Cobalt	5-40	30	Irregular Agglomerates
Diamond	50-200	150	Sharp Edges

Scanning electron microscopy of powders was performed to confirm the shapes and sizes of all powders. The powders were then weighed in a weight balance and combined in different compositions in an HDPE bottle. Compositions of samples are given in table 3.2.

Table 3.2: Segment compositions in volume percent

S. No	Copper	Bronze	Cobalt	Diamond
S1,S7,S13	30%		50%	20%
S2,S8,S14	40%		40%	20%
S3,S9,S15	50%		30%	20%
S4,S10,S16		30%	50%	20%
S5,S11,S17		40%	40%	20%
S6,S12,S18		50%	30%	20%

3.2 Mixing:

The mixture of powders of each composition was put in an HDPE bottle half filled with steel balls of sizes 3 mm and 5 mm. The bottle was then put in a horizontal ball milling machine which mixed the powders for 1 hour at 200 rpm speed. 0.7 wt % ethanol was also added to avoid the segregation of diamond grits from the metallic powder. The powder was then heated at 100 °C for an hour to evaporate ethanol.

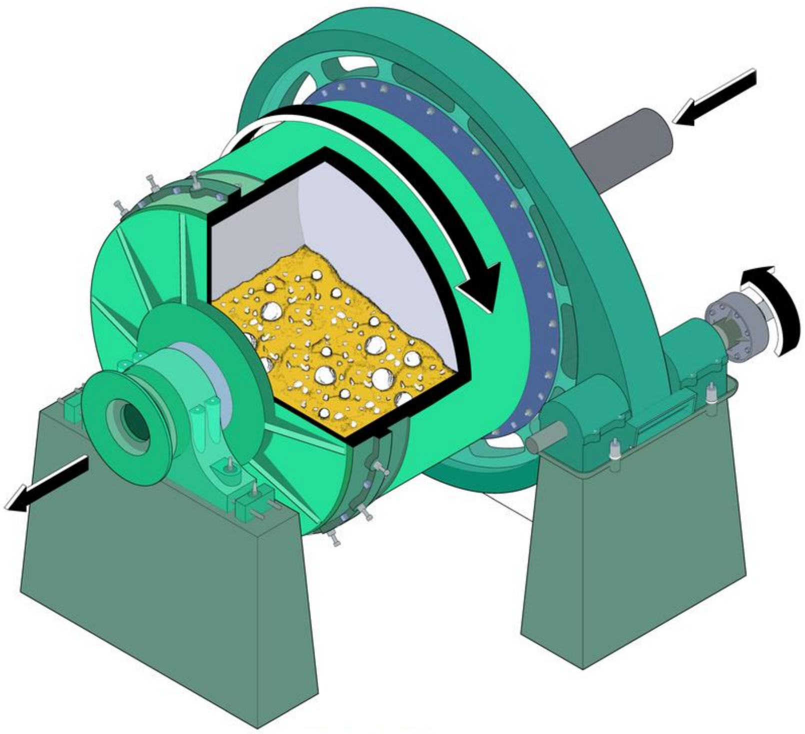

Figure 3.2: Powders Mixing Process

3.3 Cold Pressing:

A sample of 3 grams of powder was taken and pressed in a steel die of 11 mm diameter in a hydraulic press under a pressure of 4 metric ton (400 MPa) for 3 minutes. The process was repeated and 18 samples were prepared.

3.4 Sintering:

The green samples were then sintered according to the given sintering curves in figure 3.2, at different temperatures and in different environments as given in table 3.3. All the samples were furnace cooled.

Table 3.3: Sintering parameters

Samples	Temperature	Time	Environment
S1 to S6	1000 °C	2 h	Argon
S7 to S12	900 °C	2 h	Argon
S13 to S18	700 °C	2 h	Air

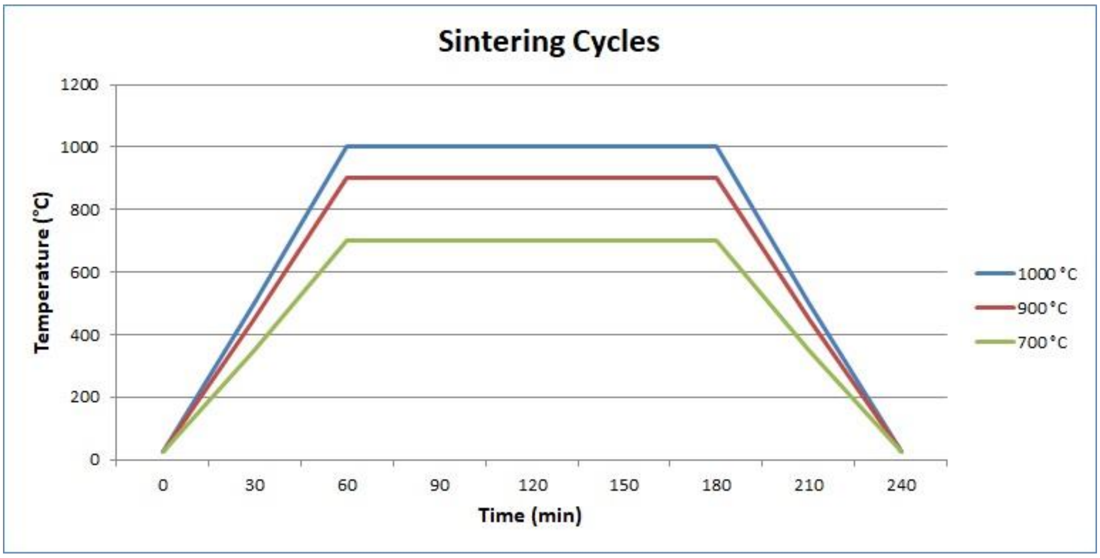

Figure 3.3: Sintering cycles for the three sets of samples

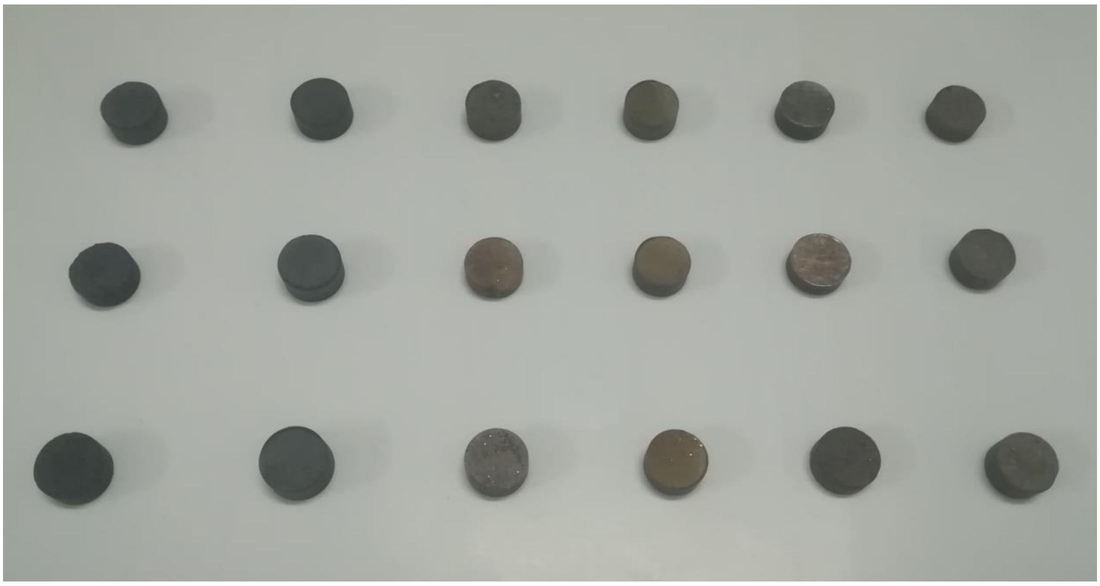

Figure 3.4: Six sets of samples after sintering

3.5 Scanning Electron Microscopy:

Samples were grinded on a grinding machine with 200, 400, and 800 grit size SiC paper. The samples could not be polished due to diamond particles. The samples were then etched with $FeCl3(17g)$+water(50ml)+HCl(50ml)+Nitric Acid(30ml)+Acetic Acid(30ml) solution for 15 seconds and then washed with distilled water. The samples were then placed in the SEM machine.

