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Technical Report

Influence of tool pin profile on the metallurgical and mechanical properties of friction stir welded Al–10 wt.% TiB_2 metal matrix composite

S.J. Vijay [a,*], N. Murugan [b,1]

[a] School of Mechanical Sciences, Karunya University, Coimbatore 641 114, Tamil Nadu, India
[b] Department of Mechanical Engineering, CIT, Coimbatore 641 014, Tamil Nadu, India

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ABSTRACT

In the present work, Al–10 wt.% TiB_2 metal matrix composites (MMCs) are joined using friction stir welding (FSW) process. Different tool pin profiles are developed to weld the MMCs and the effect of tool pin profile on metallurgical and mechanical properties of the weldments are studied. The stirred zones of MMCs joined with taper pin profiles are narrower than that are joined with straight pin profiles. Weld nugget has finer grains compared to other weld zones and TiB_2 particulates are homogeneously present in Al matrix both in weld and parent metal. The effect of pin profiles on mechanical properties are analyzed and it is found that joints welded with straight square pin profile have better mechanical properties compared to the other pin profiles.

1. Introduction

Friction stir welding is a solid state welding process, in which a rotating tool moves along the joint interface, generating heat and resulting in a re-circulating flow of plasticized material near the tool surface [1–4]. This plasticized material is subjected to extrusion by the tool pin rotational and traverse movements leading to the formation of the so-called stir zone. The formation of the stir zone is affected by the material flow behavior under the action of the rotating tool. A lot of research has been already done towards understanding the effect of tool pin profiles, tool dimension and process parameters on the material flow behavior, microstructure formation and mechanical properties of friction stir welded joints. Finding the most effective parameters for FSW, as well as realizing their influence on the weld properties, has been the major topics for researchers [5,6].

Apart from Al alloys, metal matrix composites (MMCs) were also welded using FSW process. MMCs were developed to replace the Al alloys because of their improved mechanical and thermal properties. If a proper welding process is not developed for joining these MMCs, then the potential usage of the MMCs is limited. Thus FSW process finds a very important place in the field of metal joining [7]. Since FSW is a solid state welding process, it is best suited for welding Al MMCs.

The effects of tool profiles on microstructure and tensile strength of various aluminum alloys and aluminum matrix composites (AMCs) were already reported but for the proposed Al–TiB_2 MMCs, the findings are not yet reported [8–11]. Hence, in this investigation an attempt has been made to understand the effect of tool pin profiles on microstructure and tensile strength in Al–TiB_2 MMCs. This paper presents the relation between the tool pin profile and tensile strength, percentage elongation and joint efficiency in the friction stir welded Al–TiB_2 MMC joints. This study is very useful for carrying out further studies on mechanical, wear and corrosion properties of the weldment.

2. Experimental procedure

2.1. Design and manufacturing of FSW tools

Eighteen various FSW tools are designed by varying the tool pin profile, ratio of Shoulder dia./Pin dia. (D/d) and configuration of shoulder – work piece interference surface [1,12]. The configurations of the designed FSW tools are:

1. Tool pin profiles of square, hexagon and octagon with 16° draft and without draft.
2. Tools having D/d ratios of 2.8, 3, and 3.2.
3. Shoulder – work piece interference surface – 3 concentric circular equally spaced slots of 2 mm depth on all tools.

Out of various tool materials like tool steel, high speed steel, high carbon high chromium steel (HCHCr), carbide, and carbon boron nitride, HCHCr steel is chosen as tool material because of

* Corresponding author. Mobile: +91 9944516658.
E-mail addresses: vijayjoseph_2001@rediffmail.com (S.J. Vijay), drmurugan@yahoo.com (N. Murugan).
[1] Tel.: +91 422 2574071/2574072; mobile: +91 9751824123; fax: +91 422 2575020.

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its high strength, high hot hardness, easy to process, easily available and low cost.

The FSW tools are manufactured using CNC Turning center and wire cut EDM (WEDM) machine. The tools are oil hardened to obtain a hardness of 60–62 HRC. The manufactured tools are shown in Fig. 1.

2.2. Friction stir welding of Al–TiB_2 MMC

Al–TiB_2 MMC test plates of size 50 mm × 50 mm × 6 mm are prepared using WEDM from Al–TiB_2 MMC cast blocks with 10 wt.% of TiB_2 reinforcement that is obtained from in situ stir casting process and joined by FSW using hexagonal tool. Initially a mathematical model was derived based on response surface methodology to correlate FSW process parameters like tool rotational speed, axial force and welding speed with the weld quality. Using the developed mathematical model, FSW process was optimized to have better tensile strength [13]. The optimized FSW process parameters are given below:

- Tool rotational speed = 2000 rpm.
- Welding speed = 30 mm/min.
- Axial force = 19.6 kN.

