UDK 621.762:621.762.5:669.3
Professional article/Strokovni članek

ISSN 1580-2949
MTAEC9, 48(6)977(2014)

EFFECT OF THE COPPER AMOUNT IN IRON-BASED POWDER-METAL COMPACTS

VPLIV VSEBNOSTI BAKRA V KOVINSKIH STISNJENCIH IZ PRAHU ŽELEZA

Uğur Çavdar[1], Bekir Sadık Ünlü[2], Enver Atık[3]

[1]Celal Bayar University, Vocational High School, Department of Machinery, 45400 Turgutlu, Manisa, Turkey
[2]Celal Bayar University, Technology Faculty, Department of Manufacturing Engineering, 45400 Turgutlu, Manisa, Turkey
[3]Celal Bayar University, Engineering Faculty, Department of Mechanical Engineering, 45140 Muradiye, Manisa, Turkey
ugur.cavdar@cbu.edu.tr

Prejem rokopisa – received: 2013-12-27; sprejem za objavo – accepted for publication: 2014-02-05

In this study, iron-based powder-metal (PM) compacts were sintered using a medium-frequency induction-heating system. The effects of copper amounts on mechanical properties were investigated. Iron-based powders were mixed with mass fractions w = 1 % to 6 % copper (Cu) and 0.8 % zinc stearate in a V-type mixer. During the sintering process, PM compacts were sintered at a frequency of 30–50 kHz (medium frequency), at 12 kW and 1120 °C for 400 s in an atmospheric environment. Mechanical properties, microstructural properties, densities and microhardness values were investigated for the sintered material. The highest mechanical properties were obtained for the iron-based PM compacts including 3 % Cu.

Keywords: induction sintering, powder metal, iron, copper

V tej študiji so bili kovinski stisnjenci iz prahu železa (PM) sintrani v srednjefrekvenčnem indukcijskem ogrevalnem sistemu. Preiskovan je bil vpliv vsebnosti bakra na mehanske lastnosti. Mešanica osnovnega prahu železa z masnim deležem w = 1 % do 6 % bakra (Cu) in 0,8 % cinkovega stearata je bila premešana v V-tipu mešalnika. Pri sintranju so bili PM-stisnjenci sintrani 400 s pri frekvenci 30–50 kHz (srednja frekvenca) pri 12 kW, 1120 °C, v navadni atmosferi. Preiskovane so bile mehanske lastnosti, mikrostrukturne lastnosti, gostota in mikrotrdota sintranega materiala. Najboljše mehanske lastnosti so bile dobljene pri PM-stisnjencih iz prahu železa s 3 % Cu.

Ključne besede: indukcijsko sintranje, kovina iz prahu, železo, baker

1 INTRODUCTION

Powder metallurgy (PM) is the most diverse manufacturing approach among various metalworking technologies. PM makes it possible to fabricate high-quality, complex parts to close tolerances in an economical manner.[1] Sintering, which is one of the oldest human technologies, is a technique of consolidating powder compacts using mechanical and thermal energy.[2] Mixtures of elemental iron powders are commonly used for PM applications. A small amount of copper powder is always added to develop the mechanical properties of sintered alloys owing to its relative ease of dissolving and diffusing in an iron matrix upon sintering. Extensive investigations on the sintering properties of the Fe-Cu alloy made from elemental powders are well reported.[3–7] However, few studies have been conducted to investigate the effect of copper amounts on the microstructures of sintered iron compacts. Several sintering operations are carried out using medium-frequency induction.[8–10] The high-frequency induction-heated sintering method (HFIHS), allowing a fabrication of dense materials within two minutes, has been shown to be effective in achieving this goal.[11–33]

PM compacts are heated via heat transfer during sintering in conventional sintering furnaces or continuous mesh-belt furnaces. However, PM compacts can also be heated with the magnetic current, which passes over a PM compact in an induction sintering process. The advantage of medium frequency is the improved penetration depth, which is deeper than at a high frequency. This depth, known as the reference depth or skin depth, depends on the frequency of the alternating current through a coil and the electrical resistivity and relative magnetic permeability of a work piece. The medium-frequency induction sintering process involves rapid sintering of a powder metal in a very short time with a high-temperature exposure. This process has advantages because it allows a rapid densification of the associated materials and inhibits the grain growth in powder metals.

Shon et al.,[15,29,30] Xiaopeng et al.,[16] Khalil et al.,[17,27] Kim et al.,[21–23] Abdelrazek and Won,[26] Montasser[28] and Park et al.,[31] examined the mechanical properties of high-frequency induction-sintered nano- or powder-metal compacts.

