Effect of friction stir welding on microstructure and mechanical properties of the 6061 aluminium alloy/ 15vol % SiC$_p$ reinforcement

H I Dawood[1]*, Kanaan Mohammad Musa[1], Rafid K Abbas[1], Kassim Kadhim Hameed Alshemary[1], Uday M B[2,3], Riyam I Jaddan[4] and Leana J Taklef[5]

[1]Department of Chemical Engineering, College of Engineering, University of AL-Qadisiyah, AL-Qadisiyah, IRAQ

[2]School of Mechanical Engineering, Faculty of Engineering, University Teknologi Malaysia 81310 UTM Skudai, Johor, Malaysia

[3]Centre for Advanced Composite Materials (CACM), Institute for Vehicle Systems and Engineering, University Teknologi Malaysia 81310 UTM Skudai, Johor, Malaysia

[4]Department of Materials Engineering, College of Engineering, University of AL-Qadisiyah, AL-Qadisiyah, IRAQ

[5]Department of Mechanical Engineering, College of Engineering, University of AL-Qadisiyah, AL-Qadisiyah, IRAQ

* E-mail address: hasan.dawwood@qu.edu.iq ; hassanissa1972@gmail.com

Abstract In this article, the microstructure and mechanical properties of friction stir-welded joints were evaluated after 15 vol. % of silicon carbide particle (SiC$_p$) were introduced into the joint line, then compared with another welded joint without using SiC$_p$. The rotational speed of 1750 rpm was applied during the friction stir welding (FSW) process. The microstructure was assessed at the stir zone (SZ) using Field Emission Scanning Electron Microscopy (FESEM), and results showed a banded structure of the particle-rich region of SiC$_p$. The ultimate tensile strength (UTS) was enhanced by 79.6 %, due to the presence of SiC$_p$. This strength increased significantly due to the pinning effect and enlarged nucleation sites associated with the SiC$_p$. Furthermore, the reinforced particles induced the fracturing of the primary grains and showed higher ductility when compared with the SiC$_p$ -free specimen.

Keywords: *Friction stir welding; 6061 aluminium alloy; Aluminium matrix SiC$_P$; Microstructure; Mechanical properties.*

1. Introduction

Some defects appear in the aluminium alloys after fusion welding, for example solidification cracks and porosity, which caused reduce in quality of the welded joint [1]. Welding defects are obtained when using classic fusion techniques in the welding of aluminium matrix composites. Unwanted chemical reactions between two reinforced surfaces during solidification are associated with fusion welding [2-5]. FSW is a method to combine dissimilar metals by solid state (i.e. not dissolved or recasted) and excludes the above problems [1]. The FSW method was invented at The Welding Institute in the UK in 1991[6]. This welding technique produces an uneven microstructure characterized by advancing side and retreating side. The path of the rotational tool is indicated as the advancing side if it is in the same direction as the weld; otherwise, it is referred to as the retreating side. This difference in the two sides can lead to asymmetry in material flow, heat transfer, and weld properties [7].

Several research work has been conducted to study the effect of FSW process parameters on aluminium alloys. In the reported work, the parameters of FSW process, namely tool rotational

speed and welding speed were investigated to study the effects of microstructure, tensile strength, and microhardness on the welding joint [8, 9]. Kim et al. [10] investigated the FSW of aluminium die casting alloy at different rotational speed. It was found that at different rotation speed, the size of SiC_p at the bottom of the joint was finer than other SZ regions. Moreover, the effect of rotational speed on the SiC_p particle size has no significant effect in the all area of SZ. Kumar et al [11] analyzed FSW scanning electron microscopy (SEM) of SiC_p reinforced 2124 aluminium alloy matrix. Some pores or void formation were observed in the SiC_p / matrix coarse interface in SZ. This is due to the high stirring rates that occur in the SZ of the composite. SEM observation also revealed the cracking of some coarse SiC_p in the SZ. The authors suggested that the above phenomena may be attributed to the severe stirring of SiC_p with matrix aluminium alloys in the SZ. Storjohann et al [12] studied the microstructure of the friction stir welded of 2124 aluminium/SiC_p and 6061 aluminium/Al_2O_3 alloys. In both cases, the reinforcement particles appear to be uniformly distributed and there was no evidence of adverse reactions in SZ and also agreement with other research conducted in this area. Furthermore, the hardness measurement showed some difference between SZ and base metals. Hynes et al [13] studied the effect of SiC_p reinforcements employing FSW technique, it has been reported that the appropriate mechanical properties of the welding joint depend mainly on the distribution of reinforcement particles. Barmouz et al [14] reported that the grain size of welded composite layers is finer than the welded specimen without SiC_P.