Six tools which yielded defect free weldments out of the eighteen different tools that were manufactured are selected based on trial welds using optimized FSW process parameters. The FSW tools of 16 mm shoulder diameter (D/d ratio = 2.8) having both straight and tapered configuration with various pin profiles such as square, hexagon and octagon are employed for final joining of the AMC plates.

Fig. 2 shows a work piece that is welded with straight hexagonal pin profiled tool depicting the front side of the weldment showing the impression of the tool shoulder and the hole that is created when the tool is retrieved.

Fig. 2. FSW welded specimen.

2.3. Metallographic study of the welded specimen

Welded plates are cross-sectioned at its mid point and specimens of size 20 mm × 10 mm × 6 mm are obtained for metallographic study. The samples are prepared as per standard metallographic procedure from the welded plates and are macro etched using 5% NaOH solution. The digital images of the macrograph of the etched specimen are captured using a digital optical scanner. The specimens are color etched with 2–3 g sodium molybdate, 5 ml HCl (35%) and 1–2 g ammonium bifluoride in 100 ml distilled water for microstructure analysis [14]. Color metallographic study was carried out along various zones across the cross-sections of the friction stir welded specimens using a metallurgical microscope (Olympus Microscope – BX51 M).

2.4. Evaluation of tensile strength of the friction stir welded specimen

Tensile test specimens are prepared as per ASTM E8 standard and transverse tensile properties such as tensile strength, percentage of elongation and joint efficiency of the FS welded joints are

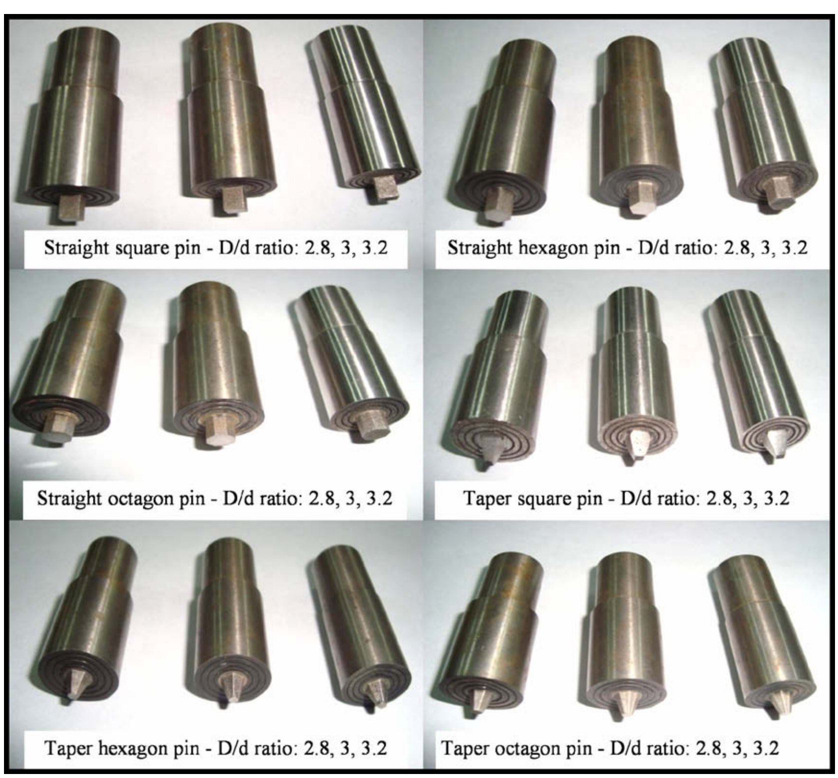


Fig. 1. FSW tools manufactured for welding.

Fig. 3. Tensile specimens: (a) before fracture and (b) after fracture.

Table 1
Mechanical properties of the friction stir welded Al–TiB_2 MMC.

Types of tool profile	Average tensile strength (MPa)	Average (%) elongation	Joint efficiency (%)
Tapered square	223.33	5.32	78.92
Tapered hexagon	247.89	6.67	87.59
Tapered octagon	245.27	6.22	86.67
Square	281.51	6.37	99.47
Hexagon	262.29	5.83	92.68
Octagon	240.00	3.39	84.81

evaluated using computerized UTM. For each welded plate, three specimens are prepared and tested. The fracture has occurred mostly in the TMAZ zone on the retreating side of the weldment. The Fig. 3 shows the tensile specimen before and after fracture for 3 set of welds. The average values of the results obtained from those specimens are tabulated and presented in Table 1.

