Working Range of Process Parameters for Composite Fabrication by FSP

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Abstract

Friction stir processing (FSP) has been being used for composite fabrication for a couple of decades. Nano size composites have been fabricated by this technique. As the principle of FSP is similar to friction stir welding (FSW), likewise process parameters and their levels play a vital role in defect free stirred zone for the fabricated composites. Values of the process parameters affect the formation of defect free zone and the properties of the fabricated composites. Different materials require different values of these parameters. Researchers have optimised these parameters for different materials and the alloys of the single metal. As the hardness and metallurgical properties of the material change, the range of these process variables gets varied considerably. Present study consists of identification of the working range of the parameters viz. tool rotation, tool feed, axial thrust, number of FSP passes and the cooling condition to provide a gateway for the optimisation of these factors for pure Mg based TiC reinforced surface composites. Working range of tool rotation was found to be 500-700 rpm, tool feed to be 10-20 mm/min, axial thrust in terms of plunge depth to be 0.25 mm to 0.35 mm, 3 passes of FSP tool and the cooling condition to be under surface cooling (USC) at -10^{o} C.

Key words: Composite fabrication, friction stir processing, parametric study of FSP, working range of parameters.

1 Introduction

Friction-stir processing (FSP), one of the recent techniques of surface modification, is based on friction stir welding principle. In this process, a defect free nugget zone has been affected by various factors including tool rotation, tool geometry, tool feed, cooling conditions, number of passes and the axial thrust on the tool shoulder.

Babu et al processed extruded AZ31B magnesium alloy of 1.5mm and 6mm and two tool shoulder diameters viz. 18mm and 24 mm. At 18 mm tool shoulder and plate thickness of 6mm, the tool rotation varied from 1000 rpm to 1800 rpm and tool transverse speed varied from 22 mm/min to 105mm/min. Whereas, for 24mm tool shoulder and same thickness of the plate, tool rotation ranged between 600 to 1200 rpm with increments of 200 rpm and the tool feed of 40-105mm/min. For the later dia and plate thickness of 1.5 mm, tool rotation range was 400-700 rpm and tool feed was ranged between 40 mm/min to 75 mm/min. It was reported that the defects as well as the tensile strength of the processed surface depends upon the blend of axial force on the tool, tool rotation, tool traverse speed and the dia of tool shoulder. Tool shoulder dia in the range 18-24 mm, resulted in a defect free nugget zone for a 6mm thick plate. An average grain size below 10µm was observed in the nugget region (S. R. Babu, Pavithran, Nithin, & Parameshwaran, 2014). Hütsch et al used AZ31, a mg alloy, in their study and found that the extrusion at 240^{o}C dynamic recrystallization (DRX) took place resulting in fine grained microstructure. FSP was carried on AZ31 at tool transverse speeds ranging from 1 m/min to 10 m/min. Deformability was tested for the increased tool feed, and a surge of about 100% than that of base material was recorded (Hütsch et al., 2014). Venkateswarlu *et al* used Taguchi optimisation for processing AZ31B by FSP. Using L9 orthogonal array, optimum factor levels and the significance of each process variable was determined by ANOVA. The rotational speed, and tool traverse speed were found to be most significant parameters, which was followed by the tilt angle. For the given AZ31B Mg alloy tool rotation of 900-1400 rpm, traverse speed of 24-40 mm/min, and the tool tilt angle of 0-20 were found to produce defect free nugget zone. Optimised values of parameters included tool rotation of 1126 rpm, tool feed of 35 mm/min and the tool tilt angle of 10^o (Venkateswarlu, Davidson, & Sammaiah, 2014).

Valle et al analysed the connection between the microstructure and mechanical behaviour in FSPed AZ91 to produce a grain size to the tune of 0.5 μm in two passes of FSP tool. The grain size was observed to decrease3 and 4 FSP passes in addition to work hardening. The Al content was reported to affect negligibly, the flow behaviour of superplastic Mg-Al alloys (del Valle et al., 2015). As-cast Mg–Nd–Zn–Zr (NZK) was FSPed at different tool rotation and traverse speeds. Three groups of parameters P1, P2 and P3 referred to 800 rpm–200 mm/min, 1000 rpm–150 mm/min and 1200 rpm–100 mm/min respectively at constant tilt angle of 2.5^o and plunge depth of 0.25mm. A defect-free nugget zone was achieved at tool rotation from 800 rpm to 1200 rpm and tool travel speeds from 100 mm/min to 200 mm/min. The highest temperature in the stir zone (SZ) was 520 °C during FSP of NZ30K alloy (Han et al., 2016).