3.6 Energy Dispersive X-ray Spectroscopy:

Energy dispersive X-ray spectroscopy was performed simultaneously with scanning electron microscopy.

3.7 Density:

The samples were first dry weighted and then wet weighted on a digital weight balance and the densities were determined by Archimedes principle. List of dry and wet weights of the samples is given in table 3.5.

Theoretical Density = ρ_1 x vol fraction + ρ_2 x vol fraction + …………….

Actual Density = Dry Weight / (Dry Weight – Wet Weight)

Table 3.4: Theoretical density calculation

Sample	Copper/Bronze Density	Cu/Br Volume Fraction	Cobalt Density	Cobalt Vol Fraction	Diamond Density	Diamond Vol Fraction	Theoretical Density
S1	8.96	0.3	8.9	0.5	3.5	0.2	7.838
S2	8.96	0.4	8.9	0.4	3.5	0.2	7.844
S3	8.96	0.5	8.9	0.3	3.5	0.2	7.850
S4	8.77	0.3	8.9	0.5	3.5	0.2	7.781
S5	8.77	0.4	8.9	0.4	3.5	0.2	7.768
S6	8.77	0.5	8.9	0.3	3.5	0.2	7.755
S7	8.96	0.3	8.9	0.5	3.5	0.2	7.838
S8	8.96	0.4	8.9	0.4	3.5	0.2	7.844
S9	8.96	0.5	8.9	0.3	3.5	0.2	7.850
S10	8.77	0.3	8.9	0.5	3.5	0.2	7.781
S11	8.77	0.4	8.9	0.4	3.5	0.2	7.768
S12	8.77	0.5	8.9	0.3	3.5	0.2	7.755
S13	8.96	0.3	8.9	0.5	3.5	0.2	7.838
S14	8.96	0.4	8.9	0.4	3.5	0.2	7.844
S15	8.96	0.5	8.9	0.3	3.5	0.2	7.850
S16	8.77	0.3	8.9	0.5	3.5	0.2	7.781
S17	8.77	0.4	8.9	0.4	3.5	0.2	7.768
S18	8.77	0.5	8.9	0.3	3.5	0.2	7.755

Table 3.5: Actual density calculation

Sample	Dry Weight (g)	Wet Weight (g)	Actual Density (g/cm^3)	Theoretical Density (g/cm^3)	Densification (%)
S1	3.076	2.578	6.18	7.84	79
S2	3.001	2.529	6.36	7.84	81
S3	3.031	2.558	6.40	7.85	82
S4	2.964	2.522	6.70	7.78	86
S5	2.929	2.485	6.60	7.77	85
S6	3.027	2.553	6.39	7.76	82
S7	2.978	2.478	5.96	7.84	76
S8	2.872	2.413	6.26	7.84	80
S9	2.983	2.511	6.32	7.85	81
S10	2.989	2.531	6.52	7.78	84
S11	2.970	2.500	6.31	7.77	81
S12	3.043	2.529	5.92	7.76	76
S13	3.234	2.672	5.75	7.84	73
S14	3.140	2.630	6.16	7.84	79
S15	3.214	2.696	6.20	7.85	79
S16	3.236	2.683	5.85	7.78	75
S17	3.247	2.659	5.52	7.77	71
S18	3.446	2.799	5.33	7.76	67

3.8 Hardness:

The samples were grinded on 200, 400 and 800 grit size SiC paper. The samples were then tested for hardness in a micro hardness Vickers testing machine. The shape of the diamond indenter was pyramid. The load was 1 kgf and the dwell time was 10 seconds.

In order to measure the hardness of the matrix only and not of the diamond, the indent was carefully placed between the diamond particles. Each sample was tested three times on different areas and the average of the readings was taken as the final hardness of the sample.

3.9 Wear:

The samples could not be tested in a normal pin on disc machine as there was a risk of the breaking of the tip of diamond pin. Therefore the samples were tested for wear resistance using a self-designed pin on disc machine.

Each sample was abraded by the revolving pin for 5 minutes. The own load of the pin and the pin holder was used to abrade the samples which was about 2 kg. To minimize the effect of blunting of the tip, a new pin was used for each sample.

Taking the diameter of the circular path and the revolutions/min, the abrading speed of the pin was 30 meters/minute. The material of the pin was high speed steel.

The wear rate was calculated from the weight loss of each sample. The calculations for the wear rate are given in table 3.6.

Table 3.6: Wear calculation

Sample	Weight Before	Weight After	Mass Lost (grams)	Volume Lost (mm3)	Wear Rate (mm3/min)	Wear Rate (mm3/N.m)
S1	2.72	1.92	0.8	123.08	24.62	0.041
S2	2.79	1.95	0.84	129.23	25.85	0.043
S3	2.74	1.84	0.9	138.46	27.69	0.046
S4	2.67	2.02	0.65	100	20	0.033
S5	2.82	2.13	0.69	106.15	21.23	0.035
S6	2.81	2.04	0.77	118.46	23.69	0.039
S7	2.78	1.92	0.86	132.31	26.46	0.044
S8	2.76	1.84	0.92	141.54	28.31	0.047
S9	2.82	1.86	0.96	147.69	29.54	0.049
S10	2.76	2.05	0.71	109.23	21.85	0.036
S11	2.73	1.95	0.78	120	24	0.040
S12	2.71	1.89	0.82	126.15	25.23	0.042
S13	3.06	2.16	0.9	138.46	27.69	0.046
S14	3.11	2.13	0.98	150.77	30.15	0.050
S15	2.97	1.93	1.04	160	32	0.053
S16	3.04	2.27	0.77	118.46	23.69	0.039
S17	3.13	2.33	0.8	123.08	24.62	0.041
S18	3.01	2.13	0.88	135.38	27.08	0.045

Chapter-4

Results & Discussion

4.1 Scanning Electron Microscopy:

Scanning electron microscope image of Cobalt powder in figure 4.1 shows that the particles are in the form of irregular shaped agglomerates. Their size ranges from 5 µm to 40 µm with average particle size of 30 µm. The surface of the particles is rough.

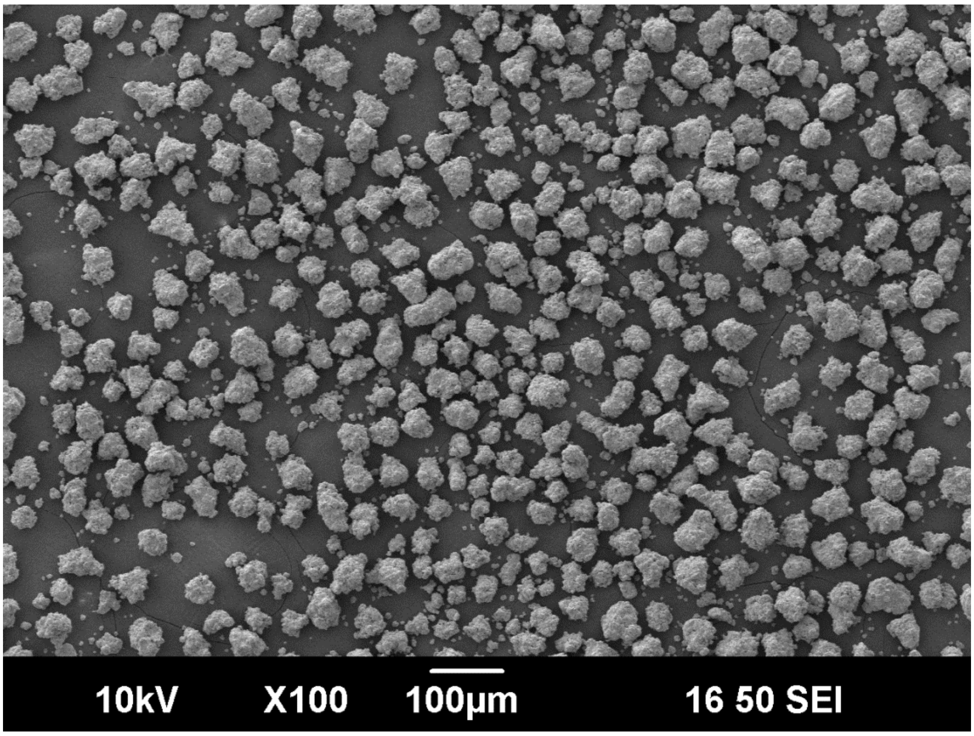

Figure 4.1: SEM Micrograph of Cobalt powder

Scanning electron microscope image of Copper powder in figure 4.2 shows that the particles are in the form of spherical shape. Their size ranges from 5 µm to 30 µm with average particle size of 15 µm. The surface of the particles is smooth.