Wang,[8] Shon et al.[30,33] and Park et al.[31] investigated the mechanical properties of high-frequency induction-sintered compacts including nano iron. Çavdar and Atik[9,10] reported about the mechanical properties of the medium-frequency induction-sintered iron or iron-based powder compacts. Zhang et al.[34] studied a conventionally sintered Fe-Cu compact.

Wang[8] investigated the effect of alloying elements and processing factors on the microstructure and hardness of sintered and induction-hardened Fe-C-Cu alloys. He determined that the volume dilation increases with the increasing compacting pressure. The hardness of sintered Fe-C-Cu-P alloys increases with the increasing compacting pressure and carbon amount. A further strengthening resulted from a strong solution-hardening effect of the phosphorus in iron. The hardness variation of the sintered alloys with carbon amounts depends on the compacting pressure. During induction hardening the surface hardness also increases with the increasing carbon amount and compacting pressure, but in a different mode compared to the as-sintered state. This is caused by a phosphorus addition.

The swelling of the Fe-Cu materials sintered at the temperatures above the copper melting point during sintering has been studied for many years. It has been shown that the penetration of liquid copper into the iron inter-particle boundaries is the dominant mechanism.[34] Zhang et al.[34] investigated the modelling of the swelling of the Fe-Cu compacts sintered at the temperatures above the copper melting point. In the model, the combined effect of copper amount, porosity, particle size and heating rate on the swelling is analyzed. The calculated volume and dimensional growths show a qualitative agreement with the published data. In addition, the calculated results can be used to predict the swelling of the Fe-Cu compacts with different copper amounts and green densities. In this model, the effect of copper amount, particle size and heating rate on the swelling is described using the particle coordination number to present the role of the porosity. The model can describe the observed influence of copper amount, porosity, particle size and heating rate on the swelling.

Çivi et al.[35] investigated the reliability of the mechanical properties of induction-sintered iron-based powder-metal parts. They reported that by increasing the sintering time, the reliability of the ultimate stress, the ultimate strain and the Rockwell-B hardness were increased by (10, 50 and 90) %. They found that the Vickers hardness values were generally not increased with the induction sintering time. In addition, they found that the microhardness (HV) test is not appropriate for the powder-metal parts that have porosity. Due to the results of the Rockwell-B hardness tests, it is also suggested that the macrohardness tests such as Rockwell-B and Brinell are more appropriate and more accurate for the powder-metal parts with porosity and alloying elements.

In Wang's study[8] the blended powder mixtures were compacted, sintered and the P-containing sintered alloys were induction hardened. They showed that the microstructure of sintered Fe-C-Cu alloys varies with the copper amount. The refined and decreased volume of pro-eutectoid ferrite was observed when the copper amount was increased. The ferrite phase is markedly hardened by the dissolved copper. The P-containing specimens exhibit a significant volume expansion after the sintering.

Kurt and Ateş[36] used the same composition as we did in our work. They found that the samples sintered at 1150 °C have a better density. They determined that the thermal conductivity decreases because of a porous microstructure. In addition, Arik and Turker[37] investigated mechanical alloying of the same composition. They reported that mechanical alloying resulted in a formation of finer powder particles containing homogeneously distributed carbon in iron. They maintained that this process also caused a high deformation of the particles which increased the internal energy. They showed that the hardness, the strength and the microstructure of sintered compact specimens were affected by the mechanical-alloying time and sintering temperature. These results are in good agreement with our work.

Feldshtein and Dyachkova[38] investigated the properties and tribological behaviors of P/M iron-based composites reinforced with ultrafine particulates. They obtained friction coefficients on the surfaces of MMCs containing nanocrystalline particulates, reduced by 2–3 times compared to the base material, while the critical seizure pressure was increased from 2 to 5 times. In addition, they observed that the presence of nanocrystalline particulates hinders the appearance of fracture microcracks on the surfaces during friction, preventing the movement of dislocations. The wear resistance of MMCs increases by 2–4 times compared to the base material.

In this study, we investigated the 1–6 % Cu iron-based powder-metal compacts that were sintered using the medium-frequency induction-heated system. The sintered compacts were compared with respect to their fracture strength, deflection at fracture, microhardness and density values. The goal of this research was to find the optimum copper amount for the iron-based powder-metal compacts.

2 EXPERIMENTAL STUDIES

In this study, 1–6 % Cu iron-based powder-metal compacts were used. The chemical compositions of the PM compacts are given in **Table 1**.