3. Results and discussion

From Fig. 4 it is clear that a defect free weld is obtained when tapered hexagonal pin and straight square pin tools are used for joining AMCs. Various zones viz., nugget, thermo mechanically affected zone (TMAZ), heat affected zone (HAZ), in the weldment, caused during the welding are also visible. The grains are coarse in the parent metal and are finer in stirred zone. The zones of nugget, TMAZ and HAZ of welded AMCs joined with tapered pin profiles are narrower than that joined with straight pin profiles.

In the photomicrograph shown in Figs. 5–8, as expected, the weld nugget has a fine equiaxed recrystallized structure, while the parent metal has a dendrite structure as it is produced using stir casting process. The dendrite structure shows the dispersion of TiB_2 particles in the Al matrix. Fig. 5 shows the interfacial boundary between the TMAZ and weld nugget revealing the difference in the grain size clearly.

Fig. 6 shows microstructure of the nugget welded using a straight square tool and tapered hexagonal tool. The presence of TiB_2 particulate of 350 nm size in the weld zone is clearly visible. In the figure TiB_2 appears as white, Si appears as bluish green and Mn appears as yellow. The microstructure clearly indicates the homogeneous distribution of TiB_2 particulate in the weld zone. Fig. 6b shows bigger grains when compared to Fig. 6a which shows the microstructure of the weld nugget welded using a straight square tool.

Fig. 7 shows the cross-section of weld nugget at 500× magnification indicating the onion ring effect which is occurred due to the stirring action of the tool [15]. Fig. 8 depicts the difference in grain size and orientation at nugget, the interfacial boundary between weld metal and TMAZ.

The effect of tool pin profile on the mechanical properties of the FSW joints can be inferred from Table 1. The joint welded by square pin profiled tool exhibits high tensile strength when compared to other joints. The joint fabricated by tapered square pin profiled tool has the least tensile strength. The tensile strength of joints, welded using hexagon, tapered hexagon, octagon and tapered octagon pin profiled tools do not change significantly. It is due to the difference in dynamic orbit created by the eccentricity of the rotating tool of the FSW process [16]. The relationship between the static volume and dynamic volume decides the path for the flow of plasticized material from the leading edge to the trailing edge of the rotating tool. This ratio is equal to 1.56 for square, 1.21 for hexagon and 1.11 for octagon pin profiles. In addition, those pin profiles produce a pulsating stirring action in the

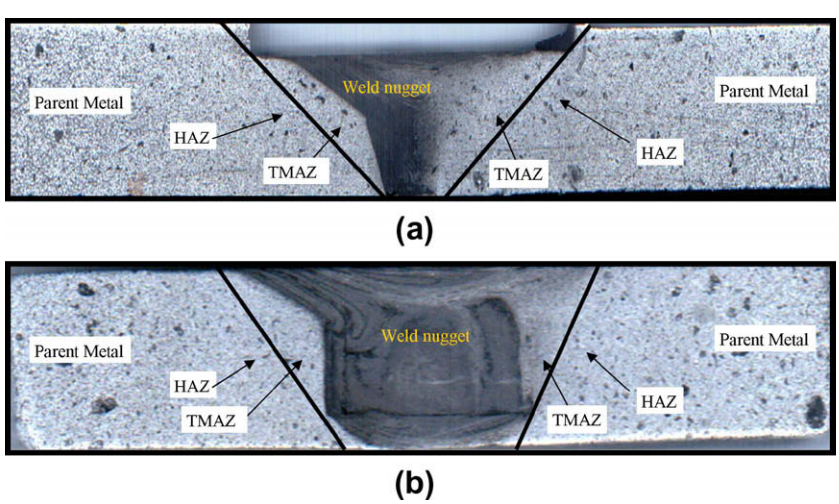


Fig. 4. Macrostructure of the friction stir welded Al–TiB_2 MMC using: (a) tapered hexagonal pin profiled tool and (b) straight square pin profiled tool.