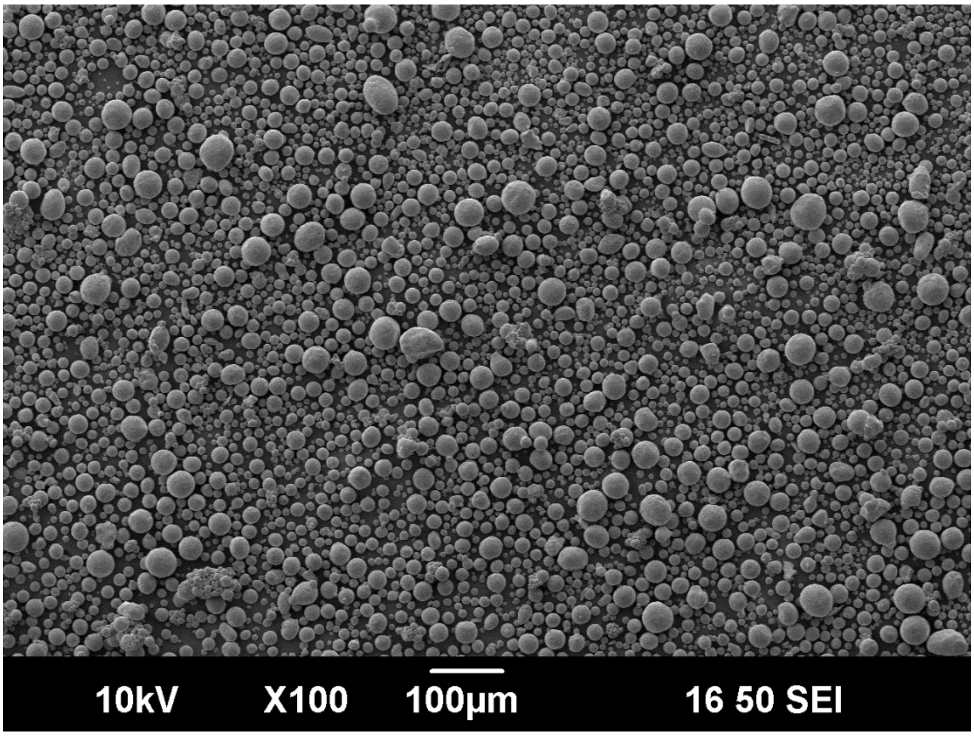

Figure 4.2: SEM Micrograph of Copper Powder

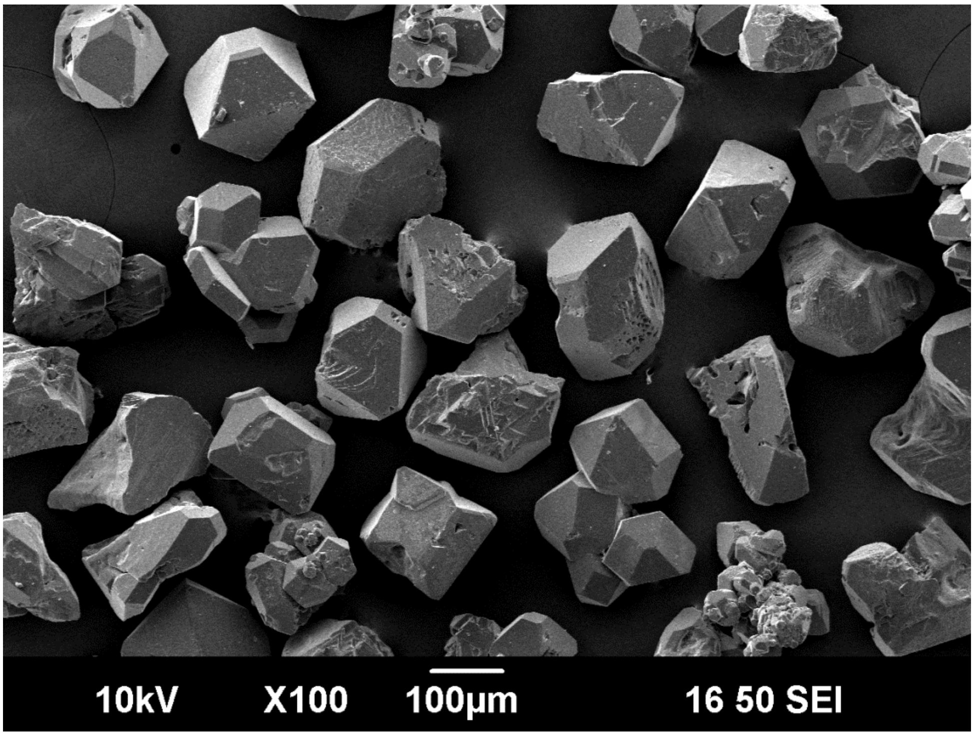

Figure 4.3: SEM Micrograph of Diamond Powder

Scanning electron microscope image of diamond powder in figure 4.3 shows that the particles are in the form of small single particles with sharp edges. Their size ranges from 50 µm to 200 µm with average particle size of 150 µm. The surface of the particles is smooth.

Scanning electron microscope image of composite sample with 30 % and 40 % bronze in figures 4.4 and 4.5 show that the diamond particles are uniformly distributed. The reason for variation in size of diamond particles is that small diamonds are embedded deep inside the surface which will be exposed further when the surface wears out after cutting. The pits on the surface are formed after the loss of diamond grains due to grinding.

