Formation and Operation Parameters of SiC Electrodes in Laser Discharge

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Abstract

In this work, laser discharge electrodes were fabricated using SiC composite as a base material. The electrodes were also fabricated by adding copper to the composite material under different formation conditions. These electrodes were employed to operate discharge system of a TEA-CO_2 laser. Operation parameters were studied considering several influences such as reduction factor, grain size, forming pressure, sintering time and temperature, and copper added ratio. Also, the electrical characteristics, such as conductivity, electric discharge uniformity and current pulse shape, were introduced. It is aimed to optimize the experimental conditions leading to produce the discharge electrodes suitable for stable and long-life operation of laser system.

Keywords*:* Silicon carbide, high power laser, high power electronics,

الخلاصة

تتضمن الدراسة تأثير مادة القطب على انتظام المجال الكهربائي، حيث تم تصميم و تصنيع أقطاب التفريغ الكهربائي على شكل نماذج أسطوانية صغيرة الحجم بمقطع عرضي(1*1سم^2) من مواد مركبة (SiC) نقية ذات حجوم حبيبة مختلفة للنحاس و بظروف مختلفة.

جرت دراسة تأثير الحجم الحبيبي لمادة الـ(SiC) على عملية تشكيل نماذج الأقطاب، إذ وجد أن (133 مايكرون) أفضل حجم حبيبي لتصنيع الأقطاب و بظروف تشغيل(1100 ^oC) , ضغط كبس (1 طن) , زمن كبس(30 ثانية) و زمن تلبيد (60 ثانية) باستخدام غاز (H_2). إذ كان الأفضل من بقية العوامل المختزلة المستخدمة في البحث (FeO, N_2, C).

Introduction

SiC has a superior property because it can be used in high-power, high-frequency, and high temperature electronics. The material has extremely high thermal conductivity, can withstand high electric fields before breakdown and also has high current densities and good mechanical properties. Also, silicon carbide is an excellent abrasive and it has been produced and made into grinding wheels and other abrasive products for periods over one hundred years [1-3].

All the above mentioned properties made SiC promising as a power device material. The electro-technical applications of high-power gas laser systems can thus in future advantageously replace metal main laser electrodes especially in TEA-CO_2 lasers with pure SiC or SiC-metal electrodes as composite material. It can be typically used in laser pre-ionization pins (electrodes) [2].

There are many techniques which have been used to fabricate the composite materials such as: reaction sintering, powder technology, melt infiltrating, chemical vapor technology, casting and hot pressing. The technique used in this work is powder technology. In this technique, producing engineering parts is achieved using metallic or ceramic powders. Mixing of such powders in small particle sizes needs heating process at different temperatures. The temperature is rather less than melting temperature of base material to get parts of high density and high strength [4-6].

There are many facilities for powder technology [7]. There is no large loss in

powders during fabrication processes since about 97% of the base material would be used. It is easy to obtain clean chemical composition, possibility by adding different materials at different rates to obtain the desired properties, and high production rate can be made using automatic machines.

In this paper, composite material (SiC) in different ratios of copper metal powder is used to fabricate the discharge electrodes of a gas laser system. The fabrication and operational parameters of these electrodes are discussed and optimized. SiC can be commercially used for high-voltage and high-power applications, so it represents a good solution to the problems related to such applications.

Experimental Work

In this work, pure (99.9999%) SiC of different grain sizes (53μm, 133μm) is used. Also, copper powder of high purity (99.999 %) is used. The copper powder of 15μm grain size is mixed with SiC powder in different weight ratios (5-40%). There are many reasons leading to use this material. First is the low melting point of copper, which decreases the temperature, required to fabricate the electrodes. The second reason is the good electrical conductivity of copper. Graphite powder is used in different weight ratios (2-5wt. %) as an aid factor for the sintering process.

The main instruments used in preparation of the samples are drying oven (280ºC), electrical hydraulic press (maximum 50 ton), electrical heating furnace (3000°C maximum), tube furnace (1800°C maximum) and mold with inside cavitations which takes on an Ernst 8th order profile. The experimental steps are indicated in the flow chart of Fig. (1).

I) Mixing, Forming and Sintering Processes

The polyvenilathelen (PVA) is used as a binder material. The weight ratio should not exceed 2-4wt. % during steady and continuous hand mixing for 5-10 minutes until the mixture becomes dense enough. In general, the wet mixing method produces a homogenous mixture. It is used here instead of the dry mixing method because of non-uniformity in the shape and size of base powder particles in the dry mixing method.

A cylindrical mold for preliminary samples was employed at pressure of about 25-30 tons during 25s pressing time. The pressure is obtained using an electrical hydraulic press to get a sample of 1cm in diameter and 1cm in thickness. The mold was finally placed inside a cavity to form Ernst 8^{th} order profile.

The dimensions of the discharge electrodes fabricated with Ernst 8^{th} profile were (120x20x5) mm3, while the preliminary samples fabricated in a cylindrical shape had dimensions of 1cm height and 1cm diameter. Figure (2) shows the mold used to fabricate the preliminary samples of electrodes and Figure (3) shows the mold used to fabricate the discharge electrodes.

In the sintering step, the sample is placed on the graphite substrate and then heated to a certain temperature (750, 800, 850 or 900) °C for different times (30, 60 and 90) minutes. Figure (4) depicts some of the fabricated samples and Figure (5) shows the main discharge electrode which was fabricated from SiC.

II) Sample Preparation and Final Checking

The final cutting process of samples was done by wire cut machine to get dimensions of 1cm height and 1cm diameter. Cleaning process was done to get clean surface without any defects. Structural examination was done for the 133μm grain size samples fabricated under vacuum at 1100ºC sintering temperature for 30 minutes and without adding copper.

The sample was hanged in air and weighted then immersed in the distilled water for one day. It was taken away and then weighed in air once and then immersed in the water. The results were used to calculate the following parameters [8]:

Apparent Density (*A.D*) is given by:

$$A.D = \frac{W_d}{W_d - W_i} \qquad (1a)$$

On the other hand, the water absorption (W_a) is given by:

$$W_a = \frac{W_s - W_d}{W_d} \quad (1b)$$

The apparent porosity ($A.P$) is given by:

$$A.P = \frac{W_s - W_d}{W_s - W_i} \quad (1c)$$

Where W_d is the weight of the dry sample in air, W_s is the weight of the water-saturated sample hanged in air, and W_i is the weight of the sample hanged and immersed in water.

