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WELDABILITY OF METAL MATRIX COMPOSITE PLATES BY FRICTION STIR WELDING AT LOW WELDING PARAMETERS

VARIVOST PLOŠČ KOMPOZITA S KOVINSKO OSNOVO PO VRTILNO TORNEM POSTOPKU PRI NIZKIH VARILNIH PARAMETRIH

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Metal matrix composites (MMCs) are engineering materials that their increasingly replacing of a number of conventional materials in automotive, aerospace, and sports industries is driven by the demand for lightweight, high specific strength and stiffness. Their wide application as structural materials needs proper development of suited joining processes. Friction stir welding (FSW) is a fairly new solid state welding process for joining metals using thermal energy produced from localized friction forces.

In this study, the weldability of AA2124 containing (volume fractions) 25 % of SiC particles with T4 heat treated aluminum MMC plates was investigated at low welding parameters by FSW process. Microstructure, ultimate tensile strength, surface roughness and microhardness determination have been carried out to evaluate the weld zone characteristics of friction stir welded MMC plates. The FSW specimens were tested without post-weld heat treatment or surface modification. The temperature dissipation at the distance of 15 mm from the weld center was also measured using K-type thermocouples to demonstrate the FSWed joining without melting. Because of microstructural modification, improvement of microhardness of the stir zone was observed in comparison to the base composite. Ultimate tensile tests indicated a joint efficiency of approximately 73 %.

Keywords: metal matrix composites, friction stir welding, welding parameters, microstructure

Kompoziti s kovinsko osnovo (MMCs) so inženirski material, ki vse bolj nadomešča številne konvencionalne materiale v avtomobilski, letalski in v športnih industrijah, pri tem pa se pojavlja veliko povpraševanje po manjši specifični masi ter visoki trdnosti in togosti. Za široko uporabo je potreben pravilen razvoj ustreznih postopkov varjenja. Vrtilno torno varjenje (FSW) je dokaj nov način za spajanje kovin v trdnem stanju s toplotno energijo, ki jo ustvarja trenje.

Raziskana je bila varivost kompozita AA2124 z volumenskim deležem 25 % SiC-delcev s T4 toplotno obdelano MMC-ploščo aluminija pri nizkih parametrih FSW-varjenja. Mikrostruktura, natezna trdnost, hrapavost površine in mikrotrdota so bile določene za ovrednotenje značilnosti območja zvara. Preiskani FSW-vzorci niso bili toplotno ali površinsko obdelani. Temperatura je bila izmerjena na oddaljenosti 15 mm od centra vara s K-termoelementom, da bi dokazali FSW-spoj brez taljenja. Zaradi spremembe mikrostrukture so bile izboljšane mikrotrdota v mešanem v primerjavi s tisto pri osnovnem kompozitu. Natezna trdnosti vara je dosegala približno 73 % trdnosti plošče.

Ključne besede: kompoziti s kovinsko osnovo, vrtilno torno varjenje, parametri, mikrostruktura

1 INTRODUCTION

Aluminium and its alloys are used commonly in aerospace and transportation industries because of their low density and high strength to weight ratio. Especially Al-based Metal Matrix Composites (MMC) exhibit high strength, high elastic modulus, and improved resistance to fatigue, creep and wear; which make them promising structural materials for many industries.[1] The high cost of current MMCs compared to aluminum alloys has inhibited production on a large industrial scale.[2] Aluminium 2124 alloy is a high strength wrought alloy generally used in aerospace industry for making structural components. Addition of high wear resistant ceramic particles, such as SiC, Al_2O_3, AlN, B_4C, TiC to the alloy is expected to increase the mechanical properties considerably. These MMCs suffer from the disadvantage of low ductility which is due to different reasons, like brittle interfacial reaction products, poor wettability, particle-matrix debonding or presence of porosity or particle clusters.[3, 4] The welding of aluminum and its alloys has always represented a great challenge for designers and technologists.[5] One of the main limitations for the industrial applications of these alloys are the difficulty in using conventional welding methods for joining. The disadvantages associated with the fusion welding of these composites include: (a) incompatible mixing of the base and filler materials, (b) presence of porosity in the fusion zone, (c) excess eutectic formation and (d) formation of undesirable deleterious phases.[6] With the aim to obtain high quality welds, MMC has recently been widened by employing solid state welding process, in which joining is obtained at temperatures substantially below the melting point of the base material.[7] In the FSW process, a special tool mounted on a rotating probe travels down through the length of the base metal plates in face-to-face contact; the interference between the welding tool and the metal to be welded generates the plastically deformed zone through the associated stirring action. At the same time, a thermo-mechanical plasticized zone is produced by friction between the tool shoulder and the top plate surface and by contact of the neighboring material with the tool edges, inducing plastic deformation. No melting takes place in the weld zone during FSW.[8] As result, the joint is produced in solid state. Due to this feature, FSW has emerged as a promising technique for joining of MMCs.[9]

