International Journal of Minerals, Metallurgy and Materials
Volume 25, Number 9, September 2018, Page 1070
https://doi.org/10.1007/s12613-018-1658-8

Mechanical properties and microstructure of composites produced by recycling metal chips

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(Received: 18 December 2017; revised: 13 February 2018; accepted: 3 March 2018)

Abstract: In this study, the processing and mechanical properties of porous metal matrix composites (MMCs) composed of spheroidal cast iron chips (GGG40) and bronze chips (CuSn10) and formed by hot isostatic pressing were investigated. Bronze chips (CuSn10) were used as a matrix component, and spheroidal cast iron (GGG40) chips were used as a reinforcement component. The MMCs were produced with different CuSn10 contents (90wt%, 80wt%, 70wt%, and 60wt%). The hot isostatic pressing process was performed under three different pressures and temperatures. The produced MMCs were characterized using density tests, Brinell hardness tests, and compression tests. In addition, the consolidation mechanism was investigated by X-ray diffraction (XRD) analysis and scanning electron microscopy. The test results were compared with those for bulk CuSn10 and bulk GGG40. Mechanical tests results revealed that the metallic chips can be recycled by using hot pressing and that the mechanical properties of the produced MMCs were similar to those of bulk CuSn10. XRD and microscopy studies showed that no intermetallic compounds formed between the metallic chips. The results showed that the CuSn10 and GGG40 chips were consolidated by mechanical interlocking.

Keywords: metal matrix composite; microstructure; metal chips; recycle; mechanical behavior

1. Introduction

A large amount of metal chips are formed during the machining of metals. Generally, these chips are considered waste. However, some recycling methods for these chips have been introduced [1]. The most commonly used recycling method is the melting and casting process [2]. However, this process is energy-intensive because the chips exhibit very low thermal and electrical conductivity as a consequence of their oxidized surfaces [3]. Thus, common melting techniques such as induction ovens and electrical resistance ovens are not efficient for this process [4]. Consequently, the melting/casting process becomes very expensive. On the other hand, detrimental gasses are released during the melting process of chips, resulting in environmental pollution. As a result of the aforementioned situation, the melted chips are converted into slag, scrap and other losses and the overall process efficiency can be as low as 54wt% [5].

The recycling of metallic chips such as aluminum chips [1], steel chips [2], bronze chips [4], and cast iron chips [5] has been investigated. Most of these studies have been focused on sintering [6–7] and hot/cold extrusion processes [8–9]. Also, the effect of chip size on the mechanical properties [10] and microstructure [11–12] have been investigated using different chips. Ti–6Al–4V chips [13] and steel chips [6] have been used to produce metal matrix composites (MMCs). However, to our knowledge, MMCs composed of cast iron and bronze chips have not been reported. A literature review revealed that recycling of metallic chips generally involves casting or sintering processes. The sintering process comprises two distinct steps of cold

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pressing to obtain green samples followed by a sintering heat treatment. Sintering is a relatively high-cost process because it is time-consuming and energy-intensive. However, hot pressing requires a very short time to complete and can be carried out at relatively lower temperatures.

In this study, GGG40 and CuSn10 chips were mixed with different contents. The mixtures were hot pressed at different pressures and temperatures. The produced MMCs were subjected to Brinell hardness testing and density testing. X-ray diffraction (XRD) analysis was used to determine the possible formation of intermetallic phases. The properties of the MMCs were compared with those of bulk CuSn10 and GGG40. Our results demonstrate that GGG40 and CuSn10 metallic chips can be successfully recycled and converted into MMCs with satisfactory mechanical properties.

2. Experimental

In this study, spheroid cast iron (GGG40) and bronze (CuSn10) chips were selected as MMC constituents. Table 1 shows the reasons why these materials were selected. The selected components were first cast as cylindrical bars for consistency of chemical composition. The constituent materials were then machined by lathe and transformed into metallic chips. The chemical compositions of the cast iron (GGG40) and bronze (CuSn10) are presented in Table 2.

Table 1. The reasons for selecting GGG40 and CuSn10

Materials	Difference	Similarities
GGG40	Good mechanical properties due to graphite form	Extensive usage in industry; suitable chip type and size; relatively clean surfaces due to machining without cooling fluids; suitable mechanical properties for journal bearing; good tribological properties
CuSn10	Lower melting temperature than cast iron	

Table 2. Chemical compositions of the CuSn10 and GGG40 used in this study [4] wt%

Materials	C	Si	Mn	S	Mg	P	Cu	Sn	Zn	Pb
GGG40	3.4	2.5	0.13	0.01	0.046	0.08	—	—	—	—
CuSn10	—	—	—	—	—	—	89.2	9.3	0.41	0.01

Because the CuSn10 and GGG40 metallic chips have various sizes, they were sifted using 1- and 2-mm sieves. Thus, the sizes of the chips varied between 1 and 2 mm. The chips larger than 2 mm were ground in a tumbling ball mill with different diameter balls for 7200 turns. The completion of the grinding process for the metal chips required approximately 2 h; the ground chips are shown in Fig. 1.