The structural characteristics of the samples fabricated from only SiC without copper were studied. The fabrication conditions were 1100ºC temperature, 60min sintering time and 1ton pressure. The mechanical characteristics, such as apparent density, water absorption and apparent porosity, were determined and the results were $A.D$=2.9742, W_a=12.9% and $A.P$=22.78%, respectively. Electrical measurements were done for the samples fabricated without adding copper under conditions of 133μm grain size SiC, 1100ºC and 30 minute. The electrical measurements included applying voltage of 10V to both sides of the sample and then measuring the current. By measuring the current and dimensions of the sample, the resistivity (ρ)could be calculated (R=ρA/L)where R is the resistance ,A is the area and L lenght of the sample. The electrical part of the discharge system includes charging circuit, trigger circuit and DC power supply. Figure (6) shows the electrical circuit and laser head used in this work.

Results And Discussion

3.1 Grain Size Distribution of SiC Electrodes

The grain size distribution of the SiC powders used to fabricate the discharge laser electrodes is depicted in Figure (7). Figure (7a) shows that the grain size of 133μm has the highest ratio (56wt. %). The grain sizes between 50μm and 100μm have a ratio of 18wt. %. Figure (7b) shows the grain size distribution of another SiC powder and it appears that the grain size of 56μm has the highest ratio. The powder of 133μm grain size is homogenous, while the second powder has a degree of homogeneity less than the first.

3.2 Effect of Forming Pressure

It was experimentally confirmed that raising forming pressure to more than 1ton would lead to failure of samples after sintering. The samples had a high degree of brittleness. Increasing pressure to more than 1ton induces static stresses at the contact point of the grains as well as weakens the binder material, which inhabits fusion process [9]. Figure (8) shows the samples of different grain sizes fabricated at 1ton pressure. The H_2 gas was used as an agent factor.

3.3 Effect of Sintering Time

The sintering time has an important role in the fabrication of laser electrodes. It was shown experimentally that at time 30-150 1minute, the sintering does not occur because there is not enough time to complete fusion process. It was found that the best sintering time is 90 minute to obtain the acceptable result with respect to hardness and brittleness. Figure (9) shows samples sintered at different times. It was shown that the sample fabricated at sintering time of 150 minute had small cracks and the grains did not attach to each other because the fusion process is as not completed successfully, as shown in Figure (9a). Figures (9b) and (9c) show that the mass diffusion processes are enhanced. In Figure (9d), it is shown that grains are attaching to each other and has some common points as diffusion process was completed better.

3.4 Effect of Sintering Temperature

From experimental results, it was found that the temperature of 1100ºC gives more acceptable result than other temperatures of (800, 850, 900, 950 or 1000ºC). The temperature of 850ºC gives unacceptable result when FeO or carbon (graphite) is used as a reduction factor. When vacuum furnace is used, the temperature of 850ºC

gives a suitable result. This explains why with a reduction factor, a high sintering temperature is required whereas using gases to fill the furnace causes the temperature to be lowered.

Fig.(10) shows the samples fabricated at sintering time of 60min, forming pressure of 2ton and carbon (graphite) as an agent factor at different temperatures. Figures (10a) and (10b) show that the samples have cracks and grains are not attached hard enough, while in Figures (10c) and (10d), the samples are attached to each other - this is attributed to the mass diffusion process. Figures (10e) and (10f) show that the samples have a large degree of wetting since the grains have many common points and no significant boundary appears. The sintering temperature of 1100ºC gives more acceptable result.

3.5 Effect of Graphite Addition

The experiments showed that adding 2wt.% of graphite would enhance the mass diffusion process. Graphite reduces the oxide layer found on the grain surface while increases the weight ratio of graphite to 5% , produceing cavities as a result of reduction in oxide by graphite which converts it to CO_2 gas.

The effect of increasing the graphite weight ratio is depicted in Figure (11), where the holes clearly appear. The production of cavities is not affected by the fabrication conditions but by the weight ratio of graphite. It was shown that increasing the weight ratio of graphite leads to reduction in the hardness of samples. The increasement of the holes leads to making the samples highly brittle due to the presence of cavities in the structure and this increases its possibility to break and distort.

3.6 Effect of Reduction Factor Type

Experiments showed that the type of agent factor has a significant effect on electrode characteristics. Figures (12a) and (12b) show samples fabricated with carbon and FeO, respectively. When FeO is used as an agent factor, the samples have a degree of hardness. With carbon agent factor, the samples suffer from high degree of brittleness. FeO has small grain size, which means a large specific surface area. So, the rate of reduction process of the oxide layer and O_2 gas increases. On the other hand, the grain size of carbon is larger and the specific area is less. The carbon burns quickly at low temperature while the FeO reduces the oxygen and relatively higher than carbon.

3.7 Effect of Copper Ratio

Different ratios of copper are added to SiC powder to fabricate the laser electrodes. The fabrication results show that increasing the copper ratio in the base mixture leads to an enhancement in the electrical and mechanical characteristics of electrode samples. This would increase the toughness by attaching the grains of SiC to copper better than using only SiC. When SiC of 133μm grain size is used, the copper was used in a whiskers form. When copper is used as particles of 15μm grain size and SiC of 133μm grain size, the mixture was non-homogenous and the copper particles concentrated in the bottom of the mixing crucible. This is due to the large difference in grain sizes between copper and SiC.

When copper is used in whiskers form, they would fold around SiC grains and attach to them. This will homogenize the mixture and reduce the interspaces between particles. Figure (13) shows samples fabricated using copper as a whisker, with SiC of 133μm grain size and copper as particles, with SiC of 56μm grain size. It appears that using 133μm SiC with copper whiskers gives acceptable results. As the copper is melted and dispersed between SiC grains, this helps to fill the pores between the grains. For 56μm SiC, the particles are efficient since the grain size of SiC and Cu are nearly equal and the copper weight ratio is high enough to fill the interspaces among SiC grains.