Khodabakhshi *et al* fabricated AA5052 Al-Mg alloy-based graphene nanocomposite by friction stir processing. FSP was done at 1250 rpm of tool and its horizontal velocity of 25 mm/min in order to curtail the machine vibrations and the amount of graphene was taken to be about 3 vol.% (Khodabakhshi, Arab, Švec, & Gerlich, 2017). Babu *et al* studied the parameters of FSP for AZ31 Mg alloy at tool horizontal speeds of 20, 30 and 40 mm/min ta tool rotation of 600 and 800 rpm. The hardness value of 63 Hv was found to increase by 50% compared with the base metal. It was found that, the higher rotational speed produced smaller precipitates due to the higher temperatures. The smallest grain size was reported at tool rotation and feed rate of 800 rpm and 40mm/min respectively (J. Babu, Anjaiah, & Mathew, 2018). Luo *et al* FSPed AZ61 Mg alloy using multi-pass FSP with overlapping ratio of 50%, for 26 overlapping passes on the workpiece which was followed by characterization of the processed alloy and testing its tensile properties. FSP was carried at 1000 rpm and its linear speed of 60 mm/min taking the tool tilt of 2.5°. Grainsize of AZ61 was fund to refine from ~75 μm into ~12.5 μm. Multipass FSP resulted in further refinement of the grain size to ~7.8 μm in the stir zone (Luo, Zhang, Zhang, Qiu, & Chen, 2018).

2 Experimental Details

As cast Mg (99.9% purity) workpieces were prepared to have dimensions 80x40x4 mm and FSP was applied to fabricate surface composite using a CNC vertical milling machine as represented in Figure 1 (a). Holes (1 mm diameter, 1.2 mm depth and 5 mm pitch) are drilled in polished these rectangular blocks by mounting them in a specially fabricated fixture as shown in Figure 1 (b). Holes are filled with Titanium Carbide (TiC) powder at 325 mesh with an approximately particle size of 45 μm. The fixture with a hollow rectangular shape for the flow of subcooled liquid facilitates the cooling of the FSPed specimen under its surface. A 250 W cryostat as shown in Figure 1 (c), with a capacity of 8 L has been used to maintain the speedy cooling to -10o C (263 K). The line diagram and the whole set up is represented in Figure 1 (c). LR grade methanol was used as the circulating the liquid in this cryostat. The fixture was connected to the cryostat bath with Polyurethane (PU) pipes fitted with thermal insulations. A cylindrical FSP tool as shown in Figure 1 (d) was used to fabricate the composite. The FSP tool used was made from High-Speed Steel of cylindrical shape without the threads having a 12 mm diameter of the shoulder with a pin of 4 mm dia and 1.7 mm long.

In the first case solidified dry ice followed the FSP tool, on nugget zone after the rotating tool passed. During this process, the temperature was found to be 10^o C (283K). The process was repeated until the FSP tool was taken back from the nugget zone and cooled immediately by dry ice. In case of under surface cooling (USC), methanol at a temperature of about -15^o C (258K) was circulated underneath in the hollow fixture to cool the specimen after the last pass of FSP tool.