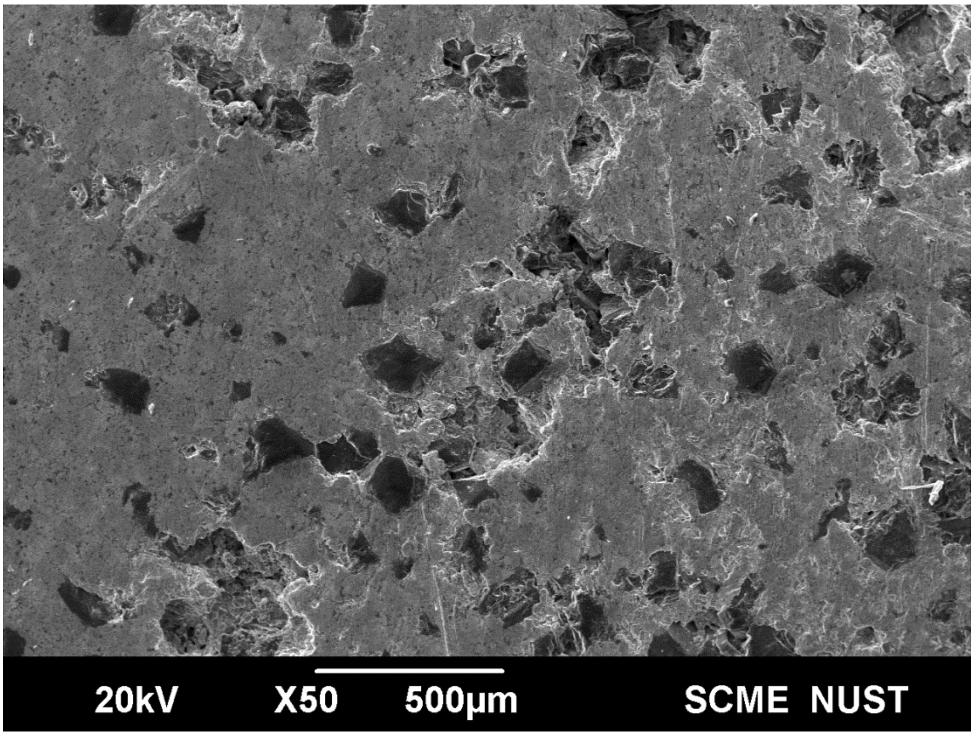

Figure 4.4: SEM Micrograph of 30% Bronze Sample

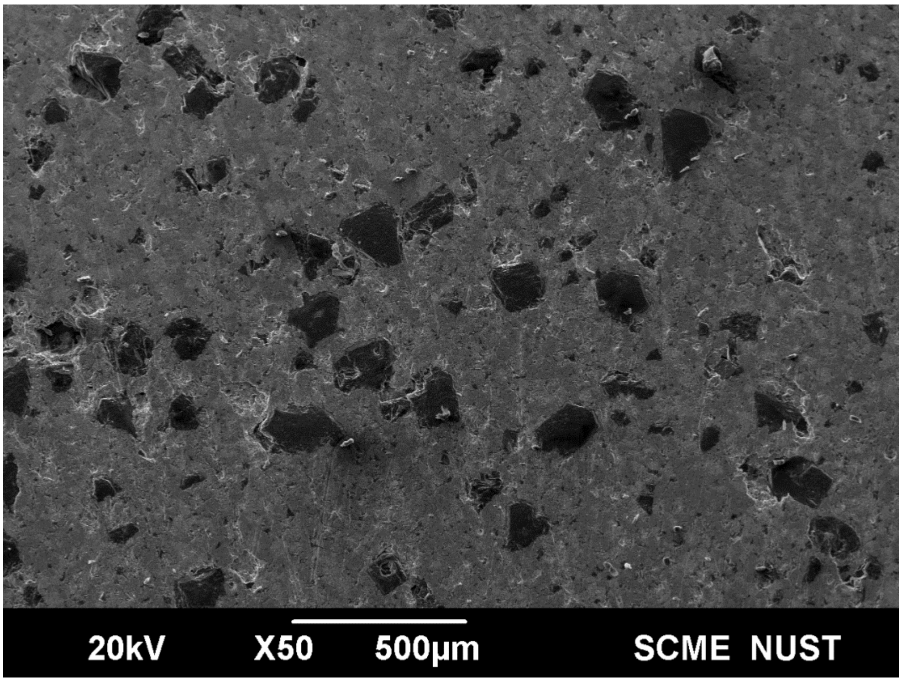

Figure 4.5: SEM Micrograph of 40% Bronze Sample

Figure 4.6 shows a scanning electron microscope image of a single diamond grain embedded inside the surface. This diamond grain will perform cutting and will not wear as long as the matrix material holds it. After the matrix material, that is holding this grain in place, wears out, the diamond grain will also be lost. But new diamond grains will be exposed which will keep the cutting process continue.

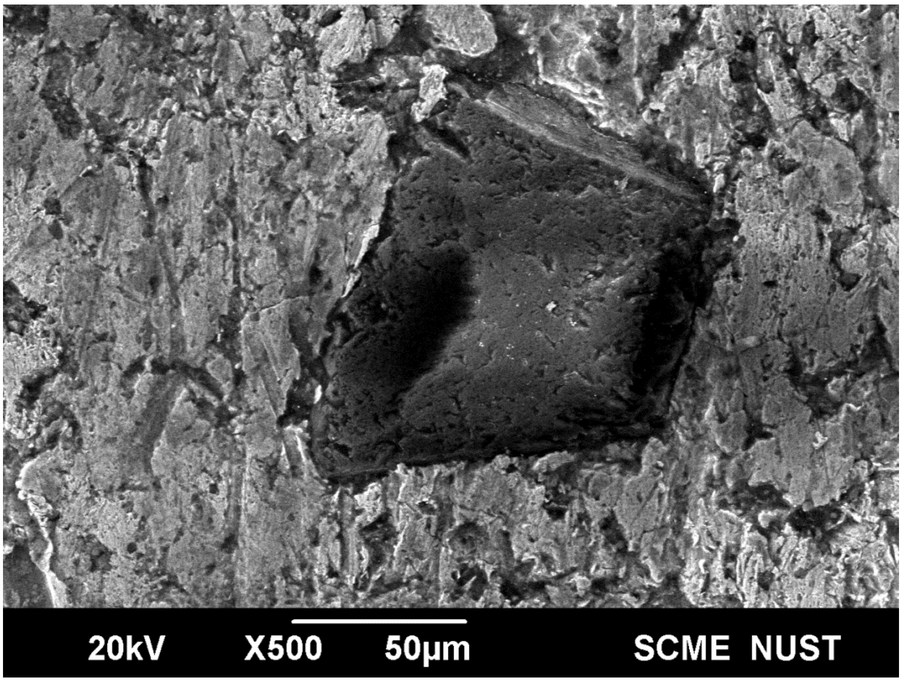

Figure 4.6: SEM Micrograph of a diamond grain inside matrix

4.2 Energy Dispersive X-ray Spectroscopy:

The EDX results of sample with 30 % Bronze detected the elements shown in table 4.1. The bronze and cobalt are in correct compositions i-e 30 vol % and 50 vol % respectively taking the error percentage into account. Other elements are present due to contamination of either the sample or the machine. But they are present on the surface only and do not affect properties of the material. The high carbon content is due to the carbon retained on the sample from the grinding paper and/or due to the contamination of SEM machine.

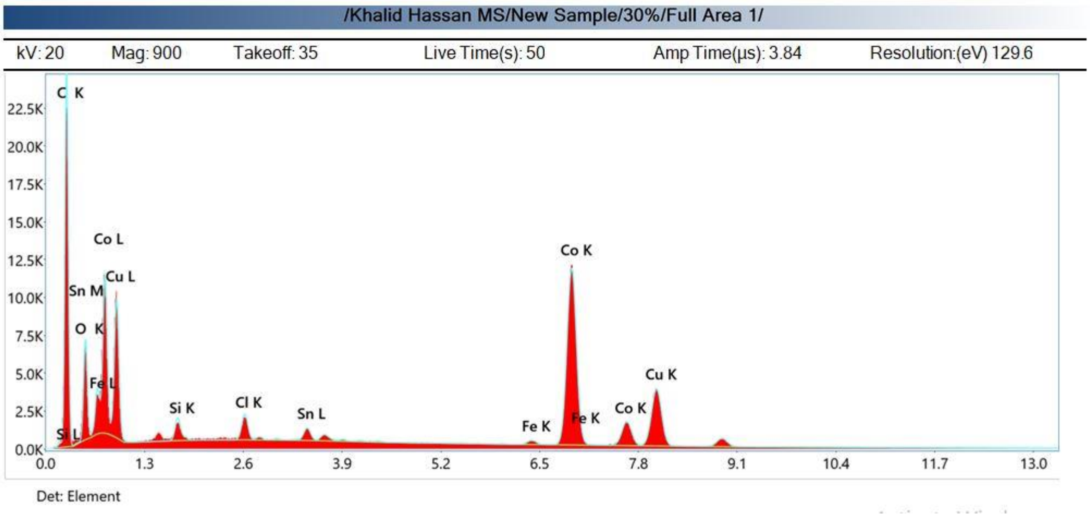

Figure 4.7: EDX Graph of 30% Bronze Sample

Table 4.1: EDX composition result of 30% Bronze Sample

Element	Weight %
C K	21.0
O K	10.4
Si K	0.7
Cl K	0.9
Fe K	0.5
Co K	35.5
Cu K	24.7
Sn L	1.3

The EDX results of sample with 40 % Bronze detected the elements shown in table 4.2. The bronze and cobalt are in correct compositions i-e 40 vol % and 40 vol % respectively taking the error percentage into account. Other elements are present due to contamination of either the sample or the machine. But they are present on the surface only and do not affect properties of the material. The high carbon content is due to the carbon retained on the sample from the grinding paper and/or due to the contamination of SEM machine.

