JMATPRO

Journal of Advanced Materials and Processing
10 (2): 19-28, Spring 2022
http://jmatpro.iaun.ac.ir
20.1001.1.2322388.2022.10.2.3.8

Research Paper

Mechanical Behavior of the Copper Matrix Composite Reinforced by Steel Particles

Vahid Norouzifard[1*], Ashkan Nazari Siahpoush[2], Amir Talebi[3]
1. Department of Mechanical Engineering, Jundi-shapur University of Technology, Dezful, Iran
2. Department of Materials and Metallurgy Engineering, Islamic Azad University-Dezful baranch, Dezful, Iran
3. Faculty of Materials & Manufacturing Technologies, Malek Ashtar University of Technology, Tehran, Iran

ARTICLE INFO

Article history:

Received 19 October 2021
Accepted 23 December 2021
Available online 1 April 2022

Keywords:
Composite
Copper
steel particles
microstructure
fatigue test

ABSTRACT

In this study, the microstructure, tensile, and fatigue behavior of the copper matrix composites reinforced by steel particles are investigated. The composite grades containing 2.5, 5.2, and 7.4 wt% steel particles up to 90 µm in size are manufactured by the casting method. The microstructure of the composite samples is studied by scanning electron microscopy. The tensile and fatigue test samples are prepared and tested based on the ASTM standard. Adding 2.5 wt% steel particles to the copper matrix increases the yield strength, tensile strength, and elongation of the pure copper by about 48, 21, and 4.8%, respectively. The fatigue test results show that reinforcing the pure copper with 2.5 wt% steel particles improves the fatigue life of the pure copper by 67, 31, and 86 percent in 60, 80, and 100 MPa amplitude stresses, respectively. On the other hand, further increasing the reinforcement particle content to 5.2 and 7.4 wt% causes unusual fatigue behavior and adversely affects the mechanical strength of the composite. Therefore, the fatigue life of the composite samples reinforced by more than 5.2 wt% steel particles is not a function of the stress level and does not increase with the decrease of the stress.

Citation: Norouzifard, V.; Nazari Siahpoush, A.; Talebi, A. (2022). Mechanical Behavior of the Copper Matrix Composite Reinforced by Steel Particles, Journal of Advanced Materials and Processing, 10 (2), 19-28. Dor: 20.1001.1.2322388.2022.10.2.3.8

---

[*] **Corresponding Author**
E-mail Address: vnorouzi@jsu.ac.ir

1. Introduction

Pure copper is known as an essential material in several industries, such as electronics, mechanics, etc., because of its high electrical and thermal conductivity. Demand for high conductive and high strength materials have been increased in the electronic industries in recent years. Due to the low mechanical strength of pure copper, efforts to strengthen the copper have been conducted to get a proper composition of conductivity and high strength. To improve the mechanical properties of pure copper, several methods can be applied, such as; alloying, aging, and reinforcing. Alloying dramatically decreases the copper's electrical conductivity. Thus, alloying cannot be an efficient method to enhance the components made from pure copper in the electronic industry. Since the solid solution strengthening mechanism decreases the conductivity of the copper alloys, aging and precipitation hardening methods have become more popular for copper alloys. The aging process increases the strength of the copper alloy and keeps its conductivity relatively [1]. Reinforcing the pure copper by adding a harder material and producing a copper matrix composite is another way to enhance the mechanical properties of the pure copper without any serious adverse effect on the copper's electrical conductivity [2].

In this regard, a lot of research has been done to strengthen pure copper with various reinforcements. Ceramic particles such as SiC [3] and alumina [4] were the first materials used as reinforcement in copper matrix composites. But, due to the low wettability and adhesion of the ceramic particles with the copper matrix, the mechanical properties of the produced composite were not improved considerably rather to the pure copper properties. In some cases, reinforcing the copper with ceramic particles adversely affects the mechanical strength of the matrix [5]. Thus, to improve the mechanical strength of the copper composites reinforced by ceramic particles, additional processes have been used, such as the implantation of the metal coatings on the particles' surface. However, utilizing such coatings needs expensive and complicated processing technology [6, 7]. In recent years, carbon-based reinforcements such as carbon nanotubes [8] and graphene nano-plates [9-12] also have been considered to produce copper matrix composites. Mass production of relatively large components from the copper composites reinforced by carbon-based particles is difficult and expensive due to the production method of the composite, which is powder metallurgy.

The metallic reinforcements can be a good choice to improve the pure copper mechanical properties because of the following reasons; 1) the wettability of the metal particles in the copper melt is more than other ceramics or carbon-based materials, 2) the metal powders are more available and cheaper, and 3) finally the composites mass production is possible using the conventional production methods such as casting. Recently, Alaneme et al. [5] investigated the applicability and performance of mechanical strengthening of metallic reinforcements in metal matrix composites. Based on Alaneme et al. [5] review, there is considerable research in the open literature on which the metallic reinforcement used in aluminum and magnesium matrices. Sparse literature, however, exists on the use of metallic reinforcements for copper matrix. The available research about copper matrix composites reinforced by metallic particles is discussed by several studied.

