

## Article

# Investigation of Friction Coefficient Changes in Recycled Composite Materials under Constant Load

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**Abstract:** The surface quality of machine elements may deteriorate over time while operating under different conditions. This deterioration adversely affects the wear behavior in the contact areas, and these materials become unusable over time. In machine elements especially, the heat transfer, wear amount and surface roughness parameters in the contact area are very important in order for the system to work efficiently. In order to understand this change, composite materials were produced by adding spheroidal graphite cast iron (GGG40) with high lubricating properties at different rates to bronze (CuSn10), which is widely used as a self-lubricating bearing material. In this study, four different mixing ratios (B60D40, B70D30, B80D20 and B90D10) and B100, which is completely produced from bronze chips, were used for comparison purposes. In addition, these produced composite materials were compared with pure CuSn10 and pure GGG40 via double-acting isostatic hot pressing, and then the results were examined. The composite materials were made at two different temperatures (400 °C and 450 °C) and three different pressures (480 MPa, 640 MPa and 820 MPa) using recycled waste chips. Composites produced by recycling waste chips both reduce costs and make a positive contribution to the natural environment. Thus, more advantageous self-lubricating bearing materials will be produced, and the efficiency will be increased in these materials. The time-dependent variation in the friction coefficient observed after the wear tests performed under constant load is explained, and the resulting surface structures are presented with SEM images and EDS analyses. After the wear tests, it was observed that the process parameters used in production effectively influenced the wear behavior. In particular, when the production pressure was low (480 MPa), the wear behavior was adversely affected because sufficient bonding between the chips could not be achieved. In addition, as the amount of GGG40 used as a reinforcement material increased, the spheroidal graphite contained in it positively affected the wear behavior. The lubricating effect provided by this spheroidal graphite reduced wear in the contact area and the friction coefficient.

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## 1. Introduction

The importance of composite materials is constantly increasing as they provide advantages in use. Both the reduction in production costs and the improvements in mechanical properties contribute significantly to this. However, in the use of these produced composite materials, different machining processes may be required, and therefore a significant amount of waste can occur. To address this, production processes that do not require machining processes should be developed, or recycling processes should be used to re-evaluate these waste materials. Therefore, more competitive products can be produced by reducing

costs, but the number of these materials are increasing day by day. On a global scale, it is important to use waste materials efficiently due to limited natural resources and the increasing human population. In addition, the damage these materials cause to nature will be reduced and waste materials can be controlled using recycling processes. For this reason, the production of composite materials from waste materials and the investigation of the mechanical properties of the produced materials are becoming widespread today [1–5].

Bearing materials are a machine element whose most important feature during operation is the lubrication characteristic. During operation, the amount of wear will increase due to the overheating of the contact surfaces over time. Therefore, heat transfer between surfaces should be ensured in the best way. If this is not the case, deformations occur on the surfaces due to overheating and the part becomes unusable [5–7]. Lubricating fluids with different properties are used to prevent such heating in the contact area. Thanks to these fluids, temperature increases in the contact area are minimized and frictional behavior is controlled [8–11]. Self-lubricating bearings are used in conditions where the use of lubricating fluid is not desired in the contact area. Since lubricating fluid is not used in self-lubricating bearings, the selected bearing material should be porous and have an appropriate wear ability [8]. Therefore, bronze is widely used in self-lubricating bearings. The high heat conduction and corrosion resistance of bronze provides an advantage in its use as a self-lubricating bearing material [11,12]. In addition, it provides advantages in lubrication thanks to its porous structures. In addition to porous structures, the mechanical and wear properties of the bearing material can be improved by alloying it with different materials [13–16]. For this purpose, studies have been conducted to improve the wear properties of bronze by adding titanium, aluminum, steel and different cast irons [1,16–22]. In bronze used as a self-lubricating bearing material, different materials have been used as lubricants [22–25]. Among them, the use of graphite as a reinforcement material resulted in significant improvements in wear properties [4,26–28]. The good distribution of graphite on the wear surface and the effect of reducing the friction coefficient provide advantages. In addition, filling the pores with graphite improves the wear characteristics of the surface in porous materials [23,29].

In this study, spheroidal graphite cast iron (GGG40) was used as a reinforcement material in the production of composite materials with bronze (CuSn10). A double-acting isostatic hot press was used in the production of composite materials, and production was carried out at different temperatures and pressure parameters. In the production of composite materials, different mixing ratios were determined in the literature and preliminary experimental studies, together with the parameters pure CuSn10 and pure GGG40, which were used as reference materials in experimental studies. In addition to the experimental parameters used in production, the behavior of spheroidal graphite with the use of reinforcement material at different rates was also investigated. In order to determine the properties of the produced composite materials, many mechanical tests were carried out and the wear test parameters were determined based on the results obtained. Thus, we aimed to provide advantages in heat conduction and wear by increasing the lubricating capacity of materials using spheroidal graphite. In addition to these advantages, the total cost of the bearing material was reduced by using a cheaper spheroidal graphite cast iron reinforcement, due to the fact that bronze is more expensive. Thus, the properties of the recycled composite material as a self-lubricating bearing material were improved, and a more environmentally friendly and economical product was obtained.

