Aluminium Matrix Composites Fabricated by Friction Stir Processing

A Review

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ABSTRACT

Aluminum alloys widely use in production of the automobile and the aerospace because they have low density, attractive mechanical properties with respect to their weight, better corrosion and wear resistance, low thermal coefficient of expansion comparison with traditional metals and alloys. Recently, researchers have shifted from single material to composite materials to reduce weight and cost, improve quality, and high performance in structural materials. Friction stir processing (FSP) has been successfully researched for manufacturing of metal matrix composites (MMCs) and functional graded materials (FGMs), find out new possibilities to chemically change the surfaces. It is shown that the technique of FSP is very promising to modify the microstructure of strengthened metal matrix composite materials. There has the benefit of decline in distortion and flaw of material when FSP uses instead of other manufacturing processes. The aim of the present work is to give a review of technology of (FSP) as a method to produce the aluminium matrix composite, and conclusions of this review will be demonstrated.

Keywords: frictions stir processing, metal matrix composite materials, aluminium alloys.

عرض للمواد المركبة ذات الاساس من الالمنيوم والمصنعة بواسطة عملية الخلط الاحتكاكي

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الخلاصة

تستخدم سبائك الالمنيوم بشكل واسع في صناعات الفضاء والسيارات بسبب كثافتها المنخفظة والخواص الميكانيكية الجيدة و مقاومة البليان والتأكل الافضل وانخفاظ معامل التمدد الحراري مقارنة بالسبائك والمعادن التقليدية. انتقل الباحثين مؤخرا من المادة المنفردة الى المواد المركبة لتقليل الوزن والكلفة وتحسين الجودة والاداء العالي للمواد الانشائية. المعالجة بالخلط الاحتكاكي كانت وما زالت تبحث بشكل ناجح لتصنيع المواد المركبة ذات الاساس المعدني والمواد المصنفة وظيفيا والذي كشفت امكانيات حديثة لاجراء تعديل السطوح كيميائيا. يبدو ان تقنية المعالجة بالخلط الاحتكاكي واعدة جدا في تعديل البنية المجهرية للمواد المركبة ذات الاساس المعدني. مقارنة مع عمليات التصنيع الاخرى، المعالجة بالخلط الاحتكاكي لها الافضلية في تقليل التشوه والعيوب في المواد. ان الهدف من هذه الدراسة هو استعراض تقنية المعالجة بالخلط الاحتكاكي كطريقة لتكوين المواد المركبة ذات الاساس من الالمنيوم، ومن ثم توضيح الاستنتاجات من هذا الاستعراض.

الكلمات الرئيسية: عملية الخلط الاحتكاكي، المواد المركبة ذات الاساس المعدني، سبائك الالمنيوم.

1. INTRODUCTION

Composites of metal matrix strengthened by particles with micro or nano size are so effective materials, proper for a many uses. These composites fabricated from metal matrix reinforced with nano particles or fibers show different physical properties and different mechanical properties compare with those of the base metal.

The composites of metal matrix (MMCs) strengthened by particles with nano-size, also called Metal Matrix nano-Composites (MMnCs), are being studied globally in late years, because they have attractive properties suitable for a many applications of function and structure. The interaction between reduced size particles and dislocations has important value because of the nano-scale of strengthening phase, when incorporated with other reinforced influences typically existed in traditional MMCs, lead to a exceptionally enhancement of mechanical properties. **Zhang, and Chen, 2008**; **Zhang, and Chen, 2006; Sanaty-Zadeh, 2012; Luo, et al. 2012**. Metal matrix composites with micron-size reinforcements have been used with outstanding success in the automotive and aerospace industries, in addition in small engines and electronic packaging applications. In the case of metal matrix nanocomposites, insertion of as little as one volume percentage of nanosize ceramics has led to a much greater increase in the strength of aluminum and magnesium base composites than was achieved at much higher loading levels of micron-sized additions **Rohatgi, and Schultz, 2007**. The greatest challenges facing the development of MMnCs for wide applications are the cost of nanoscale reinforcements and the cost and complexity of synthesis and processing of nanocomposites using current methods. As with conventional metal matrix composites with micron-scale reinforcements, the mechanical properties of a MMnC are strongly dependent on the properties of reinforcements, distribution, and volume fraction of the reinforcement, as well as the interfacial strength between the reinforcement and the matrix. Due to their high surface area, nanosize powders and nanotubes will naturally tend to agglomerate to reduce their overall surface energy, making it difficult to obtain a uniform dispersion by most conventional processing methods. In addition, due to their high surface area and surface dominant characteristics, these materials may also be highly reactive in metal matrices.