Alaneme and Odoni [13] reinforced the pure copper using steel machining chips and investigated the mechanical properties, wear, and corrosion behavior of the produced composite. According to Alaneme and Odoni's [13] results, the steel particles as reinforcement improves pure copper's mechanical strength without any significant decrease in its toughness. Cardinal et al. [14] used Ta particles as reinforcement for a Cu-Zr-Al bulk metallic glass matrix. The composites having 5 to 50% of Ta particles in volume fraction were produced by the spark plasma sintering consolidation method. The mechanical tests showed that increasing the Ta particles increases the ductility and plasticity of the composite and decreases the yield stress. Hence, the authors, based on their investigations, concluded that the composite grade reinforced by 30% Ta particles in volume fraction was optimal for a good combination of hardness and ductility. Chen et al. [15] investigated the use of AlCoNiCrFe high entropy alloy (HEA) synthesized by mechanical alloying as reinforcement for a Cu matrix. The copper matrix composites reinforced by 10 to 20 wt% of the synthesized HEA were produced by powder metallurgy. The compression test results showed that the mechanical strength increases by increasing the reinforcement content. However, the ductility decreased by increasing the reinforcement's weight percent, and the unreinforced sample had the best ductility of all the samples tested. The best combination of ductility and strength belonged to the composite grade with 10 wt% of HEA reinforcements.

As above-mentioned literature review shows that there are a few studies that investigated the use of metallic particles as reinforcement to strengthen copper. Therefore, the present research makes an effort to fill this gap in the literature. In this study, following our previous research on the investigation of the properties of the copper matrix composites reinforced by steel particles [16], the tensile and fatigue behavior of the copper matrix composites reinforced by 2.5, 5.2, and 7.4 wt% steel particles with spherical shape and maximum size of 90 µm are investigated. The steel particles were produced from machining chips. Disc mill and ball mill machines were used to change the machining chips' shape and size. The mechanical tests and sample preparation were done based on the ASTM standard. The fracture surface and microstructure of the fabricated composite are studied using optical microscopy and scanning electron microscopy, respectively.

2. Materials and experiments

2.1. Materials

The composite samples in this research were composed of pure copper, 99.9 %, as the matrix, and AISI 430 stainless steel as reinforcement particles. The chemical composition of the steel particles is listed in Table 1. The chemical composition of the steel and the copper were measured by emission spectrometry.

Table 1. Chemical composition of the reinforcement particles.

Element	Sn	Pb	W	V	Ni	Cr	S	P	C	Fe
Content (wt%)	0.00075	0.0024	0.0016	0.23	0.0041	15.34	0.0214	0.015	0.085	Base

2.2. Powder and composite fabrication

As the steel particles and composite samples fabrication are described in [16], in this paper, the procedure is presented briefly. The steel machining chips were produced by turning the steel bars into a lathe machine. Then, a disc mill (RS 200) machine manufactured by Retsch Company was used to convert the refined steel chips to steel particles. The disc mill machine product was converted to steel particles with a maximum size of up to about 90 µm by a planetary ball mill machine (PM 400 by Retsch Company). Finally, the refined particles by a ball mill machine were fed to Retsch AS200 shaker's sieves with a mesh size of 90 µm to control the size of the particles.

The copper matrix composite samples were fabricated by casting method using a coreless induction furnace and a gas gun. 22 mm in diameter copper bars were charged in the furnace and kept for about 20 minutes to ensure to be melted completely. The steel particles were carried into the copper melt by hot argon gas using the gas gun. To produce the composite grades containing 2.5, 5.2, and 7.4 wt% of steel reinforcements, 52, 117, and 173 grams of steel powder were injected into 2080, 2125, and 2162 grams of copper melt, respectively. Pure copper samples also were cast by the same manufacturing process as the composites. The melt was poured into the casing molds cavity with the dimension of 60*140*12 mm. The molds were made of low-carbon steel and preheated at a temperature of 300 °C. To homogenize the microstructure of the samples, solidified composite samples were put for 1 h in a heat treatment furnace at a temperature of 850 °C.

2.3. Characterization

Mira 3-XMU field emission scanning electron microscope (FE-SEM) was used to investigate the microstructure of the produced composite and pure copper samples. The fatigue test was performed on a fatigue test machine manufactured by Schenck Trebel company based on the ASTM E466 standard [17]. The tensile properties of the composites were also assessed by a Schenck-Trebel testing machine at room temperature and a strain rate of 3×10^{-3} s^{-1} based on the ASTM E8/E8M standard [18]. The fatigue test fracture surface of the prepared composite specimens was also studied using an RZ-BD Meiji stereo microscope. Figure 1 shows the specification and dimensions of the tensile and fatigue tests' samples.

