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Production and Mechanical Properties of Bronz/Steel Chips Composite Materials Produced by Direct Recycling

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ABSTRACT

In this study, a novel method for the direct conversion of bronze (CuSn10) and steel (S355JR) chips into finished products without melting is introduced. CuSn10 bronze and S355JR steel chips were used as the constituents for the composite materials. The chips were first pressed at room temperature and were subsequently subjected to liquid phase sintering. The composite materials were produced in three different constituent fractions. After production, the composite materials were subjected to compression, three point bending and surface hardness tests in accordance with ASTM standards to compare the results with those for bulk CuSn10 bronze. The produced composite materials have reasonable mechanical properties compared to bulk CuSn10 bronze. Additionally, the results indicate that the proposed method may be considered as an alternative to conventional production methods, such as melting and extrusion.

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INTRODUCTION

Metallic chips formed during machining are generally recycled by melting and casting. This procedure results in oxidation of the materials and degradation of the material properties. Additionally, the aforementioned procedure requires high energy consumption and the emission of harmful gases. Additionally, these processes are inefficient and expensive (Gronostajski et al, 1997). It has been reported (Lazzaro and Vittori, 1992) that the process of melting aluminum alloy chips results in 10% burning and 10% slag formation. Additionally, the direct conversion of aluminum chips into compact metal results in 40% material savings, 26–31% energy savings and 16–60% labor savings (Chmura and Gronostajski, 2006).

Solid state recycling is an effective and energy efficient process due to the prevention of oxidation compared with melting processes. Solid state recycling was first proposed by Nakanishi et al. (1995) for recycling magnesium alloy chips and scrap. Lee et al. (1995) and Liu et al. (2002) also conducted research on AZ91D and AZ80 magnesium alloys using solid state recycling. In another study, Nakanishi et al. (1998) investigated solid state recycling for a ZK60 magnesium alloy.

It has been reported that steel, copper, aluminum alloy chips and cast iron can be recycled and converted into composite materials by cold pressing and sintering (Gronostajski, et al., 2000).

Gronostajski et al. (1997) presented a new method for chip recycling. Their method consisted of the conversion of the chips directly (without any intervening metallurgical processes) into a finished product and has been applied to the production of conventional and composite materials. They described and discussed the sintering criteria required for chip recycling. Finally, the application of this recycling method for the production of bearing materials was precisely described. Gronostajski ve Matuszak (1999) investigated a new method for recycling aluminium and aluminium-alloy chips resulting from the machining of semi-finished products, which are very difficult to recycle using conventional methods. This method consists of converting the chips directly (without any melting processes) into a finished product. By using a powder metallurgy technique followed by an extrusion process, this method was used for the production of composite materials, which are characterized by their superior properties. This new method is environmentally friendly and saves material, labor and energy.

Upadhyaya and Sethi (2007) investigated the effect of different heating and homogenization processes on mechanical behavior of sintered CuSn10 alloy. Fogagnolo et al. (2003) studied the recycling of aluminum chips by cold pressing at room temperature followed by hot extrusion. They reported that the mechanical propertes of hot pressed material are better than that of cold pressed and sintered materials.