Four different mixtures were prepared using the mixer. The mixer was filled to approximately two-thirds its volume, and the process was continued for 20 min, as described by German [14]. After the mixing process was completed, the mixture was divided into 80-g samples using a Precisa XB220a scale with 0.1-mg precision. After the mixing, the average chip sizes were controlled; no noticeable change in chip size was observed.

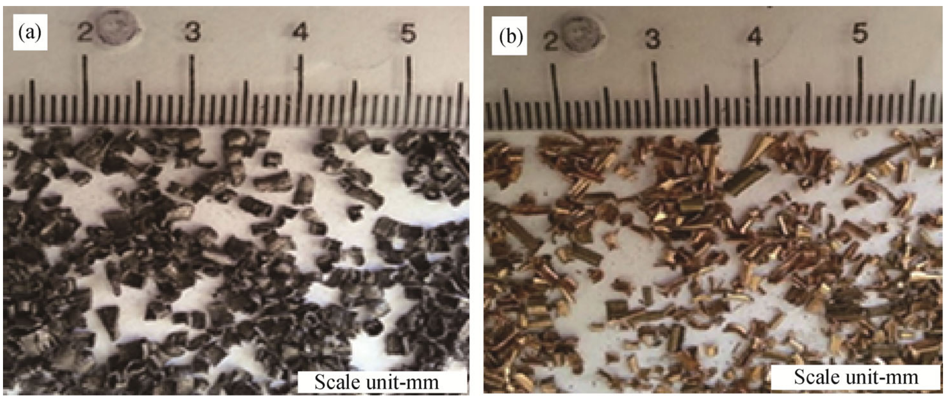

Fig. 1. Photographs of (a) GGG40 chips and (b) CuSn10 chips.

For isostatic hot pressing, a die made of hot-work tool steels was produced and heat treated to attain optimal material properties and safe operating conditions. After the die production, four bar-shaped electrical resistance heaters were placed in the die. These heaters were capable of heating the die to 650°C in 1 h. Also, the MMCs had a 19.6 mm diameter and 34–36 mm length after production. The length of the samples changed with the process parameters [15]. The whole system was covered with isolation material to avoid heat loss and to achieve homogeneous temperature distribution over the die. After all of these steps, the system was ready for production.

We observed [5] that, when the compression was applied in one direction, the highest hardness was measured at the point where compression was applied [16]. However, other parts of the specimens showed lower hardness. To obtain a homogeneous compression and hardness profile, the metallic chips were pressed in two opposite directions.

The process parameters such as the mixture ratio, time, temperature, pressure were determined by considering the melting temperature of CuSn10 because its melting temperature is lower than that of GGG40. The optimum process parameters were selected on the basis of preliminary studies; the parameters are shown in Table 3. To achieve a homogeneous temperature distribution, the chip mixture was heated in the die for 10 min before the application of pressure. The specimens were then hot pressed for 15 min. Instead, to avoid interaction between oxygen and metal, the male parts were coated with graphite.

Table 3. Production parameters

Specimen code	Mixture weight ratio / wt%	Temperature / °C	Pressure / MPa
90B10C	90% CuSn10–10% GGG40	350, 400, 450	480, 640, 820
80B20C	80% CuSn10–20% GGG40		
70B30C	70% CuSn10–30% GGG40		
60B40C	60% CuSn10–40% GGG40		

Because chips were predicted to oxidize as a result of high temperatures during the production process, we attempted to carry out the production under vacuum. However, the vacuum pump connection was congested by excessive plastic deformation within CuSn10.

3. Results and discussion

To determine the structural integrity and microstructure of the samples, XRD analysis and Brinell hardness tests were carried out. In addition, the porosities of specimens were obtained via the rule of mixture and an Archimedes scale.

3.1. Microstructure

Fig. 2 shows the microstructures of MMCs produced using different process parameters. The same and different type of metallic chips could be successfully consolidated under the conditions where the process pressure was selected sufficiently high. Under high pressures and moderate temperatures, atomic diffusion may occur over the long term. However, the XRD study reveals that no solid solution formed between Cu and Fe during the process (Fig. 3). Thus, the selected process temperatures were concluded to only affect the relative ease of plastic deformation and to help the CuSn10 chips completely cover the GGG40 chips.