FSW has attracted considerable attention in the industrial world due to its many advantages and has been successfully applied to the joining of various types of Al[10, 11], Cu[12,13], Ti[14], Mg[15], Fe[16] and different alloys[17,18] The applicability of friction stir welding to join aluminium MMCs reinforced with ceramic particles has been investigated by several authors.[8,19,20]

In this study, Friction stir welded joints on a AA2124 with 25 % (volume fractions) of SiC particles MMC plates were obtained using low welding parameters. The microstructure, microhardness profile, surface roughness, and tensile properties of the welds were examined. The objective of the present study was to clarify how the welding parameters are related to the mechanical properties of AA2124/SiC/25p-T4 MMC joints.

2 EXPERIMENTAL PROCEDURE

The plates used in this study are AA2124-T4 alloy matrix MMC strengthened with 25 % SiC particles (AA2124/SiC/25p-T4). This material was supplied by Aerospace Metal Composite Limited (UK) in form of billet with size of 400 mm × 260 mm × 50 mm. The MMC material was produced by powder metallurgy and mechanical alloying techniques followed by hot forging and tempering to T4 condition (solution heating at about 505 °C for 1 h, quenching in 25 % polymer glycol solution and room temperature aging for >100 h). The ultimate tensile strength of the base AA2124/SiC/25p-T4 MMC is of 454 MPa. The chemical composition of the AA2124/SiC/25p-T4 MMC was in mass fractions: Al-3.86 Cu-1.52 Mg-0.65 Mn-0.17 Si (%).

MMC plates of 130 mm × 50 mm × 3 mm size were cut from this billet by electro-discharge machining (EDM) technique with a feeding rate of 2 mm/min. The AA2124/SiC/25p-T4 MMC plates were friction stir butt welded using an FSW adapted numeric controlled milling machine. The FSW tool was of high speed steel with shoulder and probe diameter 22 mm and 6 mm, respectively. The tool was tilted by 2° with respect to *Z*-axis of milling machine and rotated in clockwise direction chosen according to the optimum results obtained at high welding parameters of AA2124/SiC/25p-T4 MMC joints.[8] FSW process was carried out at the tool rotation speed of 450 rpm and tool traverse speed of 40 mm/min. This welding parameters were optimized after preliminary welding tests for weldability of metal matrix composite plates at low welding parameters. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) observations were conducted on JEOL JSM-5910LV.

Temperature measurements were made during the butt welding with eight gage K-type thermocouples with a diameter of 3 mm. Holes of 3 mm diameter and 2 mm depth were drilled 15 mm away from the centerline of the weld. Four of the thermocouples embedded on the advancing side and the others embedded on the retreating side with (10, 45, 85, and 120) mm intervals as in Ref. [8].

The specimens were polished using conventional polishing methods and chemically etched. Numerous Vickers microhardness measurements ($HV_{0,5}$) were performed on the transverse cross-sections of welded joints at the centerline with a 1 mm interval using a 500 g load for a dwell time of 20 s to determine the hardness variations across the joints.

The modification of surface roughness induced by the FSW process was evaluated by means of Mitutoyo Suftest-211 for the side in contact with the shoulder. The tensile tests were carried out at room temperature according to ISO/TTA2 standard[21] by an universal type tensile test machine to determine the tensile properties of the joints. At least three specimens were tested under the same conditions to guarantee the reliability of the results.

3 RESULTS AND DISCUSSION

3.1 Microstructure

As shown in **Figure 1**, AA2124/SiC/25p-T4 MMC plates with a thickness of 3 mm were successfully joined by FSW technique. Top view of the friction stir welded composite is shown in **Figure 1**. Surface roughness measurements were performed in the FSW zone on the side in contact with the shoulder, both on longitudinal