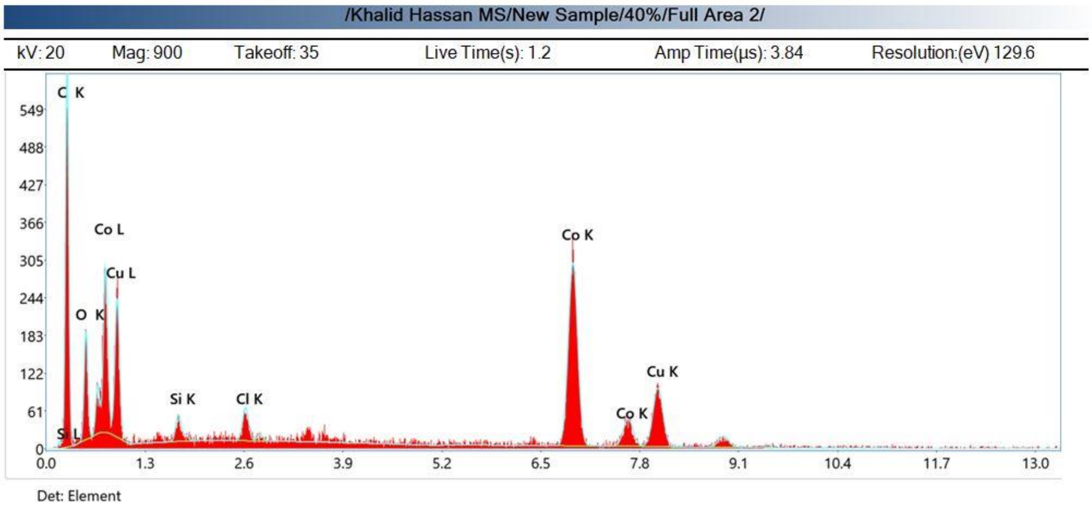

Figure 4.8: EDX Graph of 40% Bronze Sample

Table 4.2: EDX composition result of 40% Bronze Sample

Element	**Weight %**
C K	18.1
O K	11.1
Si K	0.8
Cl K	1.1
Co K	34.3
Cu K	31.9

The EDX results of sample with 50 % Bronze detected the elements shown in table 4.3. The bronze and cobalt are in correct compositions i-e 50 vol % and 30 vol

% respectively taking the error percentage into account. Other elements are present due to contamination of either the sample or the machine. But they are present on the surface only and do not affect properties of the material. The high carbon content is due to the carbon retained on the sample from the grinding paper and/or due to the contamination of SEM machine.

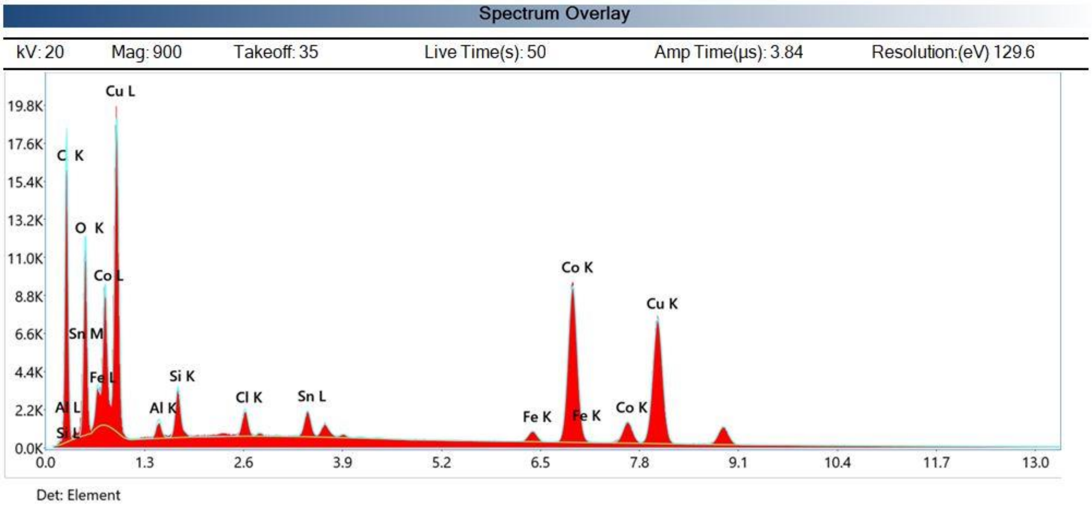

Figure 4.9: EDX Graph of 50% Bronze Sample

Table 4.3: EDX composition result of 50% Bronze Sample

Element	Weight %
C K	15.3
O K	11.0
Si K	1.4
Cl K	0.8
Fe K	1.0
Co K	28.1
Cu K	39.4
Sn L	2.3

4.3 Density:

Figure 4.10 shows the change in density with changing copper proportion and temperature. From 30 to 40 %, the density increases by a large value. The reason for this is that copper fills the voids between cobalt particles and diamond particles. Copper has high ductility and diffuses faster at sintering temperatures close to its melting point. From 40% to 50%, there is only a slight increase in density. It is due to the fact that now there are no more voids remaining. The slight increase in density is now due to the high density of copper which increases the overall density of the composite.

The figure also shows that density increases with increasing sintering temperature. It is because the diffusion during sintering process increases as the temperature increases.

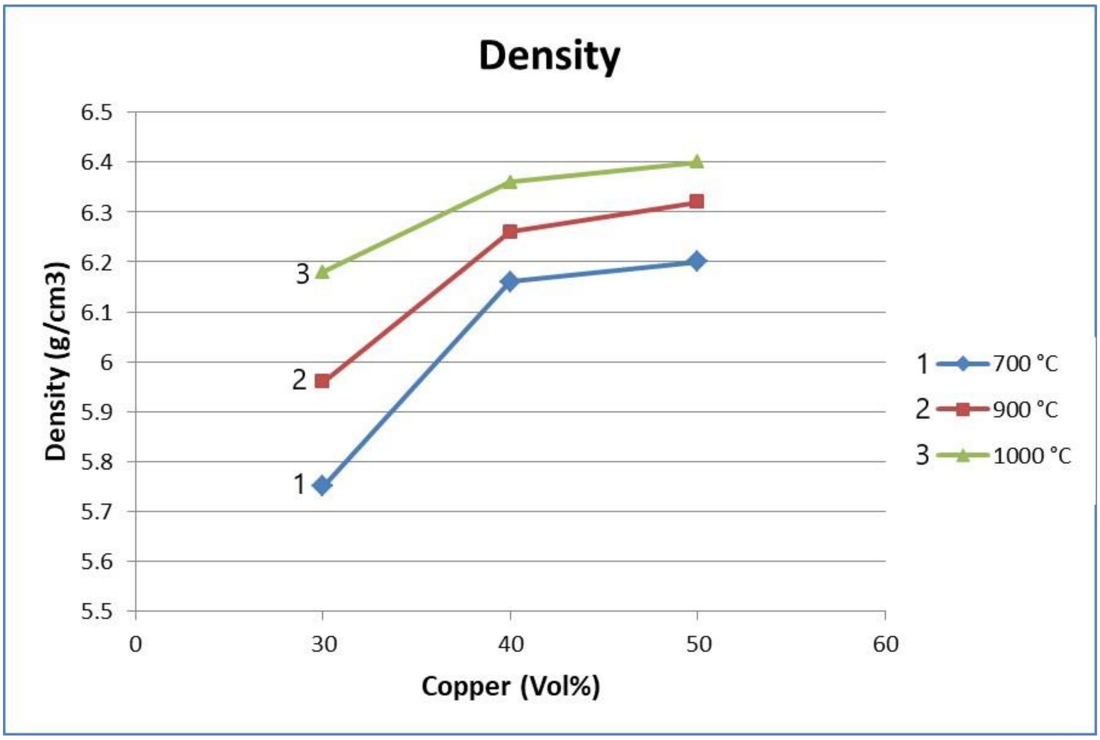

Figure 4.10: Density variation with copper

Figure 4.11 shows the change in density with changing bronze proportion and temperature. The density decreases with increasing bronze proportion. From 30 to 40 %, the density decreases by a small value. The reason for this is that bronze fills the voids between cobalt particles and diamond particles and adds to the density but its own low density cancels this effect and therefore the density decreases by a small value. From 40% to 50%, the density decreases by a large value which shows that the voids are now full and further addition of bronze will decrease the overall density of the sample due to lower density of bronze as compared to cobalt.

The figure also shows that density increases with increasing sintering temperature. It is because the diffusion during sintering process increases as the temperature increases.