Table 1: Chemical compositions of iron-based PM compacts (mass fractions, *w*/%)

Tabela 1: Kemijska sestava stisnjencev (PM) iz prahu železa (masni deleži, *w*/%)

Powder	Cu	Fe	Lubricant (Zn stearate)
Quantity 1	1	Balance	0.8
Quantity 2	2	Balance	0.8
Quantity 3	3	Balance	0.8
Quantity 4	4	Balance	0.8
Quantity 5	5	Balance	0.8
Quantity 6	6	Balance	0.8

All the powders were mixed with 0.8 % Zinc stearate, used as a lubricant during the pressing. The particle sizes

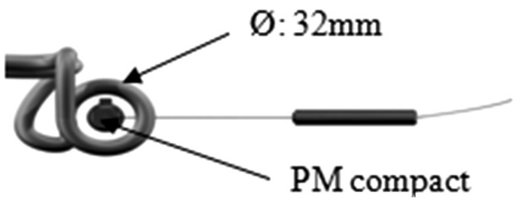


Figure 1: Schematic diagram of the apparatus for medium-frequency induction-heated sintering
Slika 1: Shematski prikaz naprave za sintranje s srednjefrekvenčnim indukcijskim ogrevanjem

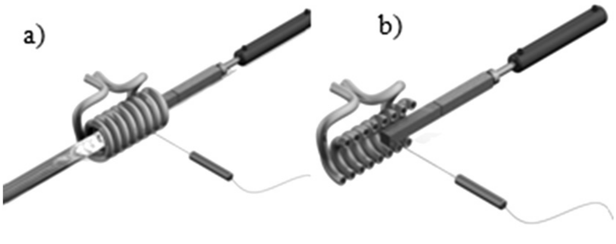


Figure 2: a) General aspect of the induction-sintering mechanism, b) cross-sectional aspect of a sintering action showing a sample and pyrometric temperature measurement
Slika 2: a) Prikaz mehanizma indukcijskega sintranja, b) prerez s prikazom sintranega vzorca in pirometrično merjenje temperature

of iron and copper powders were 45–106 μm. The powders were mixed for 20 min at 25 r/min in a V-type mixer to produce a homogeneous mixture. The mixed powders were compacted under 600 MPa using uniaxial pressure. The dimensions of green compacts were 10 mm × 10 mm × 55 mm. Green compacts were introduced into the medium-frequency induction-heated sintering system as shown schematically in **Figure 1**. PM compacts were sintered using the continuous-induction-heating system as presented in **Figure 2**. The inner diameter of the coil was 32 mm; the outer diameter was 48 mm.

An induced current (the frequency of around 30 kHz) was then activated. The induced current was a 100 % output of the total power capacity. PM compacts were sintered in air environment at 1120 °C for 400 s. The temperatures were measured (± 5 °C) with an infrared pyrometer focused on the center of a compact surface.

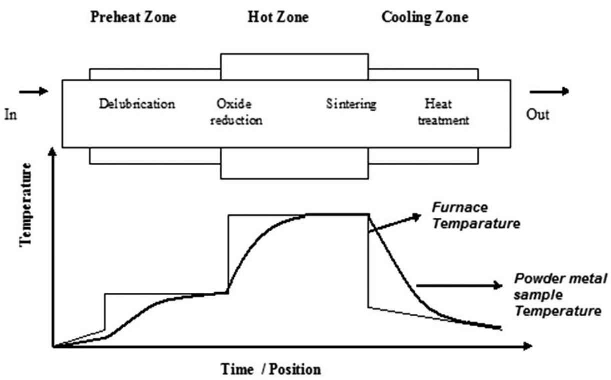


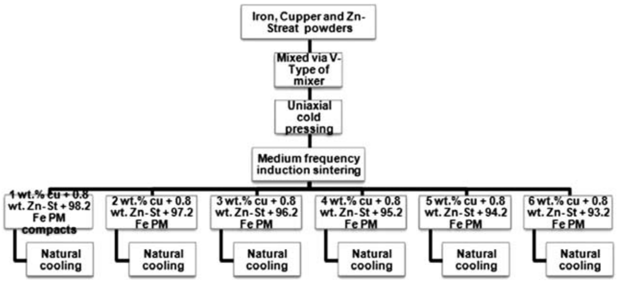
Figure 3: Schematic presentation of the temperature profile during medium-frequency induction-heated sintering[25,40]
Slika 3: Shematski prikaz profila temperature med sintranjem s srednjefrekvenčnim indukcijskim ogrevanjem[25,40]

The three major stages of sintering are shown in **Figure 3** and the typical parameters of the process are presented in **Table 2**. The sintering stages of the induction processes are shown on the flow chart in **Table 3**. Five different compacts were used for all the processes.