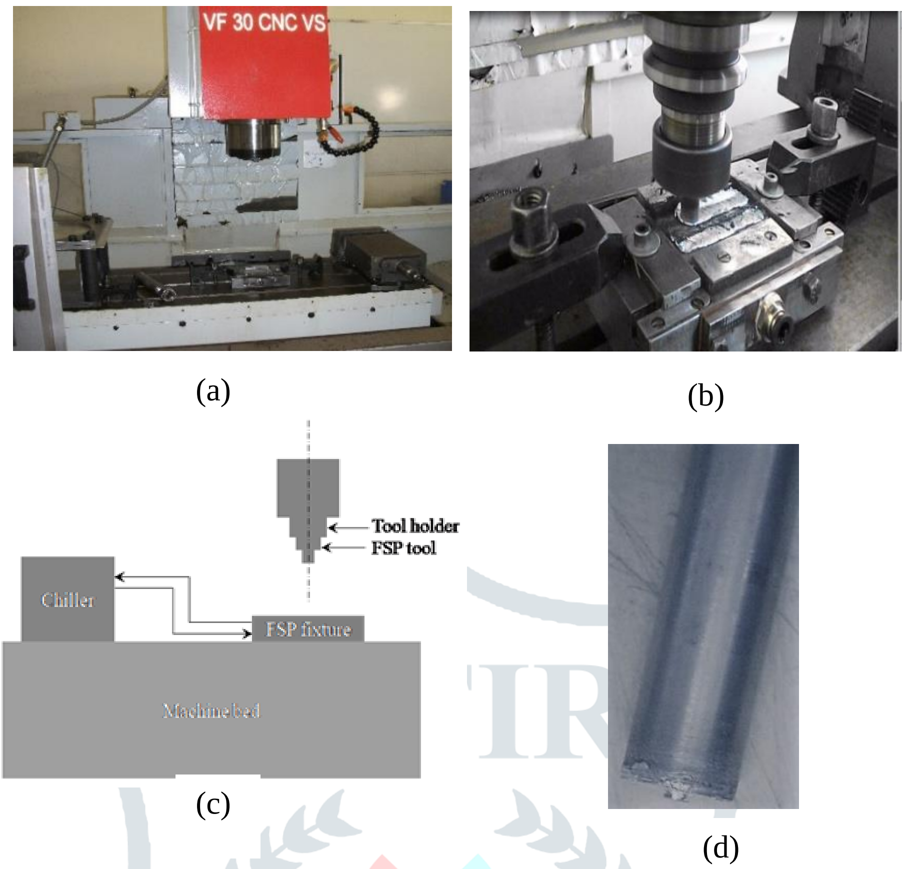


Figure 1 (a) Actual set-up on CNC vertical milling machine (b) FSP operation (c) Line diagram of the set-up used and (d) FSP tool used in experimentation.

The temperature attained in this process was -10^{o} C (263K) which resulted in rapid cooling. While in the third case; the natural cooling, the workpieces were kept at room temperature at a controlled temperature of 30^{o} C (303K) after the PSF process was carried out. Metallurgical study of the as-received Mg and the FSPed surface composite samples was done on an optical microscope (Leica make). Microstructure was taken after etching with a solution of 80 mL ethanol, 10 mL distilled water, 10 mL acetic acid and 5 g picric acid.

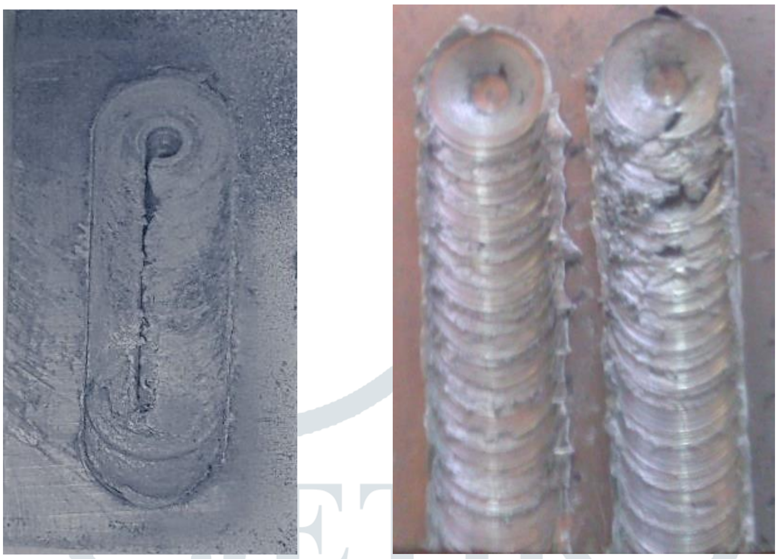
3 Results and Discussion

3.1 Identification of Significant Process Parameters

During the comprehensive survey of the literature (Cavaliere & De Marco, 2007; Freeney & Mishra, 2010; Kwon, Saito, & Shigematsu, 2002) and the results of experiments conducted on Mg-matrix-TiC composite fabrication by FSP, the major factors such as tool rpm, tool horizontal speed, plunge depth of the tool, cooling temperature after FSP and the number of passes appeared to affect the strength of the fabricated composite. These parameters are the prime factors influencing the maximum temperature achieved during the processing in addition to the strain rate applied to the processed specimen, its exposure to higher heat, mixing of the reinforcement with the matrix, the strength of the FSPed specimen and grain size. These can influence the mechanical as well as tribological behaviour of the FSPed composite.