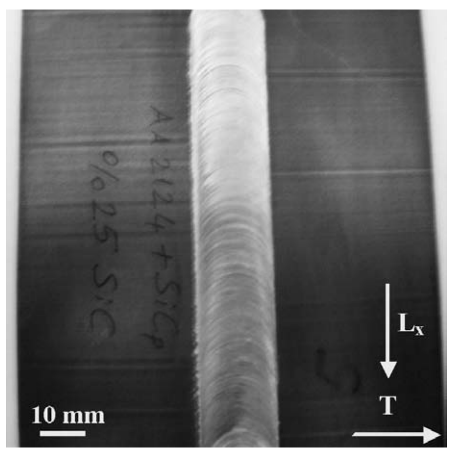

Figure 1: Top view of friction stir welded AA2124/SiC/25p-T4 MMC plates
Slika 1: Pogled od zgoraj na plošče AA2124/SiC/25p-T4 MMC zvarjene po vrtilno tornem postopku

(L) and transverse (T) directions. As revealed in **Table 1**, it should be stated that the surface in contact with the shoulder showed high values of the roughness parameters (Ra, Ry and Rz), typical of a milled surface. Similar results have also been obtained by L. Ceschini et. al.[22]

Table 1: Surface roughness measurements on FSW zone
Tabela 1: Površina hrapavosti meritve na FSW območje

Direction of material	Ra (μm)	Ry (μm)	Rz (μm)
T	2.89	20.1	20.4
	2.28	28.8	21.5
	3.69	36.1	21.1
Average values	2.95	28.3	21
L_x	6.68	23.6	19
	4	36.4	29.1
	6.6	29.1	26.3
Average values	5.76	29.7	24.76
L_y	6.26	34.5	28.4
	3.69	23	34.4
	6.58	27.8	24.6
Average values	4.51	28.43	29.13

T: transverse, L: longitudinal, ($_x$): perpendicular, ($_y$): opposite side of perpendicular

Figure2 shows the SEM and EDS results of the FSWed of AA2124/SiC/25p–T4 composite. The macrostructure of the friction stir welded AA2124/SiC/25p–T4 MMC is shown in **Figure 2a**, where the MMC material from shoulder zone moved across the joint from the retreating side (RS) against the advancing side (AS).[23] This puzzle macrostructure of FSW joint is formally divided into four zones: (1) base material (BM); (2) heat affected zone (HAZ); (3) thermo-mechanically affected zone (TMAZ); and (4) stir zone (SZ).[8,24] No visible superficial porosity or macroscopic defects have been observed in AA2124/SiC/25p-T4 MMC joints. The AA2124/SiC/25p-T4 MMC plates contain SiC particles with two different particle sizes, of 0.1–0.5 μm and of 1–5 μm, as shown in **Figure 2b**. The SEM microstructure examination revealed a non uniform distribution of SiC particles in the matrix (**Figure 2b**). The grain size changes from base MMC to stir zone can be seen clearly in **Figure 2c**. The microstructure of stir zone is greatly refined due to dynamic recrystallization.[24,25,26] According to base MMC recrystallized fine equiaxed SiC particulates structure were homogeneously distributed in stir zone due to the high deformation and stirring action.[27] Exposure to high stresses and the heat produced by stirring tool is responsible for the plastic