## 2. Materials and Methods

The CuSn10 and GGG40 waste chips were used in the production of composite materials, and the chemical compositions of these chips are shown in Table 1. In order to achieve a certain size range for these waste chips, sieves were used and chips in the 1–2 mm range were used in experimental studies. The double-acting isostatic hot press shown in Figure 1a was used in the production of composite materials, and the details of the production processes were explained in previous studies by the authors [5,30–32].

Composite materials were brought to the appropriate geometry for wear tests after their production was completed. For this, cutting (Figure 1b) and milling operations (Figure 1c) to provide the inner radius were applied.

**Table 1.** Chemical content of composite material components wt% [5].

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



**Figure 1.** Composite materials: (a) production, (b,c) preparation for wear tests, and (d) composite and abrasive disc before wear test.

CuSn10, which is widely used as a self-lubricating bearing material, significantly improves its wear properties when reinforced with GGG40 thanks to its dense spheroidal graphite. Thus, long-term working conditions will be provided without the need to add any lubricating liquid to the contact area during operation. In this section, the production of composite materials, the preparation of the produced composites for the wear tests and the applied procedure in the wear tests are explained in detail. In Figure 1a–d, these stages are shown together and their detailed explanations are given in the next sections.

### 2.1. Production of Composite Materials

In the production of composite materials, four different mixing ratios by weight (B90D10, B80D20, B70D30 and B60D40) were used. In addition, the effect of the reinforcement material on the matrix material properties was investigated by producing composite materials (B100) in which only bronze chips were used. Thus, the effect of spheroidal graphite in GGG40 was observed more clearly. In addition to the composites produced by the hot pressing of chips, pure CuSn10 and pure GGG40 were also used in experimental studies. Thus, the properties of the materials used in composite production were also evaluated independently of the process parameters used. The production parameters used were determined as three different pressures (480 MPa, 640 MPa and 820 MPa) and two

different temperatures (400 °C and 450 °C), as shown in Table 2. In experimental studies, chips in the range of 1–2 mm were used in the studies by using sieves in order to gain a certain size of waste chips. This process was applied for both matrix material CuSn10 and reinforcement material GGG40 chips. The double-acting isostatic hot-pressing method was used in the production of composite materials. The production unit seen in Figure 1a was heated to the desired temperature with the help of resistances, and temperature control was implemented with the help of the thermocouple seen on the side. The heat loss on the metal surfaces at the bottom of the mold made it difficult to control the pressing temperature. For this, the white insulation plate seen in Figure 1a was used at the bottom of the mold for temperature control in the mold, and temperature control was provided. In hot pressing processes, after the chips had filled the mold, they were kept for 10 min without pressing to reach the working temperature. Afterwards, the chips were pressed in both directions and kept under pressure for 15 min to ensure adequate diffusion between the chips. In this way, the production of cylindrical composites could take up to 30 min in total until the chips have filled the mold and been removed after pressing. After pressure had been applied in both directions, cylindrical composite materials with varying geometries depending on temperature and pressure were obtained. While the diameters of the obtained composite materials were 19.6 mm, their lengths were between 33 and 36 mm depending on the production parameter [4,23].

**Table 2.** Selected parameters in composite production.

Specimen Code	Mixing Ratio by Weight (wt%)	Pressure (MPa)	Temperature (°C)	Test Repetitions
B60D40	60% CuSn10–40% GGG40			
B70D30	70% CuSn10–30% GGG40			
B80D20	80% CuSn10–20% GGG40	480, 640, 820	400, 450	
B90D10	90% CuSn10–10% GGG40			3
B100	100% CuSn10–0% GGG40			
P-CuSn10		Pure CuSn10		
P-GGG40		Pure GGG40		