Saravanan, et al., 2010. Alloys of aluminum are very attractive for structural applications in aerospace, military and transportation industries because they are lightweight, high strength-to-weight ratio and excellent resistance to corrosion. Nevertheless, the low hardness and low strength of aluminium alloys limit their use, particularly for tribological applications. Thus, to improve these properties, several properties improvement techniques can be used, from them one is (FSP), **Deepak, et al., 2013**. Rotating pin is particular designed for FSP, as explained in **Fig.1**, it is firstly inserted into the metal to be processed with a suitable tool tilt angle and then moves along the designed paths. The pin generates heat by frictional and plastic deformation within the processing zone. When the tool pin moves, this forces the material to flow around the pin. The forced material flows to the back of the pin, where it is extruded and forged behind the tool, consolidated and cooled under hydrostatic pressure conditions.

Friction stir processing is most commonly used with aluminum**, Johannes et al., 2007**. **Ma, and Liu, 2008**. Specifically, the effects of processing parameters on the microstructure evolution, deformation behaviors and mechanical properties were investigated, **Cavaliere, et al., 2008; and Cavaliere, et al., 2009**. The use of ceramic particles, such as silicon carbide and aluminum oxide, as reinforcements to form aluminum matrix composites, has been well studied, **Alpas, et al., 1994; Sannino, and Rack, 1995; Deuis, et al., 1997; Gustafson, et al., 1997; Kouzeli, and Mortensen, 2002**. From recent research, it can be illustrated that, for a fixed concentration, fine particles usually give stronger and harder composites, **Kouzeli, and Mortensen, 2002**. Many studies for developing nano- or sub-micro-particles strengthened aluminum composites have been adopted owing to this finding. Techniques of FSP have been successfully used to promote the structure and surface of composite with fine-grains, materials with modified microstructure, and synthesizing the composite and intermetallic compound in situ. For instance, by FSP, it was obtain on a finegrained microstructure for high-strain-rate superplasticity in the commercial 7075Al alloy, **Ma, et al., 2002**. Moreover, the technique of FSP has been used to create a surface composite on aluminum substrate, **Mishra, et al., 2002** and the homogenization of powder metallurgy (PM) aluminum alloys, metal matrix composites, and cast aluminum alloys, **Berbon, eta l., 2001; Ma , et al., 2003**.

This work can be considered a reference of FSP and it supplies a review of (FSP) technique for fabrication the aluminium metal-matrix composite as well.

2. FABRICATION MMCS USING FSP

It is well documented that the volume fraction and size of reinforcing phases also the characteristics of base metal-reinforcement interface control the mechanical properties of MMCs, **Shafiei-Zarghani, et al., 2009**. Powder metallurgy (P/M) method or processing of molten metal has been the main routes to fabricate particle-reinforced metal matrix composites.

However, obtaining a uniform dispersion of fine reinforcement particles within the matrix is especially challenging through traditional casting or P/M processing. It is mainly because of the natural trend of fine particles to agglomeration during blending of the matrix and the reinforcement powders. It has been shown that FSP can be employed to fabricate aluminum matrix composites *in-situ* without supplementary consolidation process. The application of FSP to produce MMCs has the following advantages, **Yang, et al., 2010**:

a. Inducing sever plastic deformation to further mixing and refining of constituent phases in the material.
b. Generation of high temperature to ease the *in-situ* reaction to develop reinforcing particles.
c. Causing hot consolidation to establish fully dense solid.