Accordingly, this study aims to investigate the effects of SiC_P on the microstructure, tensile strength and microhardness of friction stir-welded joints of 6061 aluminium alloy.

2. Experimental procedures
The chemical composition of the 6061 aluminium alloy plate with a thickness of 4 mm is shown in table 1, was measured using an Emission Spectrometer (Q8 Magellan, Model: QM/V/L). 'Figure 1a' shows a magnified FESEM micrograph of SiC_p as-received. Medium carbon steel was machined to manufacture the FSW tool, afterward heat-treated to 60 Rockwell Hardness (HRC) as schematically illustrated in 'Figure 1b'. The pin tool has a threaded taper was inscribed in a circle with a diameter of 2 mm, shoulder diameter 10 mm, and pin height 3.7 mm.

Table 1. Chemical compositions of 6061 aluminium alloy (wt %).

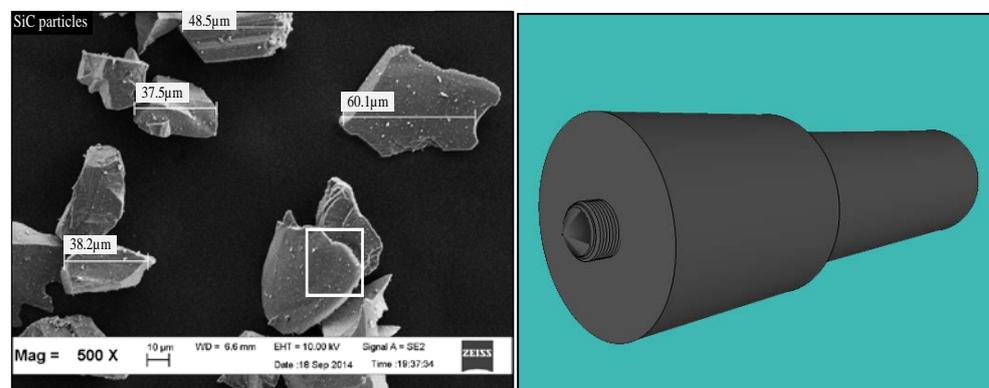| Element	Al	Si	Fe	Mg	Cu	Mn
%	97.57	0.525	0.339	1.062	0.120	0.080

Figure 1. (a) FESEM micrograph of the as-received SiC_p and (b) FSW tool.

The aluminium plate was cut into strips with dimensions of 210 mm $\times$ 200 mm using a cutting band saw machine. Afterward, 15 vol. % of SiC_P was reinforced by the size of the weld between two strips and tightly pressed using a built fixture. This part of volume fraction was also considered by Wang et al. [15]. To fix the SiC_P along the joint line without dissipation during the welding process, a tool shoulder without pin was used to submerge the powder before running the FSW process. The traverse speed of 40 mm/min and rotational speed of 1750 rpm were then tested[8, 16]. One pass was performed for the FSW process; the specimen data and processing conditions are listed in table 2. In our study, the rotational speed of 1750 rpm was adopted, based on the study conducted by Hasan et al. [16]. Furthermore, the reinforcement particles at this parameter show a continuous uniform distribution (particle-rich regions) over the interface between two pieces of 6061 aluminium alloy. Thus, friction stir welded of the specimen at 1750 rpm revealed the highest mechanical properties. Moreover, FSW was performed under high processing conditions (1750 rpm) but without SiC_P to determine the effects of particle reinforcement on the microstructure and mechanical properties.

Table 2. Review the properties of FSW joints.

Rotational speeds (rpm)	Grain size (µm)	Percentage of elongation	Average microhardness value (Hv)	UTS (MPa)
1750	1.8	5.8	105	283.158
1750 (without SiC_p)	7.371	4.8	88	151.035

The upper surfaces of the FSW joints were ground to remove delayed scratching and oxide film and were then prepared for metallographic and tensile testing. The metallographic specimens were chemically etched for 15 min using 1% NaOH, afterward a preliminary analysis was performed using FESEM apparatus (FEI Nova NanoSEM 450). The average grain size was measured according to a linear intercept method (ASTM:E112-96) by [17]. According to ASTM: E8/E8M-11, B557: ETD 2013, tensile specimens of sub-size were mechanically machined and normal to the welding direction. The microhardness of the SZ was tested by employing Vickers microhardness (Hv) tester using 1 kgf load for 15 sec.