## 2.2. Wear Tests

Many parameters were applied in the production of composite materials, and the most suitable parameters were selected for wear tests in mechanical tests and microstructure investigations [5,30]. The produced composites were thought to be useful as self-lubricating bearing materials. Therefore, the actual wear procedure was taken into account in the design of the wear test unit. The bearing material worn on the circular rotating shaft works with a certain tolerance, so that the fluid lubricant previously impregnated creates a lubricating effect in the heated contact area. Therefore, the bearing material can be used for a long time without the need for any external lubricating fluid. After the reduction or disappearance of the lubricating effect, the wear behavior changes and undesirable damage occurs in the contact area. The composites were made ready for the wear test shown in Figure 1d after the cutting and surface treatment processes shown in Figure 1b,c. Depending on the applied production parameter, the pore and sample height changed. As can be seen in Figure 1b, the composites were sliced into 10 mm widths then cut evenly in the middle with the help of a 2 mm wide saw. Afterwards, the inner surfaces of the composites were processed with CNC-Milling and brought to an inner radius of 69.05 mm for the wear test, and the inner surfaces of the composites were ground to eliminate the negative effects on the surface. Thus, roughness and notches that may occur on the surface during the formation of the inner diameter were removed from the wear surface. Finally, the ground wear surfaces were subjected to an ultrasonic bath process in order to clean the dust and particles caused by the environment or the applied processes. Thus, roughness



and notches that may occur on the surface during the formation of the inner diameter were removed from the wear surface. Finally, the ground wear surfaces were subjected to an ultrasonic bath process in order to clean the dust and particles caused by the environment or the applied processes. This process was applied in pure water for 25 min to eliminate the negative effects on the surfaces [33]. Thus, the composites were made ready for the wear test. AISI4140 steel was chosen as the abrasive disc material and the outer diameter was determined as 69 mm. The required tolerance during wear was chosen as 0.05 mm. The abrasive disc, which was brought to the desired dimensions, was then subjected to heat treatment and the surface hardness was brought to 54–55 HRC. It was intended to minimize the deformations that may occur on the surface of the abrasive disc. Since the chips used in the production of composites are on a macro scale (1–2 mm), we aimed for regional/linear contact instead of point contact in wear tests. The block-on-disk wear test device designed according to the ASTM (G77-05) standard is shown in Figure 2. Before the wear tests, many preliminary experiments were carried out to determine the experimental parameters. After these preliminary tests, a constant load of 30 kN and sliding speed of 1.06 m/s were selected. In determining the total wear distance, 2,000 m was chosen because the general behavior did not change after this distance in the preliminary experiments, and the tests carried out in these parameters took approximately 31 min. All wear tests were repeated three times and all tests were recorded instantly. From the beginning, the friction coefficient changes were noted and the obtained data were evaluated comparatively, and unexpected sudden changes were not observed under the applied constant load. The sample holder was fixed and there was a disc rotating at the bottom with a shaft powered by a 2.2 kW electric motor and with a 2.5 kW speed adjuster [5]. After the wear tests were completed, the composites and abrasive discs were meticulously preserved and prepared for future microstructure investigations. Thus, the factors that can affect the friction coefficient were examined in detail with the analysis of the surface structures.

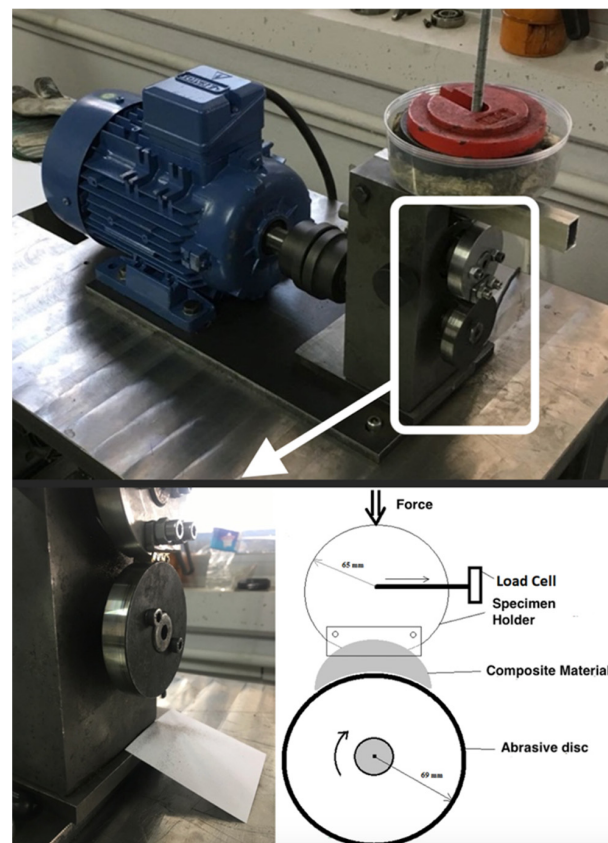


Figure 2. Block-on-disk wear test unit.

### 3. Results and Discussions

After the composites were produced at different temperature and pressure parameters, the samples produced with pure CuSn10 and pure GGG40 were used in wear tests in order to evaluate the results more efficiently. Thus, we aimed to evaluate the results by comparing the composite materials produced via double-acting hot pressing with pure materials (P-CuSn10 and P-GGG40). Figure 3 (400 °C) and Figure 4 (450 °C) show the changes in the friction coefficient obtained during the wear tests of composites pressed at different pressures. In addition, the friction coefficient changes were presented depending on the sliding distance and time.