On the other hand, the presence of the reinforcement particles in the metallic matrix leads to brittleness, which generally is not desirable. Therefore, instead of bulk reinforcement, incorporation of the particles to the surface enhances the wear properties, which is a surface dependent degradation mode, without sacrificing the bulk properties, **Dixit, et al., 2007**. Nevertheless, it is challenging to effectively distribute particles of ceramic on a metallic surface by conventional surface treatments. The processing techniques existent to produce surface composites are rely on processing during liquid phase at elevated temperatures. However, it is tough to prevent the reaction at interface between the reinforcement and base metal and the development of some harmful phases. In addition, to achieve a perfect solidified microstructure in surface layer monitor of processing parameter seems to be crucial. Apparently, processing of surface composite at low temperature, below the melting point, can prevent these problems, **Lim, et al., 2009**. In this case, FSP, as a solid state processing technique, can be successfully employed to produce surface composites.

3. FRICTION STIR PROCESSING TO FABRICATE ALUMINIUM MATRIX COMPOSITES

3.1 Fabrication Micro Composites

3.1.1 Aluminium Matrix Composite with Fine Grained and Modified

Due to substantial friction heating and severe plastic deformation during FSP, dynamic recrystallization occurs in the stirred zone (SZ), resulting in fine and equiaxed recrystallized grain of absolutely uniform size, **Mishra, et al., 2003**. **Hsu et al., 2005** observed that the Al-

Al_2Cu composite fabricated by in-situ became ultra-fine-grained composite after FSP. For the Al-Cu sintered billet, the reaction between Al and Cu was not achieved at sintering temperature 500 °C for 20 min. The reaction was significantly enhanced when sintering temperature reached at 530 °C. However, the initial coarse Cu or resultant Al_2Cu particles were heterogeneously dispersed in the aluminium matrix, **Fig.2** (a). This pointed out, that although a higher sintering temperature and a longer time can result in carry out the reaction between aluminium and copper, Heterogeneity distribution and coarseness of resultant particles of Al_2Cu are clear feature. Ultra-fine-grained Al-Al_2Cu composite obtained at two-pass FSP on the billets sintered at both 500 °C and 530 °C was owing to complete Al-Cu reaction and a uniform dispersion of the resultant Al_2Cu particles in the matrix of aluminum, **Fig.2** (b). This ultra-fine grained Al-Al_2Cu composite exhibited higher hardness and compressive strength. Lately, **Hsu, et al., 2006.** studied the influence of FSP on the in-situ reaction way between Al and Ti in an Al-Ti sintered billet. They observed that sintering at 610 °C temperature could achieve just a little amount of Al-Ti reaction came about around the Ti particles, **Fig.3** (a). The reaction the in-situ was importantly accelerated by the FSP. When a four-pass FSP occurred, the reaction between aluminium and titanium completed fundamentally, and dispersion of the Al-Ti nano-particles formed in situ in the ultra-fine-grained aluminum matrix was obviously revealed, as demonstrated in **Fig.3** (b). From results of tensile test, it can be seen that, the resultant composite of Al-Al_3Ti shows high strength and modulus Table 1. The modulus and strength increased with increase in the Ti content, while the ductility decreased. The Al-10 at. pct Ti composite showed a interconnection of high strength/modulus and good ductility. **Ma et al.**, **2006** investigated the effect of common parameters of FSP on sand-cast A356 plates. The results showed that coarse primary aluminum dendrites and coarse acicular particles of Si were broken up due to effect of FSP, in addition the closure of casting porosities, and the uniform spread of broken particles of Si in the aluminum matrix, as shown in **Fig.4** (b). With increase passes number of FSP and rotational speed, the size and aspect ratio of the Si particles and the level of porosity decreased as result of the effect of intensified stirring (see Table 3). Similarly, **Santella, et al., 2005** indicated that the coarse and heterogeneous cast structure of A319 and A356 was destroyed and then, a uniform distribution of broken second-phase particles is created due to influence of FSP, see **Fig.5** (b). In addition, the images of TEM showed the creation of a fine-grained structure of 5 to 8 lm in FSP A356 and 2 to 3 lm in FSP ADC12, **Ma, et al. 2006**. Also, they observed that the size of grain in the FSP specimens is much smaller than that in the as-cast structures, pointing out the occurrence of dynamic recrystallization during FSP. **Tewari *et al*. Lakshminarayanan, and Balasubramanian, 2008** investigated the influence of SiC particle orientation modified owing to FSP. The information of microstructure for SiC/A6061 composite materials with and without FSP singe step was obtained through high-resolution, large-area images. Anisotropic shape with an average aspect ratio approximately 1.6 to 1.8 was observed for the particles of SiC. The image of the composite by scanning electron microscopic in **Fig.6** (a) explained such a morphological feature. Orientation statistics of particle indicated that there are preferred orientations for the nonequiaxed particles of SiC after extrusion processing. As illustrated in **Fig.6** (b), the arrangement of the SiC particles is parallel to the direction of extrusion. The axis of extrusion is vertical. The passage of the friction stir tool maybe modified the preferred orientation. From **Fig.6** (c), it can be observed, that the particles were redistributed at 45◦ to the extrusion and transverse directions. The tool motion of FSP is horizontal, left to right. The microstructural information consistently point out that important microstructural change occur during FSP, contain re-orientation of the reinforcement particles, and an important decline in the levels of microstructral heterogeneity and microstructural anisotropy.