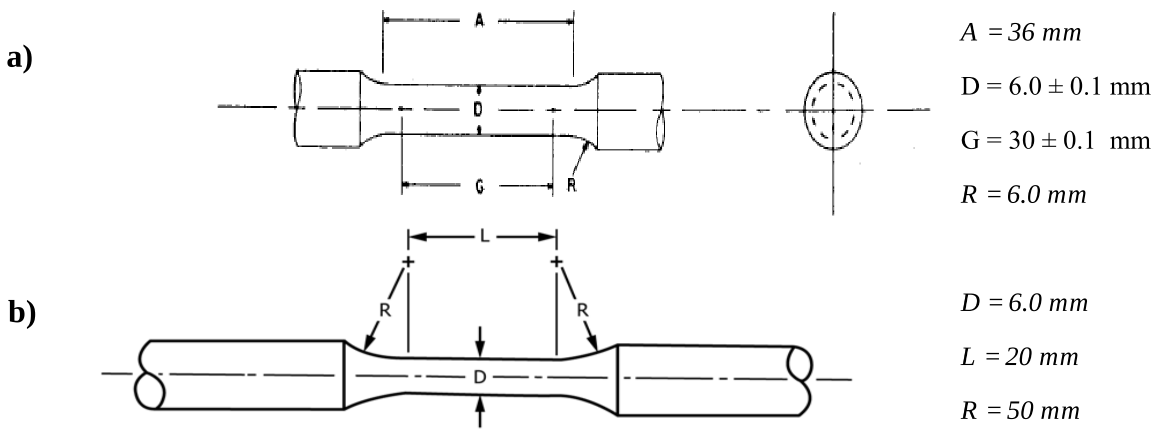


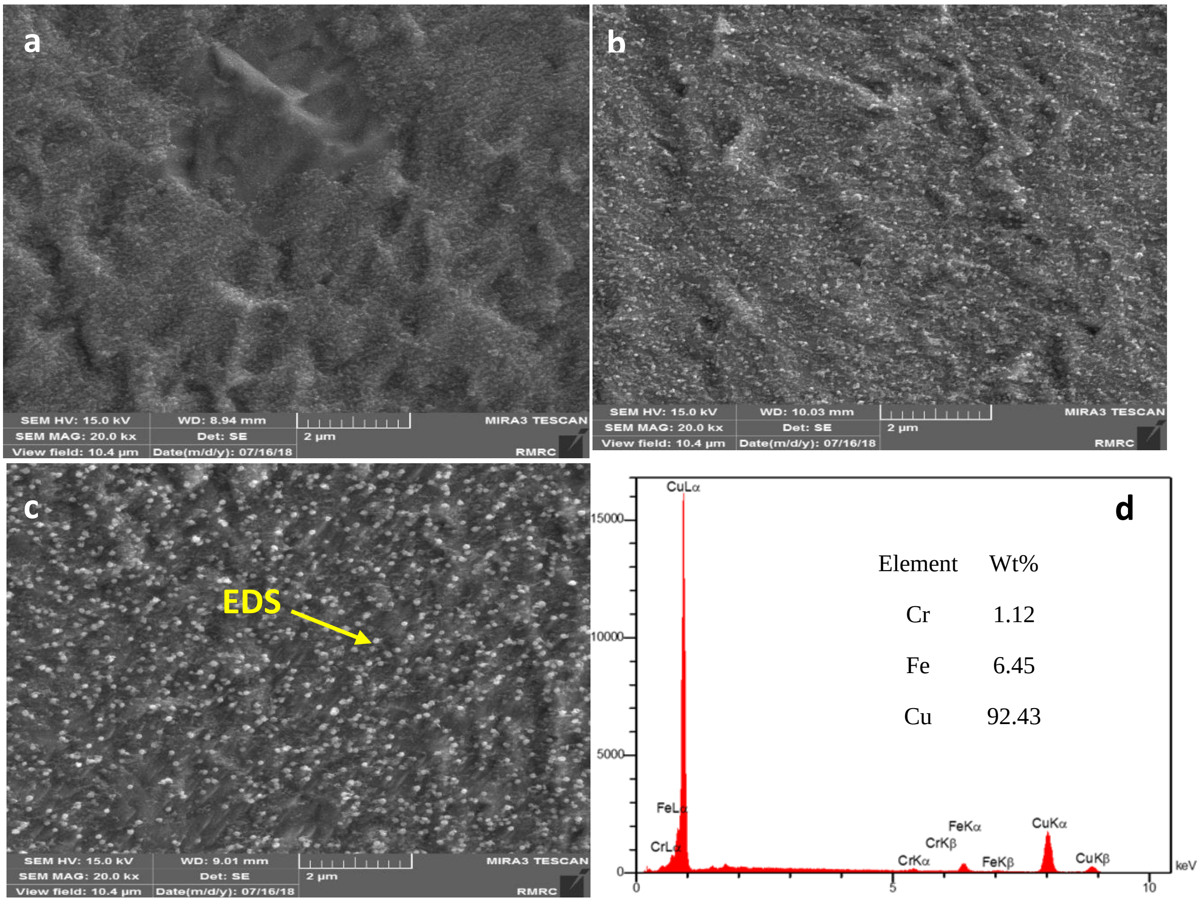
Fig. 1. Specification and dimensions of a) the tensile test and b) the fatigue test samples.

3. Results and discussion

3.1. Microstructure of the composite

Figure 2a shows the SEM micrograph of the microstructure of the composite grade containing 2.5 wt% steel particles. In the present SEM micrographs, the dark and light areas refer to the matrix and reinforcement particles, respectively. Figure 2b shows the composite microstructure in 20000x magnification, and very few small particles can hardly be seen due to the low content of the reinforcements in the composite.

Figures 2b shows the SEM micrograph of the copper matrix composite reinforced by 5.2 wt% steel particles with a magnification of 20000x. In Figure 2b, more particles are seen than in Figure 2a because of the more particle content. The microstructure of the composite grade reinforced by 7.4 wt% steel particles is also shown in Figure 2c. Unlike the previous figures, the steel particles can be seen easily in large numbers. Comparing Figures 2a, b, and c also shows the reinforcement particle content increasing in the composite grades.



Element	Wt%
Cr	1.12
Fe	6.45
Cu	92.43

Fig. 2. SEM micrograph of copper matrix composite reinforced by a) 2.5, b) 5.2, and c) 7.4 wt% steel particles by a magnification of 20000x, and d) EDS analysis results for the composite grade reinforced by 7.4 wt% particles (region shown in c).