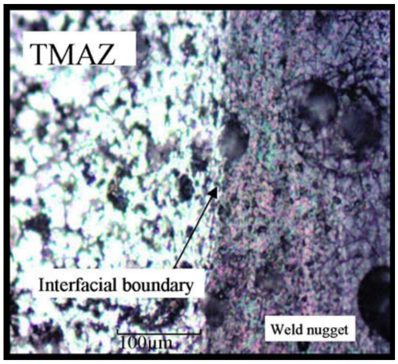


Fig. 5. Microstructure showing TMAZ and weld nugget.

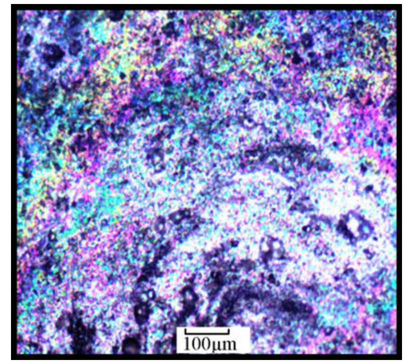
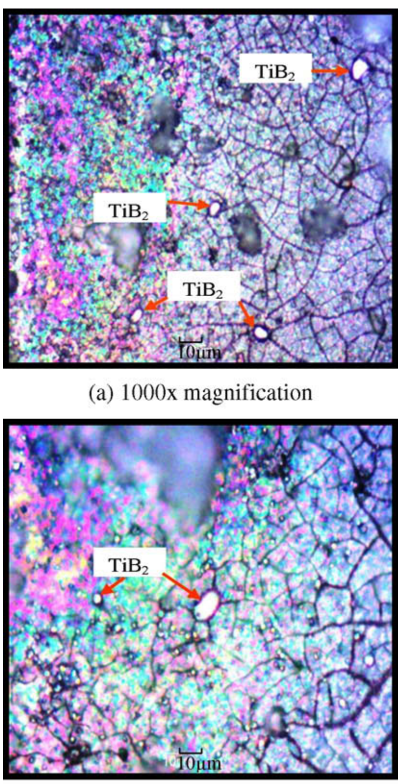


Fig. 7. Microstructure revealing the onion ring [15] effect in the weld nugget.



(a) 1000x magnification

(b) 1000x magnification

Fig. 6. Photomicrograph of the nugget welded with: (a) square pin tool and (b) tapered hexagon pin tool.

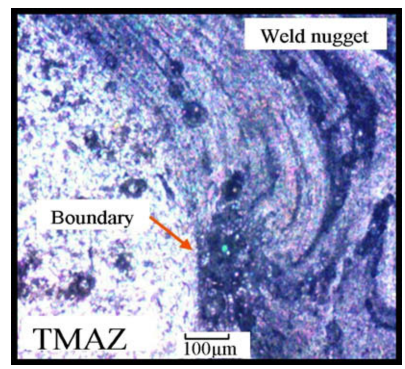


Fig. 8. Microstructure revealing the cross-section of weld zone and TMAZ.

flowing material due to flat faces. The square pin profile produces 133 pulses/s and hexagonal pin profile produces 200 pulses/s, when the tool rotates at a speed of 2000 rpm. There is not much pulsating action in the case of octagonal pin profiled tool because it almost resembles a straight cylindrical pin profiled tool at this high rpm. In the tapered pin profiled tools, the same principle affects the material flow. Since the tapered square pin tool sweeps less material when compared to that of straight square pin tool, this joint exhibit less tensile properties. The microstructure also show bigger grains which account to the poor tensile strength in the joints made out of taper pin profiled tools.

Table 1 also shows the effect of tool pin profiles on the % elongation of the welded AMCs. It is evident from the table that the effect of tool pin profile on the % elongation is insignificant except for the octagon pin tool. The reason is the presence of TiB_2 particles in the parent metal which considerably reduces the % elongation of the material [17]. The effect of tool profile on the joint efficiency is also similar to that of tensile strength. The joint efficiency is high when the AMC is welded using square pin tool and low when it is welded with tapered square pin tool.

4. Conclusions

The following conclusions can be derived from the above work:

1. Weld nugget has finer grains when compared to the cast parent metal.
2. Since the parent metal was cast by in situ stir casting process, it shows larger grains with dendrites.
3. The stirred zones are narrower for joints welded with tapered pin profiles than that of straight pin profiles.
4. The microstructure of the FS welded specimen is affected by the tool pin profile.
5. The weld made of taper pin profiled tools shows coarse grains when compared to the joints made of straight pin profiled tools.
6. The tensile strength of the friction stir welded specimen is also affected by the tool pin profile.
7. The square tool exhibited better tensile strength when compared to other tools.

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