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Abstract: Copper matrix composites (CMC) are frequently used in the automotive, aerospace, construction, and electrical-electronics industries. Properties such as low density, improved fatigue strength, high hardness, and high specific strength are the factors that make copper matrix composites important. The development of these factors is important for the industrial use of copper matrix composites. SiC_P doped metal matrix composites have better mechanical properties than pure alloys. It is also known that Ti, B powder particle additives improve the mechanical properties of the main matrix. In this study, Cu hybrid composites reinforced with Ti-B-SiC_P powders, which were not produced before, were obtained and their microstructure, density, hardness, and wear behavior were investigated. Composite materials produced by powder metallurgy method were prepared at 2-8 wt. % mixing ratios. Then each material was sintered at temperatures of 950-100-1050 °C. Microstructural images showed homogenous distribution in the composite material. The highest relative density of 93% was obtained in the composite material with a 2% reinforcement rate at 1050 °C. It was found that the hardness increased with the increase of the reinforcement rate up to 6 wt.% and then decreased after that. It was observed that the specific wear rate increased with the increasing reinforcement ratio. In addition, the lowest friction coefficient and wear temperature occurred at a sintering temperature of 1050 °C. In this study, it was reported that the sinter temperature value of 1050 °C is the optimum temperature value in terms of the tribological and mechanical performance of the materials.

Keywords: Copper matrix composites (CMC), hybrid composites, powder metallurgy, hardness, wear

1. Introduction

There is always a need for reinforced composite materials in industrial fields [1]. Meeting these needs is of great importance [2]. From this point of view, it is seen that composite materials are preferred as a more popular working area day by day [3]. Composite materials in different matrix groups (such as steel, copper, magnesium, aluminum, bismuth, bronze, titanium) are used in many areas of the industry [4]. Especially copper matrix composites are frequently used in many applications due to their low cost and ease to manufacture [5]. Copper main matrix composite materials are preferred due to their very good mechanical and physical properties [6]. In addition, it became one of the important demands in many sectors (heat sink, brake friction, conductive springs, and interconnections, etc.) due to its low density, high strength, high hardness, and increased tribological properties. Due to the increasing needs, parts used in modern machines are desired to have better mechanical properties [7]. The fact that a manufactured material is more resistant to the effects of external factors such as wear and corrosion attracts the attention of many researchers [8]. Pure copper has a low modulus of elasticity and poor strength properties. Powder particles are added to pure copper to improve its mechanical properties [9]. In a study, it was reported that the mechanical properties increased thanks to the reinforcements added to copper as a strengthening mechanism [10]. It is known that copper composites reinforced with reinforcing powder particles have very good wear resistance and hardness properties [11]. Moazami-Goudarzi and Nemati [12] produced composite materials by adding MoS_2 at different rates (0-10 wt.%) to copper in their study. As a result of the wear test applied to the produced composites, they reported that as the normal load (1-4 N) increased, the friction coefficient decreased and the wear volume increased. This topic is of interest to many researchers [13]. It also significantly increases the mechanical and physical properties of two or more (hybrid) powder particles compared to a single reinforcement [14]. Usca et al. [15] produced new composite materials by reinforcing copper with B-CrC powder particles. According to the results they obtained, they reported that the reinforcement ratios were highly effective on the wear rate (51.6%), mass loss (27.25%) and friction (79.9%).

Ti (Titanium) powder particles were the subject of many scientific studies due to their excellent corrosion resistance, low density, and high strength [16]. Rahmanullah et al. [17], reported that increasing wt.% Ti particles in the base matrix improved the tribological and mechanical properties of the material. It is known in the literature that element B (boron) has a low density and increases the hardness of the structure in which it is located. It is also known to be used as a degassing agent in copper alloys. In a study, composites with Cu-B matrix were produced and it was observed that with increasing wt.% B, the interface bond of the composites improved, and thermal conductivity increased [18].

New materials were produced by adding hybrid particles in different proportions to the matrix material [19]. For this purpose, many powder particles (TiC, TiB_2, Ti, B_4C, CNT, SiC_P, Al_2O_3, WC, MoS_2, Y_2O_3) are used as reinforcement material [20]. SiC_P (silicon carbide), a good abrasive ceramic material, is used as a strengthening mechanism in many studies [21]. Sap et al. [22], produced composite material by adding Mo-SiC_P (0-5-10-15 wt.%) powder particles into the Cu base matrix. They reported that the composite materials produced had a significant increase in hardness with increasing reinforcing powder particles. Selvakumar et al. [23], produced a new composite material by adding SiC_P (0-2.5-5-7.5-10-12.5-15 wt.%) particle reinforcement into Al main matrix reinforced with 4 wt.% Cu. They reported that microhardness and compression strength increased with increasing particle addition in the produced composite materials. Wear is a complex and inevitable phenomenon that occurs between two working surfaces. Wear of materials is extremely important in industry as it affects system functionality. In many industrial applications, system components wear out and need to be replaced. These changes are very important from an economic point of view. For this reason, it is important to learn about the wear resistance of the materials produced and to ensure that the wear resistance is constantly improved. Although one of the wear measures in materials is the coefficient of friction, the specific wear rate (SWR) was accepted as a later accepted wear measure [14]. Jamwal et al. [24], added 2-4-6-8% by weight Gr-SiC to Cu and produced hybrid composite materials. They reported that wear resistance increased with increasing reinforcement ratio. Cui et al. [25], added SiC powder particles to the Cu-Fe main matrix in their study. As a result of the study, they observed that the composite materials increased the corrosion resistance.

This study aims to produce hybrid composite materials with improved wear resistance by adding hybrid reinforcement powders to pure copper powders. Hybrid powder particles (Ti-B-SiC_P), which are used as reinforcement material in the literature, were used. New metal matrix composite materials were produced by adding hybrid powder particles (2-4-6-8 wt.% Ti-B-SiC_p) into pure copper powder. For this purpose, pure copper and hybrid composite materials were examined in terms of microstructure. In addition, its mechanical properties such as hardness, density, and wear performance were examined. Thus, microstructural properties, mechanical properties, and optimum sintering temperature were investigated for the produced composite materials.

2. Materials and Method

In this study, composite materials were produced by powder metallurgy method. Copper used as the main matrix was preferred in commercial purity and spherical form. As reinforcement particles, Ti and SiCp were chosen to provide better wear and hardness properties, and B was chosen to increase hardness and interfacing in the composite material. The selected additives all have high hardness and their density is lower than the density of the main matrix. Thus, with the reinforcements used, a lower density composite material can be obtained and various properties (hardness, wear resistance, etc.) of the main matrix can be improved. In this study, powders with purity rates greater than 99% were used. In addition, the particle sizes of the powders used are smaller than 44 μm for Cu and Ti, 1.8 μm for B powder, and 1.8 μm for SiC_p. The mixing ratios of the powder particles used in the experiments are shown in Table 1. Powder particles were supplied from Ege Nanotek companies.

Table 1. The reinforcement ratios used in the tests of the composites produced [6]

Samples	Cu reinforcement ratio (wt.%)	Ti reinforcement ratio (wt.%)	B reinforcement ratio (wt%)	SiC_p reinforcement ratio (wt.%)	Number of samples produced
0 wt.%	100	-	-	-	9
2 wt.%	98	0.50	0.25	1.25	9
4 wt.%	96	1.00	0.50	2.50	9
6 wt.%	94	1.50	0.75	3.75	9
8 wt.%	92	2.00	1.00	5.00	9

The powder particles dried in an electric oven at 100 °C were measured on a balance with an accuracy of 0.001g to obtain a mixture at predetermined ratios. SEM (scanning electron microscope) micrographs of powder used in the experiments are shown in Fig. 1 [22]. Ti-B-SiC_P (2, 4, 6, 8 wt.%) powders were added into the Cu base matrix and mixed in a turbula apparatus for approximately 4 hours. Mold surfaces used to produce the samples were oiled with zinc stearate. The mixed powders were produced in a uniaxial hydraulic press by applying 600 MPa pressure to produce composite test materials of 10 mm diameter and 21 mm length. The sintering temperature of most metals is around 80-90% of the melting temperature. However, for some heat-resistant metals, this situation may be higher. For this reason, sintering temperatures of 950 °C, 1000 °C, and 1050 °C were chosen in this study, since the melting temperatures of the hybrid powders used in the mixture are very high (Ti: 1668 °C, B: 2180 °C, and SiC_P: 2730 °C) [26, 27]. The pressed samples were sintered with an atmosphere-controlled furnace for 60 minutes. During the sintering process, argon gas was used as the protective gas. Sintered samples were sanded with SiC papers ranging from 200 to 1200 grids.