Figure 2d shows the EDS analysis of the region shown by an arrow in Figure 2c. The EDS graph shows Copper (Cu), iron (Fe), and chromium (Cr) peaks. These elements are the dominant elements of the matrix and reinforcement materials and agree with the steel particles' chemical composition listed in Table 1. Also, the absence of the oxygen peak in the EDS analysis results reveals that oxidation did not occur in the composite matrix and the steel particles during the manufacturing procedure.

Figure 3 shows the X-ray diffraction (XRD) analysis result of the composite grade reinforced with 7.4 wt% of steel particles. The XRD pattern only shows the profile of the copper and the steel particles' profiles are not visible due to the low volume fraction and dispersion of the particles. Similar XRD results are available in the literature that the reinforcement particles are not detected in metal matrix composite due to the low particle content. For example, Bagheri [19] investigated the copper matrix/TiC particles composite, and all TiC peaks have not been detected in the XRD results of the composites reinforced with lower than 20 vol% of TiC particles.

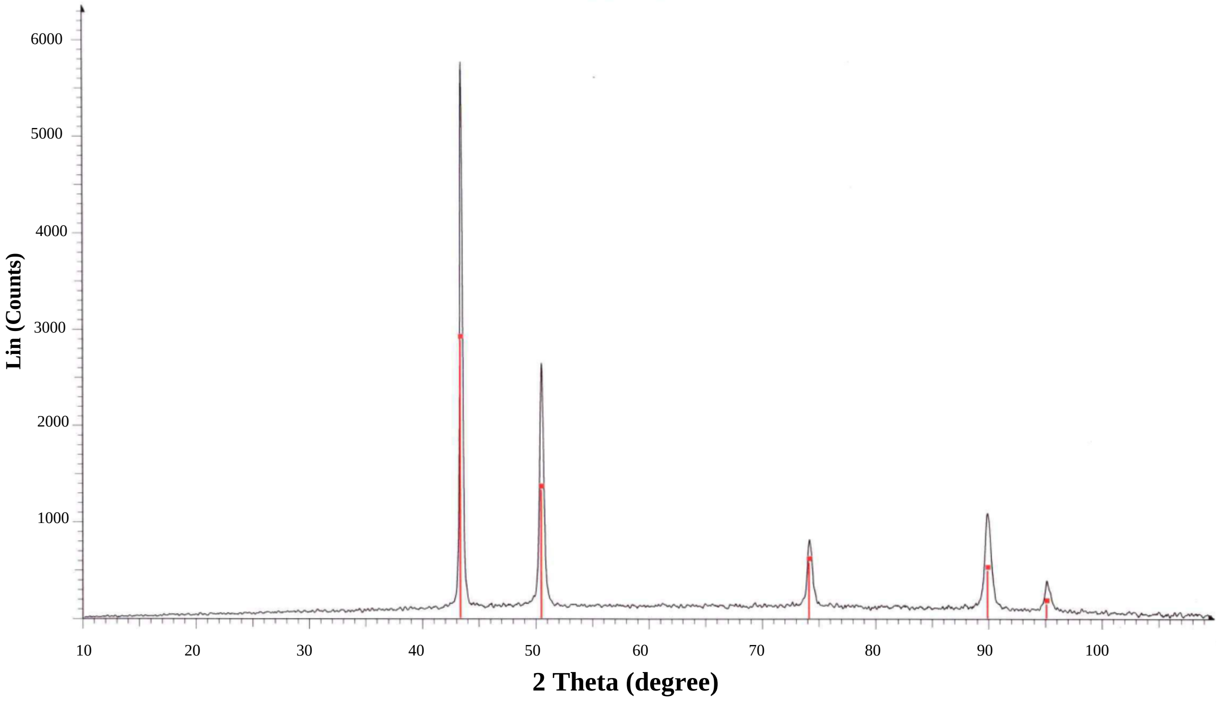


Fig. 3. XRD profile of the copper matrix composite with 7.4 wt% of steel particles

3.2. Tensile and fatigue properties

The tensile properties and fatigue test results in the reversing stresses of 60, 80, and 100 MPa for the composites and the pure copper samples are summarized in Table 2. According to the fatigue test results, the composite grade with 2.5 wt% steel particles has maximum fatigue life at 60 and 100 MPa loading, but at 80 MPa, the composite reinforced by 5.2 wt% has the longest life. The stress-strain diagrams of the composite grades and pure copper samples are shown in Figure 4. The composite grade with 2.5 wt% steel particles has the highest yield and tensile strength among the composite grades and pure copper samples. Based on the tensile test results, adding 2.5 wt% steel particles to pure copper enhances copper’s yield and tensile strength by about 48 and 21%, respectively. However, the elongation of the composite grades increases gradually by increasing the steel particles content.