At high ratio of copper, the electrical conductivity is increased as shown in Figure (14) for the fabricated electrodes at two SiC grain sizes (133 and 56μm). It is clear that the conductivity increases with increasing the ratio of copper.

3.8 Effect of SiC Grain Size on Electric Field Uniformity

Two grain sizes (133 and 56μm) have been used to fabricate the discharge laser electrodes. These electrodes were tested experimentally using mini-TEA CO_2 laser and single capacitor discharge circuit. Figure (15) shows the electrical discharge using SiC electrode in different grain sizes, while Figure (16) shows schematic diagram explaining the effect of the grain size on the uniformity of the electrical discharge.

In case of electrodes fabricated in small grain size (56μm), the discharge occurs on the surface of the electrode and this will expend the supplied current on local discharges. While in case of electrodes fabricated in grain sizes higher than 300μm, the discharge includes arcs between the electrodes, which also expend the supplied current to arcs. In case of electrodes fabricated with grain size of 133μm, the discharge is more uniform between the electrodes.

3.9 Effect of Electrode Material on Pulse Current Shape

The type of electrode material has a significant effect on the current pulse shape in the electrical discharge between laser electrodes. The resistivity of many materials changes slightly when applying external voltage. This effect is attributed to many reasons, such as activation of scattering process or changing the lattice structure of the material. In some materials such as zinc oxide and SiC, resistance is lowered exponentially with increasing the applied voltage. Hence, these materials are used in protecting circuit from electrical arcs and in switches to prevent leakage current.

Figure (16) shows the current pulse using SiC electrodes with Ernst 8th profile. It can be seen that the current pulse is narrower in comparison with the use of materials having linear resistivity such as metals. This process will cause the uniformity of discharge process and reduces losses. Adding of copper will also increase the conductivity with increasing the toughness of the electrode.

4. CONCLUSIONS

Regarding to the results obtained in this work, some concluding remarks can be introduced. Laser discharge electrodes made of composite materials have long life-time, no need for exchanging or cleaning as in metallic electrodes and no high accuracy in alignment required due to high resistivity. The current pulse of discharge between two SiC electrodes can be improved by adding copper to the base material (SiC), while narrower pulse can be obtained using SiC electrodes of Ernst 8th order profile.Also ,the optimize the experimental conditions leading to produce the dischare electrodes suitable for stable and long life operation of laser system .

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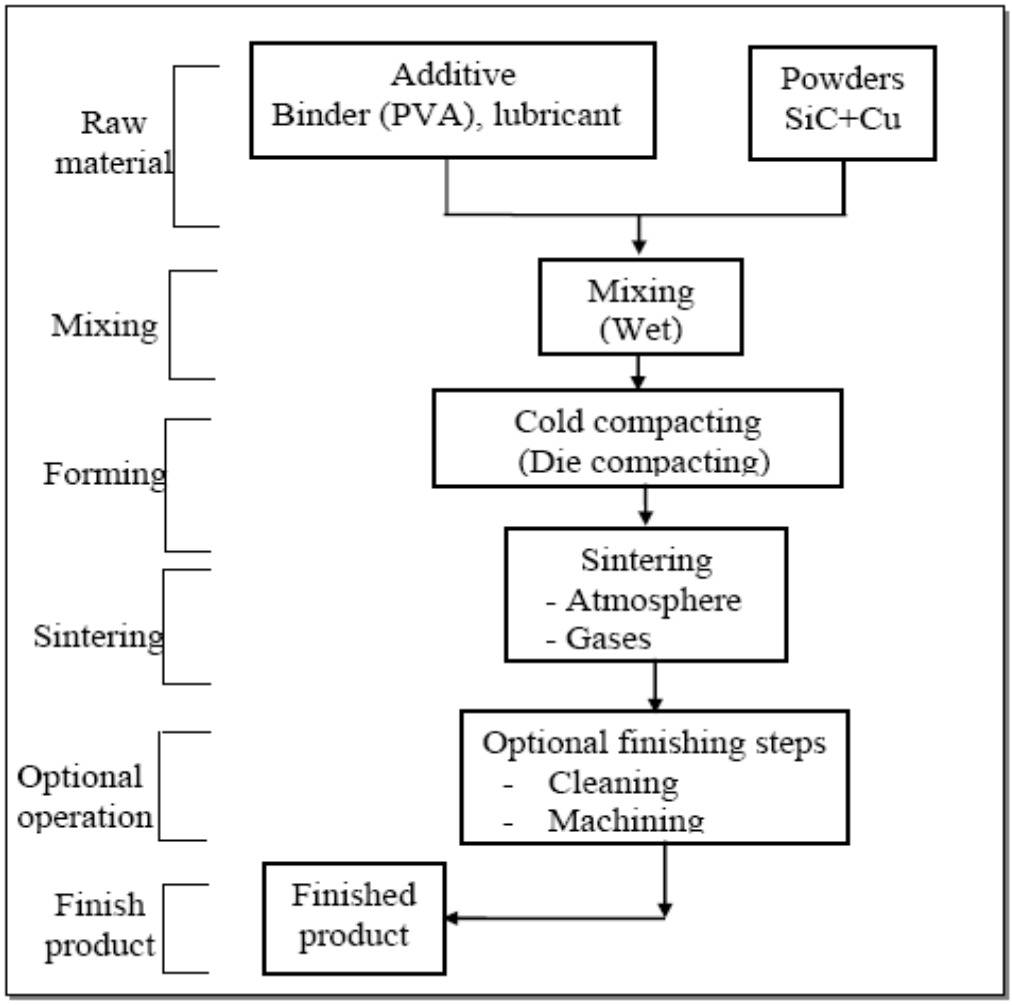