MMCs consist of two components. Prior to hot pressing, these components were mixed using the method recommended in the literature and were considered to be homogeneous after this step. However, because the components are metal chips with complex geometries, absolute homogeneity cannot be achieved at the micro scale. The reinforcement material GGG40 contains spherical graphite secondary phases. The average nodule diameter was 5–18 μm, and the nodal ratio was 65%. The homogenous distribution of the second phases was obtained before chip formation [4]. Figs. 2(b), 2(c) and 2(h) show that the CuSn10 constituent can penetrate through narrow zones by plastic deformation via the selection of an appropriate pressure and temperature. However, in some cases, pores can be formed between chips because of inappropriate selection of process parameters or localized restriction of plastic deformation, as seen in Figs. 2(d) and 2(f). By contrast, GGG40 chips did not show plastic deformation and maintained their initial shape. However, as shown in Fig. 2(e), the spherical graphite structures showed elongation during machining.

3.2. XRD analysis

XRD analysis was carried out to investigate the possible formation of intermetallic compounds. The XRD pattern of the 90B10C specimen is shown in Fig. 3. As evident in the figure, peaks were recorded at 31.3°, 36.3°, 42.8°, 44.5°, 50°, 52.2°, 62°, and 73.3°. The peaks recorded at 42.8°, 50°, 52.2°, 62°, and 73.3° represent the CuSn10 structure [17], whereas those at 36.3°, 44.5°, and 52.2° represent the elements within the CuSn10 solid solution and the peak 31.3° represents graphite in GGG40. According to the aforementioned results, no intermetallic compound was formed between the GGG40 and CuSn10 metallic chips.

3.3. Density tests

To determine the porosity values, specimens were weighed using an Archimedes scale in deionized water and the densities of MMCs were obtained. The theoretical densities of MMCs were calculated using the rule of mixture. The difference between measured and calculated densities was used to obtain the porosity.