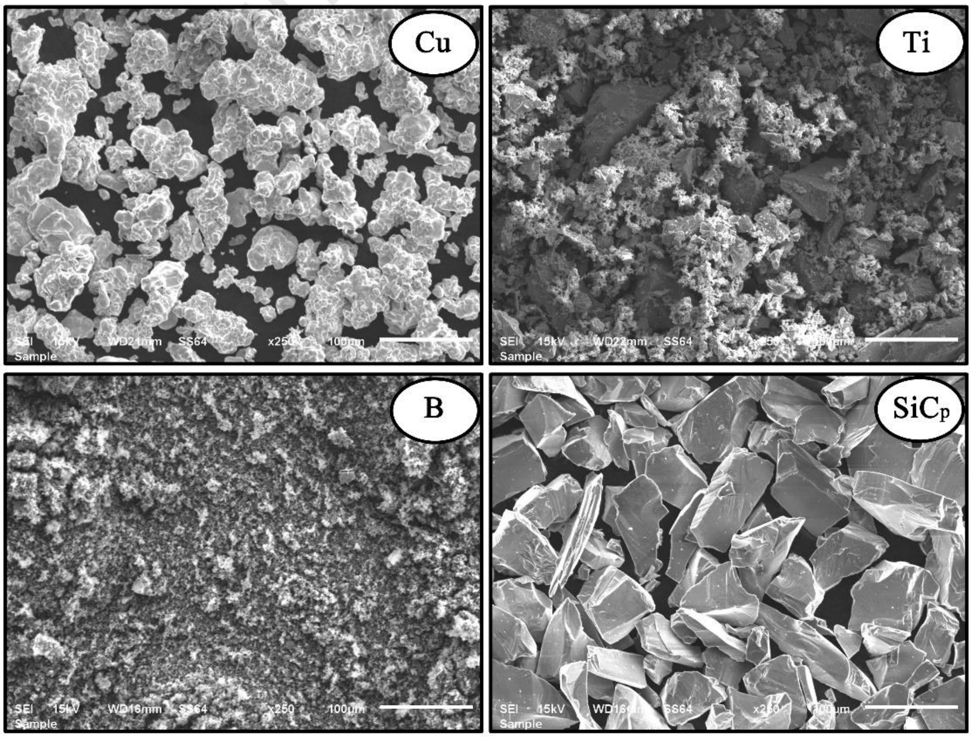


Fig. 1: SEM images of the powders used in the experiment [6, 22]

The sanded hybrid composite material surfaces were polished with 1 μm water-based diamond paste. Samples were cauterized with solution (25 ml HCl 1-2 gm Fe_3-Cl - 100 ml H_2O) [28] for metallographic analysis. Particle sizes and distribution of composite samples produced were verified by SEM, EDX, and, mapping analysis. Microstructure analysis of the composite materials was performed with a JEOL JSM 6510 scanning electron microscope. After the microstructural analysis, the densities of the composite materials were calculated according to Archimedes' principle. Eq. 1-2-3 was used for density values.

$$\rho_{theoretical} = w_{Cu} * \rho_{Cu} + w_{SiCp} * \rho_{SiCp} + w_{Ti} * \rho_{Ti} + w_B * \rho_B \quad (1)$$

$$\rho_{experimental} = \left(\frac{m_{air}}{m_{air} - m_{water}}\right) * \rho_{water} \quad (2)$$

$$\rho_{relative} = \left(\frac{\rho_{experimental}}{\rho_{theoretical}}\right) * 100 \quad (3)$$

Where *W* represents the weight fraction, ρ represent density (g/cm^3) of the ingredient, ρ_{water} represents the density of the distilled water (0.998 g/cm^3 at 20 °C), m_{air} represent the mass of the sample in air, and m_{water} represent a mass of the sample in water.

Hardness analyzes were made to determine the effect of different sintering temperatures on the composites produced. The hardness value of the samples was determined in terms of Brinell hardness value with a BMS Hardness Testers device. To make the hardness analysis more reliable, the Brinell hardness method was applied. The reason for performing the macrohardness test is to obtain more efficient results by contacting both the main matrix and the carbides with the ball (ball diameter: 2.5 mm) used in the hardness test. For each measurement, a 31.25 kg preload was applied to the samples whose surface was flat and smooth for 10 seconds. To reduce the error margin of the experiments, five different measurements were taken from each sample and the reported results represent the arithmetic mean of the five measurements. The ends of the cylindrical test specimens produced were conical to determine the wear and friction behavior. Wear tests were performed in a laboratory environment at room temperature (25 °C and 50–60% relative humidity) under dry shear conditions. Wear tests of the samples were carried out (according to ASTM G99-95a) using the pin-on-disc technique in TURKYUS model tribo test device as shown in Fig. 2.

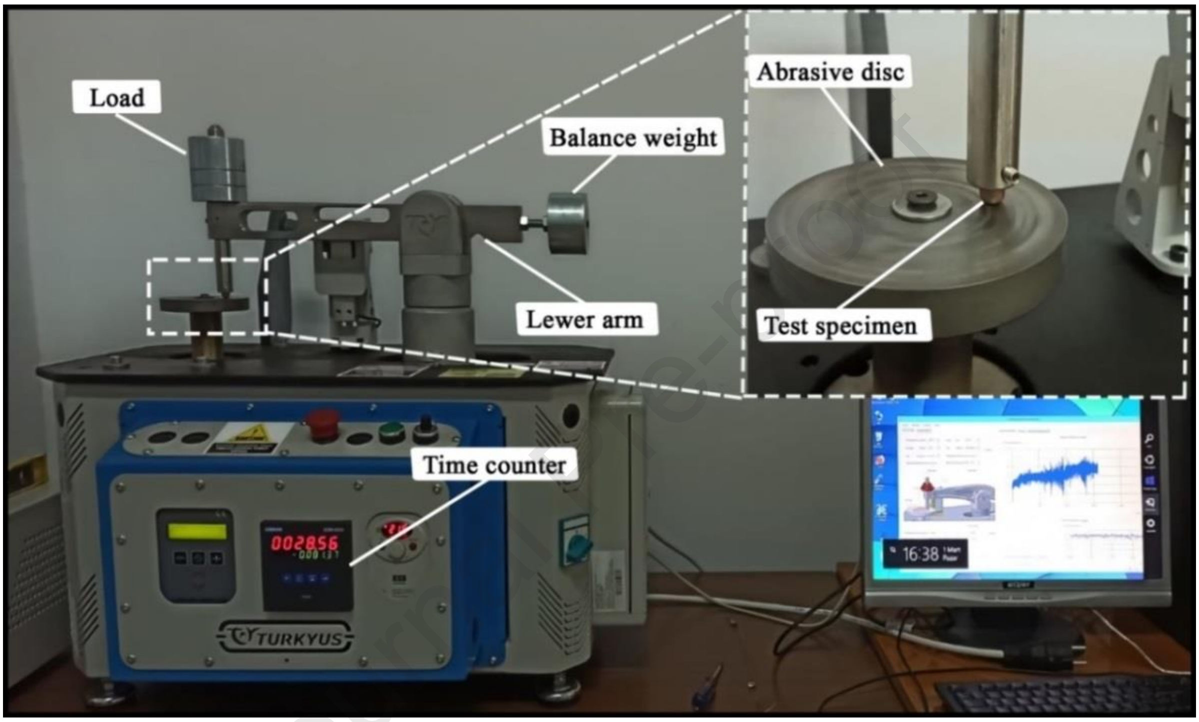


Fig. 2: Details of the wear device used in the analysis

The disc used in the wear tests was produced by wire erosion method using AISI D2 quality tool steel and the surface was hardened by nitriding. Before starting the wear test, the microhardness value of the disc used as an abrasive was measured. This value was recorded as 795 HV. The surface roughness value (R_a) of the abrasive disc was determined as 4.6 μm. 2000 m wear distance and 1.5 m/s wear rate parameters were applied to each wear sample under dry sliding conditions. Loads of 15, 20 and, 25 N were applied to each test sample produced at different rates. Results were recorded and analyzed. The friction force was determined by a strain gauge connected to the tribo tester during the wear test. Accordingly, the average friction coefficient was determined according to Eq. 4.