Several strengthening mechanisms describe the reinforcement particles' contribution to the composite strength enhancement, such as the Orowan mechanism, coefficient of thermal expansion mismatch, and load-bearing effect [16]. Distance between particles and difference between the reinforcement particles and matrix thermal expansion coefficients and particles' size, shape, and volume fraction are the main parameters that affect the strengthening of the composite. Therefore, when the particles' volume fraction increases, the distance between the particles decreases. Increasing the volume fraction and decreasing the particles' distance positively affect the mechanical strength of the composite. But, increasing the particle content increases the possibility of the particles' agglomeration in the matrix. When the reinforcement content passes a critical value, the particles’ agglomeration adversely affects the matrix/reinforcement bonding, and also the unreinforced matrix regions increase. Therefore, the yield and tensile strengths of the composite deteriorate when the reinforcement volume fraction or weight percent passes the critical value. Thus, the low mechanical strength of the composite grades with 5.2 and 7.4 wt% steel particles in comparison with the composite reinforced with 2.5 wt% particles can be justified accordingly. Increasing the composite samples' elongation by increasing the particle content can be explained as follows. When in the copper matrix, a crack meets reinforcement particles, either the particle should be split, or the crack should turn around the particle to pass. But fracture can occur in brittle reinforcements like ceramic particles. Therefore, it seems that in the present composites, the steel particles prevent crack propagation in the matrix. Thus, the ductility of the composite grades increases continuously by increasing the reinforcement particle content.

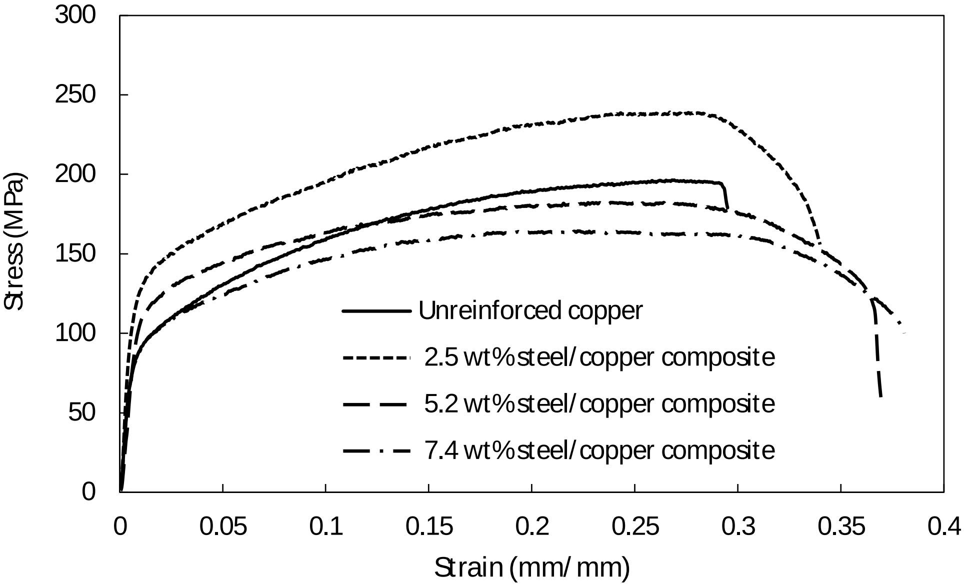


Fig. 4. Stress-strain diagrams of the composite grades reinforced by 2.5, 5.2, and 7.4 wt% steel particles and unreinforced pure copper.

Table 2. The tensile properties and fatigue test results in the reversing stresses of 60, 80, and 100 MPa.

Sample composition	Fatigue life at 100 MPa (cycles)	Fatigue life at 80 MPa (cycles)	Fatigue life at 60 MPa (cycles)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
Pure copper	102600	436050	8071200	81	198	31.5
Copper- 2.5 wt% steel particles	171000	572850	15065100	120	238	33
Copper- 5.2 wt% steel particles	116850	3437100	3659400	110	185	34
Copper- 7.4 wt% steel particles	142500	632700	615600	83	163	35.5

Figure 5 shows the stress-fatigue life (S-N) diagrams of the pure copper and the copper-2.5 wt% steel particles composite. Both diagrams shown in Figure 5 are similar to the nonferrous metals fatigue diagrams in which the curve slope changes and decreases when the fatigue life passes one million cycles. The stress ranges corresponding to one million cycles are 75 and 77 MPa for the pure copper and the composite grade reinforced by 2.5 wt% particles, respectively. The mentioned stress ranges are about 37 and 32 percent of the pure copper and the composite tensile strength.

Figure 6 shows the stress-fatigue life (S-N) diagrams of the pure copper and the copper composites containing 5.2 and 7.4 wt% steel particles. Comparing figures 5 and 6 shows that the copper matrix composites with high content of steel particles present unconventional fatigue behavior. As seen in Figure 6, the fatigue life of the composites reinforced by 5.2 and 7.4 wt% remains at the same level when the stress range decreases from 80 to 60 MPa. While, the fatigue life of the pure copper and the copper-2.5 wt% steel particles composite increases by decreasing the stress range from 80 to 60 MPa, like most pure metals and alloys.