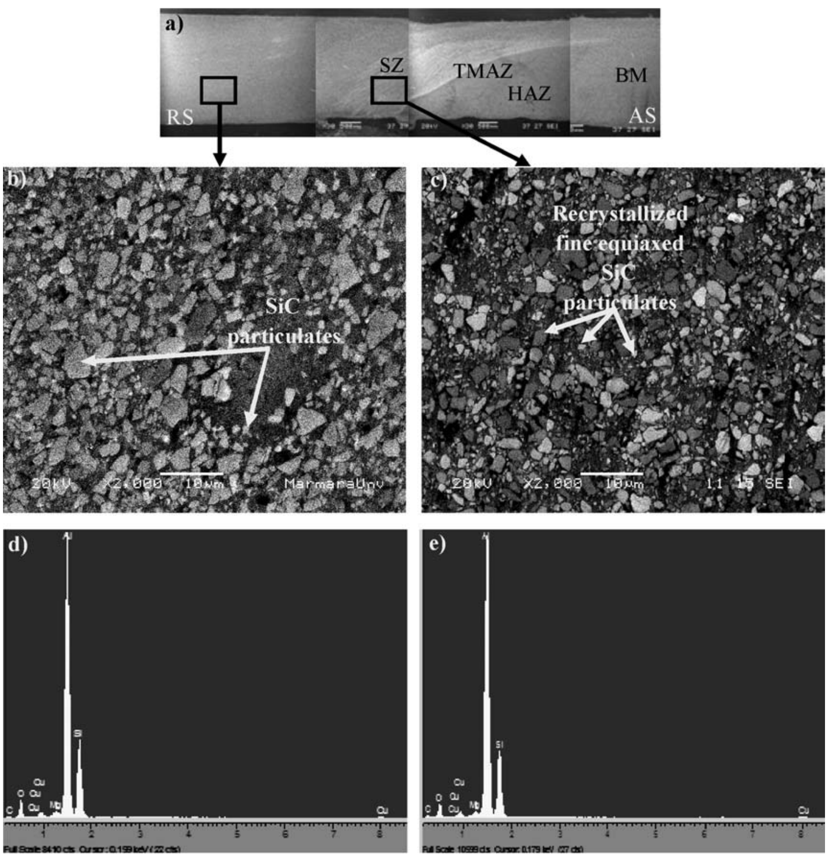

Figure 2: SEM and EDS analysis of the AA2124/SiC/25p-T4 MMC showing: (a) macrostructure of the FSW of MMC, (b) base MMC, (c) stir zone, (d) EDS analysis of base MMC, (e) EDS analysis of stir zone

Slika 2: SEM in EDS analiza AA2124/SiC/25p-T4 MMC prikazuje: (a) makro strukturo od FSW MMC compozita, (b) osnovno mikrostrukturo MMC, (c) mešamo področje, (d) EDS analizo osnovne MMC, (e) EDS analizo mešanega področja deformation which results in the rearrangement of particles.[8] **Figure 2d** and **Figure 2e** show EDS analysis results of base MMC and stir zone, respectively. The variation of elements in these zones detected by EDS analysis is given in **Table 2**. As mentioned in previous studies,[8, 28] the stir zone contains SiO_2 phase because of entrapment of O_2 from air and frictional heating at the shoulder/composite interface.

No evidence of particle cracking was found in the stir zone, as bright point in the SEM micrographs in **Figure 2c** and **Figure 2e** and by EDS analysis (**Table 2**). A few studies in the literature reported that tool wear occurs during FSW of Al matrix ceramic particulate-reinforced composites.[26,28,29] However, in this study, no tool wear was established in spite of the presence of hard SiC particulates in the stir zone.[8]

Table 2: EDS analysis of base composite and the stir zone
Tabela 2: EDS analiza z osnovna kompozitne in mešamo

Micrography	Element (%)					
	C	O	Mg	Al	Si	Cu
Base composite	13.75	12.49	0.86	47.90	22.50	2.17
Stir zone	15.23	15.69	0.62	46.19	20.50	1.77

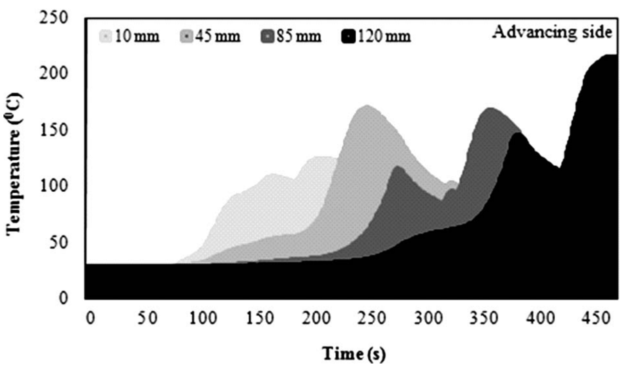

Figure 3: Temperature measurements at 15, 45, 85 and 120 mm intervals at the advancing side of the weld line
Slika 3: Temperature izmerjene na 15, 45, 85 in 120 mm na prednji strani z varilne linije

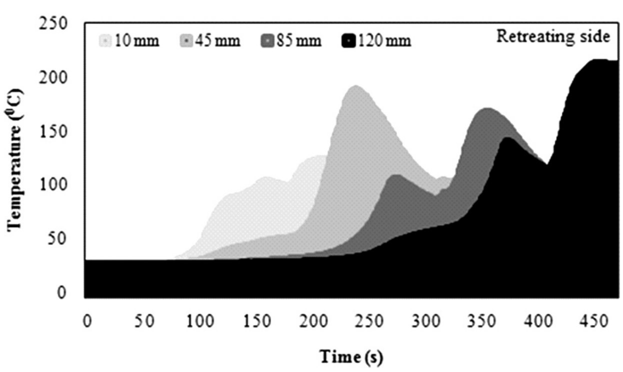

Figure 4: Temperature measurements at 15, 45, 85 and 120 mm intervals at the retreating side of the weld line
Slika 4: Temperature izmerjene na 15, 45, 85 in 120 mm na zadnji strani varilne linije