3. Results and discussions
3.1 Microstructural investigation
The FSW process typically involves four different regions, namely, base metal (BM), heat-affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and nugget zone (NZ) [18]. The micrographs of SZ from fabricated joints with and without SiC_P at 1750 rpm are shown in 'Figure 2' (a and b).
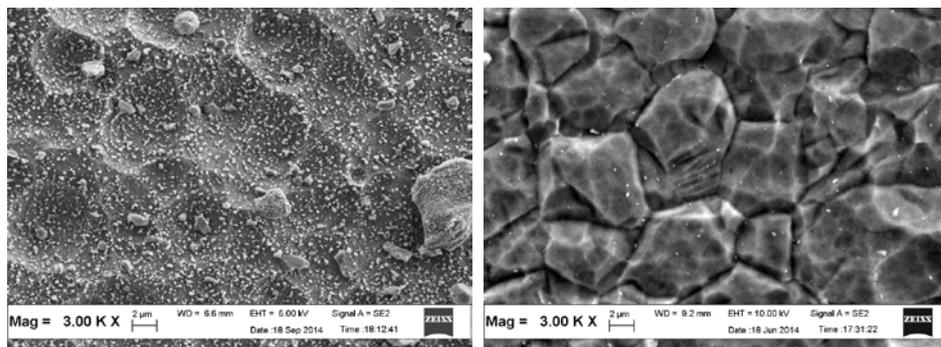
Figure 2. FESEM micrographs of SZ welded at (a) 1750 rpm with particle-rich regions of SiC$_P$ and (b) 1750 rpm without SiC$_P$.

During the FSW process, fine grains are formed when the material undergoes severe plastic deformation at high temperature. This event is known a dynamic recrystallization [19-21]. SiC$_P$ reinforcements act as fences adjacent to grain boundaries to prevent grain growth by limiting grain activities, and this phenomena is known pinning effect [21, 22]. SiC$_P$ reinforcements could break up the initial grains during plastic deformation. As mentioned earlier, the rotational speed of 1750 rpm in current work was considered as higher processing parameter [23]. The welding parameters during FSW process for the specimen performed at 1750 rpm without SiC$_P$ were similar to the welding specimen at 1750 rpm with particle reinforcement. The purpose of this work is to demonstrate the impact of SiC$_P$ enhancements on the SZ microstructure. Grain size measurements showed that grain refinement in specimen friction stir welded at 1750 rpm with SiC$_P$ was better than specimen performed without SiC$_P$. This result is due to the thermal conductivity of SiC$_P$, which dissipates high-heat flow and causes a rapid loss of temperature compared to the fabricated joint without particles reinforcement. The larger grain size of the welded specimen without reinforcement particles is related to the high heat input [24]. An excellent distribution of particles has been observed in specimen friction stir welded with SiC$_P$; thus, this specimen was referred to as the best heat input specimen.