In the graphics, the running-in zone was completed depending on the mixing ratio at 160–210 m sliding distances. Running-in is the removal of peaks or spikes on the surfaces with pre-abrasion at low loads and speeds before the actual wear behavior of the materials. Thus, the contact area can be increased and the negativity affecting the wear behavior of the materials can be eliminated. In the change curves of the friction coefficient, the amount of wear on the surfaces was low at the beginning, but the amount of wear increased with the increase in the surface area with the advancing wear distances, and this situation abruptly increased the friction coefficient. This behavior was related to the surface properties of composite and abrasive discs. The wear behavior of surfaces in contact is affected by surface hardness and pore structure. While the high surface hardness triggered the abrasive wear behavior, the adhesive wear behavior dominated since the large number of pores prevented heat transfer in the later stages of wear. The large number of pores or the wear characteristics of the composite components affected the change of this curve. Excess pore structures will reduce the contact surface area in the early stages of wear [26,30]. Thus, this will reduce heat transfer at the contact surfaces in the early stages of wear and trigger adhesive wear behavior. But in the later stages of wear, dust or particles detached from the surface will fill these pores and increase the contact surface area. In particular, the collection of spherical graphite structures in the composite will have a lubricating effect and prolong the working life of the composite [11]. As seen in the figures, the friction coefficient value of pure GGG40 was higher than that for the composites and pure CuSn10. The friction coefficient values increased with the increase in the amount of GGG40 in the mixing ratio. In addition, the sudden changes in the friction coefficient curve obtained with the increase in the wear distance in Figure 3b, where the production pressure was 640 MPa, were more pronounced than the composite materials produced at the other two pressures. It is thought that the differences in surface pore structure and hardness play an important role in this [1]. Considering the previously mentioned pore and hardness values, the more regular curves obtained in Figure 3a,c were expected. When the friction coefficient changes in the composite materials produced at 400 °C at all three production pressures were examined, it was observed that the wear samples at the mixing ratios of B60D40, B70D30 and B80D20 had similar characteristics. Especially in Figure 3c, a similar decrease in friction coefficient was observed in all mixing ratios after approximately 670–820 m sliding distances. This behavior was evaluated as the lubricating effect of the spheroidal graphite contained in the wearing reinforcing material GGG40 over time in the wear surface. This effect is clearly seen in Figure 4c, which is the test result of composite materials produced at 450 °C.

When the friction coefficient changes of P-CuSn10 and B100 were examined, there were sudden changes at each production pressure for B100. Regardless of the production parameters, these changes varied in the range of friction coefficient values of 0.12–0.27. The reason for this situation is that the eroded particles showed abrasive wear behavior in the wear area and caused deformations on the composite material surfaces [34]. In composite materials with reinforcement material, the lubrication regime formed in the advancing processes of wear prevented such situations thanks to the spheroidal graphite in the reinforcement material GGG40 [35]. In addition, when the friction coefficient curves of the composite materials produced at two different temperatures were examined, it was seen that the curves of the composite materials produced at 450 °C were more similar to each other. In particular, in Figures 3c and 4c, where the production pressure of the

