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Development of Powder Metallurgy (PM) Compacted Cu-TaC Electrodes for EDM

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Abstract: The main aim of this paper is to investigate the properties of Cu-TaC electrodes produced by Powder Metallurgy (PM) method. The design of Experiment (DOE) method was used to plan the investigation. Two different compositions of the powders (Cu-TaC with 30 and 55 % wt TaC) were used. The major properties which determine suitability of electrodes for Electro Discharge Machining (EDM) are electrical conductivity, thermal conductivity and to some extent density. These properties were measured for the green compacted electrodes, analyzed and compared with their sintered counterparts. This is the initial stage to determine the suitability or otherwise of the compacted electrodes. The results showed that the compacted electrodes in green form can be suitable for EDM, since the electrical conductivities are very high (94.96-189.92$\Omega^{-1}m^{-1}$). The thermal conductivity is good (29.70-33.20W/ m K). The density ranges between 6.13 and 9.80 g/cm^3. The sintered electrodes were found to be unsuitable at the specified conditions, because they became non-conductive electrically after sintering. Current efforts are geared towards improving these properties for the sintered ones and also determining their optimum levels.

Key words: Powder metallurgy (PM), green compact, Cu-TaC, thermal conductivity, electrical conductivity, density, EDM (electro discharge machining).

1. Introduction

Electro discharge machining (EDM) employs a pair of electrodes in the metal cutting process. Both the cutting tool and the workpiece must be electrically conductive. The efficiency of metal removal process is greatly influenced by the electrical conductivity of these electrodes [1]. During the EDM, one of the electrodes acts as the cathode while the other is the anode. The electrode has being a significant component of the EDM mechanism. It has been fabricated by quite a number of methods including conventional machining, rapid tooling [2] and powder metallurgy (PM). Several types of them used in cutting are available, ranging from copper, graphite, copper-tungsten, etc.

A good number of research works on PM fabricated electrodes have been carried out. Some of the electrodes were used for conventional EDM [3-6], where material removal was the primary objective of their production. Tsai et al. [7] reported that higher material removal rate (MRR) was realized when using Cu-Cr PM electrode compared to Cu metal electrode. In addition, better surface finish is also attainable with the use of these electrodes [8]. PM compacted electrodes have been also produced and used in pre-sintered or sintered conditions [3, 9-14], while some are being used for machining in green compacted forms [15-16]. The current trend in application of PM compacted electrodes is in area of surface modification of workpiece, where such electrodes are used during

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the machining to effect material transfer onto the work surface. Various types of powders have been compacted by researchers and used to generate layers on the workpiece [15-19]. They reported improvements in materials including increase in wear resistance, corrosion resistance and surface hardness.

This research focuses on the development of EDM electrodes from Tantalum Carbide (TaC) and Copper (Cu) powders using PM method. The suitability of Cu-TaC electrode in machining would first be determined by examining the required properties. TaC powder is an extremely hard refractory ceramic material. It is heavy and brownish in color, usually processed by sintering, and an important cermets material. It has high melting point, about 3,880 °C (4,150 K). Among its area of applications include its addition to tungsten carbide/cobalt (WC/Co) powder attrition to enhance physical properties of the sintered structures. This paper covered the first stage of the research to determine the suitable TaC composition in copper (Cu) powder for use in (EDM). Preliminary results covering the electrical conductivity, thermal conductivity and the densities of the compacted electrodes are presented here.

This paper is arranged as follows: Section 2 presents the experimental methods and the materials used in the investigation; section 3 discusses the results of the electrodes' properties; section 4 is the conclusions and the recommendations made for future work.

2. Experimental Methods and Materials

2.1 Design of Experiment

The Design of Experiment (DOE) was used to plan the investigation. The factors of consideration are powder composition, compacting pressure, sintering temperature and time. The responses of the investigation were electrical conductivity, thermal conductivity and density of the compacted electrodes. These properties were measured for the pre-sintered (green compacts) and sintered electrodes. Table 1 shows the summary of the factors and their level. With the four factors examined at two levels, a 2^4 full factorial experiments were conducted to produce the sintered electrodes. Their properties were determined before and after sintering. The responses of the green compacted electrodes are therefore equivalent to 2^2 full factorial experiments with 4 replicates. The sintered ones were un-replicated.

Table 1 Factors and their levels.