3.2 Temperature measurements

The temperature measurements at the distance of 15 mm from the weld center were carried out on four points at both advancing and retreating side to determine the peak temperature reached during welding. In **Figure 3** and **Figure 4** are shown the temperature measurements at (15, 45, 85 and 120) mm intervals at the advancing and retreating side of the weld line. The result show that the temperature is very similar on both sides of the weld bead, as shown in **Figures 3 and 4**. The temperature of 215–220 °C was determined at 15 mm from the weld center. The temperature in this zone depends on the tool rotation speed during FSW. High tool rotation speed gives rise to higher heat input into the material.[4] However, higher heat dissipation (255–270 °C) at high tool rotation speed at 15 mm from the weld center was observed.[8] As mentioned in the previous study,[30] the peak temperature during FSW was below the melting point of BM. Computer simulation of FSW has suggested that the maximum temperature in the workpiece, at the probe/workpiece interface, can reach the lower bound of the melting temperature range of the workpiece during FSW of aluminum alloys, including Alloys 6061, 7030, and 7075.[31]

3.3 Hardness

Figure 5 shows the hardness profile on the cross section of the FSWed of MMC. In the previous studies, the hardness in the stir zone was reduced at high tool rotation speed because the heat generated by rotating probe causes a reduction of cooling rate.[8,32] In this study the opposite was established, because of increased effect of dynamic recrystallization, homogeneous distribution of SiC particles and reduced dimension. A similar trend was observed by Nami et. al.[6] during FSWed of Al/Mg_2Si composites. The microhardness values were in the range of 185–190 $HV_{0.5}$ for AA2124/SiC/25p-T4 base MMC. The microhardness was decreased from base

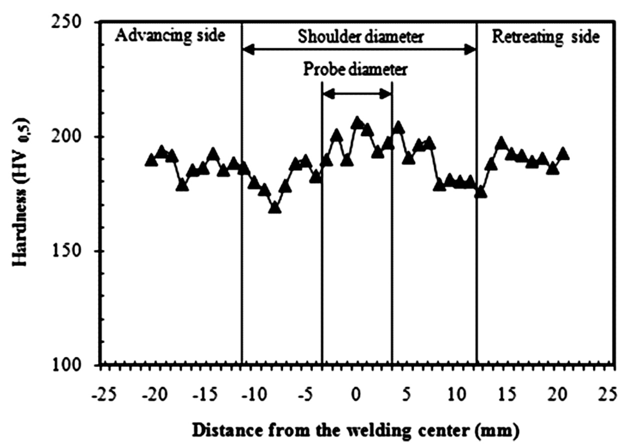

Figure 5: Hardness profiles on the cross section of the FSWed of MMC
Slika 5: Profil trdote na prerezu FSW MMC

MMC to the stir zone. The average microhardness values decreased slowly from stir zone (205 $HV_{0.5}$) to HAZ (approximately 180 $HV_{0.5}$) due to the annealing process[26] or because the shoulder supplied sufficient heat and force action.[1] As shown in **Figure 5**, the hardness from both advancing and retreating side of the HAZ to TMAZ zone was increased because of age hardening mechanism.[7]

3.4 Tensile tests

The MMCs tensile test samples were cut by EDM and tested at room temperature with the weld traverse to the welding direction without any post-weld heat treatment or surface modification. During the tensile tests, failure locations of the joints were observed in the TMAZ as shown in **Figure 6**. In this figure, can be seen clearly surface in contact with the shoulder and opposite side of the joint. As already known, the reinforcement particles have a significant impact on the strength of the MMCs.[33] For BM, an increased concentration of SiC particles increases the strength and reduces the elongation to failure of the MMC.[9] It is significant to improve the reproducibility of the weld tensile test results. The results of tensile test, carried out on the base and FSWed of MMCs plates are shown in **Table 3**. It is seen from this table that the maximum UTS value was 326 MPa which show a 73 % joint efficiency (i.e., $UTS_{FSW}/UTS_{BM} \times 100$). Because of SiC particulates probably non-uniform distributed at the TMAZ, in this region UTS and elongation was reduced. Similar results (72 %) were also obtained by some researcher[20,34] for the FSWed AA2219-T87 age hardenable aluminium-copper alloys and AA6061/20 % Al_2O_{3p} MMC plates.