$$\mu = F/N \quad (4)$$

Where μ is the average friction coefficient; F indicates the friction force (N) and N indicates the amount of load (N) applied during the wear test. Results were recorded on the device. After the wear test, the mass losses of each sample were determined. SWR (Specific Wear Rate) value was calculated for each sample using the following equations (Eq. 5-6).

$$V_L = \Delta_m \cdot \rho \quad (5)$$

$$SWR = V_L/(N \cdot X) \quad (6)$$

Where V_L is the total volume loss (mm^3); Δ_m mass loss (g); ρ , density (g/cm^3); N is the load (N) applied during the wear test; X indicates the wear distance (m) and SWR indicates the specific wear rate (mm^3/Nm). In addition, wear diameter images of the specimens whose ends were made conical were obtained. In addition, the temperature formation between the rubbing objects during the wear test was also obtained. 5 different temperature measurements were taken from each sample with a TESTO 871 thermal camera at 400 m distance intervals. Fig. 3 shows the temperature distribution graph of the image taken with the thermal camera during the wear test.

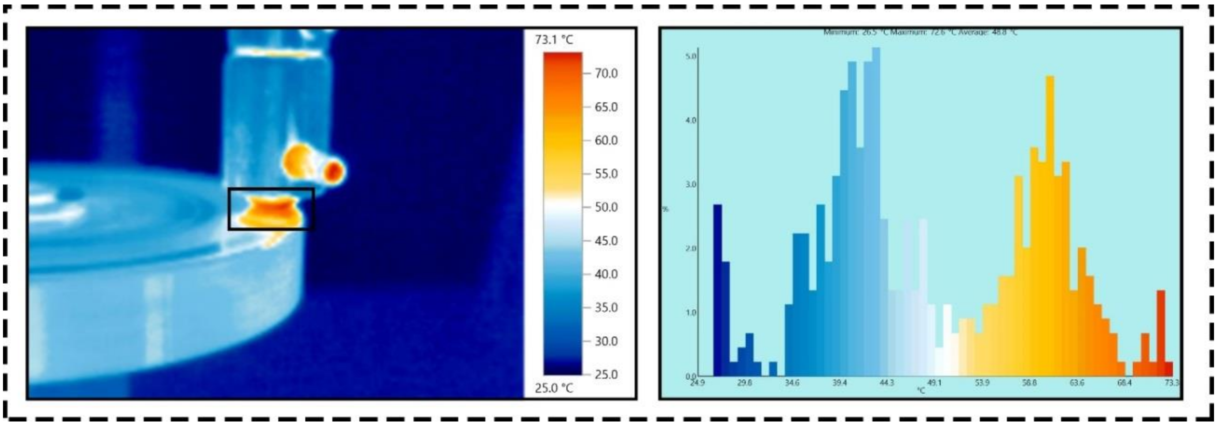


Fig. 3: Temperature distribution graph of the image taken during the wear test

3. Results and Discussion

3.1 Microstructural analysis of composite materials

SEM and optical images of Cu/Ti-B-SiC_P composite samples were shown in Fig. 4. It can be said that the particle distribution in the composite material is homogeneous without clustering anywhere. Yang et al. [29], reported that a homogeneous distribution was detected in the microstructure by producing SiC-reinforced composite materials in their study. A copper-rich matrix was seen inside the structure. It also does not appear to be agglomerated. According to the results obtained from SEM and optical images, some gaps were detected between the reinforcement particles and the matrix on the surface. Meher and Chaira [30], manufactured Cu/Gr-SiC composites and reported that gaps were detected between reinforcement particles and matrix at the microstructure interface. They concluded that these gaps were caused by sharp-edged particles. Such gaps seriously affect the density. When Figure 4 is carefully examined, it is observed that there are few pores around the SiC particles with sharp-edged structures. Gatea et al. [31], stated that these pores formed around SiC are caused by the thermal coefficient mismatch between SiC and other particles. For this reason, they stated that it is not possible to prevent such pores. Therefore, it is thought that these pores may weaken the bond formed between SiC and Cu main matrix. A study in the literature was found to prove this situation [32]. Yuan et al. [33], suggested hot rolling heat treatment as a solution for removing the pores in composite materials and increasing the mechanical properties accordingly. As can be seen in the SEM images, the dark-colored regions represent the reinforcement particles, while the light-colored regions represent the copper matrix.

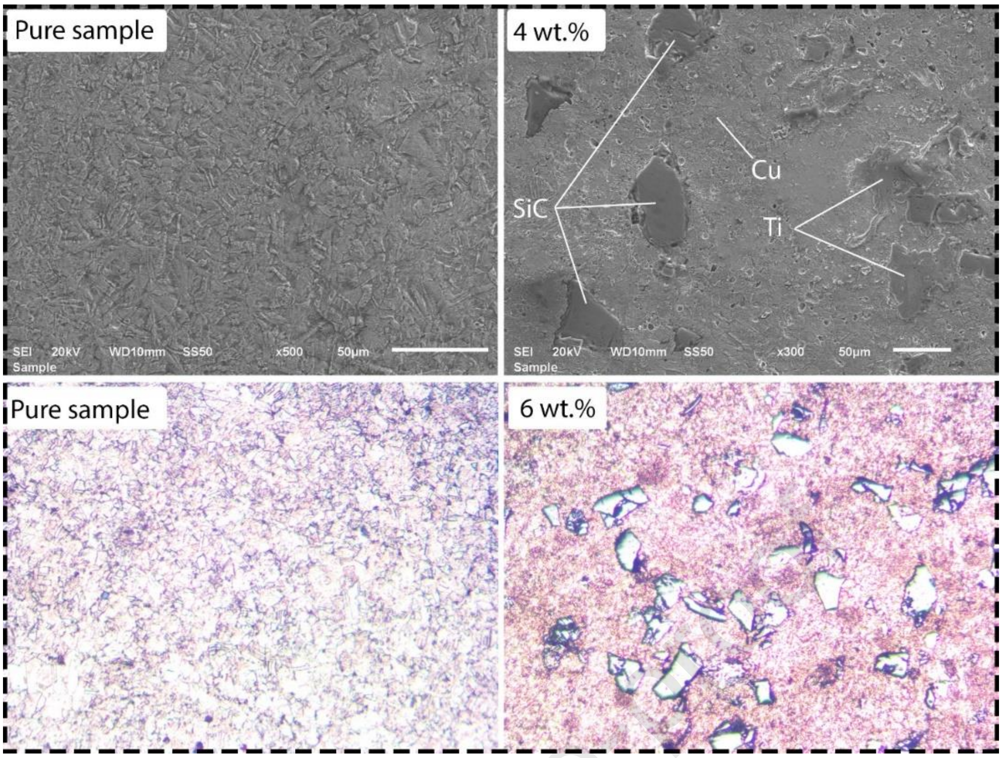


Fig. 4: SEM and optical photographs of the composite samples produced

SEM/EDX analysis photograph and peaks of composite samples produced in different proportions (6 wt.%, 950 °C) are shown in Fig. 5. In addition, according to the SEM/EDX analysis, it was determined that the copper ratio was high in the structure and there was no agglomeration in the structure. In addition, reinforcement particles in the matrix were detected and it was observed that the mixture was in the ratios indicated in Table 1. It is seen that zone 1 is Ti and zone 2 is Si-C particles. Due to the very small particle size, boron is not seen in the structure. According to the EDX images, no oxide and oxide compounds (TiO_2, BO_4. CuO, and Cu_2O) were observed in the microstructure. The use of protective Argon gas during sintering prevents oxidation. Liu et al. [34], reported that Ti-Si-C particles in the Cu alloy were detected by EDX analysis. After the addition of Ti and SiC, it was observed that two phases were formed in the Cu main matrix. The black ones were about 1–3 μm in size and the others consisted of gray particles and needles.