Fig. 1: Experimental steps for electrode fabrication

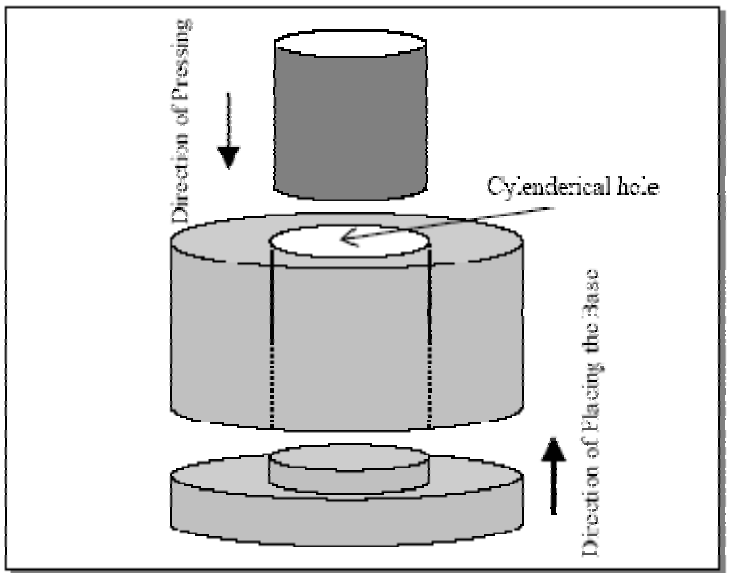


Fig. 2: Mold used to fabricate the preliminary sample

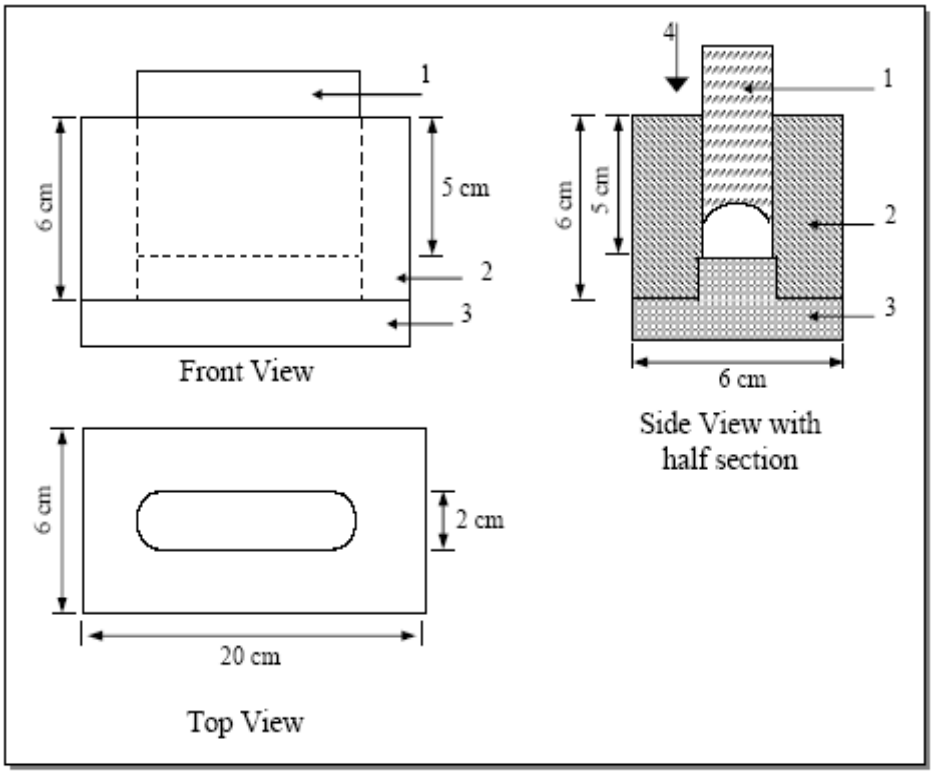


Fig. 3: The mold components, (1) moving punch, (2) die (3) base of the mold

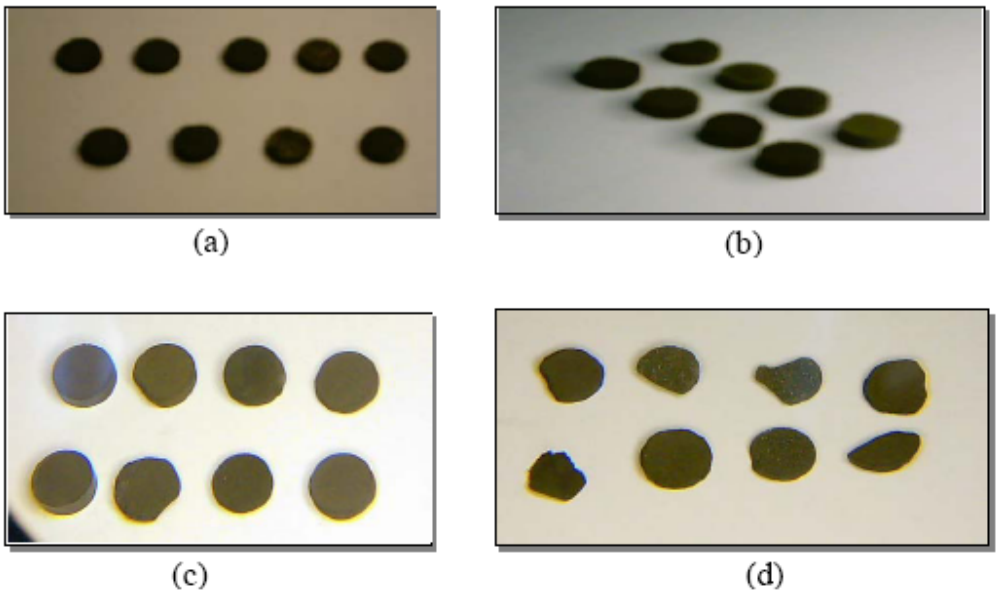


Fig. 4: Samples under 1100°C, 1ton and 1hour with, (a) carbon as agent factor (b) reduction factor (c) N_2 gas (d) H_2 gas