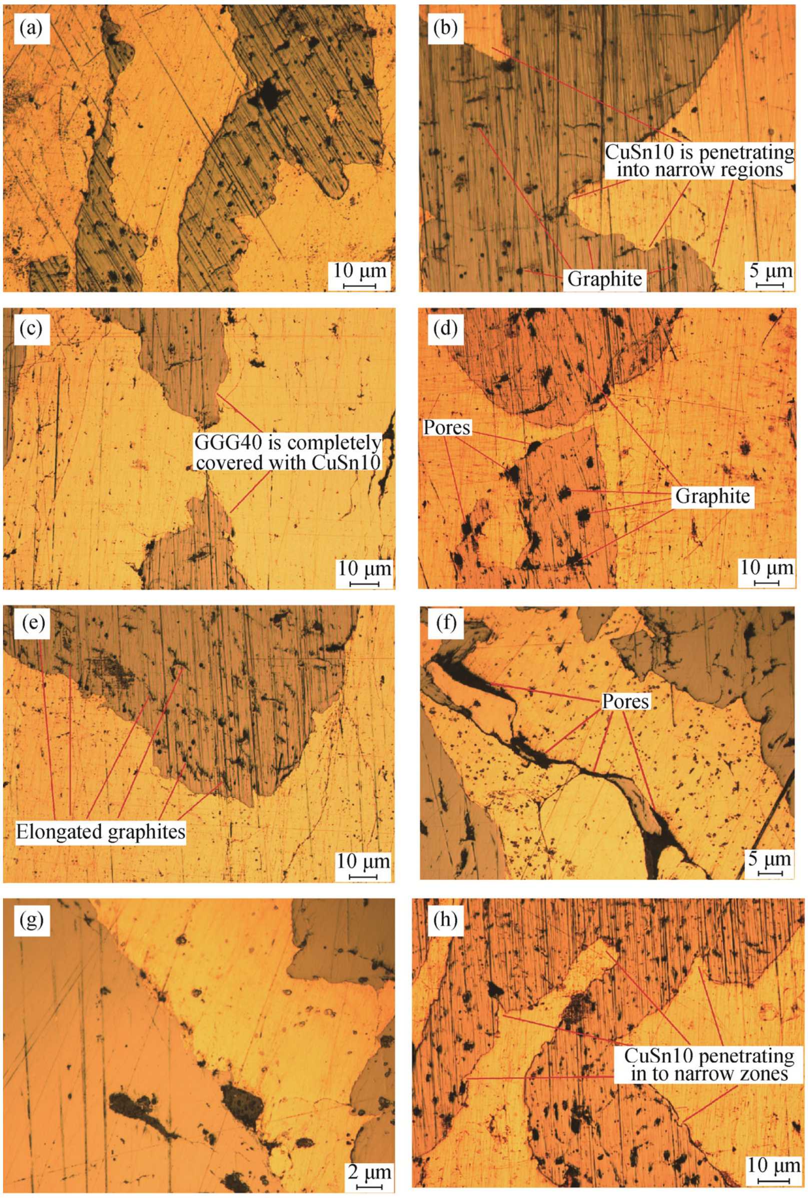

Fig. 2. Microstructures of MMC materials: (a) 90B10C produced at 350°C and 480 MPa; (b) 90B10C produced at 350°C and 480 MPa; (c) 80B20C produced at 350°C and 820 MPa; (d) 80B20C produced at 350°C and 820 MPa; (e) 70B30C produced at 350°C and 820 MPa; (f) 70B30C produced at 350°C and 820 MPa; (g) 60B40C produced at 450°C and 480 MPa; (h) 60B40C produced at 450°C and 480 MPa.

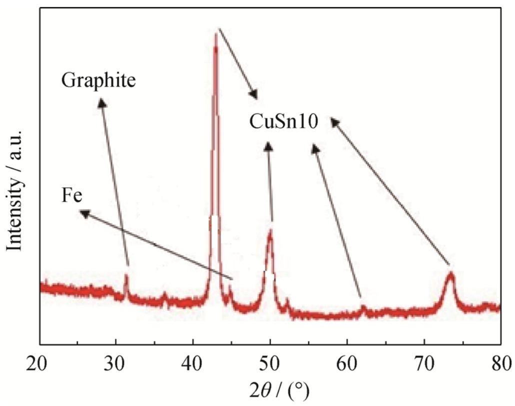

Fig. 3. XRD pattern of 90B10C produced at 820 MPa and 450°C.

The densities of specimens were calculated by weighing the specimens via Archimedes principle; the results are presented in Table 4. The specimen codes used in Table 4 represent the CuSn10 and GGG40 weight percentages. The densities of bulk CuSn10 and GGG40 were measured as 8.7 and 7.2 $g \cdot cm^{-3}$, respectively. As evident in Table 4, in general, the density of the specimens decreases with decreasing CuSn10 content. In addition, the density of the specimens increases with increasing sintering temperature (from 350 to 400°C). With increasing applied pressure, the average distance between chips decreases. Thus, this situation results in substantially fewer voids. By contrast, an increase in temperature results in softening of the chips and increases the contact areas. This situation can also result in a density increase. The highest density was obtained under sintering conditions of 400°C and 640 MPa.

Table 4. Densities and porosities of specimens

Specimen code	Pressure / MPa	Temperature / °C	Theoretical density / ($g \cdot cm^{-3}$)	Density / ($g \cdot cm^{-3}$)	Porosity / %
90B10C	480	350	8.55	8.30	2.90
		400		8.31	2.77
		450		8.14	2.78
	640	350	8.55	8.30	2.90
		400		8.38	2.02
		450		8.22	3.61
	820	350	8.55	8.33	2.55
		400		8.28	3.20
		450		8.27	3.73
80B20C	480	350	8.40	8.05	4.13
		400		8.20	3.36
		450		8.05	4.14
	640	350	8.40	8.22	3.14
		400		8.17	2.80
		450		8.07	3.93
	820	350	8.40	8.03	4.27
		400		8.12	3.30
		450		8.05	4.13
70B30C	480	350	8.25	7.94	3.78
		400		7.88	4.44
		450		7.87	4.57
	640	350	8.25	7.95	3.74
		400		8.05	2.83
		450		7.82	5.16
	820	350	8.25	7.92	3.96
		400		8.01	3.02
		450		7.84	4.93
60B40C	480	350	8.10	7.93	4.15
		400		7.74	4.49
		450		7.66	5.49
	640	350	8.10	7.75	4.35
		400		7.84	3.52
		450		7.67	5.35
	820	350	8.10	7.75	4.38
		400		7.71	4.85
		450		7.66	5.42

3.4. Brinell hardness tests

The produced MMCs contain CuSn10, GGG40, and voids. Fig. 4(a) shows a schematic of the microstructure of the specimens. The hardness values can vary by the position of measurement (Fig. 4(b)). To obtain an average hardness, we carried out Brinell hardness testing. A steel ball 5 mm in diameter was used as a tip. The hardness values measured at different positions were used as an indication of homogeneity.

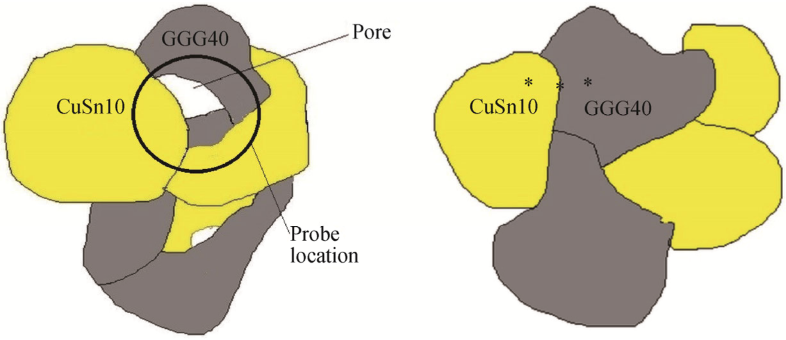

Fig. 4. Schematic of (a) the components and (b) the hardness measurement points.

Fig. 5 shows the positions of the hardness measurement points. As shown in this figure, three measurement points were located at the top and bottom surfaces and three measurement points were located 120° at three different vertical positions. The Brinell hardness values were grouped, and their averages and standard deviations were compared with each other. These measurements were conducted to provide an indication of homogeneity. As seen in Fig. 5, the measurements at different positions show a low standard deviation. This result indicates that satisfactory homogeneity was obtained and that the mechanical properties were independent of the measuring points [4].

The hardness tests were performed at ambient temperature, and the applied load was selected as 2451 N. The load was applied for 30 s. The ball diameter was selected by considering the size of the metallic chips. Because the sizes of chips vary between 1 mm and 2 mm, the ball size was selected as 5 mm.

Fig. 6 shows the variation of Brinell hardness values of MMCs produced using different process parameters. The lowest hardness values were obtained for the specimens produced at 350°C. By contrast, the highest hardness values were

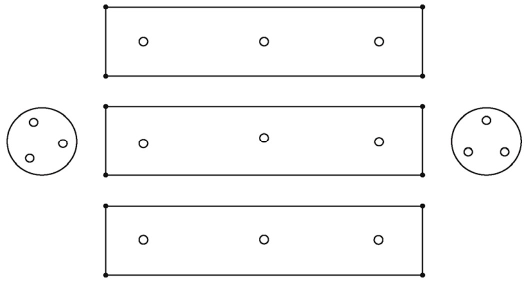

Fig. 5. Hardness measurement points.

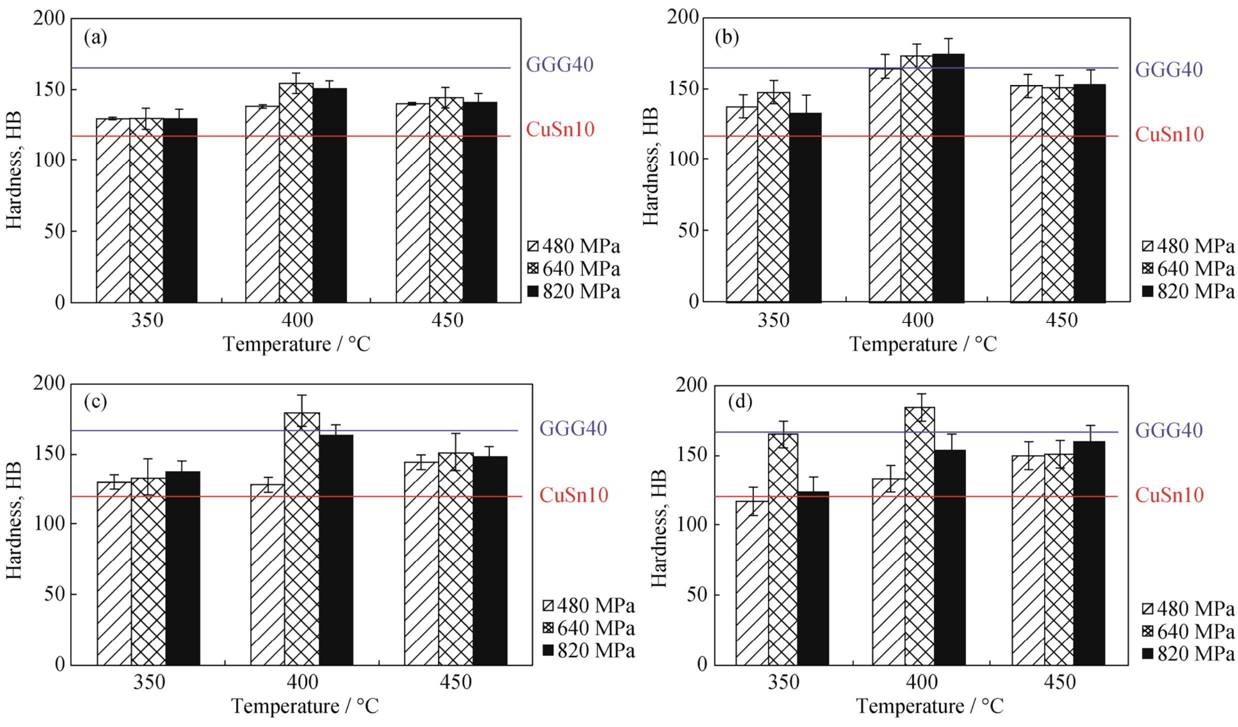

Fig. 6. Variation of Brinell hardness with production parameters: (a) 90B10C; (b) 80B20C; (c) 70B30C; (d) 60B40C.

obtained for the specimens produced at 400°C. When the production temperature was increased to 450°C, the measured hardness values tended to decrease. The process temperature is critical because the softening and resistance of chips to plastic deformation depends on the operating temperature. For CuSn10 chips to cover the GGG40 chips and provide structural integrity, the selection of the process temperature is very important. In the case of high temperatures, the resistance to plastic deformation would decrease, avoiding strain hardening and increasing strength. However, if the process temperature is low, then plastic deformation within CuSn10 chips would not be sufficient to cover GGG40 chips and result in poor integrity between different types of metallic chips. The applied pressure has a similar effect and also affects the level of plastic deformation and strain hardening during production.

As shown in Fig. 6, the highest Brinell hardness values were obtained for specimens produced under a pressure of 820 MPa, which is the highest applied pressure investigated in the production process. The average hardness of the obtained MMCs was HB 150, whereas the measured hardness of bulk CuSn10 and bulk GGG40 was HB 107 and HB 170, respectively. Thus, we concluded that the produced MMCs have hardness values between those of CuSn10 and GGG40. However, some MMC specimens show hardness values as high as HB 190. This result may be associated with high strain hardening during the production process. However, the Brinell hardness as high as HB 190 might be attributable to inhomogeneous distribution of GGG40 chips, which might has agglomerated at the site where the hardness value was measured.

3.5. Compression tests

The compression tests of the produced materials were carried out according to American Society for Testing and Materials standard ASTM-E9-89a. Experiments were performed using an Instron-8801 test machine located at Selçuk University Mechanical Engineering Laboratory. The compression test specimens had a 15-mm diameter and 25-mm length. The feed rate of the compression test jaws was set at 2 $mm \cdot min^{-1}$. To ensure the reliability of the experiment, three samples were produced with the same geometry and a total of 108 cylindrical samples were tested. Graphite is sprinkled on the surface to minimize the friction between the cross head and the specimen.

Elastic deformation first occurs when compressive force is applied to chips, followed by plastic deformation. Thereafter, voids between chips begin closing; however, the voids generally cannot completely close. Therefore, voids convert into pores during this stage. In addition, plastic deformation also results in strain hardening within chips and mechanical interlocking between adjacent chips. If the compressive force is sufficiently high, the pores can completely close and the material can function like a solid material [18]. In Figs. 7(a), 7(b) and 7(c), CuSn10 and composite materials show ductile behavior, the maximum shear stress was broken from the 45° angle plane, and the nodules did not occur. The fracture of the specimens with this angle indicates that the pores and chips in the structure were homogeneously dispersed throughout the material. Thus, we concluded that the selected mixer type and mixing parameters are sufficient to provide a homogeneous mixture.

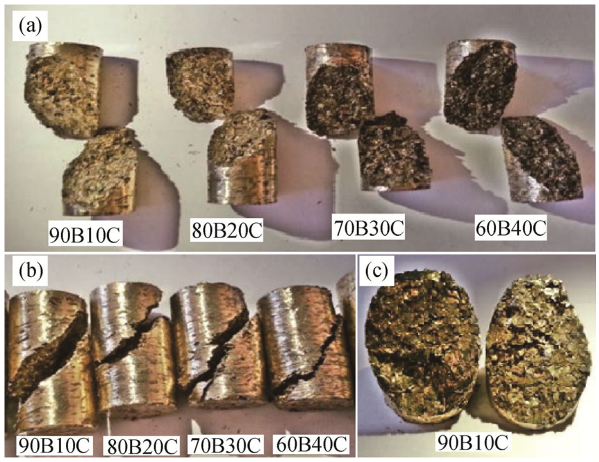

Fig. 7. Fractured images of different specimens: (a) fractured specimens; (b) broken images of produced samples; (c) fracture surface produced at 820 MPa and 400°C.

Fig. 8 shows the compressive strengths of cylindrical specimens after the compression tests. The mixing ratios of the materials were kept constant in the graphs, and the effect of pressure and temperature on the compressive strength is shown. In the graphs, the blue line represents the average compressive strength value of the CuSn10 material. This line was plotted using the obtained compressive strength values and can be compared with the results for bulk CuSn10. Experiments were repeated three times for each parameter. The standard deviations shown in Fig. 8 show that that the experimental results are reliable and consistent.

As shown in Fig. 8, the compressive strength of composite materials with different compositions was slightly affected by the production parameters. The compressive strength of the material varies between 82% and 100% of the bronze compressive strength. The high strength values indicate an effective combination within the composite material. The higher compressive strengths obtained from some composite materials than bulk CuSn10 can be explained by the plastic deformation in the bronze material which was subjected to high plastic deformation during the production.

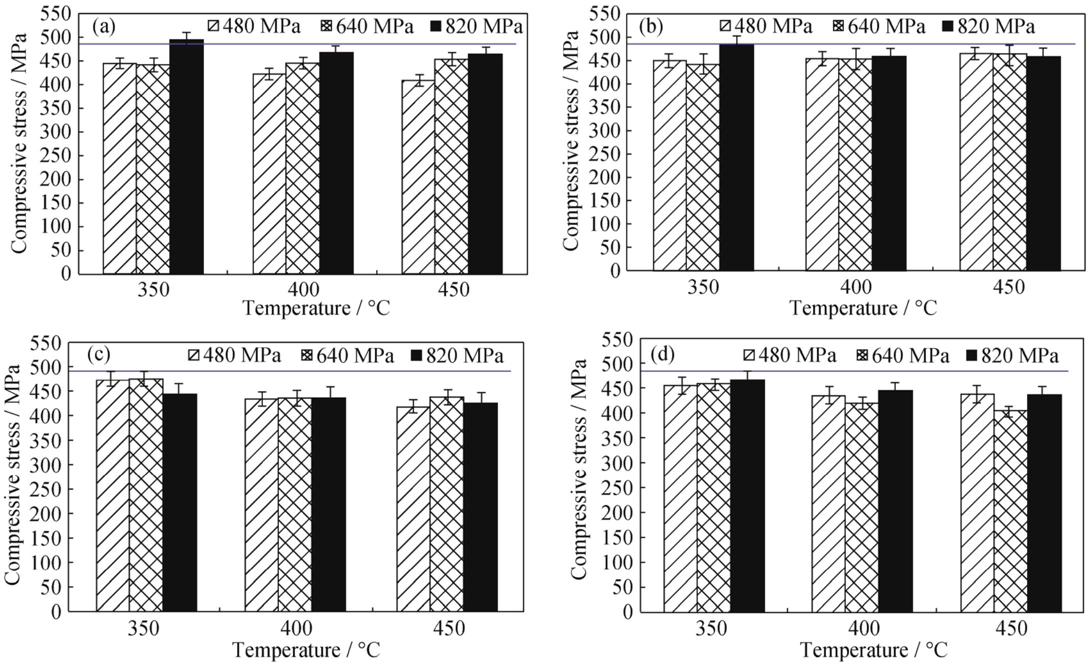

Fig. 8. Compressive strength of composite materials: (a) 90B10C; (b) 80B20C; (c) 70B30C; (d) 60B40C.

Fig. 9 shows the shortening values (ε_f) of cylindrical specimens at the end of the compression tests. The effects of composition, pressure, and temperature on ε_f are also shown. In the graphs, the averages of three trials were taken and the standard deviations were determined. The standard deviations are quite small (max. 4.2%), demonstrating the reliability of the experiments. The ε_f value of the bulk CuSn10 material was measured as 0.61; however, the maximum value obtained from the manufactured materials was determined to be 0.48, which is equal to approximately 80% of the ε_f value of pure CuSn10. This situation is likely associated with the porosity of MMCs, which is higher than that of pure CuSn10, because the pores within the material limit the plastic deformation and result in a reduction in deformability.

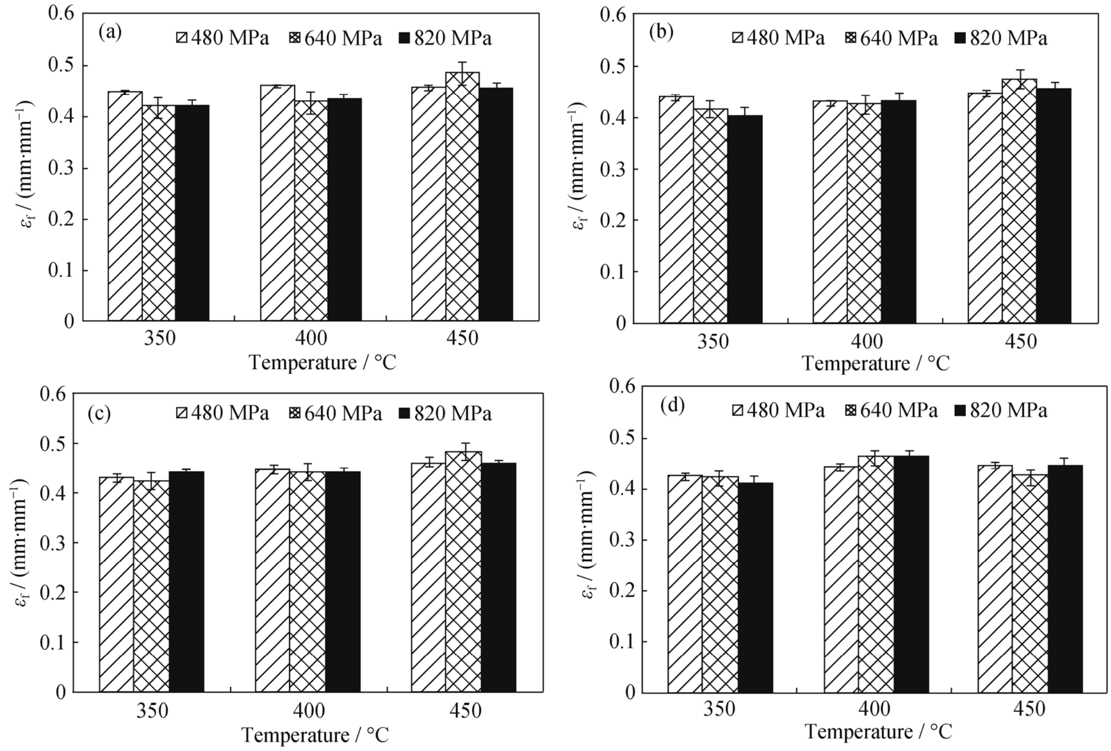

Fig. 9. Shortening values (ε_f) of cylindrical specimens at the end of the compression tests: (a) 90B10C; (b) 80B20C; (c) 70B30C; (d) 60B40C.

4. Conclusions

In this study, the application of hot isostatic pressing to the production of MMCs by recycling GGG40 and CuSn10 chips was investigated. The findings and conclusions are summarized as follows:

(1) CuSn10 and GGG40 chips can be successively recycled and converted into porous MMCs without melting. The porosity and hardness values of MMCs are dependent on the process parameters and can be changed through selection of appropriate process parameters. A porosity between 2% and 5.5% can be achieved with these production parameters. The measured Brinell hardness of MMCs is higher than that of bulk CuSn10 because of excessive plastic deformation and work hardening during production.

(2) The highest compressive strength achieved in the MMCs was 514 MPa. The compressive strength of materials reached 85% of the strength of bulk CuSn10. In this case, the results showed that bronze could be recycled without excessive degradation of its mechanical properties. In addition, the compressive strength was generally only slightly affected by the process parameters and composition, and the compressive strength was mainly dependent on the bronze behavior. And also XRD analysis revealed that no intermetallic compounds formed between the metallic chips. By contrast, CuSn10 and GGG40 chips were consolidated only by mechanical interlocking.

(3) Bulk GGG40 and CuSn10 materials are widely used as journal bearing and damper in industrial applications. The present study showed that metallic chips of these types of materials can be successively recycled and the obtained MMCs, which have satisfactory mechanical properties and considerable porosity, which makes them good candidates for self-lubricating journal bearings, dampers, and filters.

(4) The mechanical properties and porosity depend on the selected process parameters. Thus, low pressure and low percentage of CuSn10 chips can be selected for applications where porosity is a priority and high pressure and high content of CuSn10 chips can be selected for applications where hardness is a priority. The production process and mechanical properties of MMCs depend on the selection of process parameters. However, the physical and mechanical properties depend on both process parameters and each other. Thus, the selection and determination of optimal parameters is highly complex.

(5) The experimental results showed that physical and mechanical properties strongly depend on the ability and extension of plastic deformation during processing. Thus, we concluded that physical and mechanical properties are mainly affected by the composition and secondarily by the process temperature. Given the experimental results and the aforementioned explanations, we concluded that higher GGG40 contents and lower process temperatures result in relatively high porosity, whereas a sintering temperature of 400°C results in good bonding between chips and relatively higher hardness and strength.

Acknowledgements

This work was financially supported by the Scientific and Technological Research Council of Turkey (TUBITAK, No. 113M141).

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