3.1.2 Friction-Stir Surface/Bulk Composite

Since altering the parameters of FSP, vertical pressure, tool design, and active cooling/heating influence on the grain microstructure, it seems that the mechanical properties of a metallic material can be custom-made through FSP. An increase in both hardness and yield strength (YS) has been reported due to continuously reduction in the grain size of aluminum alloys by changing the FSP parameters**.** FSP has been also studied to develop layers of hard materials on soft matrix, as alloys of aluminium based.

Wang et al. Wang, et al., 2013 they used FSP to fabricate bulk SiC-reinforced aluminum MMCs. The rolled plate of 5A06Al and commercial powder of SiC were employed in this work. In the side of advancing at the pin edge a groove was machined, which had depth and width1.0 and 0.5-mm respectively. At a distance 2.8 mm from the centerline, the groove was, and before processing, the powder of SiC was put into the groove. The high-speed steel was used to make the cylindrical tool of FSP with with a screwed pin. The plate was penetrated by the tool until the head face of shoulder reached 0.5 mm under the upper surface. The travel speed was 95 mm/min along the centerline and the rotational speed of tool was 1180 rpm. The dispersion of produced MMCs did not restrict to surface composites under the shoulder of tool but, the particles of SiC could flow upwards of the thermomechanical affected zone (TMAZ) under the shoulder of tool, and it covered the range at a distance1.5 mm of the pin edge at the advancing side. Nevertheless, the in deeper position, width became narrower, and the dispersion of MMCs was about 2.5 mm at the depth of 2 mm, which was in the pin range at the advancing side. Roughly, 88 HV the value of microhardness of matrix was. The microhardness was constant, 10% higher than the matrix, on the depth of 0.5 and 1.0 mm under surface owing to integral distributed SiC.