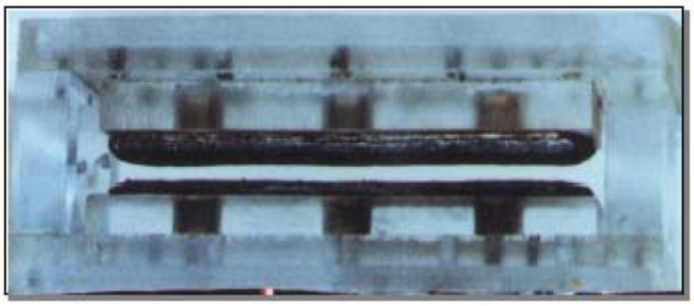


Fig. 5: SiC gas discharge electrodes

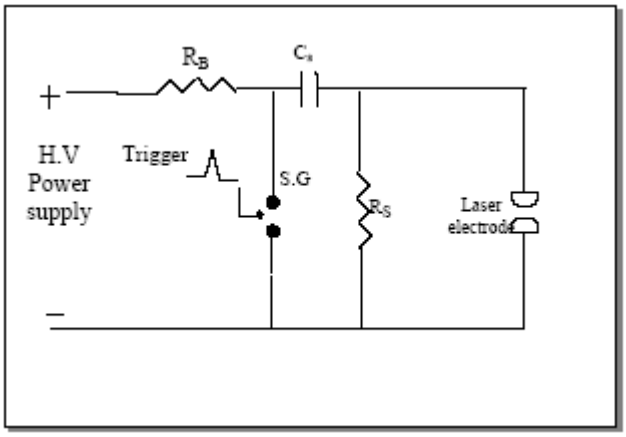
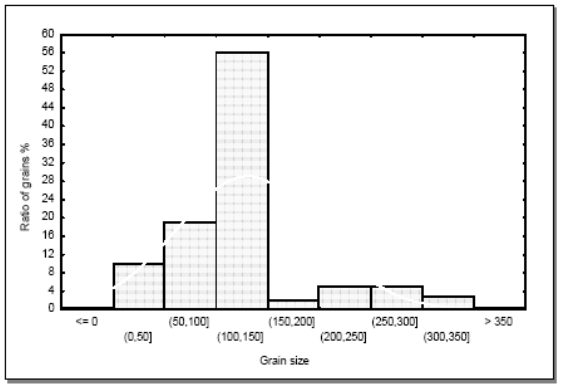
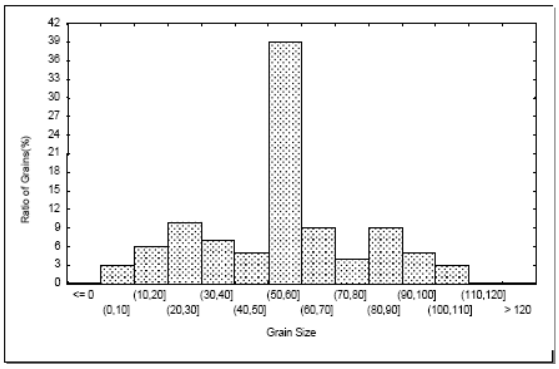


Fig. 6: The charging circuit





(a) (b)

Fig.7: Grain size distribution (a) grain size ,133μm (b) grain size , 56μm

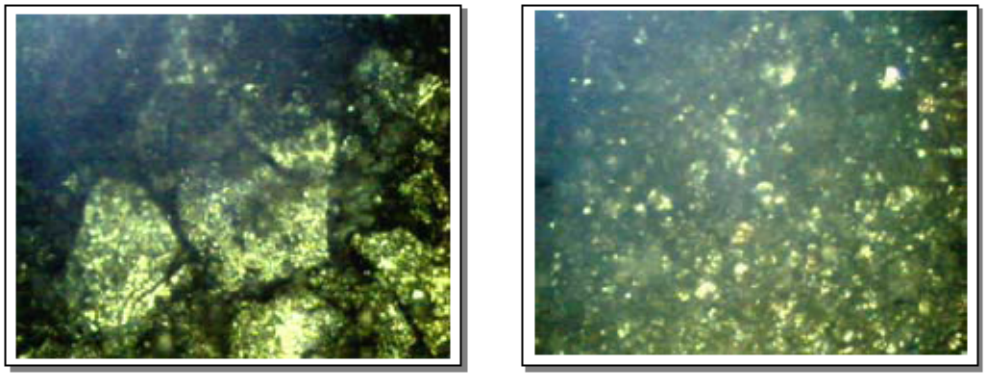


Fig. 8: Samples fabricated at 1ton pressure, H_2 gas as a reduction factor and sintering temperature 1100^{o}C (a) grain size of 133µm (b) grain size of 56µm (magnification of 400x)