Table 2: Processing parameters of medium-frequency-heated sintering of *w* = 3 % Cu iron-based PM compacts
Tabela 2: Procesni parametri pri srednjefrekvenčno ogrevanih železnih stisnjencih z *w* = 3 % Cu

Parameter	Applied value
Applied pressure	600 MPa
Maximum temperature	1120 °C
Power capacity	12 kW
Frequency	30 kHz
Presintering time	Unavailable
Duration	400 s
Maximum temperature	1120 °C
Heating rate	≈ 75 °C/s
Cooling rate	Natural
Environment	Atmosphere

Table 3: Flow chart of the sintering process
Tabela 3: Prikaz poteka postopka sintranja



The relative density of a sintered compact was measured with the Archimedes' method. The Vickers hardness was measured with the indentations at a load of 50 g and the dwell time of 10 s using a Future-Tech FM-7000-type Vickers-hardness tester. A three-point bending test was performed using a Shimadzu AG 50 kN tensile-test machine at a speed of 5 mm/min and at room temperature according to ISO 6892 and ISO 148:1983 to determine the mechanical properties.

3 RESULTS AND DISCUSSIONS

3.1 Mechanical properties of sintered compacts

The average strength, deflection percentage at fracture, HV hardness and density values for the induction-sintered samples are given in **Table 4**. Five different compacts were used for all the processes and average results.

The three-point bending results were compared (**Figure 4**). The rupture strengths of 2–4 % Cu iron-based PM compacts were very similar. The maximum bending strength was obtained for 3 % Cu iron compacts. In the compacts with different Cu amounts the strength values were reduced.

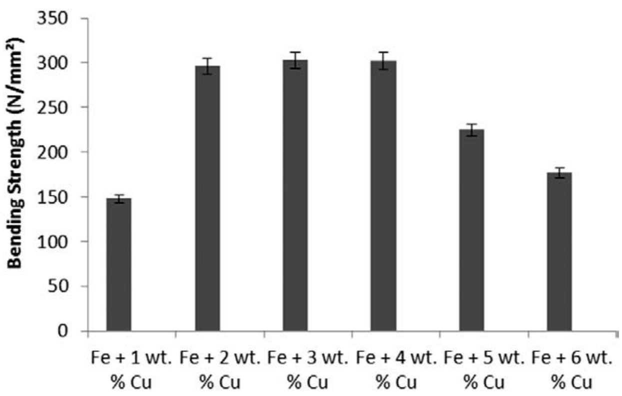


Figure 4: Bending-strength results for the PM compacts sintered with the induction system
Slika 4: Upogibna trdnost PM-stisnjencev, sintranih z indukcijskim sistemom

Table 4: Mechanical properties and densities of the PM compacts
Tabela 4: Mehanske lastnosti in gostote PM-stisnjencev

Copper amount (*w*/%)	Bending strength (N/mm²)*	Deflection at rupture (%)*	Hardness (HV)*	Density (g/cm^3)*
1	148	1.32	172	6.56
2	296	2.67	187	6.57
3	303	2.75	189	6.60
4	302	2.70	185	6.62
5	225	1.93	176	6.63
6	177	1.47	171	6.65

* Error range is ± 3 %

Deflection percentages at fractures were compared (**Figure 5**). The maximum deflection at fracture was obtained for iron 3 % Cu compacts. Deflection percentages at fractures for the components with 2–4 % Cu amounts were very similar. The other Cu amounts reduced the breaking-strain values. The highest ductility was obtained for 2–4 % Cu compacts.

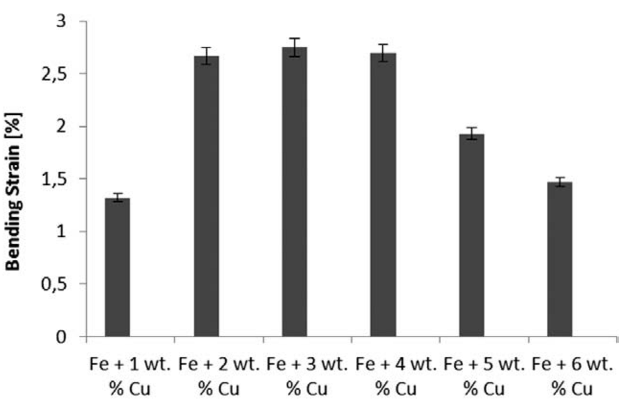


Figure 5: Bending-strain results for the PM compacts sintered with the induction system
Slika 5: Raztezek pri upogibu PM-stisnjencev, sintranih z indukcijskim sistemom