Factor	Low level	High level
A: TaC in composition (%)	30	55
B: Compacting pressure (psi)	1,500	3,000
C: Sintering temperature (°C)	450	850
D: Time (min)	30	50

2.2 Methods and Materials

The materials used are Cu and TaC powders. The Cu powder is of 99.9% purity and 200 mesh, while the TaC powder is of 99% purity, and between 200 and 325 mesh. The electrical conductivities of individual powders were first determined. This was achieved by measuring the compacted electrodes made of each of the powders. They were mixed as specified in the design (Cu-TaC: 70-30% and 45-55%). A manual pellet press (Fig. 1) was used to produce the electrodes which are of 13 mm diameter. They were then sintered at temperatures of 450 and 850 °C, at the times of 25 and 50 minutes as specified in the DOE. The densities were measured with densimeter, while the thermal conductivities were determined with the heat conduction bench model FF 105. The electrical conductivities were measured by determining the resistances of the electrodes with Ohmmeter. The resistance, R, is related with resistivity, ρ, as follow:

$$\rho = RA / L \quad (1)$$

where: ρ—electrical resistivity (Ω);

A—Cross-sectional area (mm^2);

L—Length of the electrode (mm).

For the circular cross section of the electrode, the resistivity becomes

$$\rho = 0.786\, Rd^2 / L \quad (2)$$

The electrical conductivity, σ, is the inverse of the resistivity and becomes

Fig. 1 The carver press used for compaction.

$$\sigma = 1/\rho \quad (3)$$

The design, and the observed properties of both the green compacted and the sintered electrodes are presented in the results section. The three responses measured in respect of each type of electrodes have been analyzed by Design Expert Software DX6 and presented in the figures of the following section.

3. Results and Discussions

3.1 Results and Observations

The experimental design with the results is presented in Table 2. The analyzed results are shown in 3-D response surface curves in the following sections. With the sixteen electrodes, the properties of the green compacted and sintered electrodes are shown there. Test specimens from Cu and TaC powders also indicated their electrical conductivity as 131.85 and 50.23 (1/Ω m) respectively. From Fig. 2, it is observed that the green compacts were reddish-brown in color resembling the original color of the copper powder. However, the sintered products change their colors, ranging from black (Fig. 3) to almost greenish. There were also changes in the sizes of the sintered ones, especially for those sintered at the temperature of 850 °C for 50 minutes (Fig. 4). They experienced increase in their volumes. Cracks were also found in some of them. These cracks may have resulted from high shrinkages experienced during longer sintering periods at high temperatures [20].

3.2 Electrical Conductivity of the Electrodes

The results show that the electrodes are electrically conductive within the range of experimental conditions investigated. They have therefore satisfied the major requirement of EDM electrode. The electrical conductivity ranges between 94.96 and 189.92 (1/Ω m). Analysis also showed that the composition of TaC plays significant role in electrical conductivity. In Fig. 5a, the response surface show that the electrical conductivity reduces gradually as the TaC increase in the Cu-TaC matrix. Thus, electrodes with higher TaC composition tend to exhibit less conductivity. It can even be seen from Table 2 that the least conductive electrode has TaC of 55% in composition, while the

Table 2 Experimental design and results for the compacted electrodes.

Run order	Factors				Green compact electrodes responses			Sintered electrodes responses		
	A (%)	B (psi)	C (°C)	D (min)	Therm. Cond. (W/m K)	Elect. Cond. (1/Ω m)	Density (g/cm^3)	Therm. Cond. (W/m K)	Elect. Cond. (1/Ω m) × 10^{-3}	Density (g/cm^3)
1	55	3000	450	50	30.8	120.53	7.240	29.1	1.3016	5.680
2	30	1500	450	50	31.2	157.78	8.750	30.3	2.0518	4.717
3	30	3000	850	30	33.2	154.86	8.519	29.3	0.8963	4.498
4	30	3000	450	30	30.1	178.96	6.969	30.0	1.8887	5.520
5	55	1500	450	50	31.2	94.96	9.411	30.0	1.7604	5.156
6	30	1500	450	30	30.4	157.78	8.620	29.8	1.1794	5.558
7	30	1500	850	50	30.6	123.13	8.425	31.4	0.0321	3.958
8	55	3000	450	30	29.7	129.05	9.801	30.1	6.4089	5.724
9	30	3000	850	50	31.2	132.70	8.504	29.9	0.0018	4.107
10	55	1500	450	30	30.5	124.18	8.995	31.6	2.7484	5.159
11	55	3000	850	30	31.3	143.66	9.710	30.9	0.0081	4.857
12	55	3000	850	50	31.4	175.31	7.520	30.0	0.0035	4.954
13	55	1500	850	30	32.3	144.87	6.374	31.0	0.0042	4.992
14	30	3000	450	50	30.8	189.92	7.026	29.4	4.2371	5.498
15	30	1500	850	30	32.2	150.47	6.128	29.1	0.0135	5.416
16	55	1500	850	50	31.9	107.74	8.953	28.4	0.0018	0.309

Fig. 2 Green compacted electrodes.

Fig. 3 Electrodes sintered at 450 °C for 30 min.

Fig. 4 Electrodes sintered at 850 °C for 50 min.

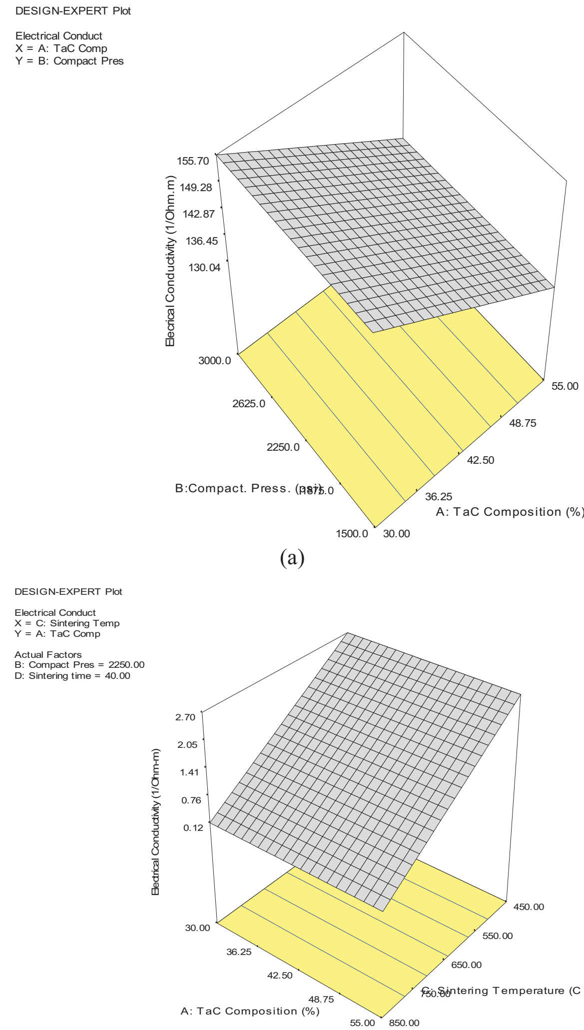

Fig. 5 3-D Surface plot of electrical conductivity of the electrodes: (a) Green compacts; (b) Sintered compacts.

most conductive electrode have 30%. These are consistent with the fact that the electrical conductivity of TaC is lower than that of Cu.

For the range of sintering conditions used, the electrodes became highly resistive to electricity. The resistivities are of the order of kilo ohms. Their conductivity ranges between 1.8×10^{-3} and 6.41×10^{-3} ($1/\Omega$ m). Fig. 5b indicated that sintering time is very significant. Most of the electrodes that failed to retain their shapes with or without cracks were sintered at the period of 50 minutes. This is an unexpected happening because crystallization and grain growth that are expected to occur across the boundaries should rather increase the strength of the compacts. This crystal growth across the inter-particle boundary bonds the particles together and the availability of free electrons for electrical conductivity is not supposed to be affected. However the reason for this lost in conductivity would be investigated.

3.3 Thermal Conductivity

A reasonable level of thermal conductivity of electrode is required to conduct the heat generated during EDM away easily [21]. If this is not attainable, the electrode wear rate would be high. This is why thermal conductivity is so important. For the range of investigation, thermal conductivity is between 29.70 and 33.20 W/m K for the green compacts (Fig. 6a), while it is between 28.40 and 31.6 W/m K at 40 °C the sintered ones. In the case of the green compacts, it is observed that the values neither dependent on the composition nor the compacting pressure. The two responses in Fig. 6 exhibit different trends in their thermal conductivities. The values are generally lower in the sintered electrodes (Fig. 6b), which also exhibit curved lines. These curved lines are brought about by the interaction effect between TaC composition and sintering time [22]. It also showed that a saddle point (minimax) exist, after which thermal conductivities shows little increment at small sintering times with increasing TaC compositions. Further exploration of the trend may not be necessary, since the sintered electrodes are not conductive.

3.4 Density of the Electrodes

The compacted copper electrode has density of 5.39 g/cm^3. This is lower than the average density of the green compacted electrodes, which ranges between 6.13 and 9.80 g/cm^3. Thus, all the green compacted electrodes have higher densities than Cu powder electrode, implying that TaC might have significantly influenced their densification. Densities are seen to be increasing with increasing TaC compositions, while the pressure is less significant. This can be clearly seen in Fig. 7a, where the densities are shown as being fairly constant over the surface of compacting pressures.

The sample densities of the sintered electrodes are generally lower than those of the green compacts. The lowest being 3.96 g/cm^3, while the highest is 5.72 g/cm^3. Hassan et al. [3] also obtained decreasing values of density when they sintered Cu-Al_2O_3 matrix. Both the sintering temperatures and times were found to have played vital roles in the density of the electrodes. Fig. 7b shows that the density of sintered electrodes decreases with increasing temperatures. This can be due to increase in volume of the electrode mass during sintering. This volume increase also led to near failure of some electrodes at higher sintering times.

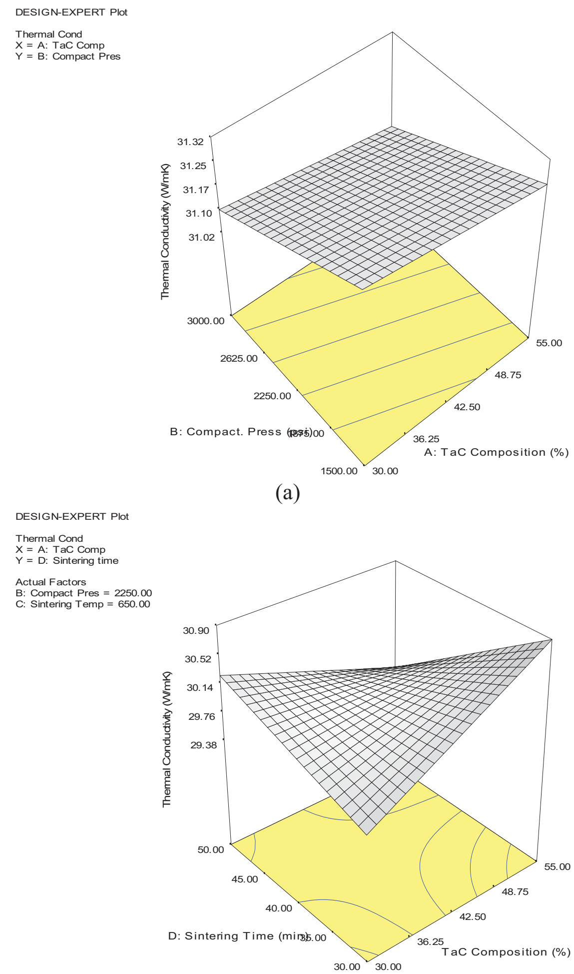

Fig. 6 3-D Surface plot of thermal conductivity of the electrodes: (a) Green compacts; (b) Sintered compacts.

4. Conclusions and Recommendations

For the range of the compacting pressures and compositions investigated, it is found that the electrodes are both electrically and thermally conductive when examined as green compacts. There are also no significant variations in the electrical

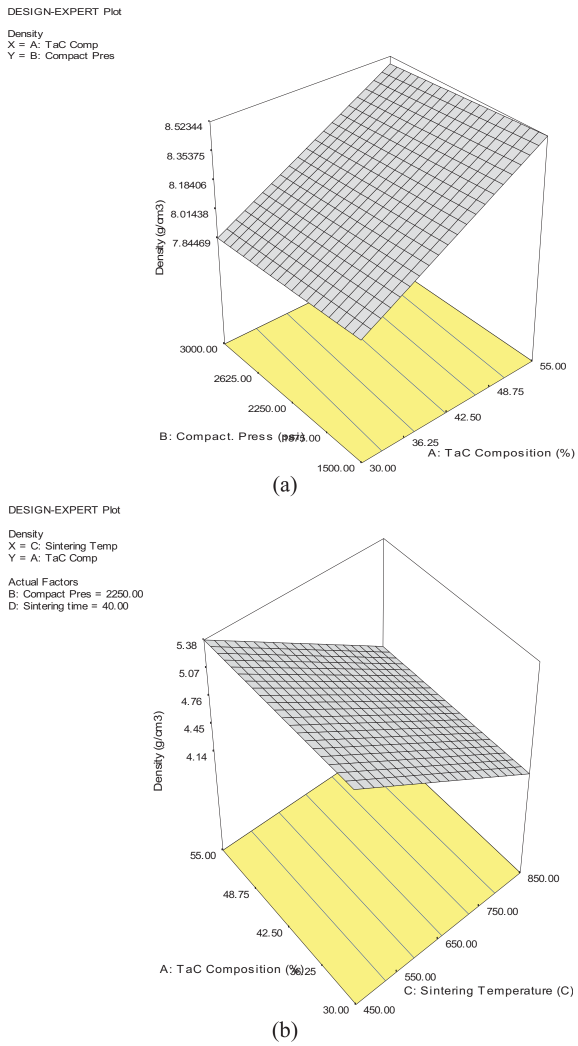

Fig. 7 3-D Surface plot of density of electrodes: (a) Green compacts; (b) Sintered compacts.

conductivities of the green compacted electrodes over the composition and pressure range used. This implies that the products can be use in EDM. However, their behavior at various levels in machining would have to be determined.

Green compacted electrodes generally possess higher densities compared to the sintered ones.

The electrodes under the current sintering conditions cannot be use for EDM, because they are not electrically conductive.

A further investigation is needed at lower temperatures and times to determine the appropriate sintering conditions for the Cu-TaC electrode.

Micro-structural investigations of the compacted electrodes should be carried out to see the particle orientation of the powder mixture.

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