Gronostajski et al. (2000) described a method for the direct convertion of aluminum alloy chips into final products. The chips were comminuted in a cutting device, and the granulated chips were used for future processing. The prepared chips were pre-pressed and hot extruded into the final products. The produced material was observed to have the high density and superior properties normally obtained at high extrusion temperatures, which allows the plastic flow of the matrix into pores and voids at relatively low extrusion rates, which permits enough time for diffusional matter transport. Gronostajski et al. (2001) investigated aluminum chip composites and used FeCr powder as a reinforcing phase. The FeCr reinforced material exhibited very good mechanical properties at both room and elevated temperatures. Gronostajski J. and Gronostajski Z. (2003) studied direct recycling, which utilizes cold press molding and hot extrusion. For aluminum alloys, they used Cu, Mg and W materials. As a result of their experiments, they determined that aluminum and its alloys can be recycled through a direct conversion method, which is characterized by low energy-consumption and large material savings. Chmura et al. (2006) studied recycling aluminum and aluminum–bronze chips generated in the fabrication of bearings. Bearing composites were produced by cold compaction and hot extrusion. Mechanical and tribological properties were determined for the end product composite bearing samples. It was found that an aluminum base with an aluminum-bronze reinforcing phase exhibited better frictional properties. Hu et al. (2008) studied the direct recycling of an AZ91D magnesium alloy without melting. This included investigating the effect of chip size upon the microstructure and mechanical properties, which showed that as the surface area of the chip increased, the oxidation increased linearly. Chmura and Gronostajski (2006) studied manufacturing and the properties of bearing materials produced by the recycling of aluminum and aluminum-bronze chips. In this study, bearing composites were produced by cold compaction and hot extrusion of comminuted and mixed aluminum and aluminum-bronze chips. The wear and the coefficients of friction for the composites were determined as a function of the percentage of the reinforcing phase (for the aluminium-bronze granulated chips).

The literature survey revealed that the production of metal matrix composites from steel/bronze chips has not yet been examined. In this study, steel and bronze chips were converted into metal matrix composites by cold pressing and sintering. The proposed method enabled the authors to alter the mass fractions of the constituents and the desired porosity at a very low cost compared to the classical melting/casting procedure. The produced metal matrix composites (MMC) can be used for self-lubricating journal bearings due to their satisfactory mechanical properties and porosity, which results in a high oil storage capacity. This type of material can also be used as a filter or bumper. Currently, the aforementioned parts are produced by powder metallurgy (PM). However, the proposed procedure can be considered as an economic alternative to PM.

In this study, steel and bronze chips were used to produce MMC by direct recycling. Three diffrenet mass fractions were used for the constituents. The mechanical properties of the produced MMC were determined by compression, three point bending and surface hardness tests, and the results were compared with those obtained for bulk bronze.

MATERIALS AND METHODS

In this study, S355JR steel chips and CuSn10 bronze chips were cold pressed at ambient temperature and subjected to liquid phase sintering. The chemical compositions of the materials are presented in Table 1.

Both materials are initially in the form of circular saw chips. The reason these chips were selected is that the cutting process results in the formation of similarly shaped chips.

The saw chips are suitable for plastic deformation during pressing due to material's ductile nature. This situation enables us to obtain the desired prosity at relatively low pressures. The plastic deformation also results in mechanical interlocking between the chips (German, 2007).

The metal chips were first sieved using an 800 μm mesh. Afterwards, the chips were cleaned with acetone (C_3H_6O) to remove any remaining cutting fluid debris.

Table 2 shows the relative compositions of the produced MMC materials. Three different compositions were selected and weighed with a precision scale. Afterwards, the constituents were cold pressed at the environmental tempe-

Table 1. Chemical composition of the MMC constituents (wt. %)

Material										
	S355JR	C	Si	Mn	$P_{(max)}$	$S_{(max)}$	N Fe		Fe	
		0.24	0.55	1.6	0.04	0.04	0.009		Balance	
	CuSn10	Cu	Sn	Pb	Ni	Fe	Zn	Si	P	Mn
		87.95	10.45	0.36	0.67	0.025	0.45	0.053	0.012	0.026

rature. Generally PM products have porosity as high as 35 vol.% (German, 2007). In this study, an open porosity value of as 17 vol.% was chosen. The pressing pressure was determined by preliminary testing to obtain the desired porosity. The selected porosity was maintained for all MMC's.

Table 2. The relative compositions of the MMCs and types

Name	CuSn10 chips (w. %)	S355JR chips (w. %)
b70s30	70	30
b60s40	60	40
b50s50	50	50

To reduce the friction between the die and constituents, 1.5 wt. % graphite particles were added. Afterwards, the constituents were blended in conical blender for 15 mins to obtain a homogenous mixture.