3.2. Mechanical properties
3.2.1. Tensile properties
The results of the tensile test of friction stir-welded joints are shown in 'Figure 3'. The results showed FSW specimens with and without SiC$_P$ reinforcement, gives a higher and lower threshold of UTS values. Higher UTS of the specimen was achieved at 1750 rpm with SiC$_P$, most likely due to the size of finer grains. According to Hall–Petch relationship, a decrease in grain size improves tensile properties [25]. Relative to BM, UTS of specimens performed with and without SiC$_P$ was improved by 79.6% and 42.4%, respectively, [12].
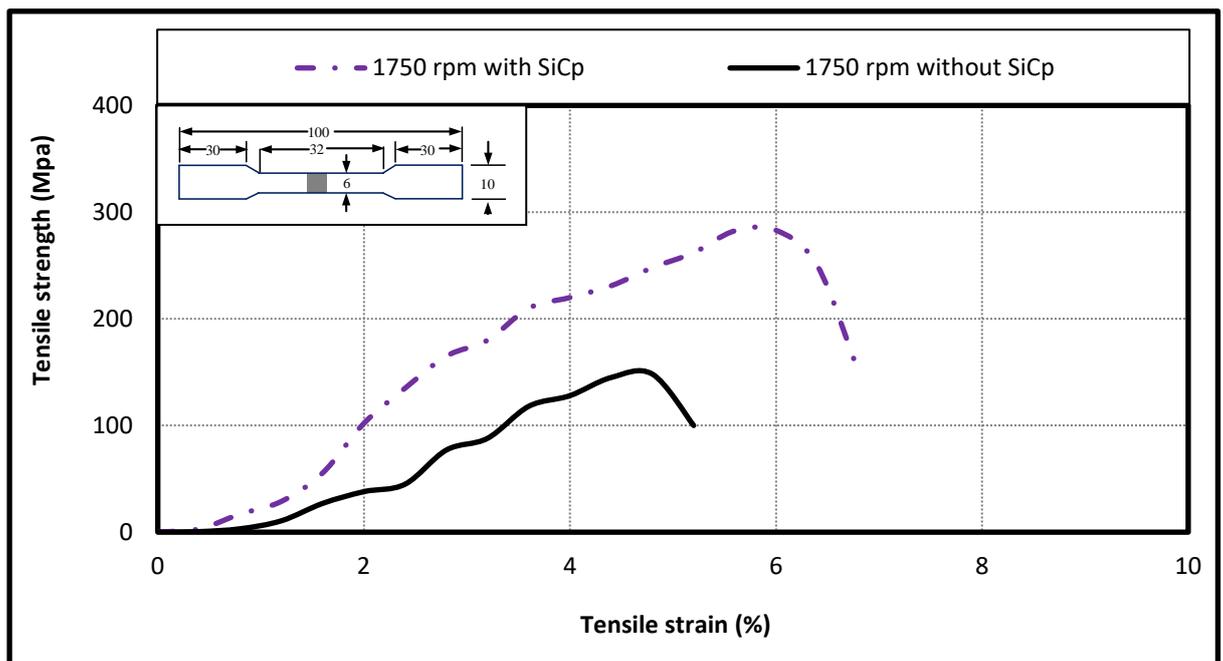
Figure 3. Comparison of tensile strain-stress curves of reinforced specimens with SiC_P and without SiC_P.

3.2.2. Vickers Microhardness
The average microhardness of 6061 aluminium alloy BM was found after a hardness test of about 94 Hv. The behavior of microhardness specimens is depicted in 'Figure 4' and a declined in microhardness distributions along the SZ can be realized. The microhardness of the SiC_P reinforced joint is extremely correlated with the grain size, the presence of particles reinforcing, dislocation density and heat input. According to the Hall–Petch equation, smaller grains are associated with higher microhardness values [26].