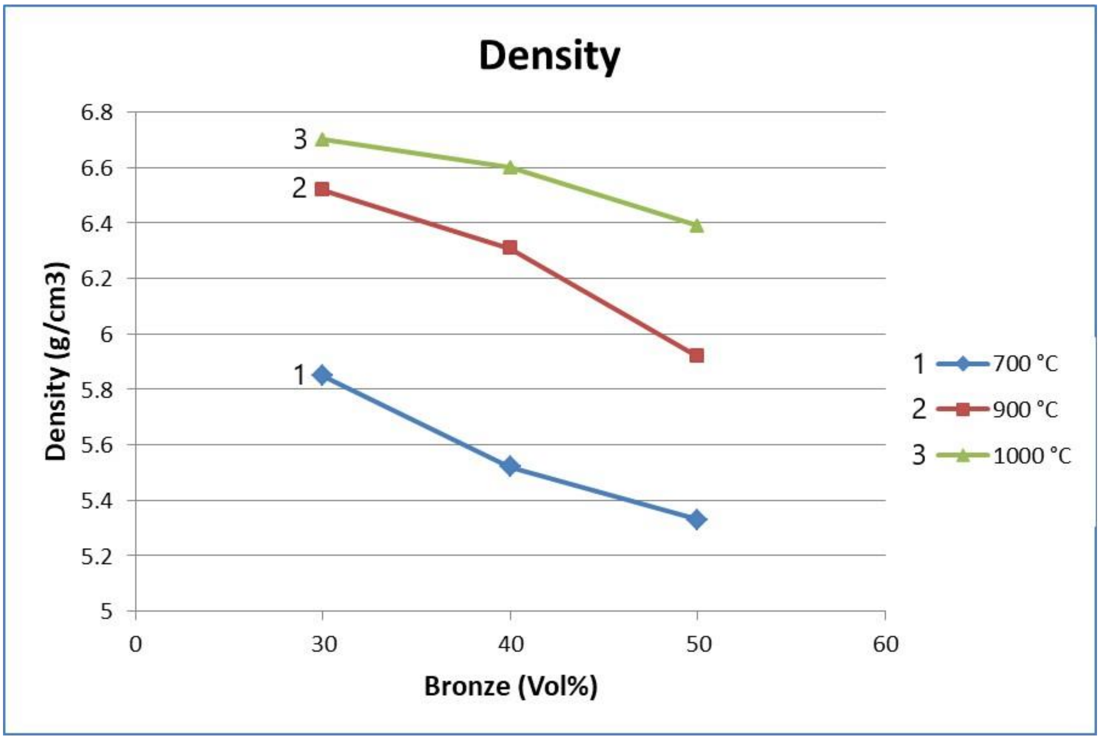

Figure 4.11: Density variation with bronze

Figure 4.12 shows the change in density with changing cobalt proportion and temperature. The samples with bronze have higher densities as compared to those with copper. The reason is that the melting point of bronze is lower than the melting point of copper. Therefore bronze is in molten form and will flow faster to fill voids.

The density increases with increasing sintering temperature. It is because the diffusion during sintering process increases as the temperature increases.

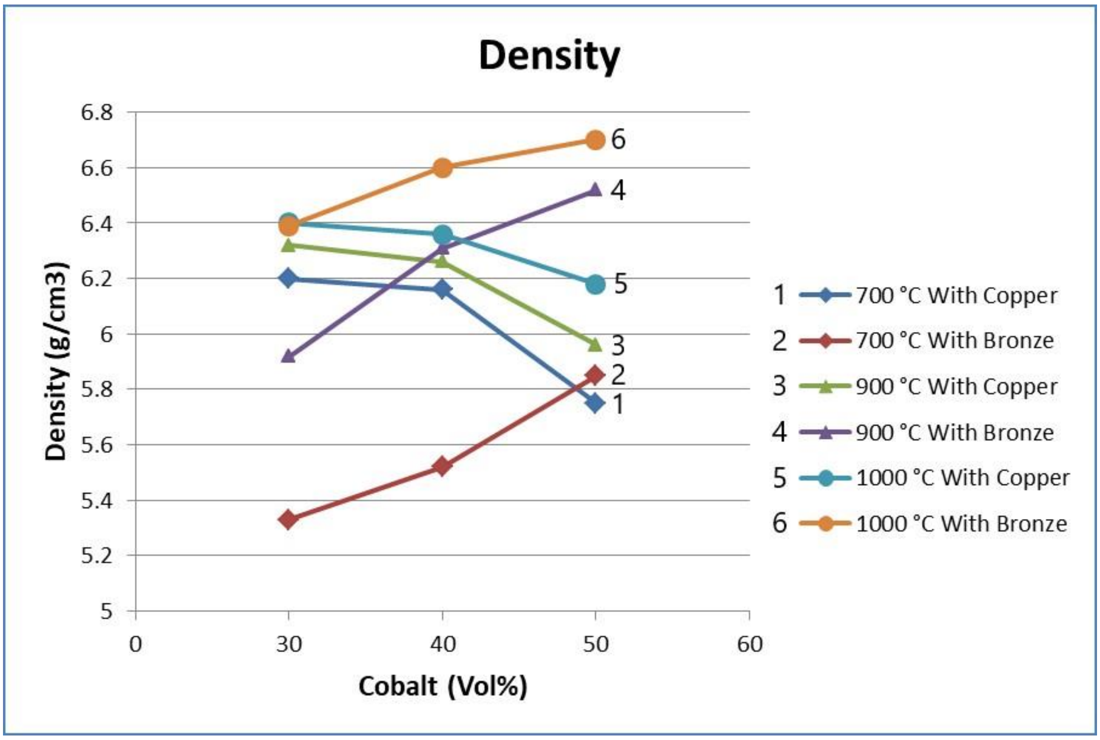

Figure 4.12: Density variation with cobalt

4.4 Hardness:

Figure 4.13 shows the change in hardness with changing copper proportion and temperature. The hardness decreases as the copper percentage increases. The reason is that copper is a soft material as compared to cobalt. Therefore the overall hardness of the matrix decreases. Secondly, the hardness increases with increase in sintering temperature due to better consolidation (increased diffusion, necking and bonding) of the composite materials at higher temperatures.

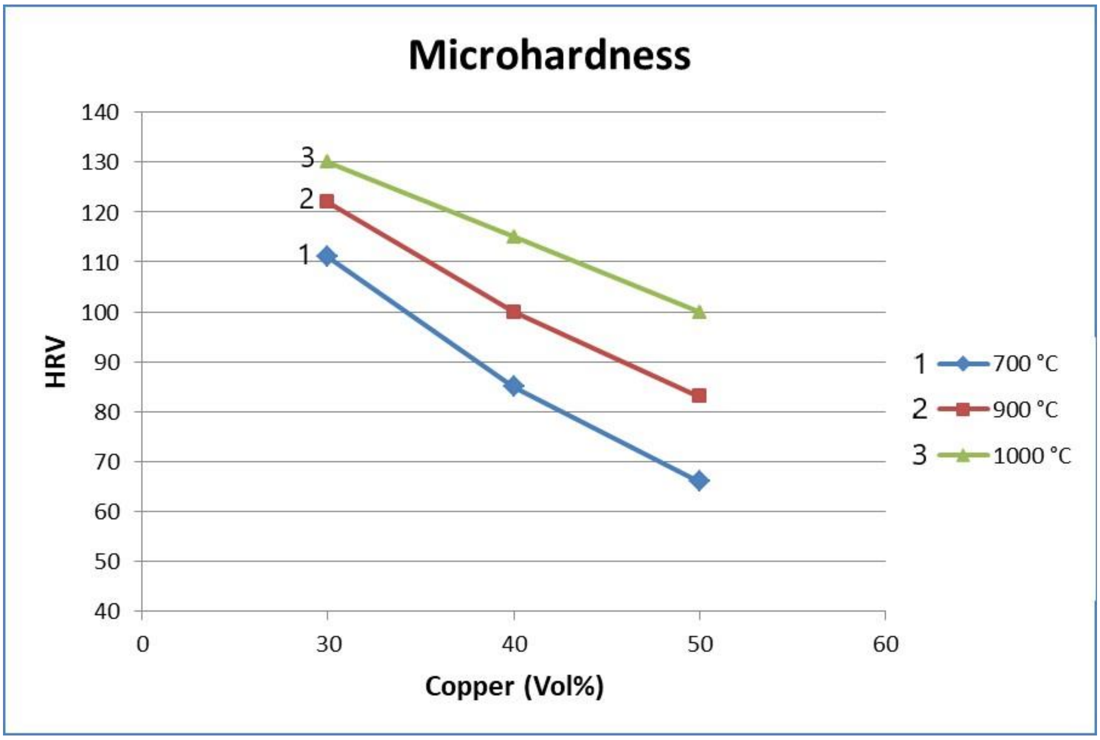

Figure 4.13: Hardness variation with copper

Figure 4.14 shows the change in hardness with change in the percentage of bronze and temperature. The hardness of the overall matrix decreases with increasing bronze. The reason is that bronze is a soft material as compared to cobalt. Therefore the overall hardness of the matrix decreases. Secondly, the hardness increases with increase in sintering temperature due to better consolidation (increased diffusion, necking and bonding) of the composite materials at higher temperatures.