3.2 Fabrication Nano Composites

3.2.1 Fine grained and modified structure of aluminium matrix composite

Shahraki et al., 2013 used the friction stir processing (FSP) to produce AA5083/ZrO_2 nanocomposite layer. The sheet of 5083- H321 aluminum alloy with 5 mm thickness was used for the FSP experiments. The rectangular sheets with 300 mm in length and 300 mm in width were used as samples in this work. Commercially, powder of ZrO_2 with nano average diameter ~ (10 to 15) nm and purity ~99.9 pct was provided by the TECNON, S.L. Company. A groove of 1 mm width and 2 mm depth was machined on the AA5083 plate and then filled by the ZrO_2 powder before the FSP was carried out. The 2436 steel alloy was used to make the rotational tool in the process, encompasses a concave shoulder with a diameter of 18 mm and a triangle pin with diameter and length of 6 and 3.3 mm, respectively. The angle of tilt was approximately 3°. The pin was inserted into the groove filled with the nanopowder of ZrO_2. Two passes of the FSP was carried out at traverse speeds of 40, 80, 125, and 160 mm/min and tool rotation rates of 800, 1000, and 1250 rpm. It was indicated that the best choice to distribute the nanoparticles homogeneously in the matrix could be increasing the passes number of FSP. **Faraji et al., 2011** to investigate the microstructures of Al/ZrO_2, both optical microscopy (OM) and scanning electron microscopy (SEM) were used, as shown in **Fig.7** (a). also, VEGA II LMH SEM (Tescan, a.s., Brno, Czech Republic) equipped with an energy dispersive X-ray spectroscopy (EDS) analysis system was used to analysis the chemical composition of local areas in the specimens. In **Fig.7** (b), it can be seen the nanosized ZrO_2 particles distribution in the SZ. Depending on the parameter of Zener-Holoman, the grain size decreases with increasing the volume fraction of ZrO_2 particles, **El-Danaf, et al., 2010**. The corresponding mechanical properties of FSP specimens were assessed through tensile test and microhardness measurements. Samples of tensile were machined to the depth that FSP was applied along the longitudinal direction. The samples of the FSP with nano-particles of ZrO_2 showed that microstructures refined to a much smaller scale than the base metal alloy. The recrystallized grains were equiaxed and had a similar size dispersion. The substrates microhardness was clearly increased after the FSP with ceramic particles. In majority of the processed samples, the hardness was greater with the maximum rise to be approximately 30 pct. The maximum value of microhardness for Al/ZrO_2 composite was approximately 134 HV, whilst that of the parent alloy was about 93 HV, as shown in **Fig.8** (a). For the samples without any defect and with uniform dispersion of ZrO_2 particles, FSP increased the ultimate strength of the parent material by approximately 10 pct this, as shown in **Fig.8 (b)**. **Zarghani, et al., 2009**. Used nanosized powder of Al_2O_3 with 50 nm average diameter and a extruded rod of commercial 6082 Al with 7 mm a thickness as reinforcement particulates and matrix, respectively. The Quenched H-13 tool steel was used to fabricate the pin with length and diameter 4 and 5 mm respectively. The pin traverse speed was set to be 135 mm/min and its rotational speed was 1000 rpm. To insert nano powder of Al_2O_3, a groove was machined with a width of 1mm and depth of 4 mm, in which the required amount of Al_2O_3 particles was crammed in. A tool without pin was used to close the groove to prevent sputtering of powder during the process. Various numbers of passes FSP from one to four have been carried out on the specimens, with and without powder of Al_2O_3. After each pass, at room temperature air-cooling was used. **Fig.9** (a). illustrated the optical micrograph of the parent 6082 Al. The using of FSP resulted in refine the size of grain of matrix, as explained in **Fig.9** (b). The distribution of Al_2O_3 particles in the surface composite layer was better when three FSP passes than that one FSP pass. Aggregation of nanosized Al_2O_3 particles occurred in some region. Furthermore, it could be observed that the FSP carried out by four passes, resulted in layer of surface composite with good distribution of nano-sized particles of Al_2O_3, as explain in **Fig.9** (c). As indicated by other researchers **Java, et al., 2002; Sato and Kokawa, 2001**, it was reported that the dynamic recrystallization occurred during FSP resulted in grain refinement. In fact, the FSP with the nanosized particles of Al_2O_3 has seen to be significant in reduction of the grain size of the 6082 Al matrix up to less than 300 nm this can be seen clearly in **Fig.9** c and d. It has been considered that, the pinning impact by the nanosized Al_2O_3 particles prevent the growth of the grains for the considered 6082 Al matrix. the considered microhardness results have been obtained from the central cross-sectional zones of the friction stir processed specimens as shown in **Fig.10** (a). the hardness value have increased by about three times as compared to its value in the parent Al alloy. This has been carried out in the surface composite layer produced by four FSP passes. In the case of 6082 Al alloy where no alumina powder is added, after four passes of FSP, the microhardness image depicted a softening and decline of hardness in the SZ contrary to that of the base Al metal. In this work, the wear kinetics have been compared due to the weight loss as the specimen has been used to be the pin and the material of disk from the GCr15 steel, as can be seen in **Fig.10** (b). The wear weight loss has increased with sliding distance. For the parent Al metal, the wear rate (weight loss/sliding distance) was of low value at the initial period of wear as it is increased then. At the nanocomposite layer surface produced by four FSP passes, the wear rate tends to be constant within sliding time. The wear resistance against a steel disk has been enhanced by about two to three times in the Al/ Al_2O_3 surface nanocomposite layer produced by four FSP passes. This has been in comparison to with the base Al metal. In fact, the wear mechanism was considered to be a combination of abrasive and adhesive wear. The enhancement in the wear resistance of the surface composite layer might be explained due to the lower coefficient of friction and hardness increment.

3.2.2 Surface/Bulk aluminium matrix composite

Sahraeinejad, 2014 used friction stir processing for fabricating of Surface Metal Matrix Composites. Different particles at sizes ranged between 130 nm and 4.3 μm, and different process parameters, were employed to have a uniform distribution of particles within the processed region. In this study, the FSP was used to fabricate the composite by insert the reinforcement powders into the matrix of aluminum through a groove machined with 4 mm width and 2 and 4-mm depth in the matrix to contain the reinforcement. A cylindrical tool without pin was used with plate of material to close the groove to prevent the powder from sputtering out the groove. Mechanical properties of the composites of Al 5059 matrix reinforced with Al_2O_3, SiC, and B4C were got and compared. From results of tensile tests, it cab observed that demonstrated yield strength increases by 20, 32, and 38 percent compared to the matrix alloy for composites containing Al_2O_3, SiC, and B4C, respectively, three passes of FSP were carried out using different tools explained in Table 4, also the Process parameters are summarized in Table 5.

The effect of particle type and size dispersion was investigated in Al alloy matrix composites fabricate by FSP. The mechanical and fracture behaviour was compared between the composites, and the main results were that:

- Reinforcement particles were homogenously distributed in the lower and upper parts of the stir zone when the number of FSP passes increased.

- 3-pass FSP composites made with a 2-mm groove and reinforced by particles illustrates an increase of ~15% in the hardness profile as compared with FSP composite with no powder. This obviously proves the influence of powder inclusion on the hardness profile.
- Composites reinforced by B4C particles showed the highest tensile yield strength; however, their ductility drastically declined to 2.5% elongation in comparison to the parent considered
- When using 4.3-µm Al_2O_3 particles, the FSP technique lead to a 10 multiply refinement in the particle, whilst 1.1-µm Al_2O_3 particles are only refined to about half of their original size owing to the less effective attrition within the severely deformed stir zone.

Samiee et al., 2011 FSP was employed to fabricate surface layer of Al/AlN nano-composite on 6061 Al alloy matrix. FSP was carried out on 10 mm thick rolled plates of commercial 6061 aluminum alloy as base metal, chemical composition of Al alloy is shown in Table 6. Nano-sized AlN particles with an average diameter of ~50 nm and 99.9% purity was used as particulate reinforcement. The tool was machined with 16 mm shoulder diameter, pin tool 5 mm diameter and 4 mm length. A 3° tilt angle of the fixed pin tool was used. Nano-sized AlN particles were inserted in matrix through a groove machined with 1and 3 mm width and depth respectively. The FSP were carried out with two passes at travel speed of 310 mm/min and rotation rates of 900, 1120 and 1800 rpm, respectively. From optical micrographs, it can be observed that the SZ contain fine, uniform and equiaxed grains, **Fig.11** (c), because of the dynamic recrystallization. The grain became smaller compared to the parent metal, this due to serious plastic deformation and high temperature. The stirred zone is surrounded by the thermo-mechanically affected zone (TMAZ), **Fig.11** (d) and by a small heat affected zone, (HAZ), **Fig.11** (e). Since recrystallization doesn't occur in this region owing to low temperature, the grains of the TMAZ are larger and less equiaxed than the stirred zone. In **Fig.12**, it can be seen that the agglomeration of nano-sized AlN particles observed in the SZ owing to decrease in rotational speed. Uniform dispersion of nano-sized AlN particles and less agglomeration of nano-sized AlN particles in the SZ have arised from the higher rotational speed **Faraji and Asadi, 2010 Barmouz, et al., 2010**. From **Fig.12** (c) and **Fig.11** (c), it can be reported that the grain refinement in the SZ has arisen from presence the powder of the nano-sized AlN.