Two different dies were used: a prismatic die with dimensions of 19x19x75 mm and a cylindrical die with a 15 mm diameter and a 45 mm height. The preliminary tests revealed that the prismatic shaped specimens required a pressure of 490 MPa and the cylinderical specimens required a pressure of 1070 MPa. Fig. 1 shows the prismatic and cylindrical test specimens.

Figure 1. Cold pressed specimens: (a) prismatic and (b) cylinderical

After cold pressing, the specimens possess a degree of structural integrity due to the mechanical interlocking processes (German, 2007). The specimens were then sintered in an atmospheric-controlled oven to a temperature of 925°C over 45 min in an Argon environment. The specimens were held at this temperature for one hour. After the sintering, the specimens were slowly cooled down to ambient temperature inside the oven.

At this temperature, the type of sintering that occurs is liquid phase sintering. Therefore, the bronze chips partially melt and envelop the steel chips, which have a higher melting temperature, to create a strong matrix to bind the constituents together.

After production, the specimens were machined by milling or turning to achieve the specified dimensions required for testing.

The specimens were subjected to compression testing at room temperature in accordance with the ASTM (E9-89a) standard, which stipulate a 2 mm/min crosshead speed and specimens with a 13 mm diameter and 39 mm height. The compression tests were repeated three times for consistency and force-displacement curves were obtained for all the tested specimens. These data were utilized to obtain true stress and strain values from formulas 1 and 2:

$$\sigma_{true} = \frac{4Fh'}{\pi d_0^2 h_0} \tag{1}$$

$$\varepsilon_{true} = \ln \frac{h_0}{h'} \tag{2}$$

where h_0, d_0, F and h represent the initial height, initial diameter, applied force and instantaneous height, respectively.

The three point bending tests were done in accordance with the ASTM (E290-97a) standard, which stipulates a 55 mm span width, a diameter of support of 8 mm and a 3 mm/min crosshead speed. The tests were repeated three times for consistency.

One result was that the compressive force can cause the chips to change their orientation (see Fig. 2). The presence of these chips can result in material anisotropy. Therefore, the bending force was applied on both the surface where the compressive force was applied during production and on the side surface. The three point bending tests were continued until fracture and the strength was calculated using the maximum force.

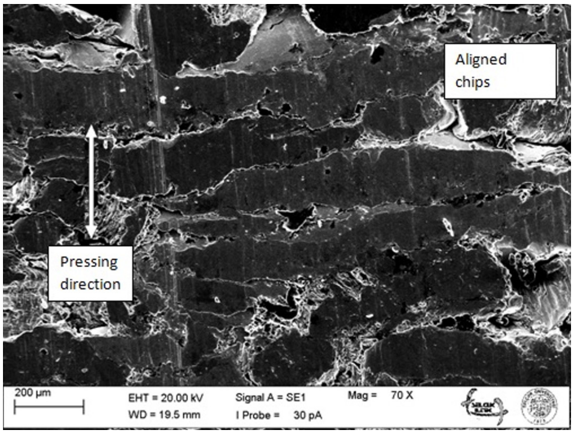

Figure 2. Chip orientation resulting from the effect of the pressing force

After production, the hardness of the composite materials was measured using a Brinell steel sphere with diameter of 5 mm and an indention force of 250 kgf. This diameter was selected because it permits a homogeneous determination of the hardness that examines the constituents and the pores.

RESULTS AND DISCUSSION

Determination of the density and open porosity

The density and open porosity of the produced MMC specimens were determined by gas pycnometer named "Micromeritics AccuPyc II 1340". The densities of the specimens are shown in Table 3. The volume, and thus the densities were measured both before and after sintering. The density of powder metal parts is known to increase after sintering (German, 2007). However, in this study, the density of the MMC was found to have decreased after sintering.