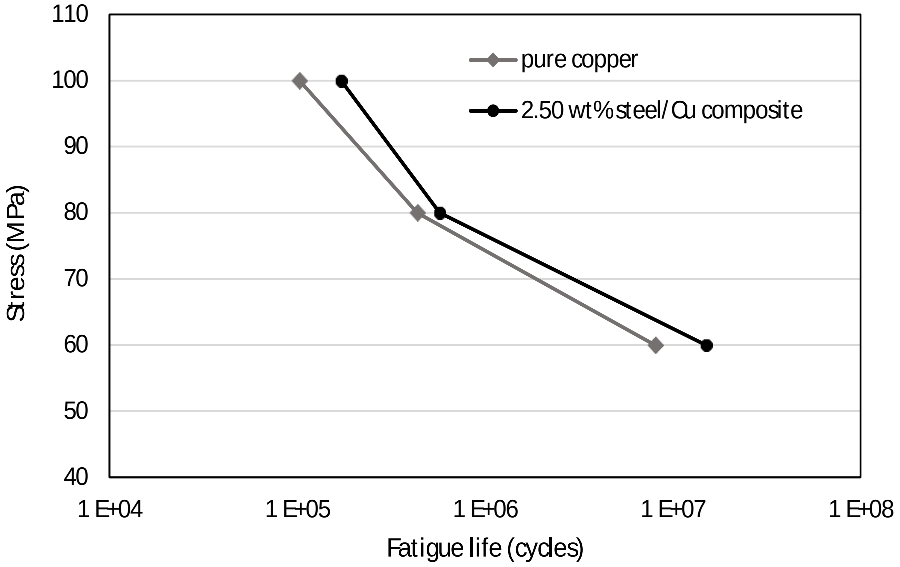


Fig. 5. Strength versus fatigue life diagrams of the pure copper and copper-2.5 wt% steel particles.

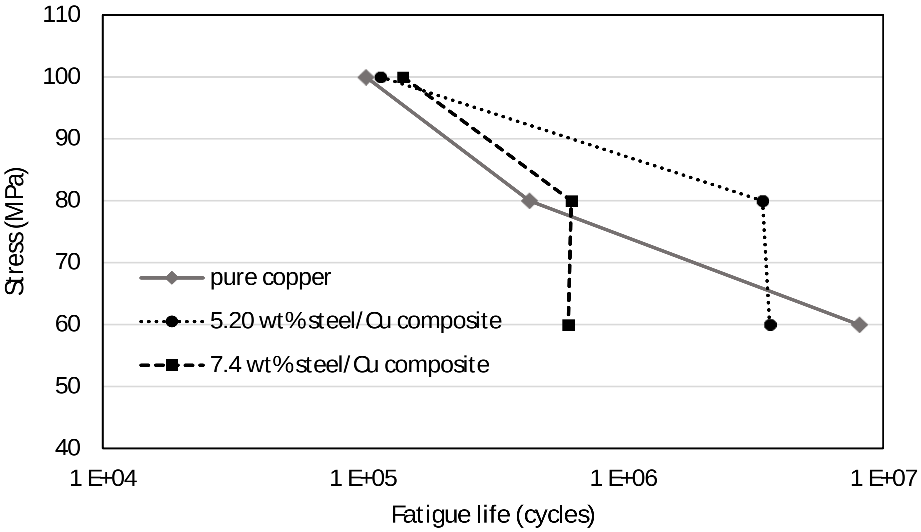


Fig. 6. Strength versus fatigue life diagrams of the pure copper and the composite grades with 5.2 and 7.4 wt% steel particles.

Fatigue failure has three stages; crack initiation, crack growth, and final ultimate failure. Decreasing the stress range increases the stress cycles required for crack initiation and growth. Therefore, the fatigue life increases by decreasing the stress level in the pure copper and the copper-2.5 wt% steel composite. On the other hand, when the content of the reinforcing particles in the composite increases, as mentioned, the possibility of the steel particles' agglomeration increases. The agglomeration of the reinforcement particles weakens the matrix/reinforcement bonding, enhances the possibility of microcracks creation in the composite structure, and adversely affects the composite yield and tensile strengths, as seen in the tensile test results listed in Table 2. Therefore, to explain the abnormal fatigue behavior of the present composites reinforced by 5.2 and 7.4 wt% steel particles, two reasons can be mentioned; 1) decreasing the loading cycles required to fatigue crack nucleation and crack growth due to the existence of the micro-cracks in the composite structure, and 2) the low mechanical strength of the composite.

3.3. Fatigue samples fractography

Figure 7 shows the fatigue fracture surfaces of the pure copper and the produced composites. According to Figure 7, the fatigue fracture surfaces have two recognizable zones the first one is light and glossy, and the last is rough and dark. The first and second zones represent the crack initiation and crack growth zone and the final fracture zone, respectively. In the fracture surface of the pure copper sample, the rough surface that refers to the final fracture is small than the rest of the total surface, which is for the crack initiation and growth zone, as shown in Figure 7a.