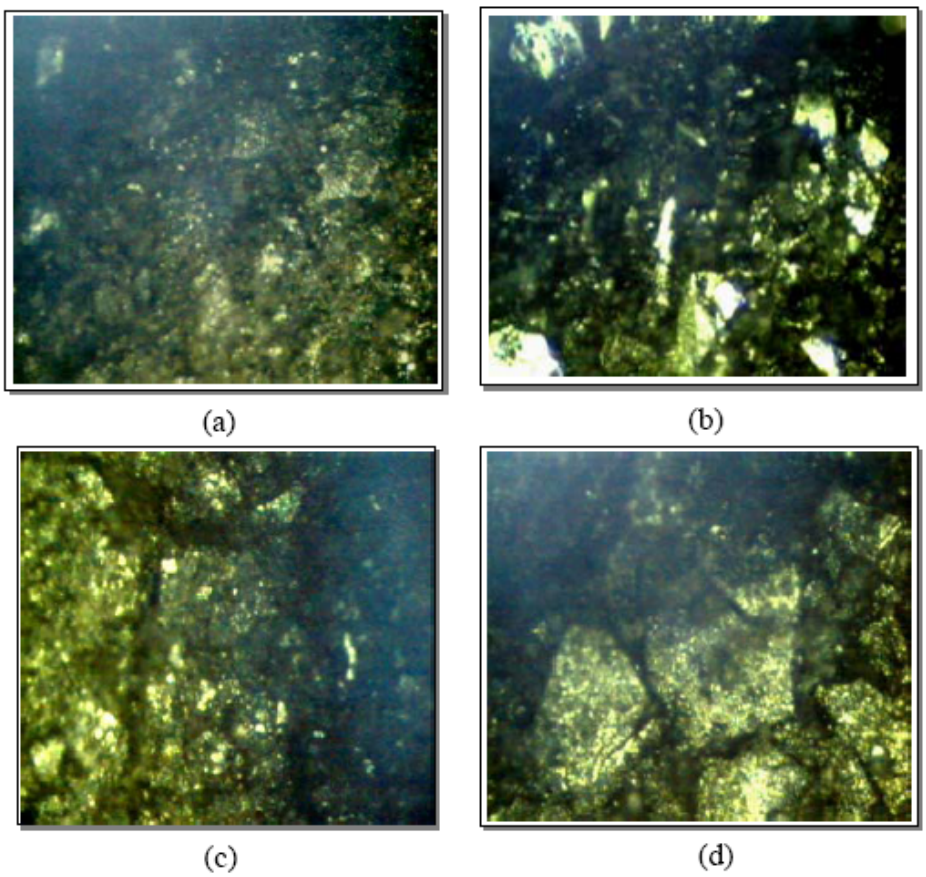


Fig. 9: Samples of grain size 133µm fabricated at sintering temperature of 1100ºC, H_2 gas filled the furnace and sintering time (a) 15min (b) 30min (c) 60min (d) 90min (magnification of 400x)

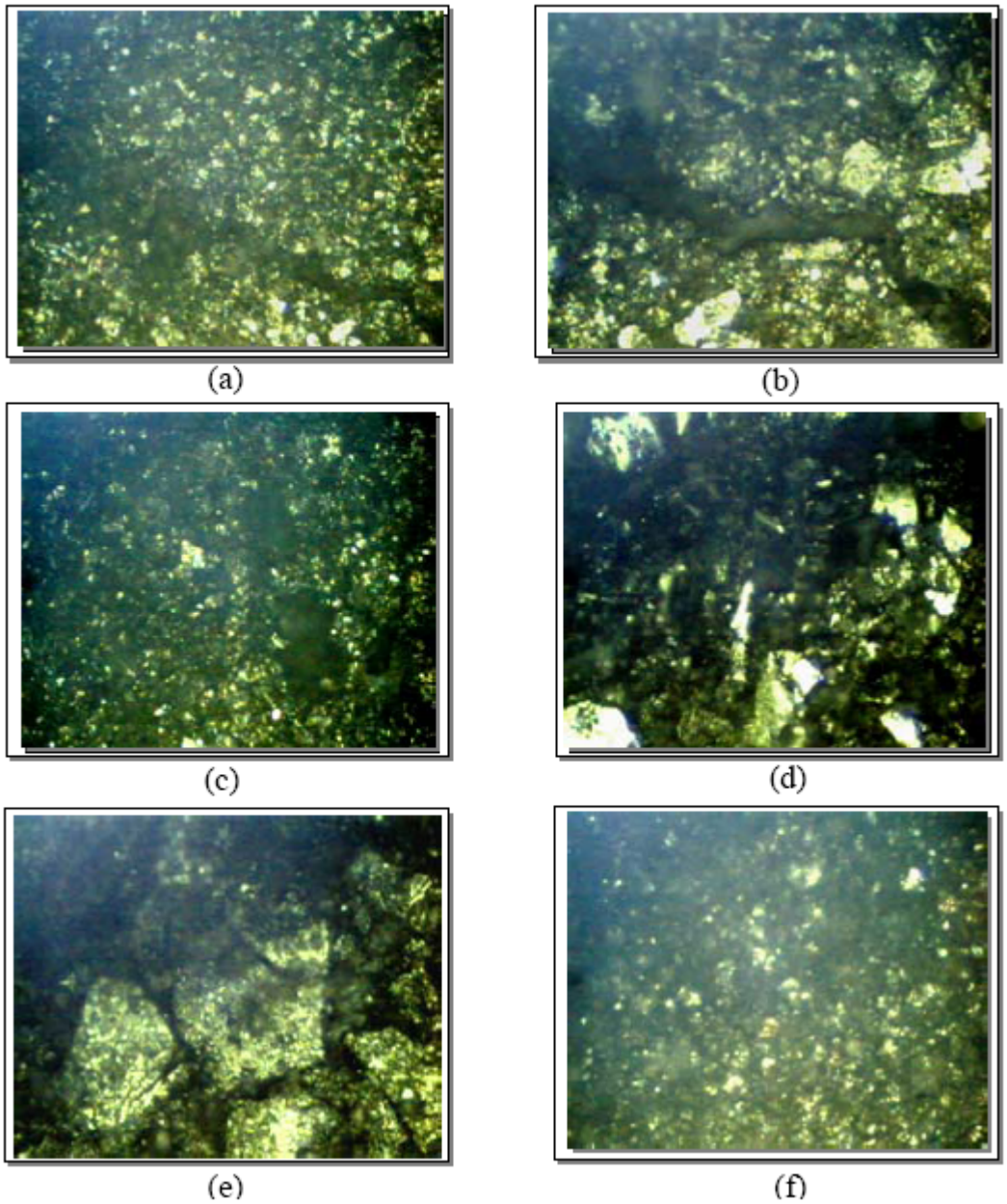


Fig. 10: Samples fabricated at 60min, forming press 2ton and carbon as a reduction factor (a) grain size of 56µm, sintering temperature of 800ºC (b) 133µm, 800ºC (c) 56µm, 950ºC (d) 133µm, 950ºC (e) 133µm, 1100ºC (f) 56µm, 1100ºC (magnification of 400x)