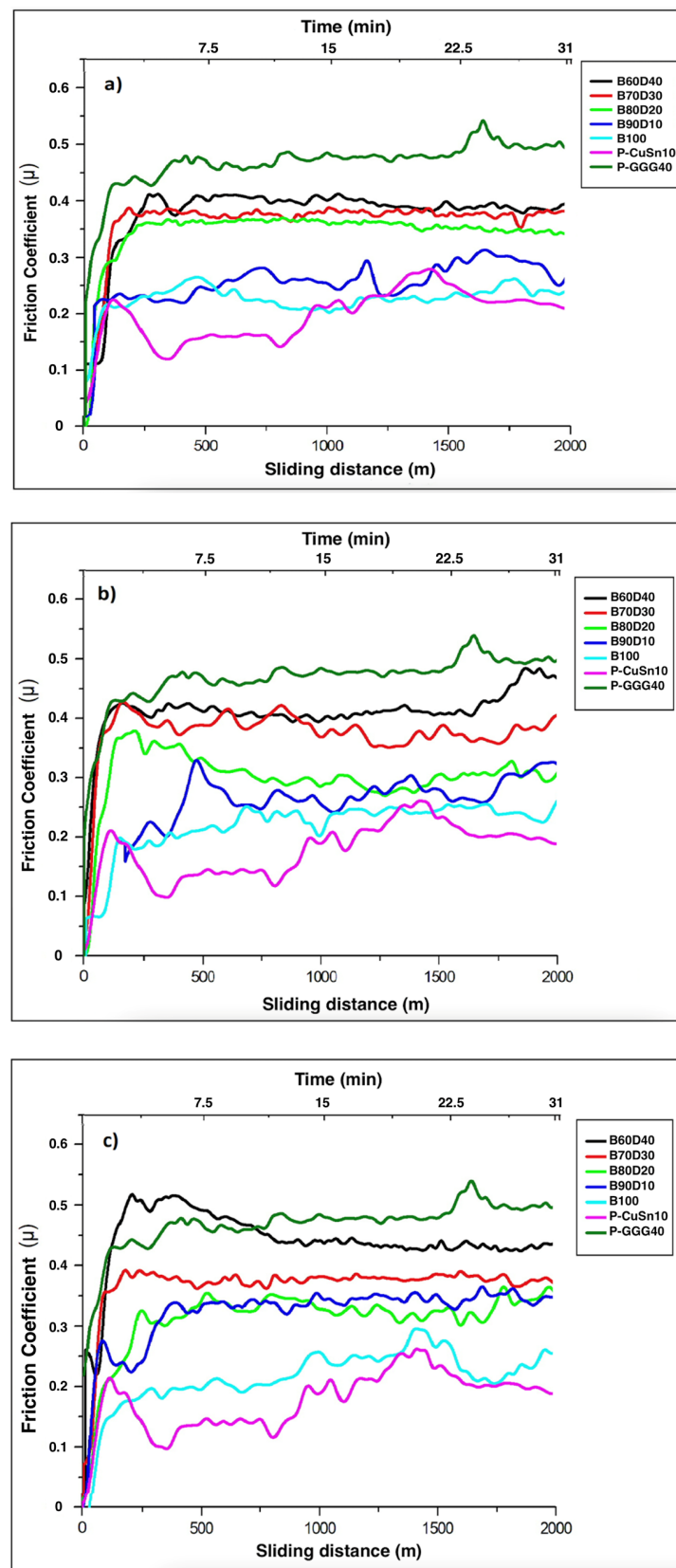
composite material was 820 MPa, it was determined that the curves were closer to each other with different amounts of reinforcement material. The emergence of this behavior has been evaluated as a better lubricating role of the graphite in the abraded powders on the surface due to better bonding between the chips at high production pressures and the partial filling of the pores of the abraded structures in the post-wear environment [31].

In self-lubricating bearing materials, when the bearing material heats during operation, the lubrication task is performed in the lubricating fluid contact areas from the pores. On cooling after wear, this lubricating fluid is directed back to the pores of the bearing material [15,35]. In these operating conditions, radial bearing materials are widely used at low rotational speeds and high loads. In experimental studies, at 820 MPa, where the production pressure of composite material is high, this behavior has been observed as a linear decrease in the friction coefficient at different mixing ratios with advancing sliding distances, and is consistent with previous studies [8,34,35].

After the wear tests were completed, the surface morphologies of the composites and abrasive discs were examined in detail under the SEM (scanning electron microscopy) microscope and the results are presented in Figure 5. The microstructure images of composites with a B80D20 mixing ratio produced at 450 °C temperature and 820 MPa pressure are presented in Figure 5a–c. In addition, SEM images of the abrasive discs used to erode these composites are shown in Figure 5d,e. In all analyses, the wear direction was from left to right and the images have been interpreted accordingly. After the wear tests, the porous structures in the composite were filled with snapped particles during wear and the surface area was increased in the contact area [26]. In addition, the plastering of CuSn10 due to plastic deformation was observed on the surfaces. This behavior caused adhesive wear and stratification on the wear surface [5,36–39]. In addition, abrasive wear zones were observed in some regions and it was noted that some particles detaching from the composite surface caused this. It has been observed that this wear behavior creates traces parallel to the wear direction. The graphite observed on the surfaces of the composites, which are intended to be used as self-lubricating bearing materials, significantly reduces the friction coefficient, and this decrease is clearly observed in the later stages of wear.