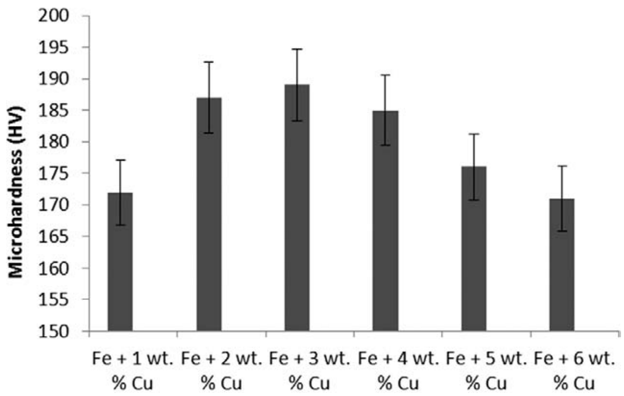


Figure 6: Microhardness results for the PM compacts sintered with the induction system
Slika 6: Mikrotrdota PM-stisnjencev, sintranih z indukcijskim sistemom

Microhardness results are compared in **Figure 6**. The highest HV microhardness results were obtained for 3 % Cu PM compacts. Higher or lower Cu amounts decreased the hardness.

Density results are compared in **Figure 7**. The highest density results were obtained for 6 % Cu PM compacts. It is clearly seen that Cu amounts increase the density of iron-based compacts. Cu powders were molten into the compacts at the sintering temperature of 1120 °C.

During the medium-frequency induction-heated sintering 400 s, the maximum fracture strength, deflection percentage at fracture and HV microhardness of the iron-based compacts with 3 % Cu were as expected. The incremental Cu amounts reduced the fracture strength, deflection percentage at fracture and HV microhardness.

These results are in good agreement with the previous works.[9,10,39,40] Compared with the references, the density results for the copper-iron PM compacts[9,10,40] are quite similar. An increased sintering time increased the fracture strength, microhardness and density of PM compacts[35,39] and the best values were obtained during medium-frequency induction sintering 500 s. In indu-

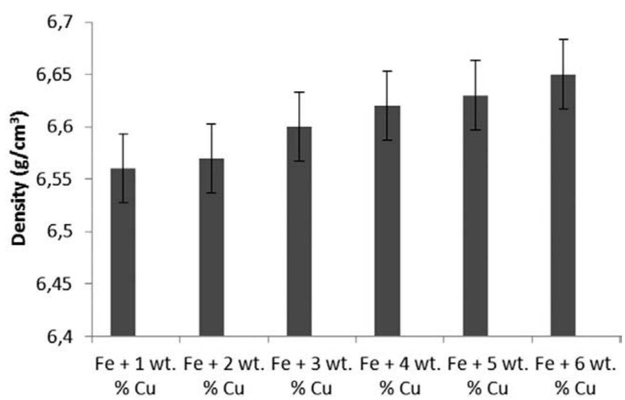


Figure 7: Density results for the PM compacts sintered with the induction system
Slika 7: Gostota PM-stisnjencev, sintranih z indukcijskim sistemom