The metallic chips lose the most of their ductility due to the plastic deformation that occurs during machining operations. This situation makes plastic deformation during pressing more difficult. However, the geometry of the chips leads them to behave more elastically. The aforementioned explanations lead us to conclude that the chips behave as an elastic spring and the chips deform elastically during cold pressing. Therefore, when the material heats up during sintering, the elastically deformed chips relax and spring back. This situation results in a volume increase, which results in a decrease in the density. Another reason for the volume increase are the chemical interactions between the constituents, which contain copper and iron (German, 2007). The deformation during sintering supports this idea. The change in volume results in a change in the porosity of the MMC. The open porosity values after pressing and after sintering are shown in Table 4 and increased by approximately 47% after sintering. Generally, densification takes place after sintering. However, due to the shapes and residual stress states of the metallic chips, a spring back effect leads to an increase in the open porosity. Therefore, we can conclude that the oil storage capacity of the specimens has increased.

Table 3. Densities of MMC's before and after sintering

Specimen	After Pressing (g/cm3)	After Sintering (g/cm3)
b70s30	6.51	6.09
b60s40	6.50	6.05
b50s50	6.50	6.05
Bulk CuSn10	8.7	

Table 4. Open porosity percentages of the prismatic and cylinderical specimens

Type		After Pressing (%)	After Sintering (%)
Prismatic	b70s30	16.9	24.9
	b60s40	16.9	25.0
	b50s50	17.0	25.1
Cylindrical	b70s30	16.8	24.8
	b60s40	16.8	24.8
	b50s50	17.0	24.9

Compression Testing

The true stress-true strain responses obtained from the compression testing for the MMC and the bulk CuSn10 are seen in Fig. 3. The initial stages of the stress-strain response for all the materials are linear. However, all the material exhibit ductile characteristics. The overall response of the CuSn10 can be assumed to be bi-linear. However, the other materials exhibit non-linearity after the start of plastic deformation.

The numerical results are summarized in Table 5. Both the yield and ultimate strengths of the MMC are lower than the bulk CuSn10 material. However, the higher strength values obtained for the b70s30 material are comparable to the bulk CuSn10. During production, the bronze constituent partially melts and envelops the steel chips, creating a bronze network which results in load transfer between the chips (German, 2007). As the bronze content decreases, the load transfer between the chips decreases. However, there are stress concentrations around the partially covered steel chips. Therefore, as the bronze content decreases, the strength values decrease. The partially covered chips are examined in detail in later chapters. Table 5 shows that the moduli of elasticity for the MMC exhibit similar behavior. It can be concluded that the decrease in bronze content increases the effect of the pores on the elastic behavior of the MMC between the chips and results in a decrease in the elastic moduli. It can also be concluded that the elastic behavior of the MMC are generally controlled by the bronze content and the steel chips do not affect the elastic moduli.

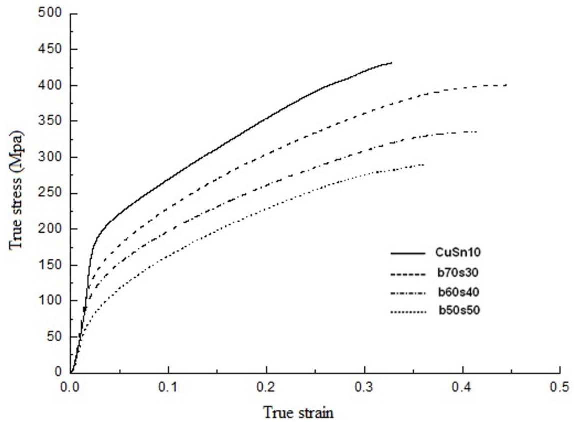

Figure 3. True stress-true strain behavior for the MMC and the bulk CuSn10 under compressive loading

Table 5. Mechanical properties of the MMC materials under compressive loading

	Elasticity Modulus (GPa)	Yield point (%o,2 offset) (MPa)	Ultimate strength (MPa)
b70s30	70,78	152,0	397,90
b60s40	53,64	132,3	335,10
b50s50	39,33	90,0	289,02
CuSn10	90,74	178,66	431,32