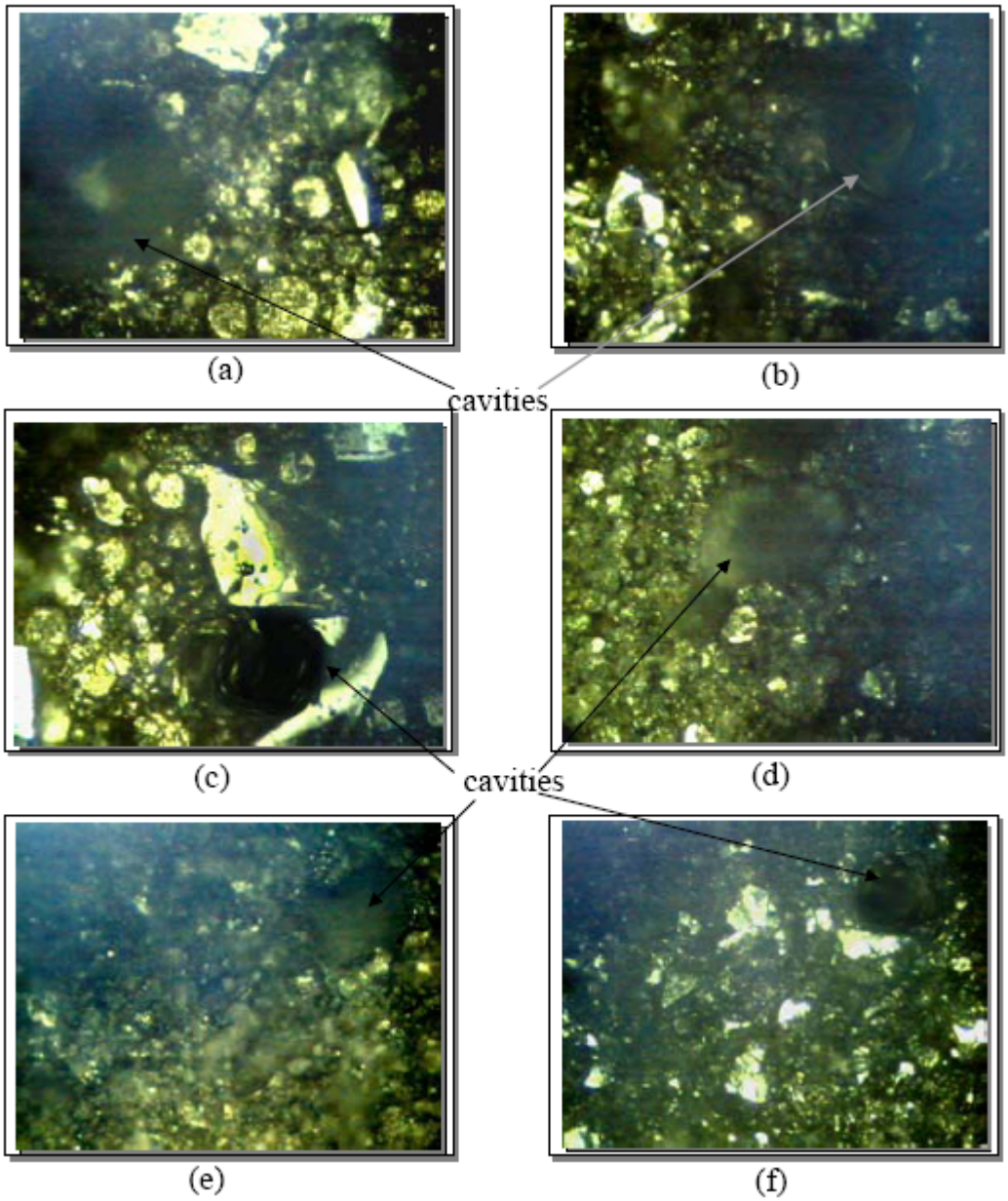


Fig. 11: Samples fabricated at sintering temperature 1100ºC, sintering time 90 minute (a) grain size of 133µm, carbon reduction factor (b) 56µm, carbon reduction factor (c) 133µm, N_2 gas (d) 133µm, N_2 gas (e) 133µm, H_2 gas (f) 56µm, H_2 gas (magnification of 400x)

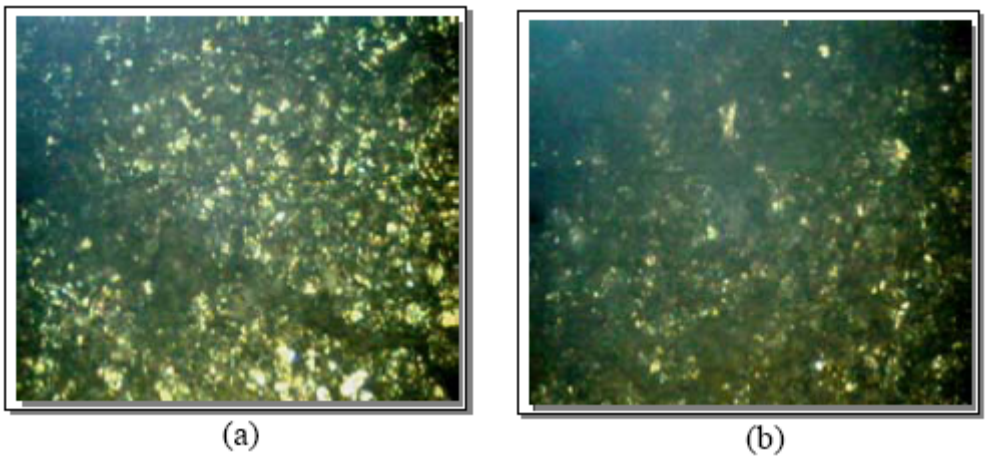


Fig. 12: Samples fabricated with (a) grain size of 133μm, carbon as a reduction factor (b) grain size of 56μm, FeO as a reduction factor