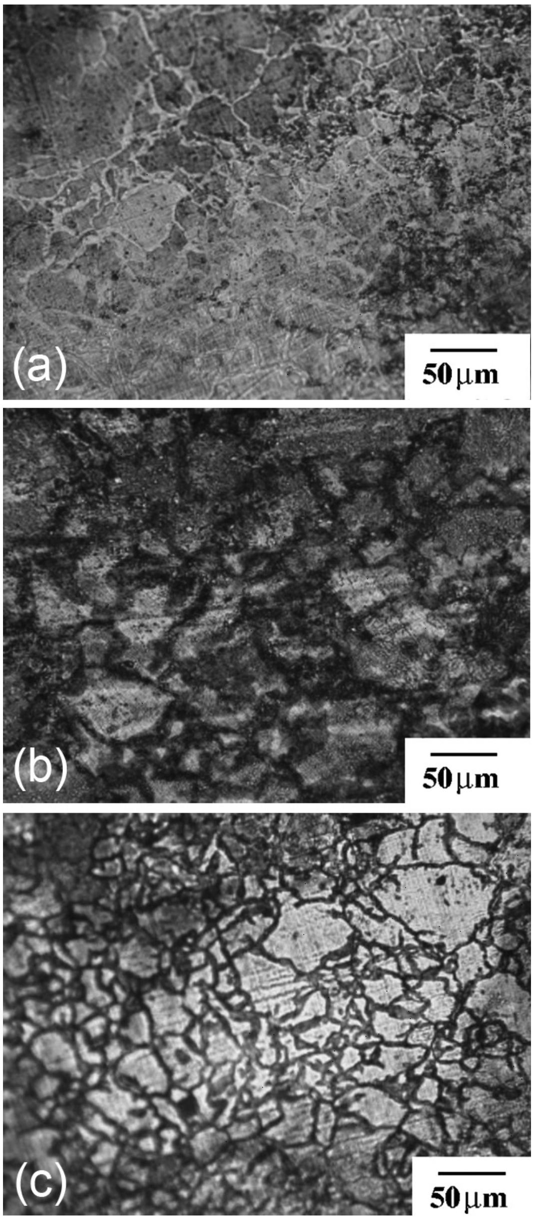


Figure 8: Microstructures of induction-sintered iron-based PM compacts including: a) w = 1 %, b) 3 % and c) 6 % Cu

Slika 8: Mikrostruktura indukcijsko sintranih PM-stisnjencev iz železnega prahu z: a) w = 1 %, b) 3 % in c) 6 % Cu

strial applications iron-copper PM compacts could be sintered using medium-frequency induction system as shown in Çavdar and Atik's study.[39,40]

3.2 Microstructural properties of the sintered compacts

Light microstructural images of the polished surfaces of PM compacts are given in **Figure 8**. SEM microstructural images of the polished surfaces of PM compacts are given in **Figure 9**. We observed a homogeneous microstructure in the part including 3 % Cu. Melted and bonded Cu grains are observed in this microstructure. Cu grains are uniformly distrubuted.

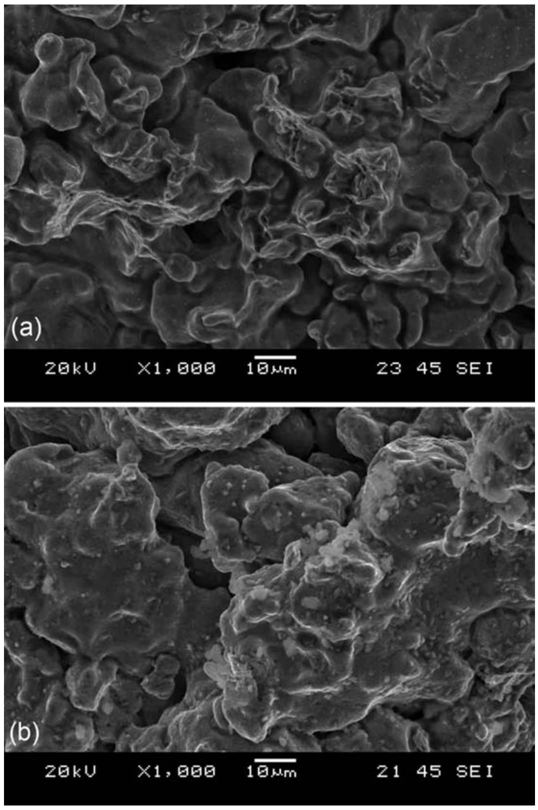


Figure 9: SEM microstructure of the fracture surface of an induction-sintered specimen: a) centre and b) edge of an iron-based PM compact including w = 3 % Cu (× 1000)

Slika 9: SEM-posnetka preloma indukcijsko sintranega PM-stisnjenca z w = 3 % Cu: a) sredina in b) rob (povečava 1000-kratna)

More bonding is observed at the edge of the part than in its centre. A brittle fracture is observed on the broken surface of the part. This is presented with a SEM image in **Figure 9**.

4 CONCLUSIONS

Iron-based powder-metal compacts including w = 1 % to 6 % Cu were produced using medium-frequency induction system. Based on the results, the conclusions are as follows:

The highest fracture strength, deflection percentage during bending and microhardness were obtained with 3 % Cu amounts. In some tests involving 2–4 % Cu amounts, the results were similar.

In the other medium-frequency induction-sintered PM compacts, the Cu amounts increased the density of the iron-based compacts.