Fig. 4 shows the strain percentage after fracture for the composite materials and bulk CuSn10 during compression testing. The composite materials exhibit significantly more plastic deformation and exhibit more ductility than the bulk CuSn10. This behavior can be associated with the porous nature of the MMC because the pores within the materials can close and see large plastic deformation when subjected to compressive loading. The most ductile behavior is exhibited by the b70s30. As the bronze content decreases, the MMC materials become less ductile. However, the bulk CuSn10 material exhibited the least ductility. Therefore, we can conclude that the MMC material exhibit two different plastic deformation mechanisms: plastic deformation within the bronze constituents and that associated with the closure of the pores.

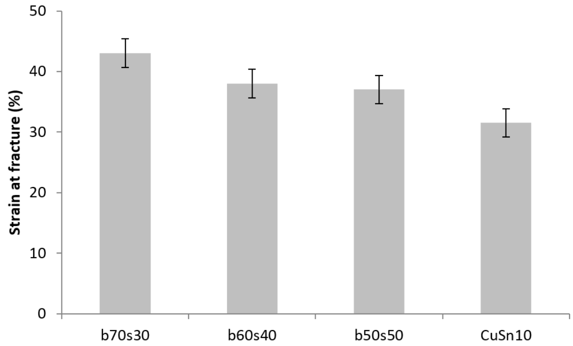

Figure 4. Strain percentage after fracture for the composite materials and the bulk CuSn10 under compressive loading

In order for a material to have a high toughness, it should have both high strength and ductility. The toughnesses of the MMC material are shown in Fig. 5. As stated, the b70s30 material and the bulk CuSn10 exhibit similar strengths. However, the MMC material exhibited more ductility due to its porous nature. The highest toughness is obtained for the b70s30 materials. As the bronze content decreases, the toughness decreases. However, all MMC materials exhibited higher toughnesses than the bulk CuSn10. Therefore, we can conclude that bronze constituent is very important to ensure the material's structural integrity.

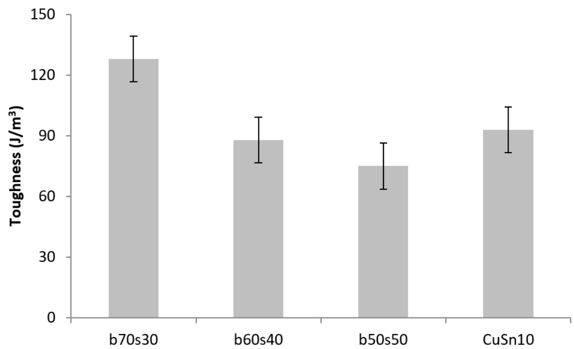

Figure 5. Toughness of the MMC materials

Fig. 6 shows the fracture morphologies of the MMC materials and the bulk CuSn10. The compression tests revealed that the materials experienced ductile deformation. As seen in Fig. 6, the compressive load resulted in shear stress on the plane oriented 45° from the loading direction. No notable barreling is observed. This situation shows that the damage is localized over the 45° plane and that the pores have not completely closed. Additionally, this type of fracture shows that the pores distribute approximately homogenously over the specimens. However, the distribution of the pores is not perfect and a small amount of bending takes place after the compression test.

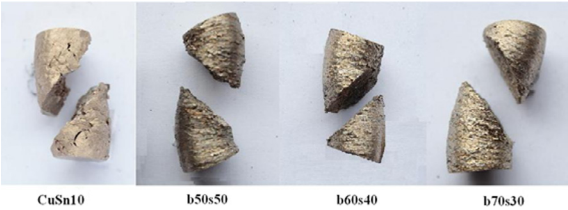

Figure 6. Fracture morphologies of the MMC materials

Three Points Bending Test

The tests were performed in accordance with the ASTM-E290-97a standard, which stipules dimensions of 13x13x70 mm. During the manufacturing process, the metallic chips change their orientation, which can lead to anisotropy in the mechanical properties. To obtain the mechanical properties, the 3PB testing was been repeated for the lateral direction (Fig. 7). The 3PB test results are shown in Table 6. The bending strength of the MMC materials was observed to be lower than that of the bulk CuSn10. As stated, the pores within the structure can result in decreases in the overall strength.

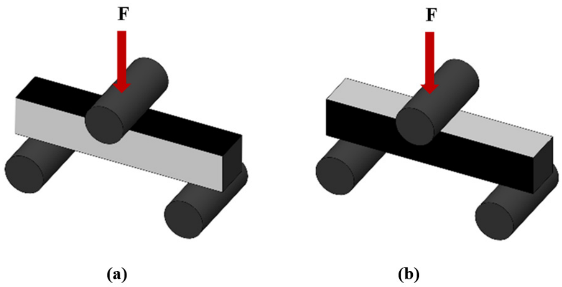

Figure 7. 3PB test application surfaces (a) dark colored area-the upper surface which subjected to force during the pressing process (b) grey colored area-lateral surface

As seen in Table 6, the bending strengths are lower than the compression strengths. We can therefore conclude that the pores in MMC material are more effective under bending. As in the compression test, the highest bending strength was obtained for the b70s30 material. However, bending strength of the b70s30 is lower than the bulk CuSn10.

We can conclude that the pores increase the deformation under compressive loads and restrict the deformation under bending loads, which causes the material to behave in a less ductile fashion. This is mainly due to the creation of tensile stress over the pores and steel chips, which have been partially enveloped by the bronze matrix.

Based on the bending strengths measured in different directions, we observe that the MMC material has anisotropic properties. The strength values obtained from the tests applied on the pressed surface (Fig. 7-a) are higher than the values obtained from the lateral surfaces. During production, compressive loading is applied over the metallic chips placed in the die. As a result, the metallic chips mechanically interlock and are partially cold welded. However, in the transverse direction, interlocking and cold welding occurs as a result of the transverse force that arises between the metallic chips and the die walls.

Table 6. Three point bending test results

Test applied surface	Configuration	Bending Strength (MPa)	Max.Disp. at Fracture (mm)	Max.force (kN)
Pressing surface	b70s30	276.8	0.99	8.13
	b60s40	243	0.76	7.12
	b50s50	215.5	0.63	6.34
Lateral surface	b70s30	271	0.76	7.90
	b60s40	227	0.70	6.71
	b50s50	171.5	0.61	5.23
	CuSn10	310.7	1.92	9.11

Micro Structure and Fracture Morphologies

The microstructure and orientation of the constituents and the integrity between the chips were investigated microscopically. Figs. 8-9 shows the microstructure of the b50s50 and the b70s30 materials after three points bending testing, respectively. We can see from this figure that the constituents were satisfactorily unified. Additionally, the bronze chips have partially melted during sintering, covered the steel chips and partially filled the voids between the chips. However, some larger voids were not completely filled by the bronze. As the bronze content decreased, the steel chips were not fully covered by the bronze.

Figs. 8-9 show that crack initiation takes place at pores and the crack propagates along steel/bronze interface and/or pores. There is no interphase formation between the metallic chips.

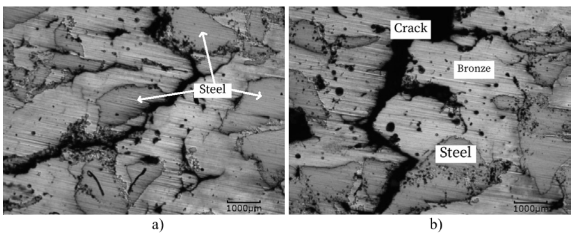

Figure 8. Microstructure of the b50s50 material (50X)