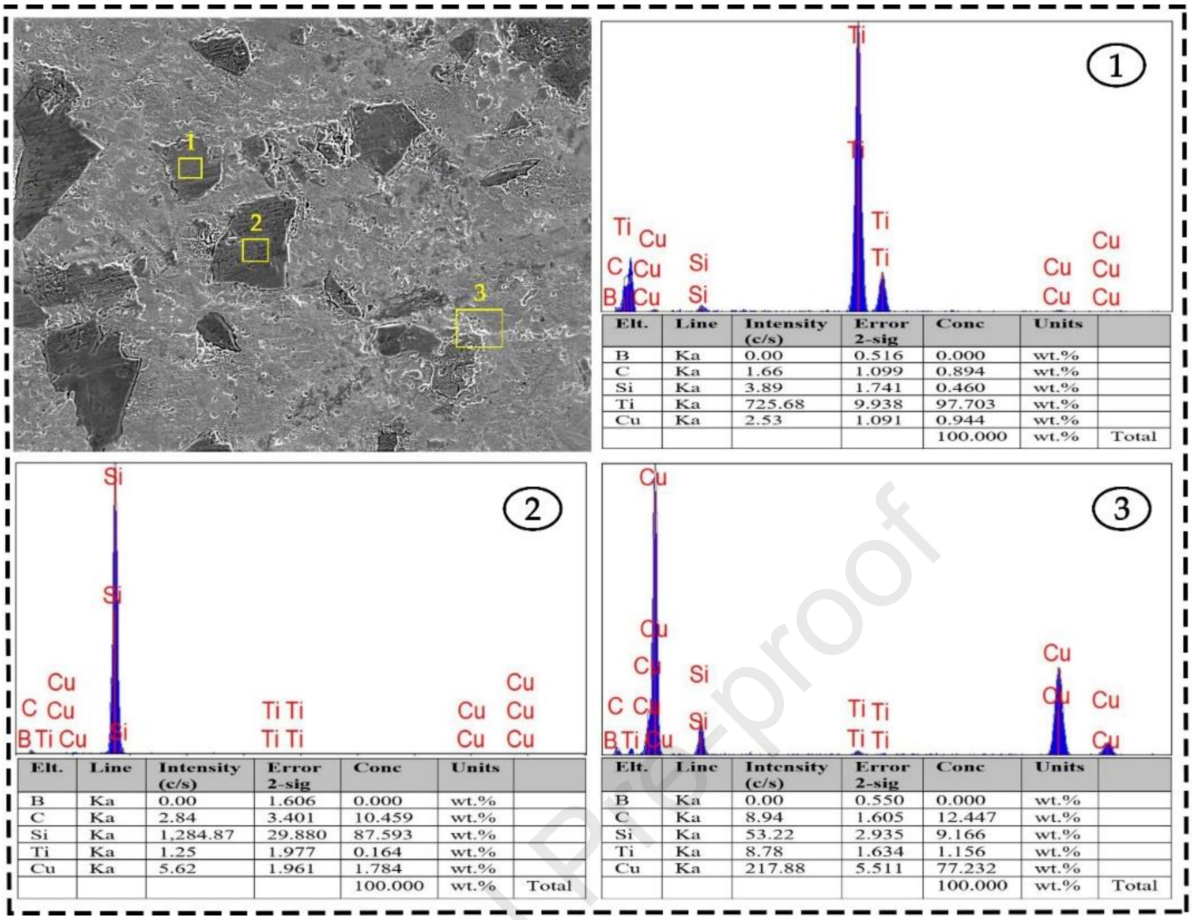
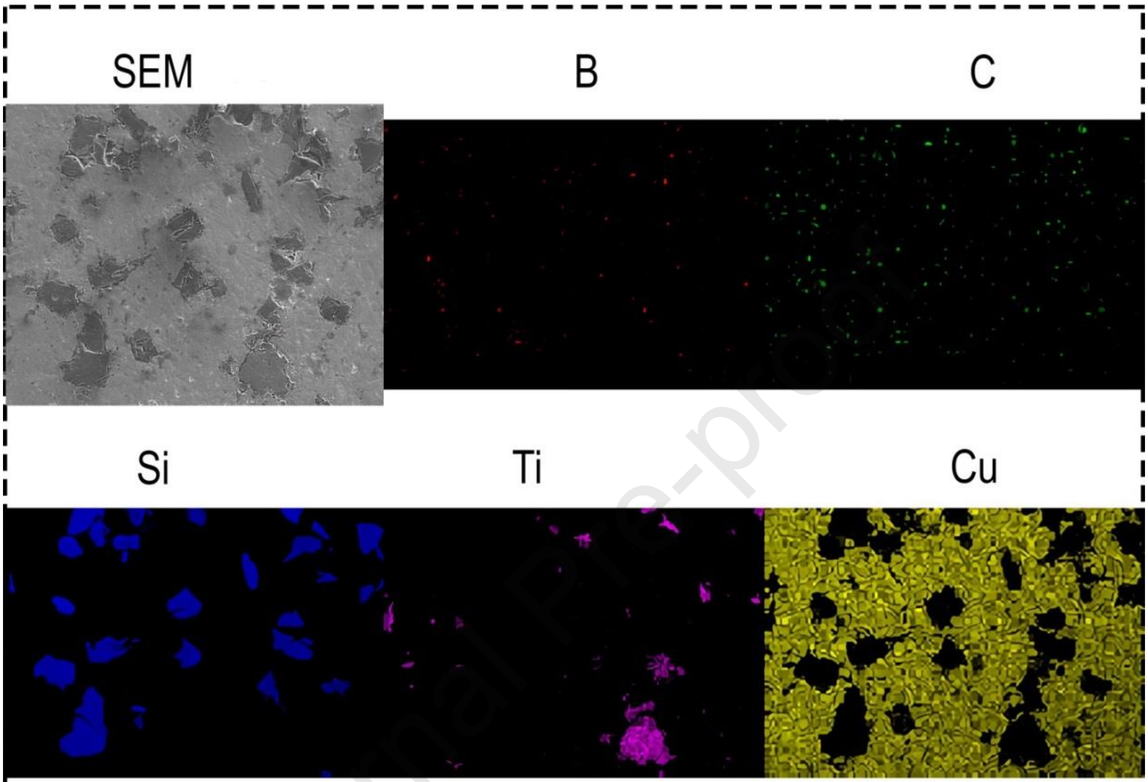


Fig. 5: The EDX photographs taken from different regions

In figure 6, a Mapping analysis was performed to support the presence and distribution of particles in the produced sample. Other particle entities can be determined by mapping analysis. In the mapping analysis, the yellow areas show the Cu main matrix. It was determined that the density of Cu was 226.14 c/s and the weight percent ratio was 67.471%. In addition, when the Cu grain boundaries obtained by mapping analysis are carefully examined, it will be seen that liquid phase sintering does not occur. Porosity also seems to be quite high in this composite sample with the highest reinforcement ratio (8 wt.%, 950 °C). Therefore, it was the sample with the lowest relative density. Red, green, blue, and pink colored regions represent B, C, Si and, Ti particles, respectively. Thus, particles detected by EDX analysis were verified by mapping analysis. In a study, the presence of particles was determined by mapping analysis in the production of SiC reinforced composites [29]. Essam and Mohammed [35], produced nanocomposite materials by adding certain proportions (0-1-2-4-8 wt.%) of SiC into copper in their study. They detected the presence of particles in nanocomposites using mapping analysis. In this study, it was determined by mapping analysis that SiC particles were homogeneously dispersed in a certain region of the material without agglomeration.



Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units
B	Ka	0.32	0.116	0.000	wt.%
C	Ka	3.14	0.264	4.816	wt.%
Si	Ka	188.25	1.156	25.185	wt.%
Ti	Ka	21.92	0.498	2.528	wt.%
Cu	Ka	226.14	1.252	67.471	wt.%
				100.000	wt.% Total

Fig. 6: Mapping analysis photos of test samples (8 wt.%, 950 °C)

3.2.Density analysis

Density is known as an important property in composite materials. It is known that the pores that may occur due to the necking of the powder particles during the sintering process change the mechanical properties of the materials [26]. Indirectly, the sintering temperature has a great influence on density. The relative density graph of the produced samples is given in Fig. 7. Each density experiment was repeated three times to reduce the margin of error. Density values increased with the increase of sintering. When the graph is examined, it is seen that the densities decrease with the increase in the reinforcement ratio. Similar results between density and particle reinforcement ratio were reported in the literature. [24, 36, 37]. Densities may decrease due to the increasing rate of reinforcement in composite materials cold-pressed by the powder metallurgy method. The highest relative density value was recorded as 93.13% in the composite material with 2% reinforcement at 1050 °C sintering temperature.

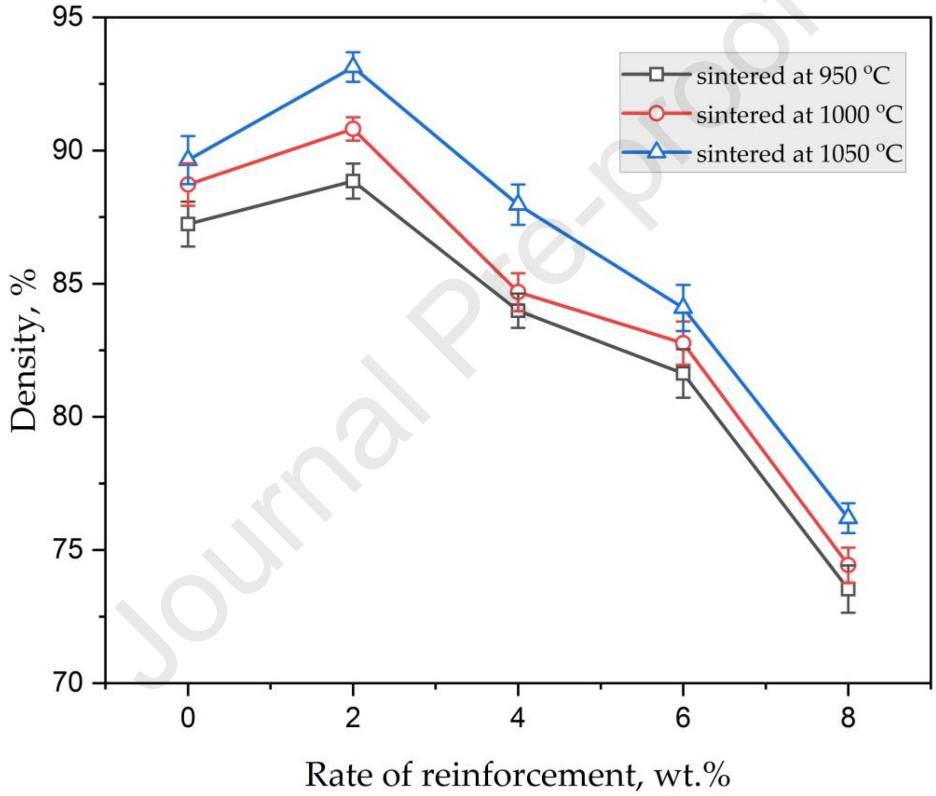


Fig. 7: Relative density graph of produced composite materials

3.3.Hardness analysis

As a result of the experiments, it was determined that the highest hardness value was observed in the samples sintered at 1050 °C (Fig. 8). When Figure 8 was examined in detail, it was determined that the hardness of all test samples increased significantly in composites reinforced with 6% by weight powder particles and then decreased again. The measured hardness values depend on the strong cohesion force between the main matrix and the reinforcement particles [38]. In general, it is reported that the hardness increases when the reinforcement particle ratio increases [2]. It was observed that the hardness increased as the amount of reinforcement additive increased between 0-6 wt.% additive ratio. However, in this study, it was determined that the B supplement, which acts as lubrication, causes brittleness in the material after a certain ratio (8 wt.%), reducing the resistance of the material to plastic deformation. It was observed that the test samples strengthened with reinforcement powder particles adversely affected the mechanical characterization after a certain level and the optimum ratio was determined. It was seen that the powder particles used as the strengthening element decrease the plastic deformation resistance of the composite produced after the determined optimum ratio. Among the test samples used in the experiments, the maximum hardness value was found in the sample, which was sintered at 1050 °C and strengthened by 6%. It was determined that the material with the lowest hardness was in the pure sample, which was sintered at 950 °C. It is known that the mechanical properties increase with increasing sintering temperature [6]. This study also supports this opinion. With increasing sintering temperature, a more regular structure is formed between the composite material particles. At high sintering temperatures, a good interface is obtained due to the increase in neck formation between particles in the material. It is known that a homogeneous distribution and a good interface increase the mechanical properties [26]. Thus, the resistance of the material against plastic deformation increases. In addition, due to the crystallization of the grains, which are effective in reducing the crystallite size, the crystallite size decreases [39], thus increasing the material hardness. It has been observed that the reinforced powder particles play an important role in hardness up to a certain extent. In other studies, it was reported that reinforcement rates caused a decrease in hardness after certain levels [30, 40, 41]. Prosviryakov [37], reported that increases in hardness values were detected in composites produced by adding SiC into Cu due to the increasing rate of reinforcement. The higher the proportion of reinforcement particles, the higher the increase in hardness. The greatest increase (up to 300 HV) was observed for Cu–20%SiC material with the most homogeneous microstructure.