5 REFERENCES

[1] R. M. German, Sintering theory and practice, 1^{st} ed., A Wiley-Interscience Publication, John Wiley & Sons, Inc., USA 1996, 313–362, 373–400, 403–420

[2] S. J. L. Kang, Sintering: Densification, Grain Growth and Microstructure, 1st ed., Elsevier Butterworth-Heinemann, 2005, 3

[3] D. Berner, H. E. Exner, G. Petzow, Swelling of iron-copper mixtures during sintering and infiltration, In: H. H. Hausner, W. E. Smith (Eds.), Modern Developments in Powder Metallurgy, vol. 6, Metal Powder Industries Federation, Princeton, NJ 1974, 237–250

[4] W. A. Kaysser, W. J. Huppmann, G. Petzow, Analysis of dimensional changes during sintering of Fe-Cu, Powder Metall., 23 (**1980**) 2, 86–91

[5] 5Y. Trudel, R. Angers, Comparative Study of Fe-Cu-C Alloys made from mixed and pre-alloyed powders, In: H. H. Hausner, W. E. Smith (Eds.), Modern Developments in Powder Metallurgy, vol. 6, Metal Powder Industries Federation, Princeton, NJ 1974, 305–322

[6] N. Dautzenberg, H. J. Dorweiler, Dimensional behavior of copper-carbon sintered steels, Powder Metall. Int., 17 (**1985**) 6, 279

[7] R. L. Lawcock, T. J. Davie, Powder Metall., 33 (**1990**), 147

[8] W. F. Wang, Effect of alloying elements and processing factors on the microstructure and hardness of sintered and induction-hardened Fe-C-Cu alloys, Materials Science and Engineering A, 402 (**2005**), 92–97

[9] U. Çavdar, E. Atik, Sintering with induction, Proceedings Euro PM2008, Mannheim, Germany, 2008, 33–38

[10] U. Çavdar, E. Atik, Induction sintering of Fe-2CuPM compacts, International Congress & Exhibition Euro PM2009 Sintering, Copenhagen, Denmark, 2009, 13–19

[11] J. Y. Yoo, C. K. Cho, I. J. Shon, K. T. Lee, Preparation of porous Ni–YSZ cermet anodes for solid oxide fuel cells by high frequency induction heated sintering, Materials Letters, 65 (**2011**), 2066–2069

[12] M. M. Dewidar, J. K. Lim, Manufacturing processes and properties of Copper-Graphite composites produced by high frequency induction heating sintering, Journal of Composite Materials, 41 (**2007**) 18, 2183–2194

[13] I. J. Shon, B. R. Kim, J. M. Doh, J. K. Yoon, Consolidation of binderless nanostructured titanium carbide by high-frequency induction heated sintering, Ceramics International, 36 (**2010**), 1797–1803

[14] I. J. Shon, I. Y. Ko, S. M. Chae, K. I. Na, Rapid consolidation of nanostructured $TaSi_2$ from mechanochemically synthesized powder by high frequency induction heated sintering, Ceramics International, 37 (**2011**), 679–682

[15] I. J. Shon, D. M. Lee, J. M. Doh, J. K. Yoon, I. Y. Ko, Consolidation and mechanical properties of nanostructured MoSi2–SiC–Si3N4 from mechanically activated powder by high frequency induction heated sintering, Materials Science and Engineering A, 528 (**2011**), 1212–1215

[16] W. Xiaopeng, C. Yuyong, X. L. Juan, X. Shulong, K. Fantao, K. D. Woo, Ti–Nb–Sn–hydroxyapatite composites synthesized by mechanical alloying and high frequency induction heated sintering, Journal of the Mechanical Behavior of Biomedical Material, 4 (**2011**), 2074–2080

[17] K. A. Khalil, A. A. Almajid, Effect of high-frequency induction heat sintering conditions on the microstructure and mechanical properties of nanostructured magnesium/hydroxyapatite nanocomposites, Materials and Design, 36 (**2012**), 58–68

[18] J. Y. Yoo, I. J. Shon, B. H. Choi, K. T. Lee, Fabrication and characterization of a Ni-YSZ anode support using high-frequency induction heated sintering (HFIHS), Ceramics International, 37 (**2011**), 2569–2574

[19] I. J. Shon, H. S. Kang, Properties and fast low-temperature consolidation of nanocrystalline Ni–ZrO_2 composites by high-frequency induction heated sintering, Journal of Alloys and Compounds, 509 (**2011**), 2964–2969

[20] I. J. Shon, I. Y. Ko, H. S. Kang, K. T. Hong, J. M. Doh, J. K. Yoon, Properties and rapid consolidation of nanostructured Al_2O_3-Al_2SiO_5 composites by high frequency induction heated sintering, Ceramics International, 37 (**2011**), 2159–2164

[21] H. C. Kim, D. Y. Oh, I. J. Shon, Sintering of nanophase WC–15 vol. % Co hard metals by rapid sintering process, International Journal of Refractory Metals & Hard Materials, 22 (**2004**), 197–203

[22] H. C. Kim, I. J. Shon, Z. A. Munir, Rapid sintering of ultra fine WC-10 wt % Co by high frequency induction heating, Journal of Materials Science, 40 (**2005**), 2849–2854