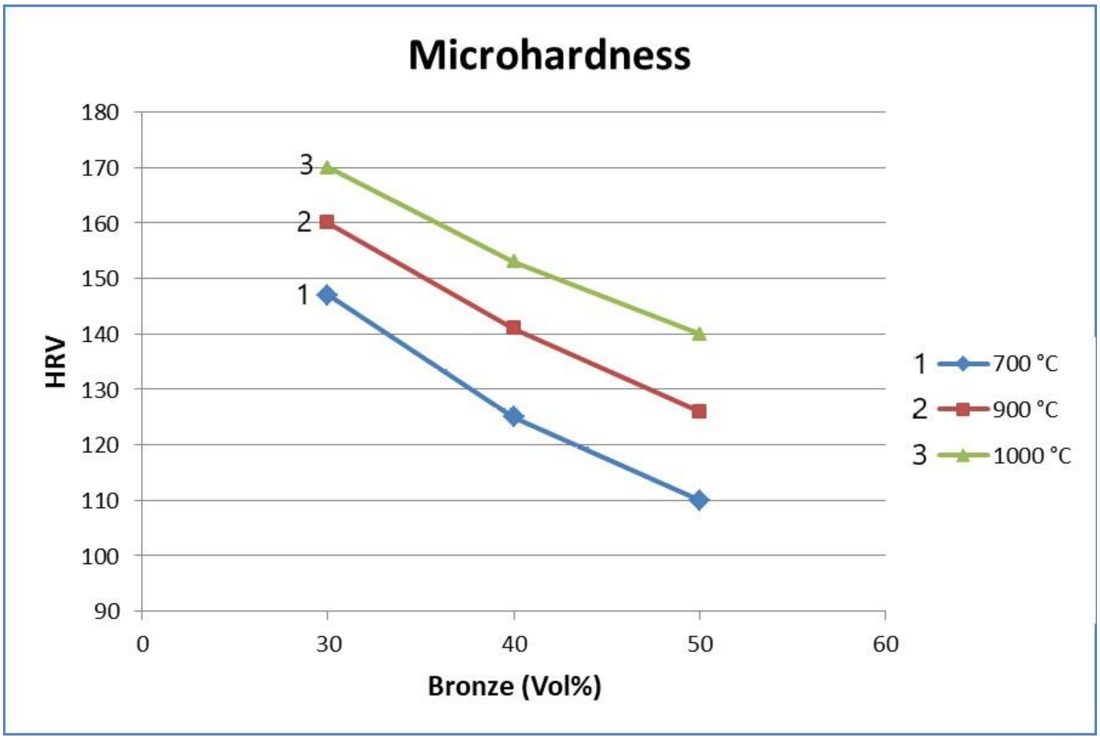

Figure 4.14: Hardness variation with bronze

Figure 4.15 shows that hardness increases with increase in the percentage of cobalt. It is because cobalt is a harder material as compared to copper and bronze. The figure also shows that hardness of the samples containing bronze is greater than the samples containing copper. The reason is that bronze is a harder material as compared to copper due to the formation of different intermetallic compounds between copper and tin especially Cu3Sn.

The figure also shows that hardness increases with increase in sintering temperature. It is due to better consolidation (increased diffusion, necking and bonding) of the composite materials at higher temperatures.

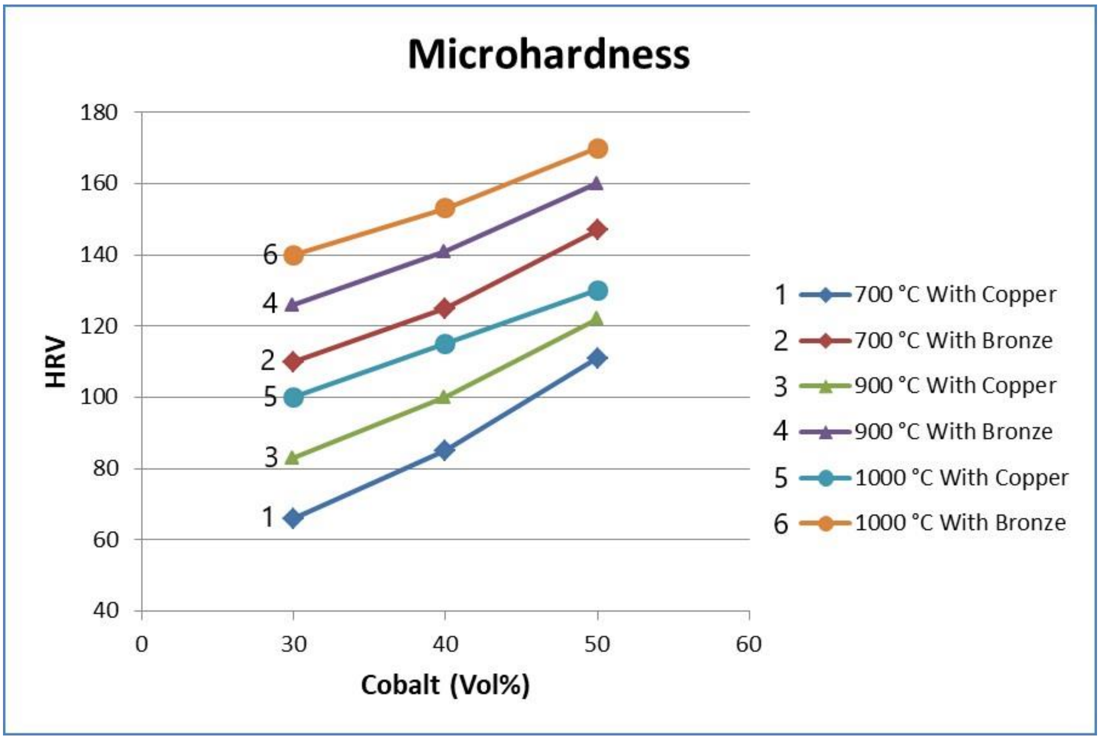

Figure 4.15: Hardness variation with cobalt

4.5 Wear:

Figure 4.16 shows the change in wear rate of the samples with change in the proportion of copper and sintering temperature. The wear rate increases as the percentage of copper increases because of the reason that copper is a softer material as compared to cobalt. The wear rate also increases as the sintering temperature decreases because of poor consolidation of the composite materials at lower temperatures.