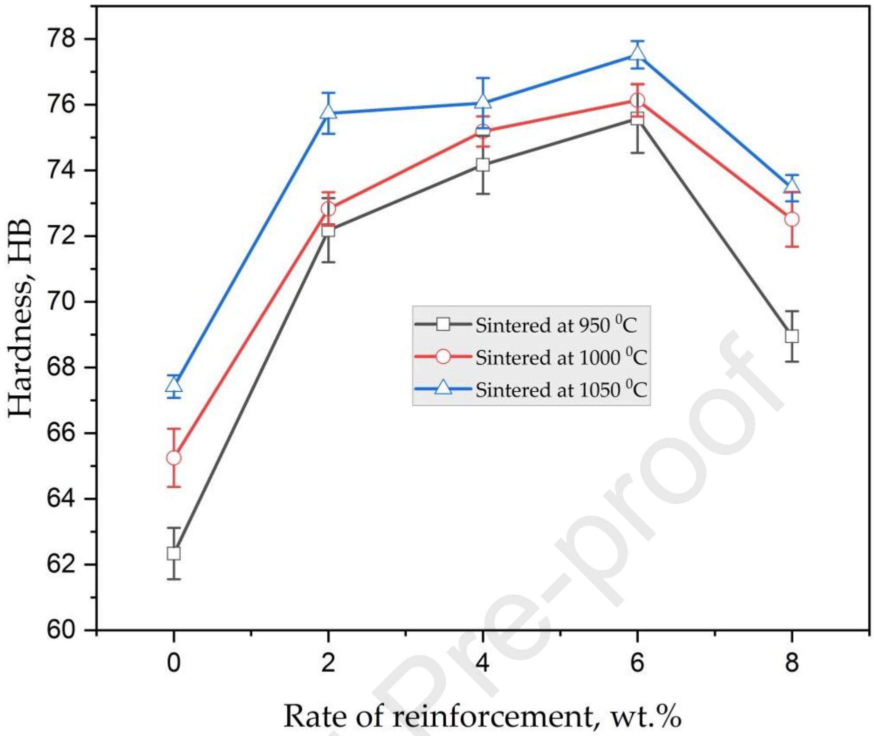


Fig. 8: Hardness graph of produced composite materials

3.4.Wear analysis

Wear of materials is generally found by weight loss and wear rate. It plays a more important role in determining the wear property of the composite material, as the specific wear rate, applied load and, wear distance are also taken into account. Radhika and Raghu [42], successfully produced Al-based LM13/AlN reinforced metal matrix composites. They emphasized that the load applied during the wear test is of great importance on the wear rate and wear distance. Fig. 9 shows the graphs of the SWR results of composites produced at different sintering temperatures with the applied load and reinforcement ratios. When the graph is examined, it is seen that there is a decrease in SWR values with the increase of sintering temperatures in general. The lowest SWR values were determined as 1.9590×10^{-6} mm^3/Nm for 950 °C, 1.7248×10^{-6} mm^3/Nm for 1000 °C, and 1.5545×10^{-6} mm^3/Nm for 1050 °C, respectively. According to the findings, it was seen that the optimum sintering temperature for the specific wear rate and coefficient of friction was 1050 °C. The lowest SWR values were observed in 8 wt.% reinforced samples under 20 N load. Decreases in SWR values were observed inversely with the increase in reinforcement. Based on this, it can be said that the increase in reinforcement rates has a positive effect on wear resistance. Uzun et al. [43], added CrC into the Cu master matrix. They reported significant increases in wear resistance with increased CrC particle reinforcement. When the wear resistance of the CrC particle reinforced samples were compared with the pure copper samples, it was seen that the CRC particle reinforced samples showed better wear resistance. Xie et al. [44], reported that corrosion resistance increased with TiB_2-Fe_2B hybrid particles increased into the Cu main matrix. Zhao et al. [45], the effect of Cu–Ti_3AlC_2 composites on electrical friction and wear behavior was investigated. It is reported that the wear rate of composites gradually decreases from the initial state with increasing particle reinforcement and then remains stable.

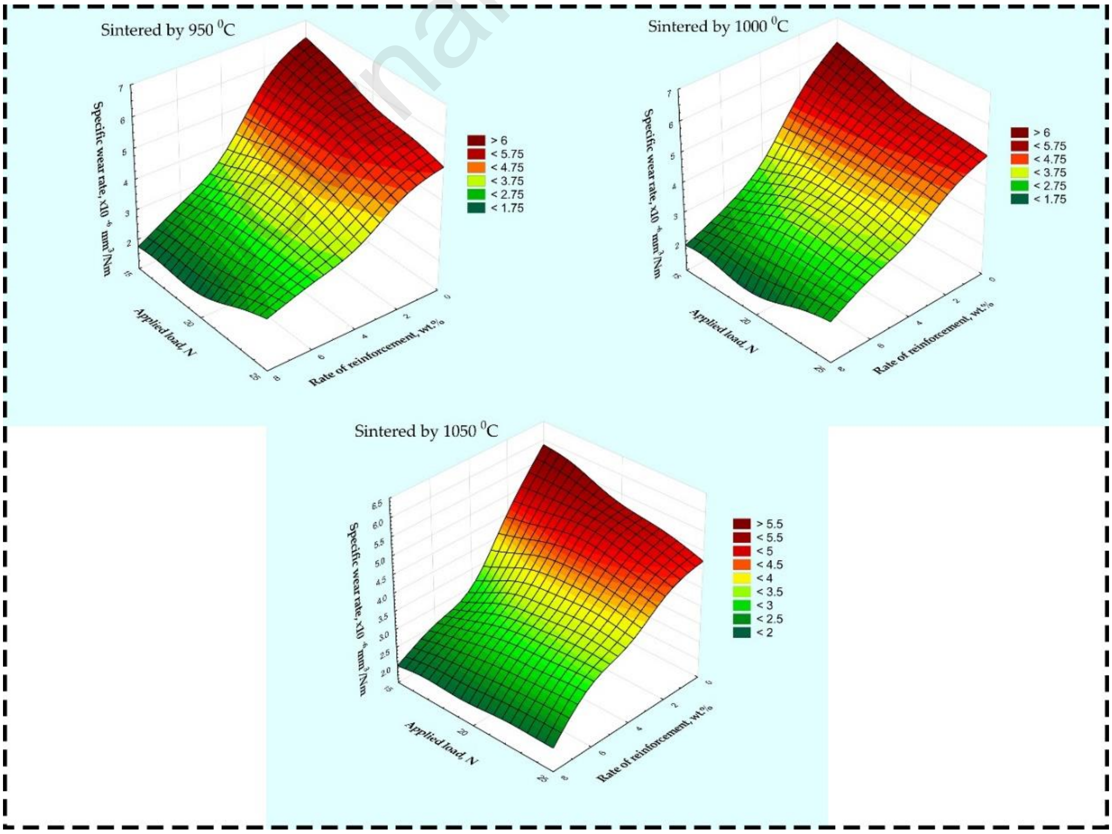


Fig. 9: SWR graph of produced composite materials

The wear data of the composite materials were recorded by the tribometer device during the wear test. Average friction coefficient (μ) values obtained according to Eq. 3 are shown in the graphics in Fig. 10. As can be seen from the graph, as the applied load increases, the friction coefficients also increase. Cui et al. [25], reported that as a result of the wear test of Cu-Fe-SiC composites, the friction coefficients increased as the sliding speed and nano-SiC content increased. It has been stated that factors such as thermomechanical deformation and wear may cause changes in the friction coefficient [46]. A marginal increase in the average friction coefficient was reported for each test after the friction profile was stabilized by the sliding contact function. [40]. It is seen that reinforcement particles cause increases in the friction coefficient. Compared to pure copper, an increase in the friction coefficient of the samples containing 2 wt.% reinforcement and a decrease in the subsequent ratios were detected. It is seen that the friction coefficients of the samples with a reinforcement ratio of 8 wt.%. Hard reinforcement particles are known to show high resistance to wear. In general, with an increase in the weight ratio of the particle reinforcement, it is expected that the resistance to wear will increase and it will have a low coefficient of friction [26]. In this study, it was seen that the friction coefficient decreased as the weight ratio of the reinforcement particles increased.

Machine elements are friction when working with each other. This creates a frictional force between them. The greater the friction coefficient, the greater the friction force, and the machine elements cannot slide easily on each other. Thus, the machine elements wear out more easily. In this context, the sintering temperature with the lowest coefficient of friction can be determined by examining the graphics given in Figure 10. As it can be seen from the graphical data provided in Fig. 10, when evaluated in terms of friction coefficient, the optimum sintering temperature was determined as 1050 °C.