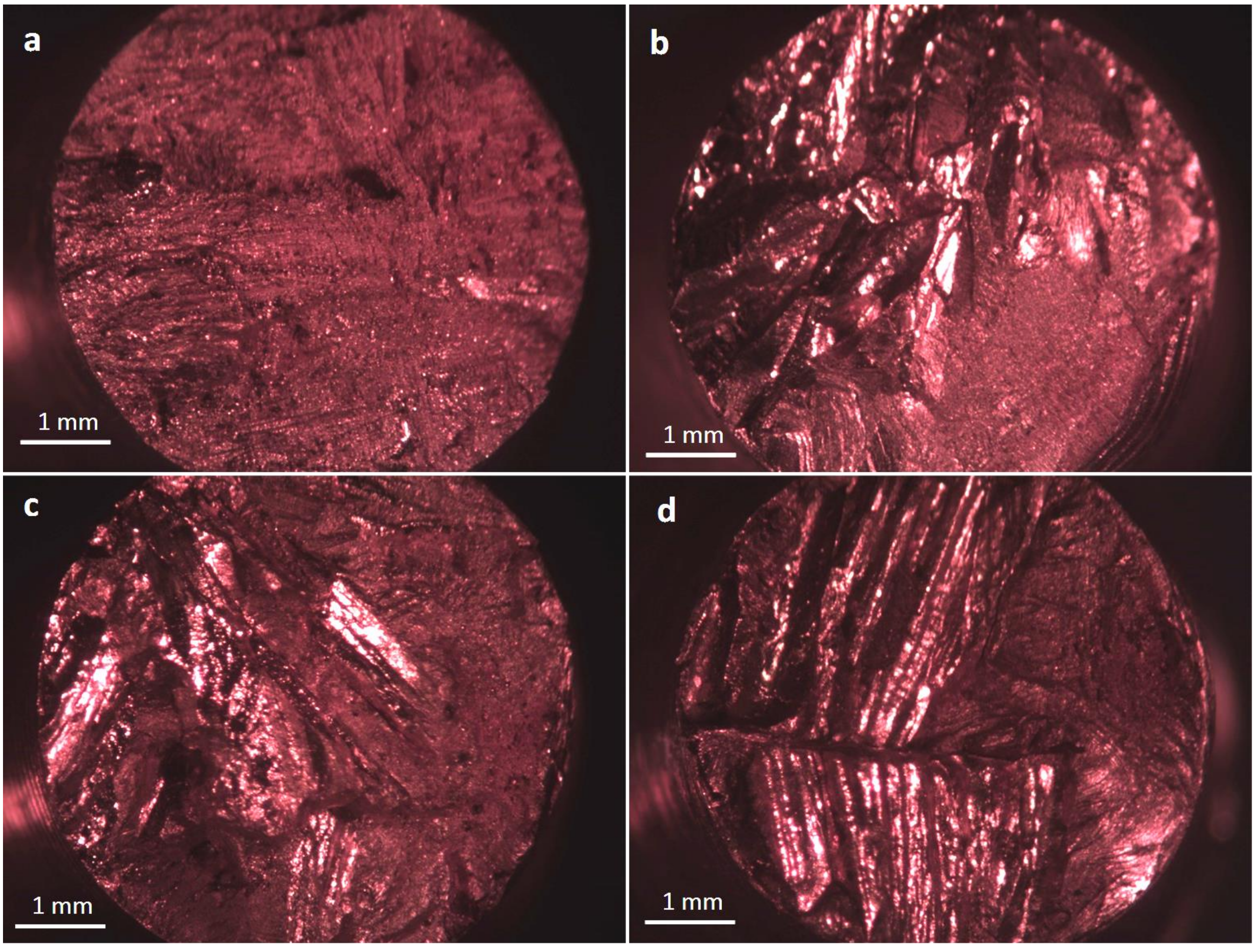


Fig. 7. The fatigue failure surface of (a) the pure copper and the composite grade reinforced with (b) 2.5, (b) 5.2, and (c) 7.4 wt% steel particles.

Figure 7b shows the fracture surface of the composite grade with 2.5 wt% steel particles. As seen, the crack growth zone is glossier than the pure copper fracture surface. The gloss of the fracture surface can be related to the shear plastic deformation of the crack tip in the crack proportion area. It means that adding the steel particles to the pure copper blocks the crack growth pass and causes more shear plastic deformation in the crack growth area. The irregular patterns in the crack growth zone of the copper-2.5 wt% steel particles fracture surface also reveal the fact that the steel particles changed the crack pass.

The fracture surface of the composite grade reinforced by 5.2 wt% steel particles is shown in Figure 7c. The glossy surface is also seen at this grade, but several dimples are also seen at the fracture surface. Dimples can be the result of the steel particles' agglomeration. In the particles' agglomeration regions, the agglomerated particles compose a hardcore that is surrounded by the soft unreinforced matrix material. Therefore, during the fatigue loading, a microcrack can be created in the core, but the soft and ductile matrix surrounds it, and its propagation pass is blocked. As a result, the matrix experiences shear stresses, and its final fracture develops a dimple [20, 21]. In addition, dimples are also seen in the final fracture area.

Figure 7d shows the fracture surface of the composite grade reinforced by 7.4 wt% steel particles. Wavy patterns in the glossy region can relate to the crack edge plastic strain and the growth of cyclic crack fatigue [22, 23]. In the composite grade with 7.4 wt% steel particles, unlike the other grades, the glossy region patterns are parallel lines with large distances that reveals faster crack growth in this region.

4. Conclusions

This paper investigates the microstructure, tensile properties, and fatigue behavior of the copper matrix composite reinforced by the processed steel particles from steel machining chips and achieves the following conclusion.

1. The SEM micrographs of the produced composites microstructure and the EDS analysis results confirm the steel particles' presence and absence of oxidation.
2. Adding 2.5 wt% steel particles as the reinforcement to the copper matrix increases the yield strength, tensile strength, and elongation of the pure copper by about 48, 21, and 5%, respectively. Increasing the steel particle content in the matrix to 5.2 and 7.4 wt% decreases the yield and tensile

strengths of the composite. The elongation, however, increases continuously by increasing the reinforcement particles' weight percent.

3. The fatigue test results show that by adding 2.5 wt% steel particles to the pure copper, the fatigue life of the pure copper increases by 67, 31, and 86 percent in 60, 80, and 100 MPa amplitude stresses, respectively. Further increasing reinforcement particle content to 7.4 wt% causes unconventional fatigue behavior in the composites as by decreasing stress range from a specific level (80 MPa for the present composites), the fatigue life does not increase. This unusual behavior can be the result of non-uniform distribution and agglomeration of the steel particles in the matrix, which facilitate crack initiation and decrease the mechanical strength of the composite.