$$H_v = H_0 + K_H d^{-1/2} \tag{1}$$

Where H_v is the hardness, H_0 and K_H are the appropriate constants associated with the hardness measurements, and d is the grain size. Reinforcing particles have double effects on microhardness due to SiC_P pinning effect on grain boundary [26]. The greater microhardness of SZ compared to BM is due to the excellent bonding behavior between SiC_P dispersant and aluminium matrix composites. However, the reduction of microhardness may occur due to the annealing effect associated with the heat input [27].
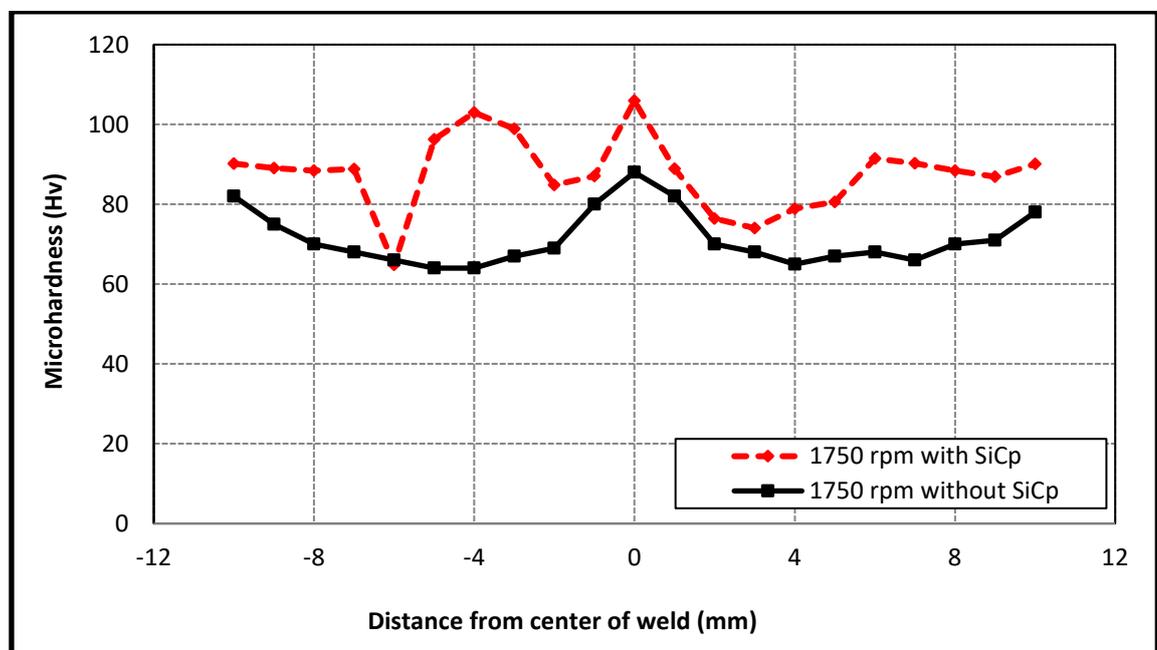

Figure 4. Microhardness behavior of specimens welded at 1750 rpm with SiC_P and without SiC_P.

4. Conclusions

In this study, SiC_P was used during FSW to improve the mechanical properties of the specimens. The microstructure and mechanical properties, namely tensile strength, and microhardness behavior, were examined. The 6061 aluminium alloy matrix reinforced with SiC_P was developed in the SZ. At 1750 rpm, the particle distribution was enhanced due to pin stirring action. The SiC_P reinforcement decreases the size of grains by preventing grain growth and segmentation original grains during deformation. The UTS of the specimen friction stir-welded with SiC_P was 37.2 % greater than the specimen friction stir-welded without SiC_P reinforcement.

References

[1] Elangovan K and Balasubramanian V 2008 Influences of tool pin profile and welding speed
    on the formation of friction stir processing zone in AA2219 aluminium alloy *J. of mater.s process. technol.* **200** 163-75

[2] Ceschini L, Boromei I, Minak G, Morri A and Tarterini F 2007 Effect of friction stir welding
    on microstructure, tensile and fatigue properties of the AA7005/10vol.% Al_2O_3p composite
    Compos. sci. and technol. **67** 605-15

[3] Ellis M 1996 Joining of aluminium based metal matrix composites *Inter. Mat. Reviews* **41** 41-
    58

[4] Dawood H I, Mohammed K S, Rajab M Y and Ismail N R 2014 A comparison study between
    friction stir welding and metal inert gas welding in joining similar Al-Al strips. In: *Advan. Mater. Resea.*: Trans Tech Publ) pp 180-4

[5] Dawood H I, Mohammed K S and Rajab M Y 2014 Advantages of the green solid state FSW
    over the conventional GMAW process *Advan. in Mater. Sci. and Eng.* **2014**

[6] Mishra R S and Ma Z 2005 Friction stir welding and processing *Mater. Sci. and Eng.: R:*
    Reports **50** 1-78

[7] Cho J-H, Boyce D E and Dawson P R 2005 Modeling strain hardening and texture evolution
    in friction stir welding of stainless steel *Mater. Sci, and Eng.: A* **398** 146-63

[8] Dawood H, Mohammed K S, Rahmat A and Uday M 2015 Effect of small tool pin profiles on
    microstructures and mechanical properties of 6061 aluminium alloy by friction stir welding
    Trans. of Non. Met. Soci. of Chin. **25** 2856-65

[9] Dawood H I, Mohammed K S and Wahab Z A 2013 The Effect of Rotational Speed on Flow
    Behavior and Weld Properties in Friction Stir Welding of Pure Aluminium. In: *Advan.*
    Mater. Rese.: Trans Tech Publ) pp 182-9