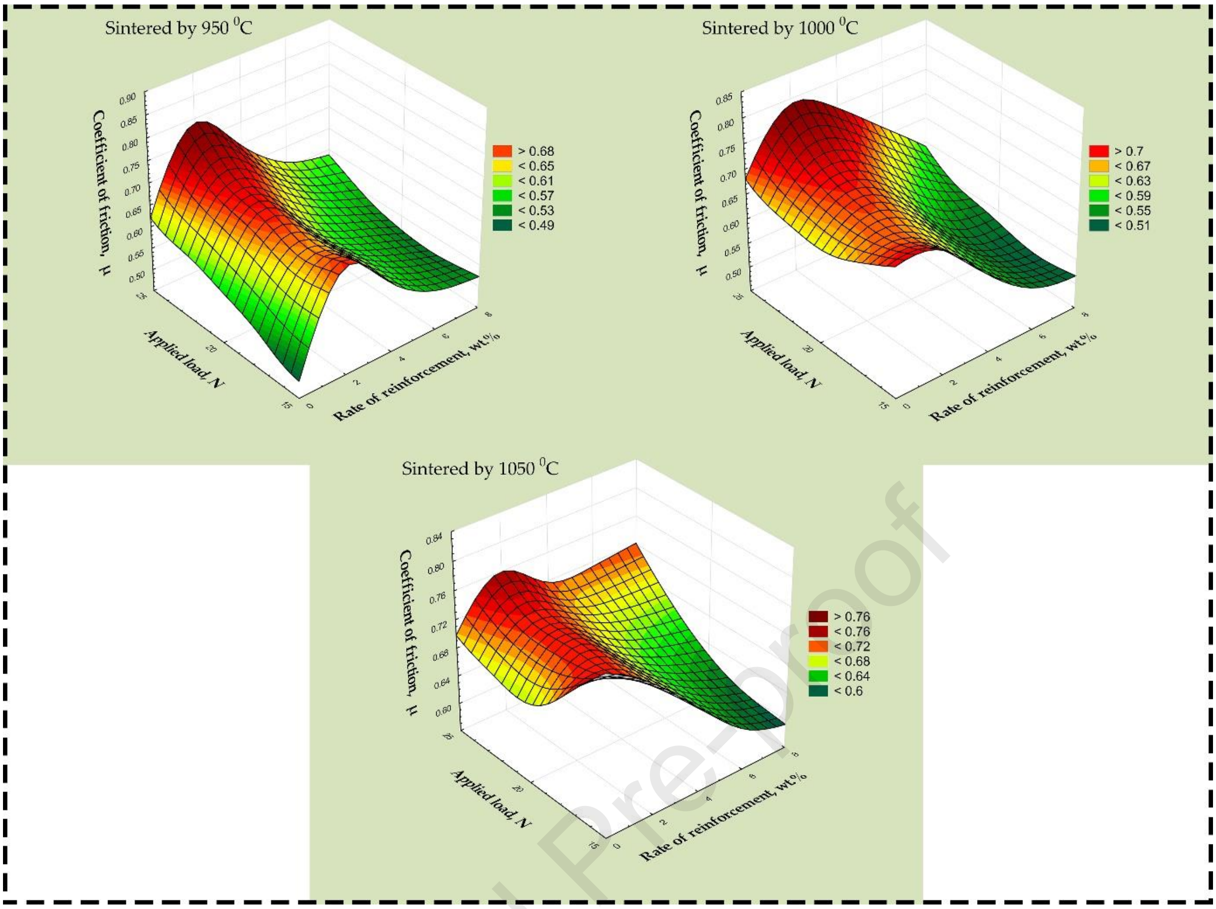


Fig. 10: Friction coefficient graphics of composites produced at different sintering temperatures

Temperature increases that occur during the wear test are a very complex process. Many parameters such as applied load, shear rate, strengthening ratio, and thermal conduction affect this process. In the graphics in Fig. 11, the changes in temperatures occurring during the wear test depending on the applied load and the strengthening ratio can be seen. Figure 11 shows that the temperatures increase in parallel with the increase in the load applied in all test samples. When figure 11 is examined, it was seen that 1050 °C was an optimum sintering temperature value in terms of the temperature formed during wear.

Cheng et al. [47], reported that the temperatures occurring during the wear test on the Cu–15Ni–8Sn–0.8Nb alloy increased with the shear rate and normal loads. It was observed that the highest temperatures were in the samples with a 25 N load. With the increase in the strengthening ratio, an increase is observed in the temperature values in general. The minimum and maximum temperatures that occurred during the wear test were recorded as 53.9 °C and 95.4 °C, respectively. Jayashree et al. [48], reported that during tribo-oxidative wear of a Cu-based metal-matrix composite that slides dry against a steel surface, the pin temperature increases with the sliding speed and was not significantly affected by the contact pressure.

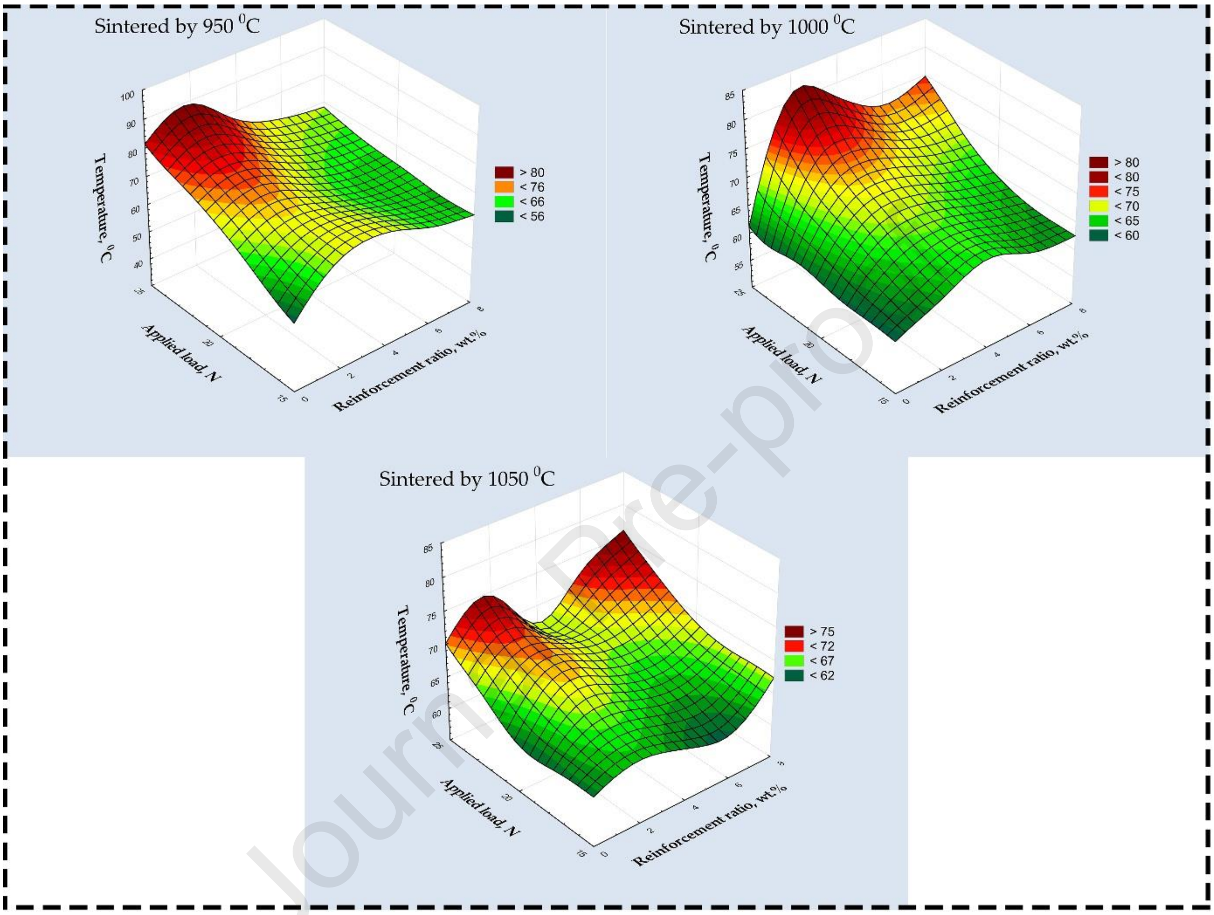


Fig. 11: Temperature graphs generated in the wear test of composites

After the wear test of copper composites produced in different proportions, lines parallel to the slip direction is seen in the optical images of the wear surface (Fig. 12). Since the ends of the samples have been conical before, the mass losses from the surface are seen after wear. As it can be seen from the optical photographs, the wear marks are more uniform and distinct in the pure Cu sample. With the increase in the reinforcement ratio, other samples have more irregular structures (Fig. 12.e). It was concluded that with the increase of the particle reinforcement, the reinforcement elements detached from the surface in the event of wear make the wear surface more uncertain compared to the pure Cu sample. This situation is shown in Fig. 13.