3.2 Evaluation of the Operational Limits of the Factors

In order to find the operational range of process parameters a number of experiments were conducted for the above-listed FSP parameters on the Mg-based surface composite to get the defect free composite. The working limits of various factors under investigation are mentioned in Table 1. Three levels of each variable were contemplated as presented in the table. It was observed during experiments that composite fabrication by FSP within 500-700 rpm, 10-20 mm/min and 0.25-0.35 mm, respectively for tool rpm, tool feed and tool penetration (plunge depth) yielded a defect free zone; macrograph of which is represented in Figure 2 (b). However, outside these parameters limits, a defective zone was produced mostly consisting of cracks and long tunnel defects in the processed zone as presented in Figure 2 (a).



(a) (b)

Figure 2 a) Unsuccessfully fabricated Mg-based composite by FSP having grove in nugget zone. b) Successfully fabricated Mg-based composite by FSP.

Number of passes of the tool is also an important parameter for material performance through proper mixing of reinforcement particles (TiC) and microstructural evolution by grain refinement and thence, cannot be overlooked. In an investigation by Arora et al, it was established that FSP tended to splinter the in-situ precipitates.

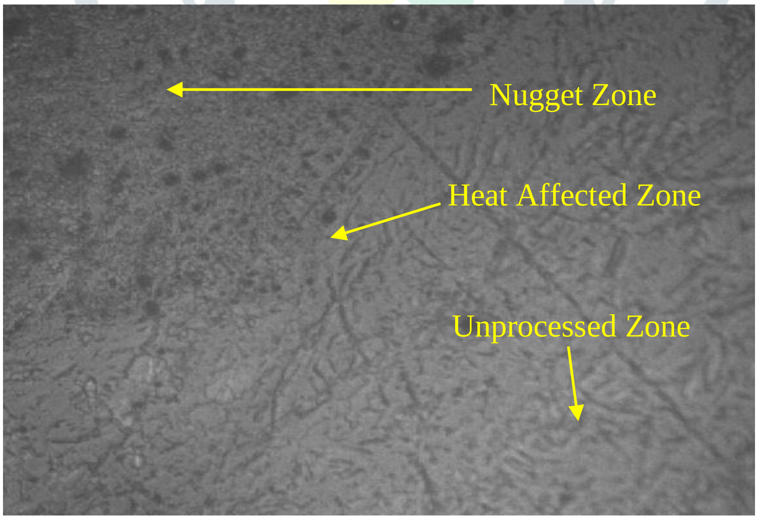


Figure 3 Optical micrograph of surface of the fabricated composite.

The FSP parameters like tool rotation and the number of FSP passes expressively influenced the size and dispersal of precipitates (Arora, Singh, & Dhindaw, 2011). Optical micrograph of the fabricated TiC reinforced pure Mg composite is shown in

Figure 3. This image has been taken at a magnification of 50 and shows the grains of micro sized structure. Nugget zone as shown in the image is the main FSPed part which contains TiC particles and the refined grains. Heat affected zone is the transition zone from nugget to the unprocessed zone as shown in the figure.

Table 1 Operational limits of the considered Parameters.

Name of Parameter	Level I	Level II	Level III	Unit
Tool rotation (A)	500	600	700	Rpm
Cooling condition (Temp) (B)	-10 (263)	10 (283)	30 (303)	^{o}C (K)
Linear speed of Tool (C)	10	15	20	mm/min
Tool Penetration (D)	0.25	0.3	0.35	mm
Number of FSP runs (E)	1	2	3	

Investigators such as Yuan et al have created an FSP zone free from defects, at a high speed of up to 204mm/min and a tool rotation of 700 rpm for grain refinement of AZ31 Mg alloy which is around 15 to 20 times the linear speed of tool used in this investigation (Yuan et al., 2011). Since Mg alloy and pure Mg have different properties, the speed will for sure be different. It was also noticed that the range of each variable contracted with the increase in number of parameters which may be attributed to the greater interaction effect between process parameters.

4 Conclusion

Trial experiments for the study of feasibility of the composite fabrication were conducted successfully. Parameters playing a significant role were identified by an exhaustive survey and from the trial experiments. Safe working range of tool rotation was found to be 500-700rpm, tool feed to be 10-20 mm/min, axial thrust in terms of plunge depth to be 0.25mm to 0.35mm, 3 passes of FSP tool and the cooling condition to be under surface cooling (USC) at -10^{o} C. It was found that defect free zone was obtained for this range of parameters.

5 Future Scope

The study finds a scope of further research for the optimisation of these parameters by taking hardness as an output response. The effect of the reinforcement can also be studied for tribological behaviour of the fabricated composite.

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