ICEAT 2020

IOP Conf. Series: Materials Science and Engineering **870** (2020) 012162

IOP Publishing

doi:10.1088/1757-899X/870/1/012162

[10]   Kim Y, Fujii H, Tsumura T, Komazaki T and Nakata K 2006 Three defect types in friction stir
         welding of aluminium die casting alloy *Mater. Sci. and Eng.: A* **415** 250-4

[11]   Kumar R, Singh R and Ahuja I 2019 Friction stir welding of ABS-15Al sheets by introducing
         compatible semi-consumable shoulder-less pin of PA6-50Al *Measurement* **131** 461-72

[12]   Storjohann D, Babu S, David S and Sklad P 2003 Friction stir welding of aluminium metal
         matrix composites. In: *Proceeding of the 4th International Symposium On Friction Stir*
         Welding, Utah,

[13]   Hynes N R J, Sankaranarayanan R, Tharmaraj R, Pruncu C I and Dispinar D 2019 A
         comparative study of the mechanical and tribological behaviours of different aluminium
         matrix–ceramic composites *J. of the Brazi. Soci. of Mech. Sci. and Eng.* **41** 330

[14]   Barmouz M, Asadi P, Givi M B and Taherishargh M 2011 Investigation of mechanical
         properties of Cu/SiC composite fabricated by FSP: Effect of SiC particles' size and volume
         fraction *Mater. Sci. and Eng.: A* **528** 1740-9

[15]   Wang D, Xiao B, Wang Q and Ma Z 2013 Friction stir welding of SiCp/2009Al composite
         plate *Mater. & Desi.* **47** 243-7

[16]   Dawood H I, Mohammed K S, Rahmat A and Uday M 2015 The influence of the surface
         roughness on the microstructures and mechanical properties of 6061 aluminium alloy using
         friction stir welding *Sur. and Coat. Technol.* **270** 272-83

[17]   Bailey S J and Baldini N 2007 Annual book of ASTM standards *ASTM International, PA,*
         USA

[18]   Khodaverdizadeh H, Heidarzadeh A and Saeid T 2013 Effect of tool pin profile on
         microstructure and mechanical properties of friction stir welded pure copper joints *Mater.*
         & Desi. **45** 265-70

[19]   Morisada Y, Fujii H, Nagaoka T and Fukusumi M 2006 Effect of friction stir processing with
         SiC particles on microstructure and hardness of AZ31 *Mater. Sci. and Eng.: A* **433** 50-4

[20]   Morisada Y, Fujii H, Nagaoka T and Fukusumi M 2006 MWCNTs/AZ31 surface composites
         fabricated by friction stir processing *Mater. Sci. and Eng.: A* **419** 344-8

[21]   El-Rayes M M and El-Danaf E A 2012 The influence of multi-pass friction stir processing on
         the microstructural and mechanical properties of Aluminium Alloy 6082 *J. of Mater.*
         Process. Technol. **212** 1157-68

[22]   Morisada Y, Fujii H, Nagaoka T, Nogi K and Fukusumi M 2007 Fullerene/A5083 composites
         fabricated by material flow during friction stir processing *Composites Part A: Appl. Sci.*
         and Manuf. **38** 2097-101

[23]   Zhao Y, Lu Z, Yan K and Huang L 2015 Microstructural characterizations and mechanical
          properties in underwater friction stir welding of aluminium and magnesium dissimilar
          alloys *Mater. & Desi. (1980-2015)* **65** 675-81
[24]   Mohammed K S, Dawood H I and Darus Daud M 2015 The microstructure and mechanical
          properties of Al/Al2O3 surface composite layer produced by FSP green technique. In:
          Mater. Sci. Forum: Trans Tech Publ) pp 91-6
[25]   Rollett A, Humphreys F, Rohrer G S and Hatherly M 2004 *Recrystallization and related*
          annealing phenomena: Elsevier)
[26]   Shamsipur A, Kashani-Bozorg S F and Zarei-Hanzaki A 2011 The effects of friction-stir
          process parameters on the fabrication of Ti/SiC nano-composite surface layer *Surf. and*
          Coat. Technol. **206** 1372-81
[27]   Barmouz M, Besharati Givi M K and Seyfi J 2011 On the role of processing parameters in
          producing Cu/SiC metal matrix composites via friction stir processing: Investigating
          microstructure, microhardness, wear and tensile behavior *Mater. charact.* **62** 108-17