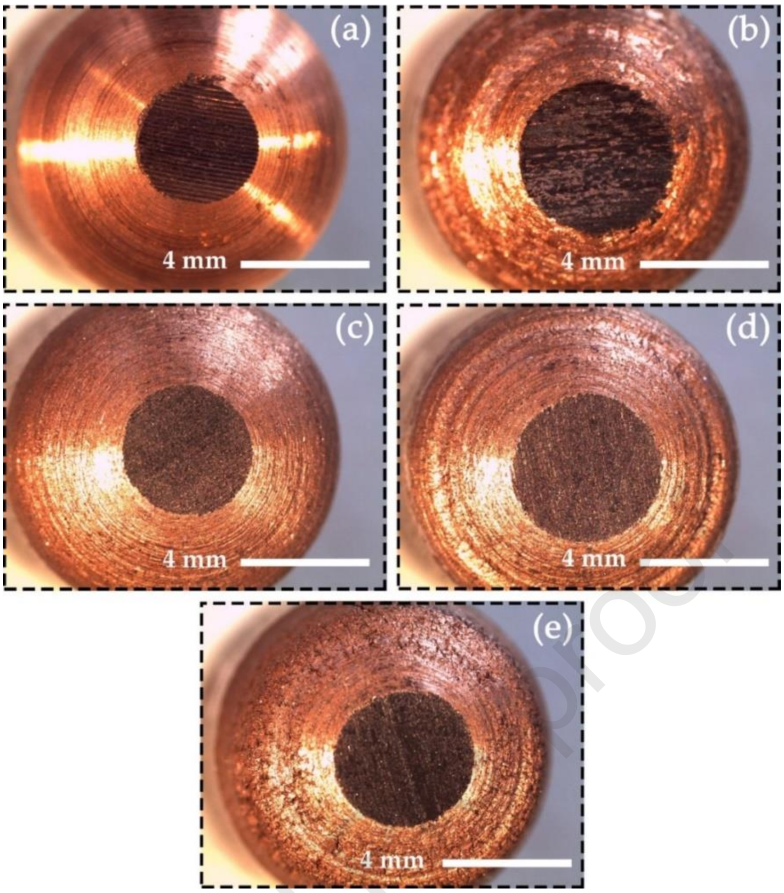


Fig. 12 Wear diameter photographs of composites produced in different proportions: a) Pure sample, b) 2 wt.%, c) 4 wt.%, d) 6 wt.%, e) 8 wt.%

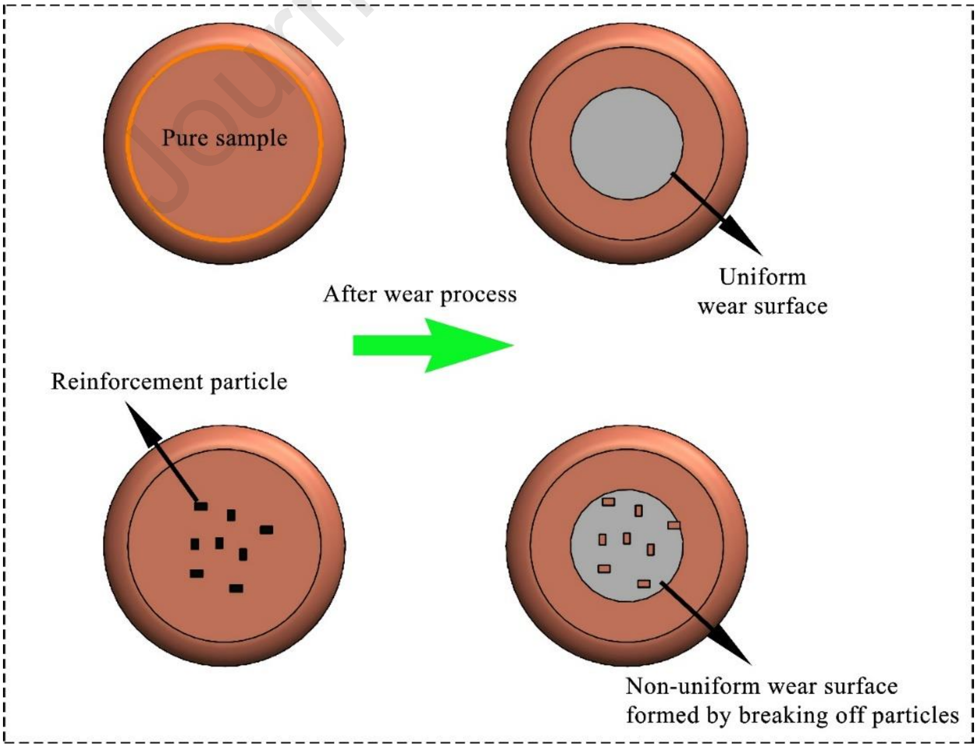


Fig. 13: Uniform surface formation after wear process

4. Conclusion

In this study, Cu/Ti-B-SiC_P composite materials were successfully produced at different sintering temperatures and at different rates for the first time in the open literature. Ti-B-SiC_P hybrid reinforcing powders were added into the main copper matrix at 2, 4, 6, 8 wt.%. After these composite materials were compressed by cold press method, sintering process was carried out at three different (950, 1000, 1050 °C) sintering temperatures The mechanical properties of the produced composite materials such as density, hardness, and wear were examined and microstructural examinations were carried out using SEM and EDS techniques. The following results can be drawn from the study.

- As a result of the microstructure analysis, it was observed that the particles were homogeneously distributed in the composites produced. The presence of powder particles in the composite was proven by EDX analysis. This evidence was confirmed by mapping analysis.
- As a result of the Brinell macrohardness test, an increase in the hardness value was observed until the sample strengthened with 6% by weight reinforcement, and a decrease was observed in the sample strengthened with 8% by weight reinforcement among the materials with different ratios. Among the materials sintered at 1050 °C, the maximum hardness was determined as 77.517 HB. Based on these results, it is seen that the increase in sintering temperature and the ratio of strengthening elements significantly increase the hardness.
- As a result of wear analysis, the increase in reinforcement bars caused a decrease in SWR rates. Thus, wear resistance increased compared to pure copper. Compared to pure copper, an increase in the friction coefficient of the samples containing 2 wt.% reinforcement and a decrease in the subsequent ratios were detected.

- The friction coefficients of the samples with a reinforcement ratio of 8 wt.% among the test samples were lower. It was observed that the temperatures increased in parallel with the increase in the load applied in all test samples.
- The highest temperatures were in the samples with a 25 N load. A general increase in temperature values was observed with the increase in the strengthening ratio. The minimum and maximum temperatures that occurred during the wear test were recorded as 53.9 °C and 95.4 °C, respectively. Sintering temperature and reinforcement rates increased wear resistance.

5. Future work

The Chemical, thermal and electrical properties of hybrid composite materials produced for this study can also be examined. In particular, wear behavior under different lubrication conditions, corrosion resistance in different environments, and machinability applications will contribute to its practical use in the industry. In addition, these composite materials produced;

- Determination of impact resistance
- Performing fatigue tests
- Determining the effect of these methods on mechanical properties by using different production methods (hot pressing and ball milling etc.)

It is thought that studies such as these can be used to expand the usage areas of these composites and to obtain optimum utilization from these composites.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: