UDK 67.017:661.665.1:691.73 ISSN 1580-2949
Original scientific article/Izvirni znanstveni članek MTAEC9, 50(4)585(2016)

FABRICATION AND PROPERTIES OF SiC REINFORCED COPPER-MATRIX-COMPOSITE CONTACT MATERIAL

IZDELAVA IN LASTNOSTI S SiC UTRJENEGA KOMPOZITNEGA MATERIALA NA OSNOVI BAKRA

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Prejem rokopisa – received: 2015-07-01; sprejem za objavo – accepted for publication: 2015-07-28

doi:10.17222/mit.2015.175

This study aims at improving mechanical properties of electrical contacts through copper and copper-matrix silicon-carbide-reinforced composites produced with powder metallurgy. Copper powder was produced with the cementation method. Pure copper and mixtures of copper with 3 % of mass fraction of SiC powder were pressed with a uniaxial pressure of 280 MPa and sintered at 700 °C for 2 h in an atmospheric environment. After the sintering, these compacts were immediately pressed at a load of 850 MPa while the samples were hot. The characterization of the samples was made with microstructural investigations, relative-density experiments, electrical-conductivity and hardness measurements. XRD analyses revealed that there are no other phases besides Cu and SiC in the sintered samples. Electrical conductivity of pure copper was reduced from 91.7±1.8 % IACS to 66.4±0.9 % IACS but the hardness of pure copper was increased from 127±1.2 HVN to 142±6.0 HVN with the addition of 3 % of mass fraction of SiC. Contact-count experiments were made with these samples to determine the contact performance for (3000, 6000, 9000, 12.000 and 21.000) turns-on/off. The loss of the contact material increased with the increasing number of turn-ons, related with the increased copper oxide amount formed on the contact surfaces.

Keywords: Cu-SiC composite, hardness, relative density, electrical conductivity, IACS, contacts test

Namen študije je izboljšanje mehanskih lastnosti električnih kontaktov iz bakra in kompozita bakra, ojačanega z delci silicijevega karbida, izdelanih iz prahov. Prah bakra je bil izdelan z metodo cementacije. Čisti baker in mešanice bakra s 3 masnimi odstotki SiC so bili enoosno stiskani s tlakom 280 MPa in sintrani 2 h na 700 °C v atmosferskem okolju. Po sintranju so bili vzorci še vroči stisnjeni z obtežbo 850 MPa. Vzorci so bili karakterizirani s preiskavo mikrostrukture, z eksperimenti relativne gostote, z meritvijo električne prevodnosti in z meritvijo trdote. Rentgenska difrakcija je odkrila, da v sintranih vzorcih ni drugih faz, razen Cu in SiC. Električna prevodnost čistega bakra se je zmanjšala iz 91,7±1,8 % IACS na 66,4±0,9 % IACS, trdota čistega bakra se je povečala iz 127±1,2 HVN na 142±6,0 HVN z dodatkom 3 masnih odstotkov SiC. Preizkusi števila kontaktov so bili izvedeni s temi vzorci za določitev zmogljivosti kotaktov pri (3.000, 6.000, 9.000, 12.000 in 21.000) vklopih in izklopih. Izguba materiala kontakta se povečuje s povečanjem števila vklopov, kar je posledica povečanega obsega tvorbe oksida bakra na kontaktni površini.

Ključne besede: Cu-SiC kompozit, trdota, relativna gostota, električna prevodnost, IACS, preizkus kontaktov

1 INTRODUCTION

There are many electrical contact materials subject to relative motions and used in a variety of applications, such as electrical switches, contactors, circuit breakers, connectors, relays, chips in cards, voltage regulators, arcing tips and switch gears.[1,2] Electrical contact materials used in these applications must have a good combination of wear strength, high electrical conductivity, and erosion and welding resistance. On the contrary, low electrical conductivity and wear resistance cause poor contact and arcing, and thus the contacts erode. An electric arc is the form of an electric discharge with the highest current density that takes place when contacts are in the process of establishing a current flow interrupting the flow of the current. Depending on high temperature and mass flow on the contact material surface, an erratic contact resistance and a material loss occur, thus the contact material surface is severely corroded and eroded. Hence, a contact material should have a high resistance to corrosion as well as a high arc-erosion resistance to maintain the contact integrity by having high electrical and thermal conductivity, a high melting point and also a certain strength.[2,3] As copper has a high thermal conductivity, a low electrical resistance, a lower coefficient of thermal expansion (CTE) than aluminum and can easily be formed or machined into complicated lead frames or base plates, it is extensively used for cables, wires, electrical contacts and a wide variety of other parts that are required to pass electrical current.[4,5]

Cu-based composites were feasible to be used as electrical-contact materials in relays, contactors, switches, circuit breaks and other switch-gear components.[6] As SiC has a high thermal conductivity and offers good availability, low price and possible machinability, it can be used as a reinforcement in copper-based composites for high-performance heat-sink materials and packages. Dispersion of fine SiC particles improve the copper-matrix strength through impeding the dislocation movement and also prevent the grain growth of the copper matrix at high temperature so that the composites can maintain a relatively high strength at elevated temperature.[3,7–9] In the present work, the effects of SiC particles on the electrical, mechanical and also contact performance of Cu-SiC composites were investigated.

2 EXPERIMENTAL DETAILS

The copper powder used in this study was produced, with the cementation method, from $CuSO_4$ solutions using metallic-iron powder. Cemented Cu powder and 3 % mass fractions of SiC powder with a 99.5 % purity and a 1 μm particle size were mechanically mixed and cold pressed. The sintering of pure copper and copper 3 % mass fraction of SiC was performed at 700 °C for 2 h, embedded in the graphite powder. In order to increase the relative density and mechanical properties of test samples, they were hot pressed after the sintering. The presence of the phases formed within the sintered samples was determined with X-ray diffraction using Cu-K_α radiation with a wavelength of 1.5418 A over a 2θ range of 10–90°. The relative densities of the composites were measured with a method based on Archimedes' law.

The microstructure analysis of the composites was performed with a JEOL JSM-5600 model scanning electron microscope (SEM). The microhardness of both pure copper and the composite was measured with a Leica WMHT-Mod model Vickers-hardness instrument under an applied load of 50 g. The measurements of electrical conductivity of the specimens were performed with a GE-model electrical-resistivity measurement instrument. The experimental set-up for the contact test consisted of a square 555-wave oscillator turning on/off the contactor, a counter and a contactor, on which the samples were mounted. The contact counter was adjusted to the desired number (3000, 6000, 9000, 12.000 and 21.000) before the experiment. When the selected count number was reached, the operation was automatically ended. The electrical load over the counter was 1600 W (at 220 V) for all the experiments. The experimental set-up used in this study is shown in **Figure 1**. The weight loss of the samples was determined. Subsequently, surface and oxide evaluations of the samples were carried out with SEM-EDS.

3 RESULTS AND DISCUSSION

SEM micrographs of Cu and the SiC reinforcement agent used in the experimental studies and the sintered Cu-3 % of mass fractions of SiC composite are given in **Figure 2**. It is seen from **Figure 2a** that copper powder has a spherical shape and a particle size of 5 μm; and it is seen from **Figure 2b** that SiC particles have an angular and irregular shape, and a diameter of 1 μm. In **Figure 2c** light-grey areas indicate the Cu matrix and dark-grey and cornered shapes indicate the SiC reinforcement component.

XRD patterns of the Cu-3 % of mass fractions of SiC composite consist of copper and SiC peaks (**Figure 3**). No oxide peak was observed in the XRD analysis of the Cu-3 % of mass fractions of SiC composite sintered at 700 °C for 2 h. The relative density, hardness and % IACS (the international annealed copper standard) of the samples are given in **Table 1**. The relative density of the sintered samples decreased with the addition of SiC because SiC particles behave as an obstacle for the Cu atom diffusion. On the contrary, the hardness was found to increase with the SiC addition. The SiC addition strongly impeded the plastic flow, causing the hardness of the Cu-SiC composite to increase with the amount of reinforcing particles. It is known that the higher the relative density the higher is the electrical conductivity.

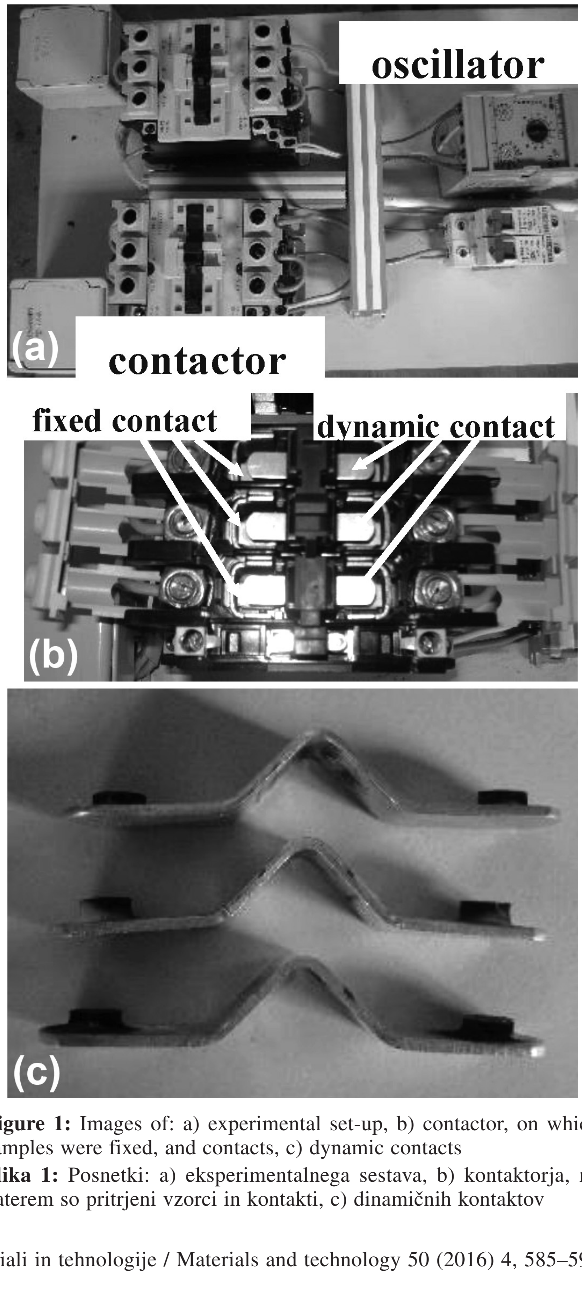

Figure 1: Images of: a) experimental set-up, b) contactor, on which samples were fixed, and contacts, c) dynamic contacts

Slika 1: Posnetki: a) eksperimentalnega sestava, b) kontaktorja, na katerem so pritrjeni vzorci in kontakti, c) dinamičnih kontaktov

The electrical conductivity of the composites decreased with the increment in the SiC content because ceramic-based SiC forms a barrier to the motion of copper electrons, providing electrical conductivity.

Generally, the weight loss increased with the increasing contact count for both Cu and Cu-3 % of mass fractions of SiC composite. But it is obvious that the material loss of the Cu-3 % of mass fractions of SiC composite is higher than that of pure Cu (**Figure 4**).

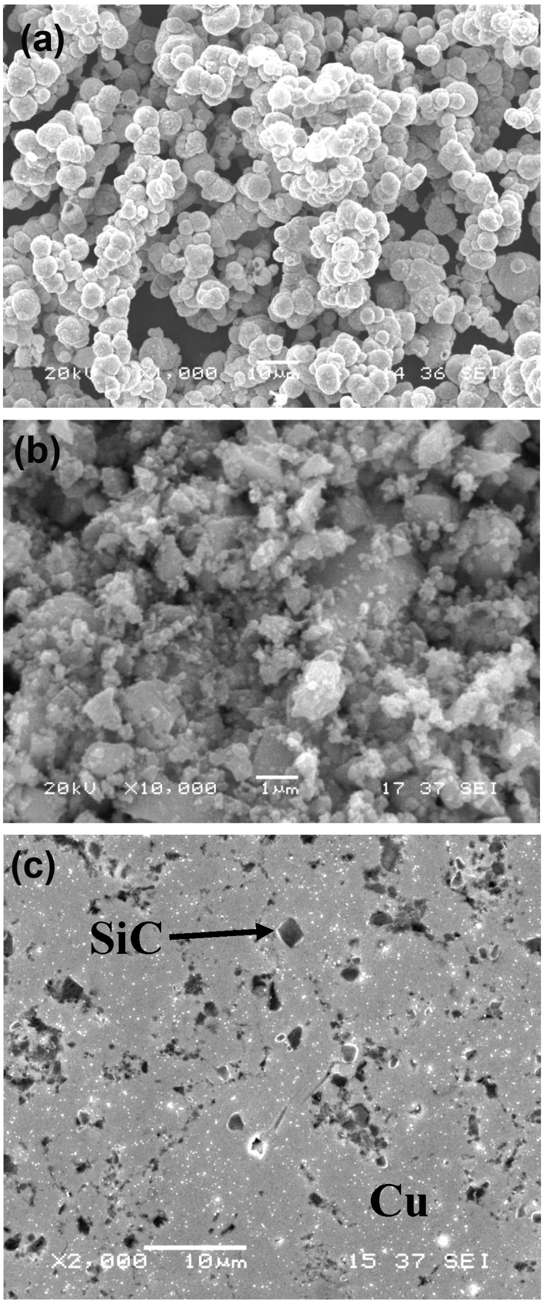

Figure 2: SEM micrographs of: a) copper powder, b) SiC particles and c) Cu-3 % of mass fractions of SiC composite

Slika 2: SEM-posnetki: a) prah bakra, b) delci SiC in c) kompozit Cu-3 % masnega deleža SiC

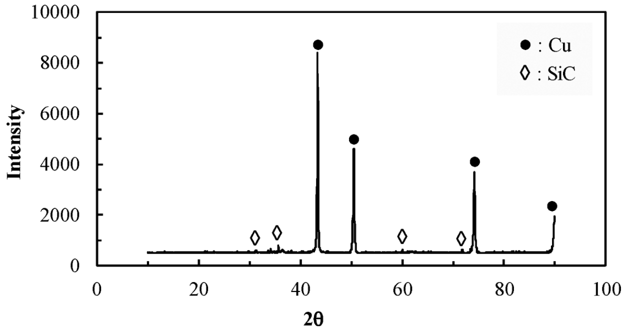

Figure 3: XRD patterns of Cu-3 % of mass fractions of SiC composite sintered at 700 °C for 2 h

Slika 3: Rentgenogram kompozita Cu-3 % masnega deleža SiC, sintranega 2 h na 700 °C

Table 1: Relative density, hardness and electrical-conductivity values of Cu and Cu-3 % of mass fractions of SiC composite sintered at 700 °C for 2 h

Tabela 1: Relativna gostota, trdota in električna prevodnost Cu in kompozita Cu-3 % masnega deleža SiC, 2 h sintranega na 700 °C

Samples	Relative density (%)	Hardness (HV)	% IACS
Cu	97.5 ± 0.8	127 ± 1.2	91.7 ± 1.8
Cu-3% of mass fractions of SiC	92.3 ± 1.1	142 ± 6	66.4 ± 0.9

SEM photographs of the sample surfaces after (3000, 6000 and 9000) turns-on/off are given in **Figures 5** and **6**. When SiC reinforced contact materials heat up, they have to absorb heat, cool down the contact and delay the arc formation; thus, their material loss is lower than that of pure copper.[2] But it can be seen from the SEM micrographs that the surface of the Cu-3 % of mass fractions of SiC composite is destroyed to a larger extent than the surface of pure Cu; in addition, spherical formations, which got smaller with the increasing contact count number, were detected on the contact surfaces. With the increasing contact count number, deformed regions

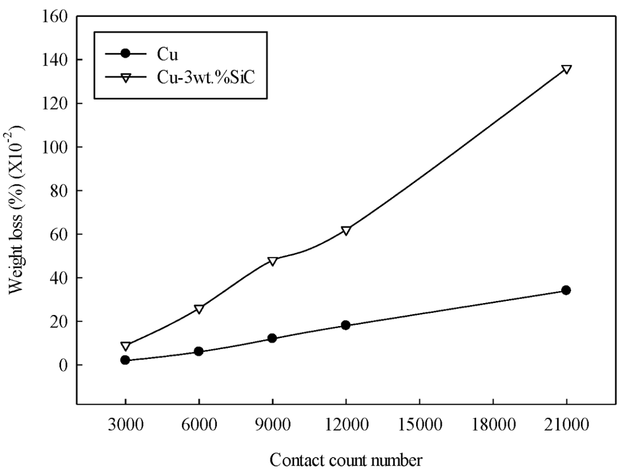

Figure 4: Weight loss of the contact via the contact count number

Slika 4: Zmanjšanje teže kontakta v odvisnosti od števila vklopov

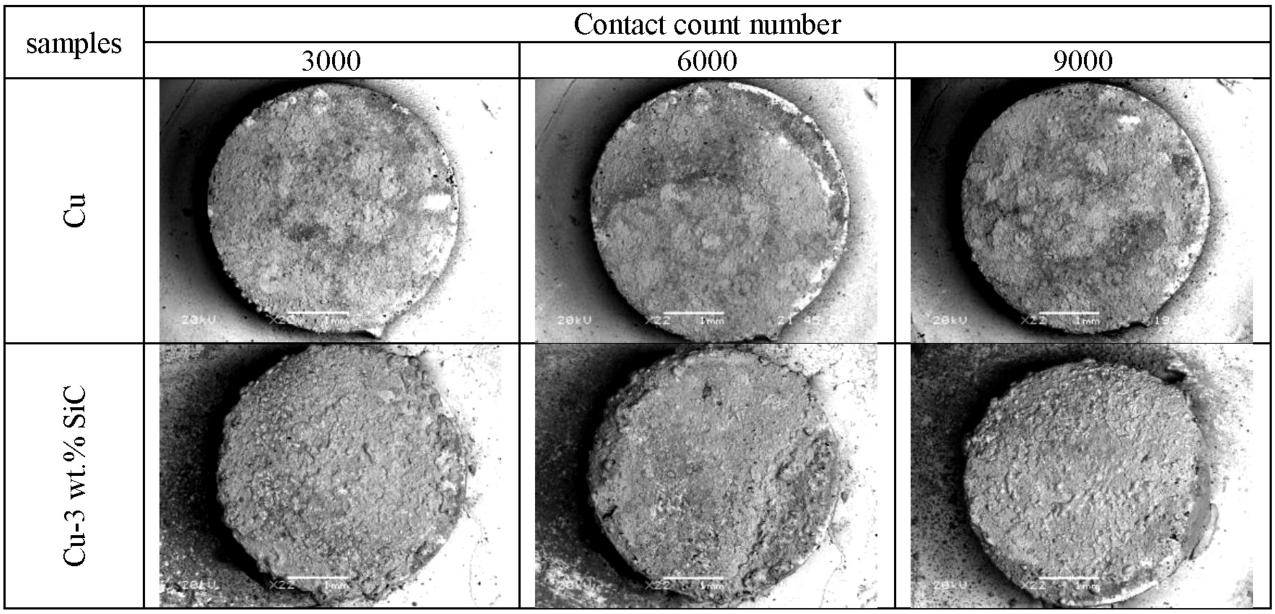

Figure 5: SEM micrographs of Cu and Cu-3 % of mass fractions of SiC composite at a low magnification after 3000, 6000 and 9000 turns on/off
Slika 5: SEM-posnetki Cu in kompozita Cu-3 % masnega deleža SiC pri majhni povečavi, po 3000, 6000 in 9000 vklopih in izklopih

increased and local melting and smearing areas were formed.

EDS result taken from the surfaces of the contact samples are given in **Figures 7** and **8**. It was found that the weight loss increased with the increasing number of turns on/off in the contact-count experiments. Surface evaluations showed that oxide increased when the number of turns on/off increased and the arc formation got easier. O. Guler and E. Evin[2] claimed that an increased copper oxide amount simplifies the arc formation between the contacts by increasing the contact resistance. An increasing arc or a high resistance on a contact-material surface during a turn on/off heats up the contact surfaces. When the contact number is increased, particles on the surface become coarser. Brittle oxide layers on the contact material are broken by the impact force formed during turns on/off and removed from the surface. This causes a mass loss. This situation continues with a feedback mechanism.[2] The EDS analysis of the sphere formations on the pure Cu surface after 9000 contacts show that these regions are O- and Cu-rich areas (**Figure 7**). The EDS analysis shows that many Cu-rich regions

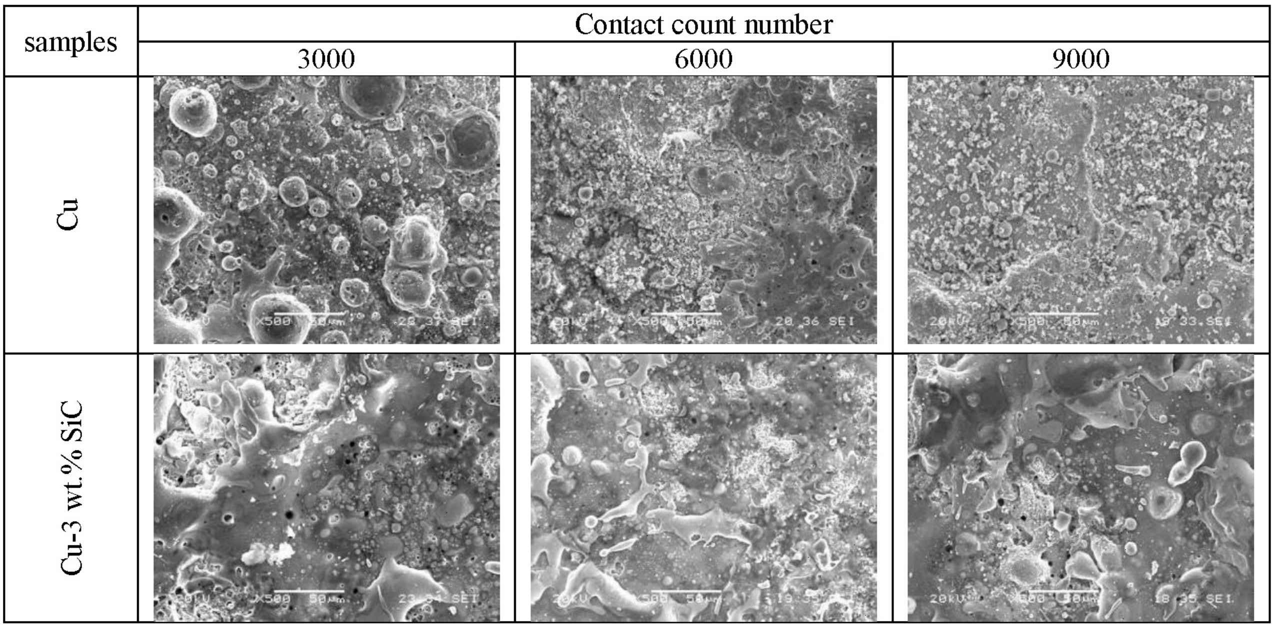

Figure 6: SEM micrographs of Cu and Cu-3 % of mass fractions of SiC composite after 3000, 6000 and 9000 turns on/off
Slika 6: SEM-posnetki Cu in kompozita Cu-3 % masnega deleža SiC po 3000, 6000 in 9000 vklopih in izklopih

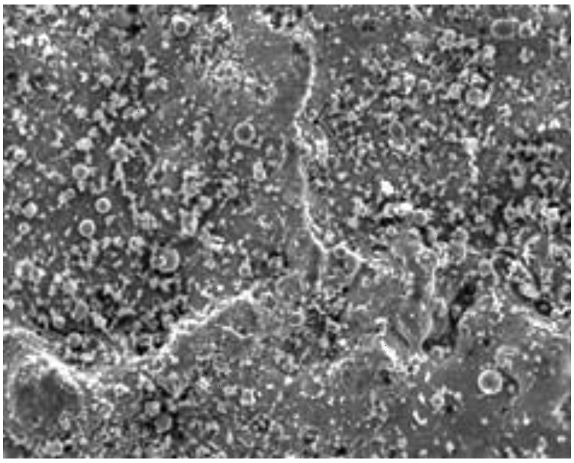

Figure 7: SEM micrograph and EDS analysis of Cu contact after 9000 turns on/off

Slika 7: SEM-posnetek in EDS-analiza Cu kontakta po 9000 vklopih in izklopih

w/%	Marks					
	1	2	3	4	5	6
C		15.66				
O	16.25	17.68	23.900	20.87	17.87	1.641
S			0.328			
Fe	1.181	0.845	1.035	1.158	0.765	0.510
Cu	82.56	65.79	74.737	77.96	81.35	97.85

remain intact because they are under the average contact level. The remaining Cu-rich areas show that the contact material can resist more turn on/off cycles.

In **Figure 8**, glassy regions rich with silicon, verified with the EDS analysis, are obvious. SiC particles probably oxidized with the increasing arc, the heat effect and/or the Cu and Si compounds formed. A. K. Kang and S. B. Kang[10] indicated that SiC particles decompose into Si and C and merge with Cu. T. Schubert et al.[5] claimed that SiC is not stable at elevated temperatures and forms Cu-Si solid solutions due to its decomposition. In **Figure 8**, Si-rich areas indicated with arrows have some bubbles and pores. These pores may result from gas reactions. It is thought that the gases in these bubbles leak towards the surface with the increasing heat/arc and bulge on the material surface. During the contact test, decomposed C reacts with O, which results in CO_2 and CO gas formations.[10] The microcracks in the micrographs indicate that the contact surfaces are brittle and may be coated with a thin oxide film (**Figure 8b**).

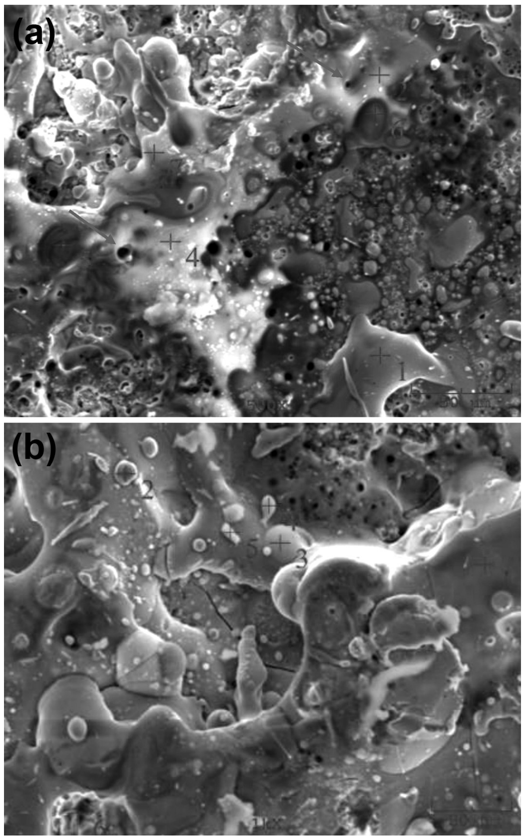

Figure 8: EDS analysis of Cu-3 % of mass fractions of SiC composite after: a) 3000, b) 9000 turns on/off

Slika 8: EDS-analiza kompozita Cu-3 % masnega deleža SiC po: a) 3000 in b) 9000 vklopih in izklopih

w/%	Marks						
	1	2	3	4	5	6	7
C	2.364						
O	8.36	42.1	16.9	39.4	31.9	24.0	21.8
Si		16.1	4.39	17.8	11.9	6.00	11.2
Fe	0.86	4.08	0.83	5.86	2.90	1.83	5.85
Cu	88.4	37.6	77.8	36.8	53.1	68.1	60.9

w/%	Marks					
	1	2	3	4	5	6
O	42.05	7.707	8.085	49.89	51.44	11.06
Si	17.77	0.939	1.630	15.83	14.76	0.219
Fe	8.527	1.152	1.024	6.112	5.813	0.226
Cu	31.64	90.20	89.26	28.15	27.97	35.09

4 CONCLUSIONS

A cemented Cu-SiC composite was manufactured successfully with the powder-metallurgy method. The presence of Cu and SiC was verified with an XRD analysis. All of the samples manufactured had a remarkably high relative density. The hardness of the composite was increased with added SiC. It was observed that the electrical conductivity of the Cu-SiC composite is in good agreement with the literature. During the contact-count experiments, the weight loss and oxidation increased with the increasing number of turns on/off for both samples. Also, the surface of the Cu-3 % of mass fractions of SiC composite was destroyed to a larger extent than the surface of pure Cu.

Acknowledgment

The authors thank expert Fuat Kayis for performing the XRD and SEM-EDS studies and special thanks are extended to technician Ersan Demir of the Sakarya University for assisting with the experimental studies. This work was conducted as a project supported by TUBITAK, with the contract number of 106M118.

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