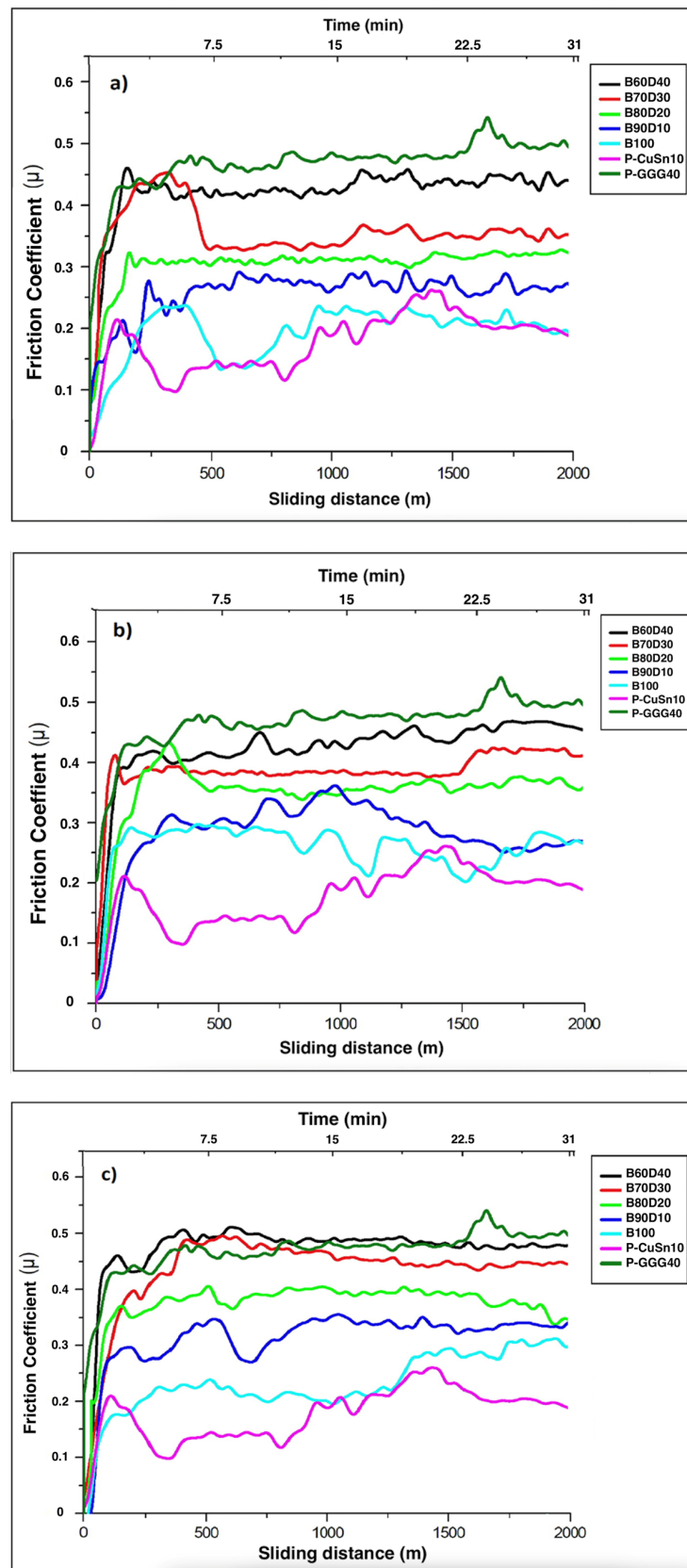
In order to better understand the surface morphology of the materials after the wear tests, EDS (Energy Dispersive Spectroscopy) analyses were also performed together with SEM. In these analyses, the surface area of the composite (B60D40) and the chemical contents of the worn particles (B70D30) were examined. The region where the analyses were made and the results are presented together in Figure 6. Figure 6a–c show the region where the analysis of B60D40 composite was made and the EDS results. In the EDS analysis, the materials that make up the matrix material content were measured as 19.03% Cu, 7.89% lead, 1.92% tin and 0.73% Si. In addition, it was observed that the Fe and graphite structures in the reinforcement material GGG40 were quite dense (61% Fe) in this region. Thanks to the lubricating effect of this structure, which is common in the wear zone, heat conduction was facilitated and the general wear behavior was improved. In addition, the oxide structures (2.90% oxygen) in the environment originated from the environment conditions of wear test and their amounts could change with the effect of temperature [5].

In addition, the particles formed after the wear of the B70D30 composite were investigated by performing EDS analysis in the region shown in Figure 6b–d. In the analysis, 49.49% Cu, 9.58% lead, 4.17% tin and 0.52% Si were measured. Considering the other minor alloying elements in CuSn10 and with a Fe content of 26.78%, the present wear particles were very close to the composite content. Therefore, it was observed that the wear tests of the composites were performed quite homogeneously. In addition, 7.45% oxygen detected in the particles occurred due to the effect of the wear tests performed at room temperature and the increasing temperature in the contact area [26].



**Figure 3.** Time-dependent variation in the coefficient of friction in the wear process (400 °C): (a) 480 MPa, (b) 640 MPa and (c) 820 MPa.





**Figure 4.** Time-dependent variation in the coefficient of friction in the wear process (450 °C): (a) 480 MPa, (b) 640 MPa and (c) 820 MPa.

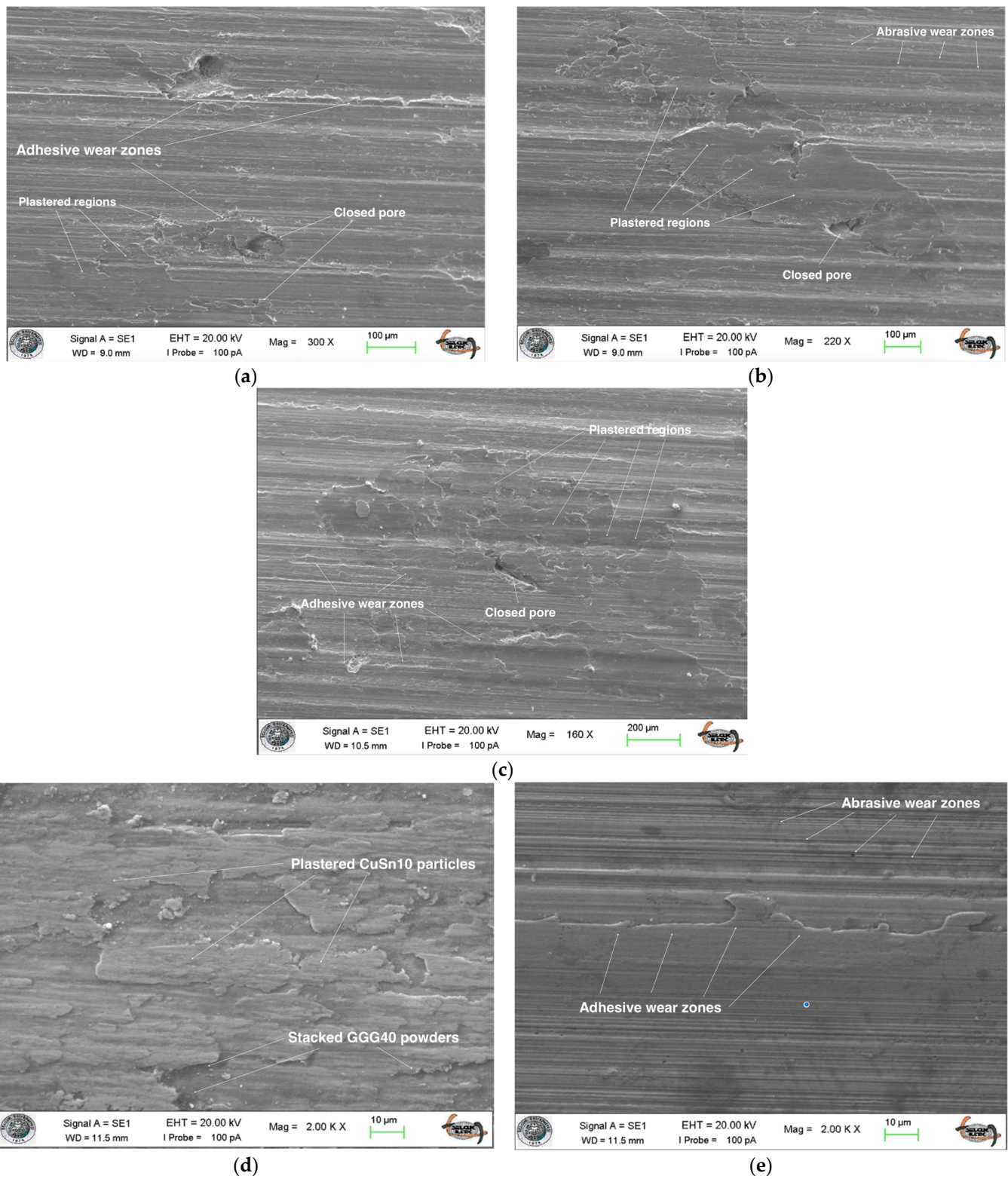
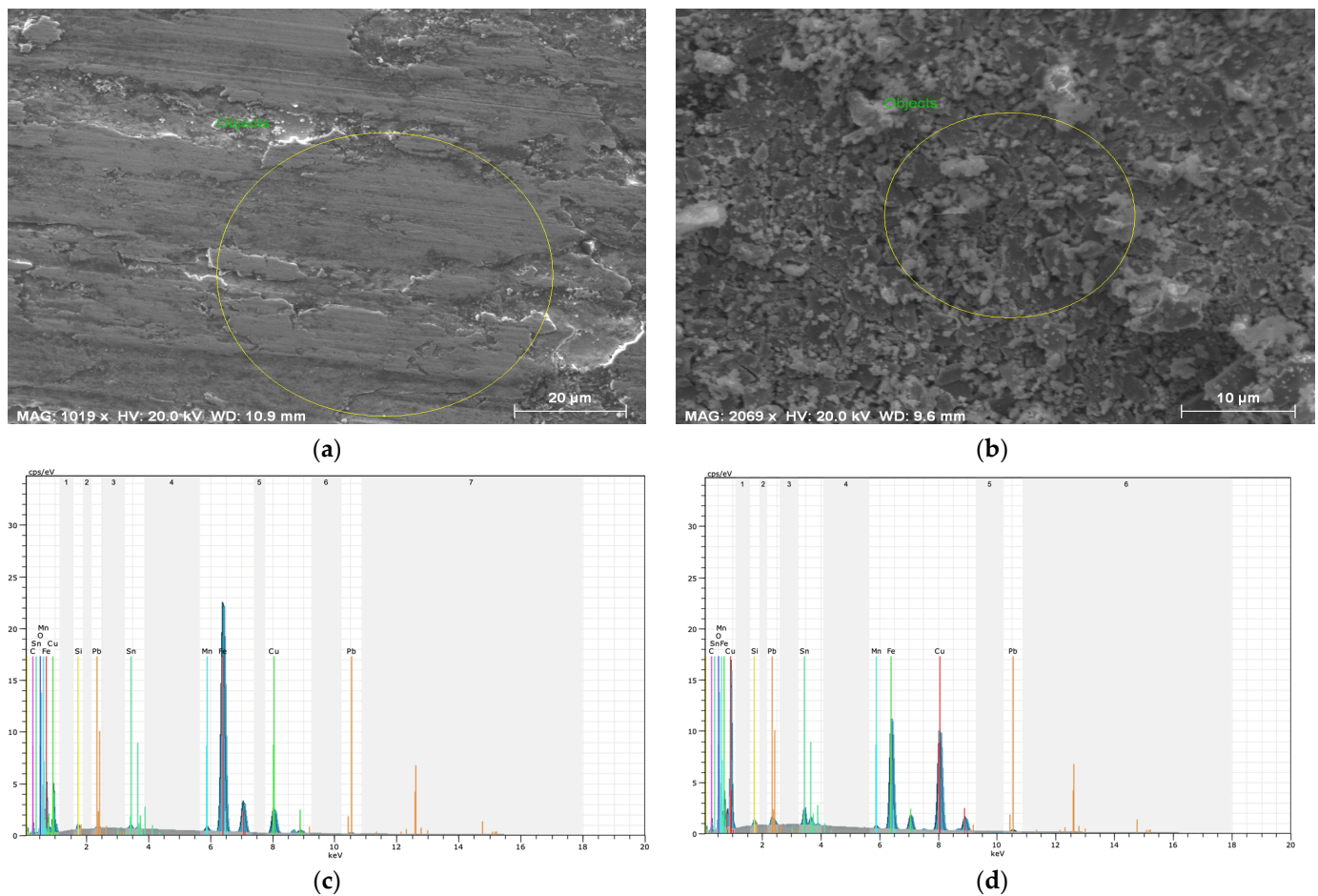