Fig. 10 shows the crack formation and propagation in the bending specimens. The crack started at the mid-point of the specimen where the maximum tensile stress occurs and then propagated towards the upper side. The crack initiated from the stress concentration present around a pore. The cracks propagated in a zig-zag manner in the bulk CuSn10 and MMC materials. From a fracture mechanics

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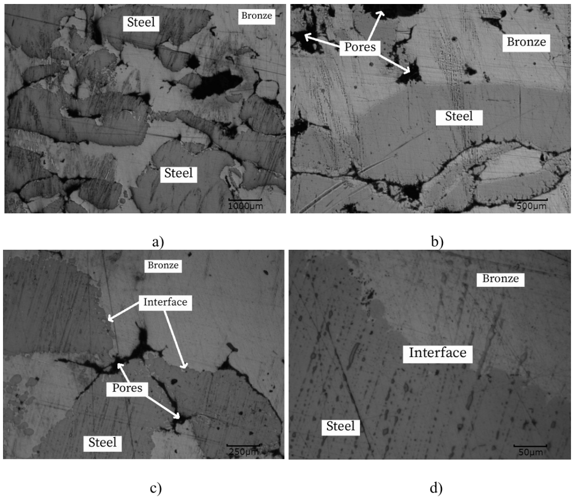

Figure 9. Microstructure of the b70s30: a) 50X, b) 100X, c) 200X and d) 1000X

perspective, the global load equilibrium requires this type of propagation. However, the crack propagation in the MMC materials followed steel/bronze interface and/or pores.

Fig. 10 shows that the bulk CuSn10 exhibited significantly more deformation than the MMC materials when subjected three point bend loading. As the steel content of the MMC materials increased, the material exhibited a more brittle nature. The bending load is a superposition of tensile and compressive loading. The pores result in stress concentrations and the three dimensional stress state masks the ductility. As a result, crack formation takes place.

The CuSn10 constituent is more ductile than the steel constituent. Therefore, we can conclude that as the amount of the CuSn10 constituent decreases, the MMC material becomes less ductile.

Figure 10. Crack formation in the bending specimens

Surface Hardness Measurement

The metallic chips used for production have an average size of 2 mm. Therefore, to obtain reliable surface hardness measurements, the response of the material must be examined over a relatively large area. For this purpose, a Brinell hardness test was utilized with a 5 mm steel ball indenter. In this manner, the effects of local inhomogeneities on surface hardness measurements are eliminated.

The average Brinell hardness test results are presented in Table 7. The highest hardnesses were obtained for the bulk CuSn10. This is explained by its bulk nature, which contains no pores and perfect structural integrity. As for the MMC materials, the b70s30 material exhibited the highest hardness. This result is consistent with both the compression and 3PB test results. Additionally, it is noted that the hardnesses of the MMC materials are similar. Therefore, we can conclude that the hardness is greatly affected by porosity.

Table 7. Average Brinell hardness test results

	CuSn10	*b70s30*	*b60s40*	*b50s50*
Brinell Hardness	*87*	*48*	*42*	*40*

CONCLUSION

In this study, the production and mechanical properties of MMC materials fabricated from recycling steel and bronze chips without melting was investigated. The major conclusions are as follows:

- The production of MMC materials via the recycling of steel and bronze chips is possible.
- MMC materials can be produced with different amounts of porosity by changing the production parameters. Therefore, this type of material can be used as a filter or bumper. The produced MMC materials can absorb a considerable amount of oil, which makes this type of material suitable for use as a self-lubricating journal bearing.
- The mechanical properties depend on the relative fraction of the constituents. As the bronze content increases, the mechanical behavior of the MMC is similar to that of bulk bronze.
- During the sintering, the bronze chips melt and create a strong matrix which binds the constituents together. Therefore, we can conclude that the mechanical properties are primarily controlled by the bronze constituents and the steel chips act as filler.
- The produced MMC composite material b70s30 is more ductile and tougher than the bulk bronze due to its porous nature. For the MMC to be tougher than the bulk bronze, it must include at least 70% bronze content.

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