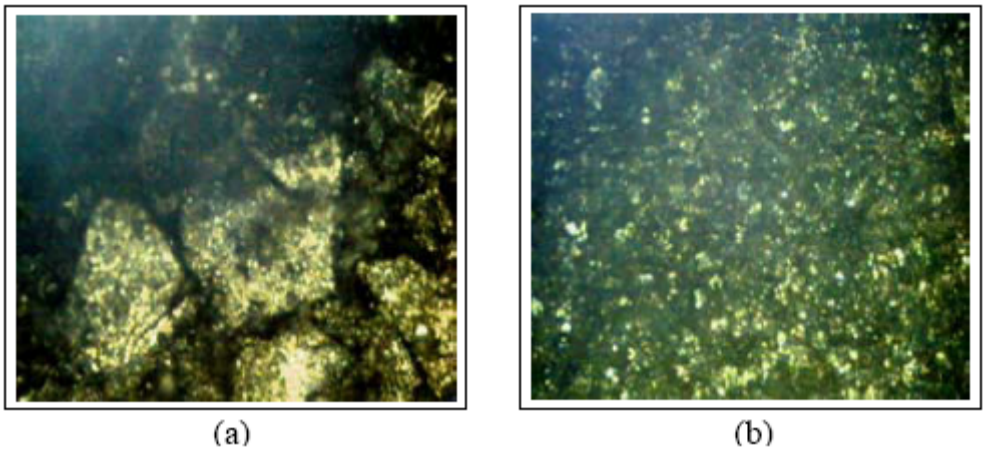


Fig.13: Samples fabricated with copper ratio 40% and two copper forms (a) whisker and SiC grain size of 133μm (b) particles with SiC grain size of 56μm

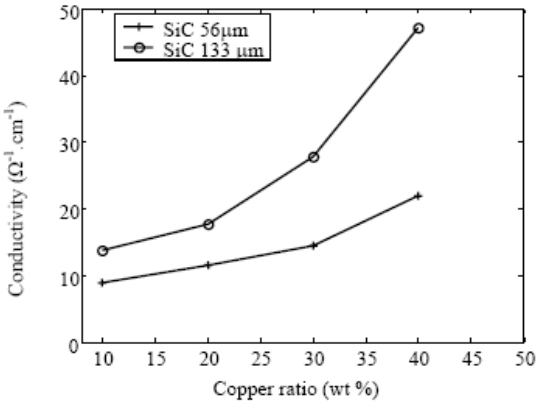


Fig. 14: Effect of copper ratio on conductivity

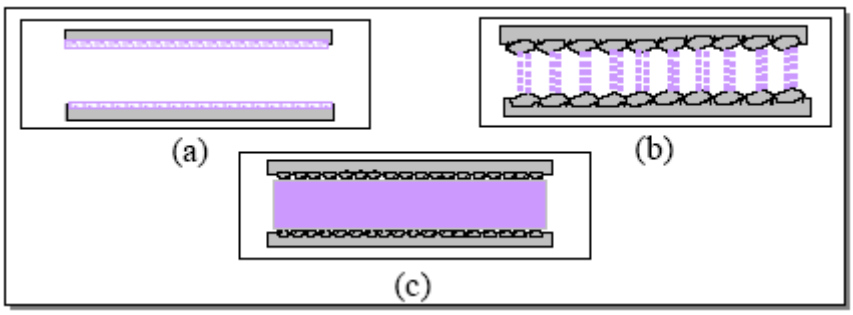


Fig. 15: The shape of discharge between the electrodes with grain sizes

(a) less than 56μm (b) 300μm (c) 133μm

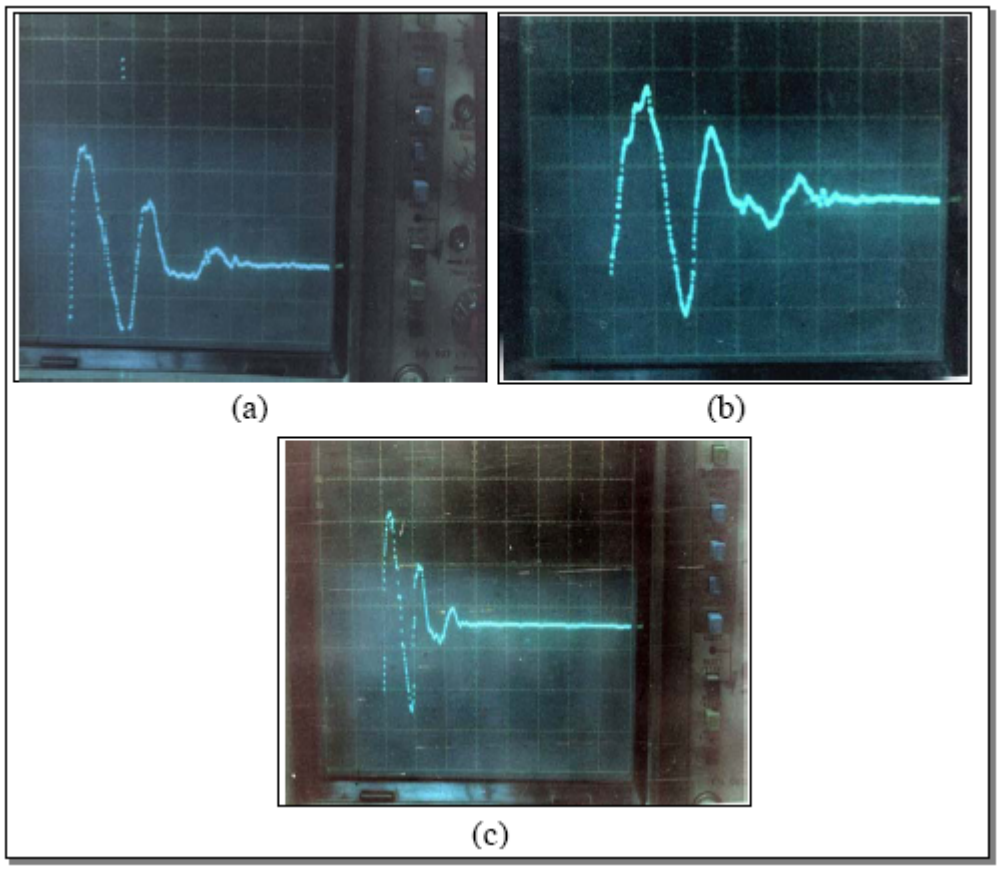


Fig. 16: Current pulse for SiC electrode (x-axis 100 ns/div),
(a) copper ratio of 5% (y-axis 0.80727 kA/div.) (b) copper ratio 10% (y-axis 0.001 kA/div.)
(c) SiC only (y-axis 0.0012 kA/div.)