Figure 5. SEM images of B80D20 composites (a–c) and abrasive discs (d,e) after wear tests.



**Figure 6.** SEM image and EDS analysis of B60D40 composite (a–c) and worn dust of B70D30 (b–d) after wear.

#### 4. Conclusions

Composite materials were produced by mixing GGG40 and CuSn10 metal chips at different mixing ratios and recycling them in a double-action isostatic hot press at two different temperatures and three pressure parameters. The results obtained after the wear tests of the produced composite materials are presented in the relevant sections. In addition, SEM analyzes were made together with the test results, contributing to the evaluations, and the results are given below.

- The changes in the friction coefficient measured instantaneously during the wear tests were significantly affected by the production pressures of the composite materials. The friction coefficient changes in the materials produced at a low pressure, 480 MPa, showed a more uneven distribution. It is thought that as a result of the insufficient bonding between the chips, which causes easier wear, the effect of the abraded dust on the wear area and the amounts of excess pores it has is effective. In the composite materials produced at 820 MPa pressure, linear decreases were observed in the friction coefficient after a certain distance, with the effect of the graphite wearing away with the progression of the wear distance.
- When the wear zones of the composite materials were examined after the wear tests, it was observed that the wear behavior was significantly affected by the lubricating effect of graphite, and this effect increased with the increase in the reinforcement material, GGG40. In composite materials with different mixing ratios, the wear zone shifted towards the first contact zone with the lubricating effect of graphite.



- The increase in the matrix material CuSn10 in the mixing ratio affected the wear behavior. With the decrease in GGG40, which is used as a reinforcement material, the wear behavior changed and the lubricating effect of the spheroidal graphite decreased. As a result, it was observed that CuSn10's adhesive wear on the abrasive disc surface and the amount of plastering increased due to the increased temperature in the contact areas during the wear tests.
- The composite materials we produced can have many uses, but the main purpose of use is considered to be as a self-lubricating bearing material. Composite materials produced according to the wear test results demonstrated that by recycling from waste metals, the production process can be more efficient than the widely used melting method, and the friction coefficient changes are more stable and the graphite in the reinforcement material provides advantages due to the lubricating effect.

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