Therefore, according to the above-mentioned results, it can be concluded that reinforcing copper matrix with the proper weight percent of steel particles improves not only the mechanical strength but also the elongation, ductility, and fatigue life of the copper.

References

[1] S. Fu et al., “Effect of aging process on the microstructure and properties of Cu–Cr–Ti alloy,” Mater. Sci. Eng. A, vol. 802, 2021, p. 140598.
[2] X. Gao et al., “Mechanical properties and thermal conductivity of graphene reinforced copper matrix composites,” Powder Technol., vol. 301, 2016, pp. 601–607.
[3] N. Somani, Y. K. Tyagi, P. Kumar, V. Srivastava, and H. Bhowmick, “Enhanced tribological properties of SiC reinforced copper metal matrix composites,” Mater. Res. Express, vol. 6, no. 1, 2018, p. 016549.
[4] R. kumar L and A. K. S, “Corrosion and wear behaviour of nano Al2O3 reinforced copper metal matrix composites synthesized by high energy ball milling,” Part. Sci. Technol., vol. 38, no. 2, 2020, pp. 228–235.
[5] K. K. Alaneme, E. A. Okotete, A. V. Fajemisin, and M. O. Bodunrin, “Applicability of metallic reinforcements for mechanical performance enhancement in metal matrix composites: a review,” Arab J. Basic Appl. Sci., vol. 26, no. 1, 2019, pp. 311–330.
[6] A. Brendel, C. Popescu, H. Schurmann, and H. Bolt, “Interface modification of SiC-fibre/copper matrix composites by applying a titanium interlayer,” Surf. Coatings Technol., vol. 200, no. 1-4, 2005, pp. 161–164.
[7]T. Köck, A. Brendel, and H. Bolt, “Interface reactions between silicon carbide and interlayers in silicon carbide-copper metal-matrix composites,” J. Nucl. Mater., vol. 362, no. 2–3, 2007, pp. 197–201.
[8] M. Abolghasem, A. Rashidi, S. M. Abbasi, and M. Mihanpanah, “Manufacture and mechanical properties study of copper-matrix nanocomposites reinforced with carbon nanotubes by means of powder metallurgy,” emergencias, vol. 6, 2013, pp. 22–27.
[9] G. Shao, P. Liu, K. Zhang, W. Li, X. Chen, and F. Ma, “Mechanical properties of graphene nanoplates reinforced copper matrix composites prepared by electrostatic self-assembly and spark plasma sintering,” Mater. Sci. Eng. A, vol. 739, no. August 2018, 2019, pp. 329–334.
[10]C. Salvo, R. V. Mangalaraja, R. Udayabashkar, M. Lopez, and C. Aguilar, “Enhanced mechanical and electrical properties of novel graphene reinforced copper matrix composites,” J. Alloys Compd., vol. 777, 2019, pp. 309–316.
[11] K. Zhang, G. Shao, W. Li, X. Chen, F. Ma, and P. Liu, “Wear and Corrosion Behavior of Graphene-Nanoplate-Reinforced Copper Matrix Composites Prepared Through Electrostatic Self-Assembly,” J. Mater. Eng. Perform., vol. 28, no. 3, 2019, pp. 1650–1660.
[12] N. Vijay Ponraj, A. Azhagurajan, S. C. Vettivel, X. Sahaya Shajan, and P. Y. Nabhiraj, “Study of Processing and Microstructure of Copper Composite Reinforced with Graphene Nanosheet by Powder Metallurgy Technique,” Powder Metall. Met. Ceram., vol. 56, no. 9–10, 2018, pp. 523–534.
[13] K. K. Alaneme and B. U. Odoni, “Mechanical properties, wear and corrosion behavior of copper matrix composites reinforced with steel machining chips,” Eng. Sci. Technol. an Int. J., vol. 19, no. 3, 2016, pp. 1593–1599.
[14] S. Cardinal, J. M. Pelletier, G. Q. Xie, F. Mercier, and F. Dalmas, “Enhanced compressive plasticity in a Cu-Zr-Al – Based metallic glass composite,” J. Alloys Compd., vol. 782, 2019, pp. 59–68.
[15] J. Chen et al., “Fabrication and mechanical properties of AlCoNiCrFe high-entropy alloy particle reinforced Cu matrix composites,” J. Alloys Compd., vol. 649, 2015, pp. 630–634.
[16] V. Norouzifard, H. Naeinzadeh, and A. Talebi, “Fabrication and investigation of mechanical properties of copper matrix nanocomposite reinforced by steel particle,” J. Alloys Compd., vol. 887, 2021, p. 161434.
[17] Annual Book of ASTM Standards. E 466, 2016.
[18] Annual Book of ASTM Standards. E8/E8M, 2016.
[19] G. H. A. Bagheri, “The effect of reinforcement percentages on properties of copper matrix composites reinforced with TiC particles,” J. Alloys Compd., vol. 676, 2016, pp. 120–126.
[20] D. Hull, Fractography: Observing, Measuring

and Interpreting the Fracture Surface Topography. Cambridge: Cambridge University Press, 1999.
[21] H. ASM, Volume 12: fractography. ASM international, 1987.
[22] A. Echeverría and J. M. Rodriguez-Ibabe, "The role of grain size in brittle particle induced fracture of steels," Mater. Sci. Eng. A, vol. 346, no. 1–2, 2003, pp. 149–158.
[23] N. Chawla and K. K. Chawla, Metal Matrix Composites. Springer, 2006.