[23] H. C. Kim, D. Y. Oh, J. Goujian, I. J. Shon, Synthesis of WC and dense WC-5 vol % Co hard materials by high-frequency induction heated combustion, Materials Science and Engineering A, 368 (**2004**), 10–17

[24] D. Y. Oh, H. C. Kim, J. K. Yoon, I. J. Shon, Simultaneous synthesis and consolidation process of ultra-fine WSi_2-SiC and its mechanical properties, Journal of Alloys & Compounds, 386 (**2005**), 270–275

[25] M. G. Randall, Powder Metallurgy Science, 2nd ed., Metal Powder Industries Federation, Shrewsbury, UK 1997, 17

[26] K. K. Abdelrazek, K. S. Won, Effect of processing parameters on the mechanical and microstructural behavior of ultra-fine Al_2O_3-(ZrO_2+8 % Mol Y_2O_3) bioceramic, densified by high frequency induction heat sintering, Int. J. Appl. Ceram. Technol., 4 (**2006**), 22–30

[27] K. A. Khalil, S. W. Kim, Mechanical wet-milling and subsequent consolidation of ultra-fine Al_2O_3-(ZrO_2+Y_2O_3) bio ceramics by using high-frequency induction heat sintering, Science Press, Trans. Nonferrous Met. Soc. China, 17 (**2007**), 21–26

[28] D. Montasser, Microstructure and mechanical properties of biocompatible high density Ti–6Al–4V/W produced by high frequency induction heating sintering, Materials and Design, 31 (**2010**), 3964–3970

[29] I. J. Shon, I. K. Jeong, I. Y. Ko, J. M. Doh, K. D. Woo, Sintering behavior and mechanical properties of WC-10Co, WC-10Ni and WC10Fe hard materials produced by high-frequency induction heated sintering, Ceramics International, 35 (**2008**), 339–344

[30] I. J. Shon, T. W. Kim, J. M. Doh, J. K. Yoon, S. W. Park, I. Y. Ko, Mechanical synthesis and rapid consolidation of a nanocrystalline 3.3Fe0.6Cr0.3Al0.1–Al_2O_3 composite by high frequency induction heating, Journal of Alloys and Compounds, 509 (**2011**), 7–10

[31] H. K. Park, I. J. Shon, J. K. Yoon, J. M. Doh, I. Y. Ko, Z. A. Munir, Simultaneous synthesis and consolidation of nanostructured $NbSi_2$-Si_3N_4 composite from mechanically activated powders by high frequency induction-heated combustion, Elsevier, Journal of Alloys and Compounds, 461 (**2008**), 560–564

[32] Y. I. Lee, J. T. Lee, Y. H. Choa, Effects of Fe–Ni alloy nanoparticles on the mechanical properties and microstructures of Al_2O_3/Fe–Ni nanocomposites prepared by rapid sintering, Ceramics International, 38 (**2012**), 4305–4312

[33] I. J. Shon, I. K. Jeong, J. H. Park, B. R. Kim, K. T. Lee, Effect of Fe_2O_3 addition on consolidation and properties of 8 mol % ytria-stabilized zirconia by high-frequency induction heated sintering (HFIHS), Ceramics International, 35 (**2009**), 363–368

[34] Z. Zhang, R. Sandström, L. Wang, Modeling of swelling of Fe–Cu compacts sintered at temperatures above the copper melting point, Journal of Materials Processing Technology, 152 (**2004**), 131–135

[35] C. Çivi, N. Tahrali, E. Atik, Reliability of mechanical properties of induction sintered iron based powder metal parts, Materials and Design, 53 (**2014**), 383–397

[36] A. Kurt, H. Ateş, Effect of porosity on thermal conductivity of powder metal materials, Materials and Design, 28 (**2007**), 230–233

[37] H. Arik, M. Turker, Production and characterization of in situ Fe–Fe_3C composite produced by mechanical alloying, Materials and Design, 28 (**2007**), 140–146

[38] E. E. Feldshtein, L. N. Dyachkova, On the properties and tribological behaviors of P/M iron based composites reinforced with ultrafine particulates, Composites: Part B, 58 (**2014**), 16–24

[39] U. Çavdar, Identification parameters for the induction sintered iron based powder metal compacts, PhD thesis, Celal Bayar University, Institute of Science, Department of Mechanical Engineering, 2009

[40] U. Çavdar, E. Atik, Induction Sintering of 3 % Cu Contented Iron Based Powder Metal Parts, Modern Applied Science, 4 (**2010**), 63–70