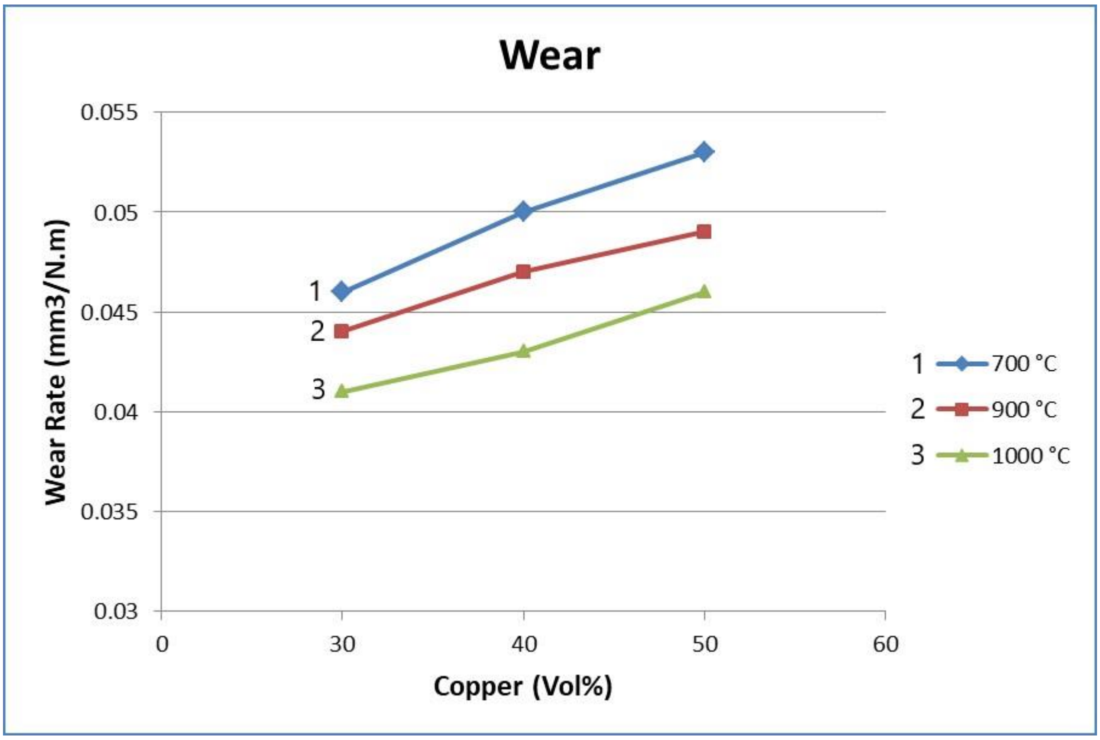

Figure 4.16: Wear variation with copper

Figure 4.17 shows the change in wear rate of the samples with change in the proportion of bronze and sintering temperature. The wear rate increases as the percentage of bronze increases because of the reason that bronze is a softer material as compared to cobalt. The wear rate decreases as the sintering temperature increases due to better consolidation (increased diffusion, necking and bonding) of the composite materials at higher temperatures.

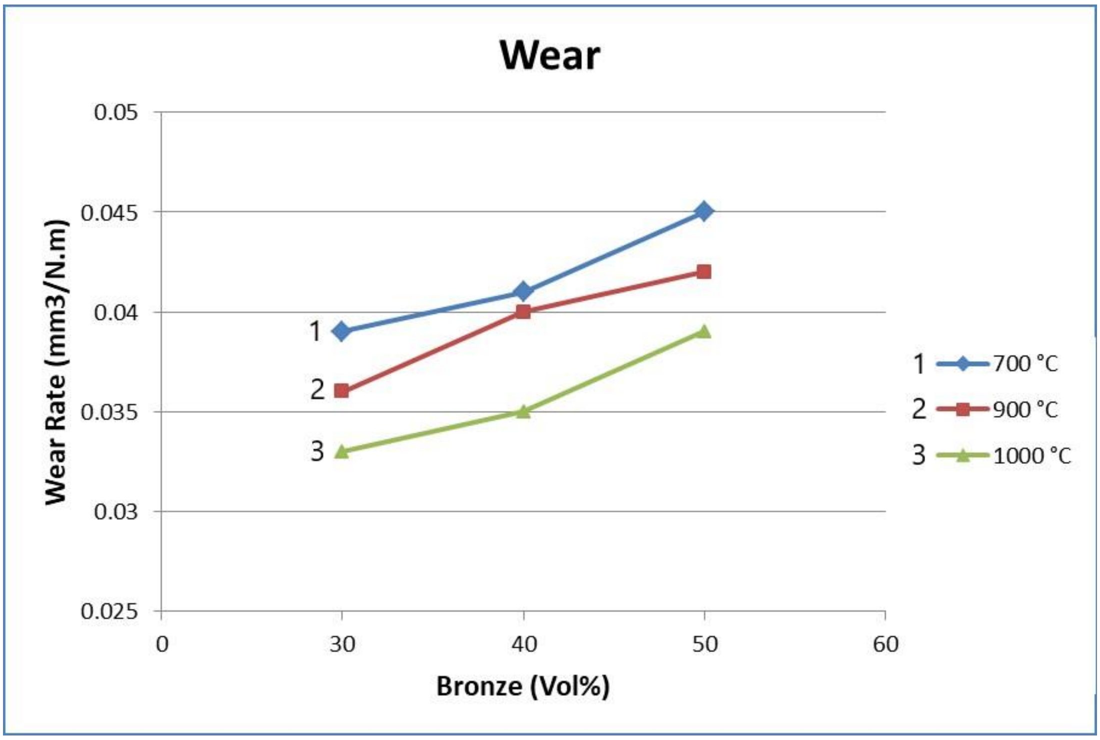

Figure 4.17: Wear variation with bronze

Figure 4.18 shows the change in wear rate with change in sintering temperature and the proportion of cobalt. The wear rate decreases with increase in the percentage of cobalt because of the reason that cobalt is a harder and more wear resistant material as compared to copper and bronze.

The figure also shows that the wear rate is smaller in samples containing bronze as compared to the samples containing copper. The reason is that bronze is harder and more wear resistant as compared to copper due to the formation of different intermetallic compounds between copper and tin especially Cu3Sn.

The data also shows that the wear rate decreases as the sintering temperature increases. It is due to better consolidation (increased diffusion, necking and bonding) of the composite materials at higher temperatures.

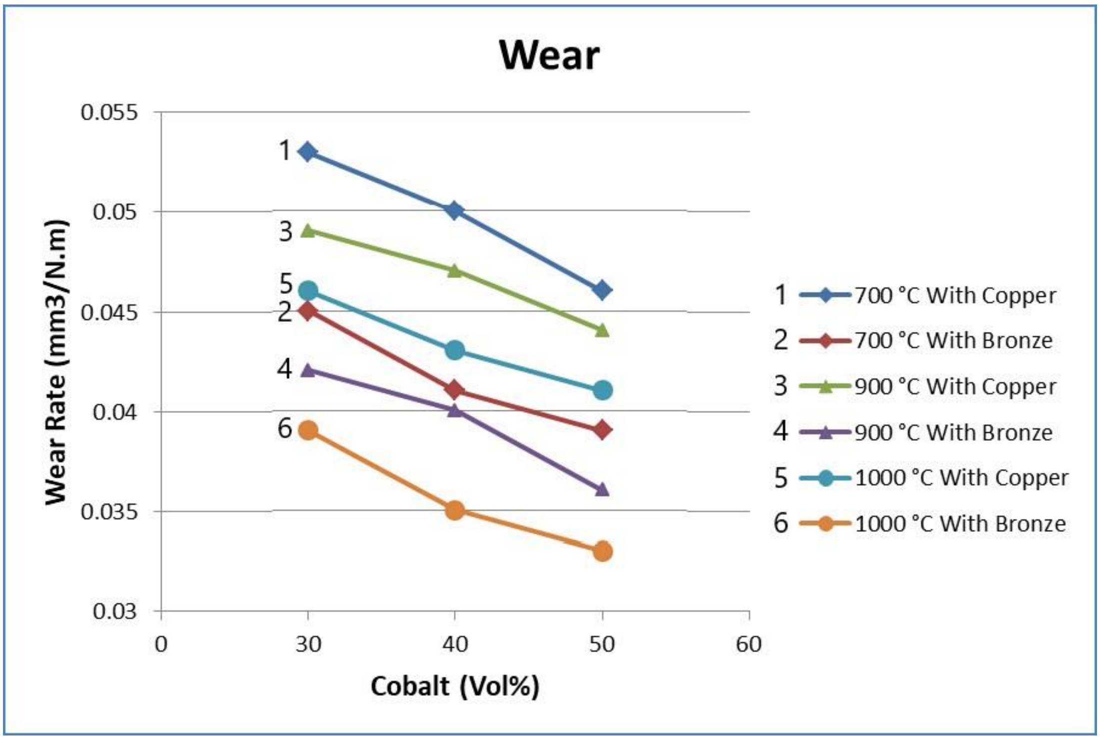

Figure 4.18: Wear variation with cobalt

Conclusions:

- Diamond segments containing copper, bronze and cobalt have the best properties as compared to segments made of other elements.
- Hardness of the segments decreases as the percentages of copper and bronze increase.
- Hardness of the segments increases as the percentage of cobalt increases.
- Wear resistance of the segments decreases as the percentages of copper and bronze increase.
- Wear resistance of the segments increases as the percentage of cobalt increases.
- Diamond tip samples containing bronze instead of copper have better properties.
- The 40 vol % bronze with 40 vol % cobalt composition has the best set of properties i-e density, hardness and wear resistance.
- There is no significant change in properties at 900 °C vs 1000 °C sintering temperatures. Therefore 800-900 °C temperature is the best for sintering process of these tips.
- The samples with air as sintering environment were extremely oxidized. Therefore air should not be used as sintering environment.

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