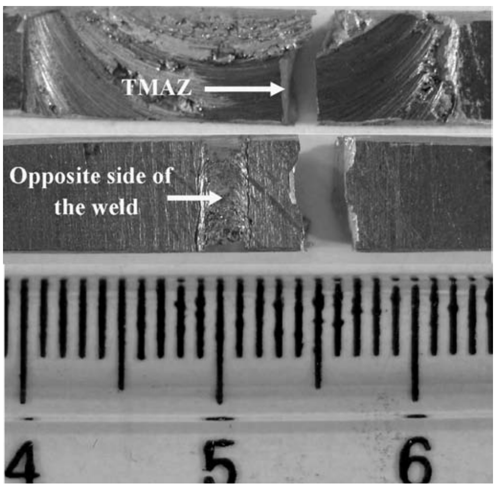

Figure 6: Surface in contact with the shoulder and opposite side of the joint
Slika 6: Površina na stiku z ramenom in z nasprotno stranjo varjenja

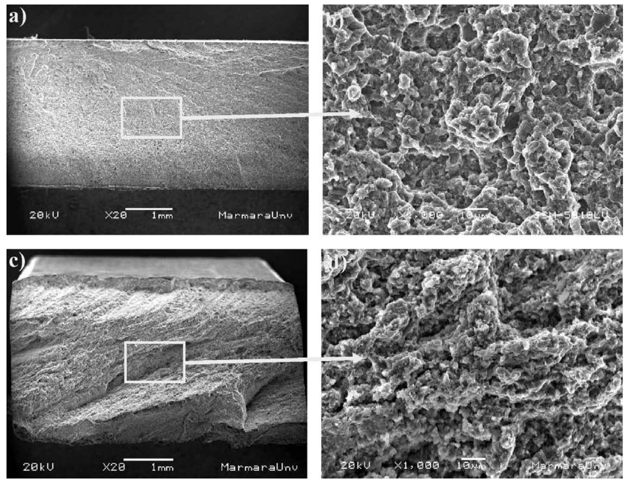

Figure 7: SEM micrographs of the tensile fracture surfaces; (a) Low magnification of BM, (b) High magnification of BM, (c) Low magnification of the stir zone, (d) High magnification of the stir zone
Slika 7: SEM posnetki nateznega peloma; (a) Majhna povečava z BM, (b) Velika povečava z BM, (c) Majhna povečava mešanega področja, (d) Velika poečaba mešanega področja

A better comprehension and understanding of the mechanical fracture and defect nucleation properties are strongly dependent on purposed analyses of the rupture surfaces, since the influence of microstructural morphology of the joined interfaces on the endurance time results to be fundamental.[35] **Figure 7** shows SEM micrographs of the tensile fracture surfaces. Different magnifications of fracture surfaces in BM and stir zone are shown in **Figure7 a, b and c, d**, respectively. The fracture surfaces revealed a mixed brittle-ductile fracture mode and showed also the superiority of bonding

Table 3: Tensile test results of the base and the FSWed composite
Tabela 3: Natezne rezultati testov z osnovna in FSWed kompozitne

Material	Test (N)	Tool rotation speed (rpm)	Tool traverse speed (mm/min)	Ultimate tensile strength (MPa)	Elongation (%)	Joint efficiency (%)
AA2124/SiC/25p-T4 (Base Composite)	1	–	–	450	2.5	–
	2			461	2.5	
	3			450	2.3	
Average values				± 454	± 2.4	
FSW-AA2124/SiC/25p-T4	1	450	40	337	2.4	75
	2			330	2.7	74
	3			312	2.6	70
Average values				± 326	± 2.6	± 73

between the SiC particles and the Al matrix. A similar fracture morphology was observed in other studies.[8,33]

4 CONCLUSIONS

In this research, weldability of 25 % of SiC particles MMC plates by friction stir welding at low tool rotation and traverse speed were investigated. The obtained results can be summarized as follows:

– The AA2124/SiC/25p-T4 MMC plates were successfully joined by friction stir welding at low welding parameters.
– Surface roughness measurements showed on the surface in contact with the shoulder high values of roughness parameters.
– In microstructural examination no visible superficial porosity or macroscopic defects have been observed in AA2124/SiC/25p-T4 MMC joints. Grain size changes from base MMC to stir zone have been observed.
– The temperature measurement was determined as 215–220 °C at 15 mm away from the weld center.
– The hardness from both advancing and retreating side of the HAZ to TMAZ zone was increased because of age hardening mechanism.
– The maximum tensile strength of 326 MPa was obtained which shows a 73 % joint efficiency.
– After tensile testing the specimen fracture surfaces have revealed a mixed brittle-ductile fracture mode.

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