5. CONCLUSIONS

FSP has been one of successful and significant processes for fabrication of Aluminium Matrix Composite (AMC) and modification the microstructure of reinforced metal matrix composite materials. Most of the results revealed that for different alloys of aluminium, FSP produces grain refinement equiaxed as a result of dynamic recrystallization and homogeneous grain structure. These resulted in enhancement of the mechanical properties of aluminium alloys, such as hardness and tensile characteristics. The new advances in adding reinforcing particles to manufacture surface alloys and base metal composites are a breakthrough in this technology finding new possibilities to manufacture composites nanostructured with huge and attractive properties. FSP parameters such as rotational speed of tool, travel, linear speed of tool, spindle tilt angle, and depth are decisive parameters to prepare the MMCs with good properties (mechanical properties and structural characteristics) and product free defects. In addition, the type and vol. pct of ceramic powder as well as the interfacial strength between the base metal and the reinforcement powder play role to improve the properties of MMCs.

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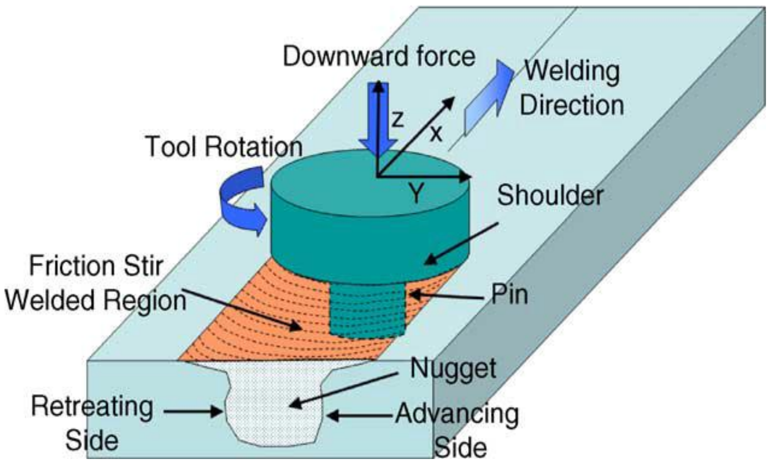

Figure 1. Schematic drawing of friction stir processing. **Mishra, et al., 2003**.

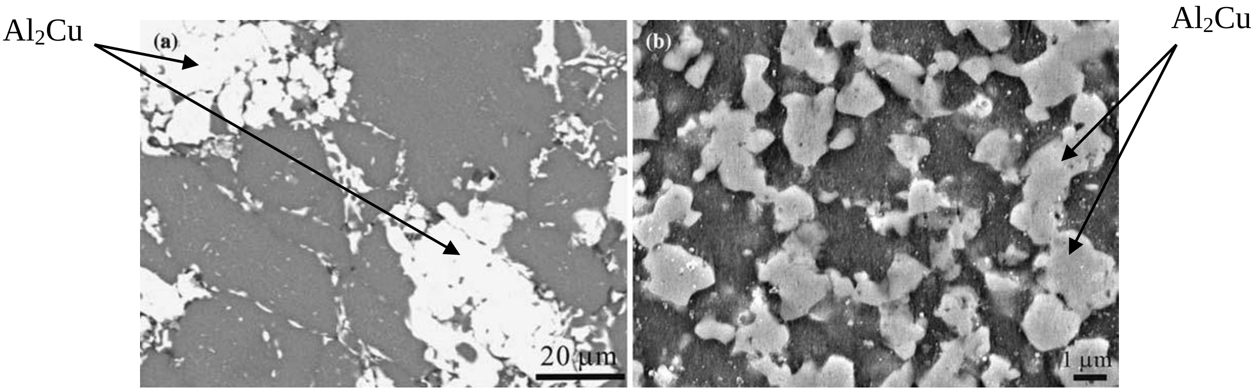

Figure 2. Backscattered electron imaging (BEI) of Al-15 at. pct Cu samples sintered at 530 °C, showing (a) coarse Al_2Cu/Cu particles under as-sintered condition and (b) fine and uniformly distributed Al_2Cu particles after a subsequent two-pass FSP. **Hsu, et al. 2005**.

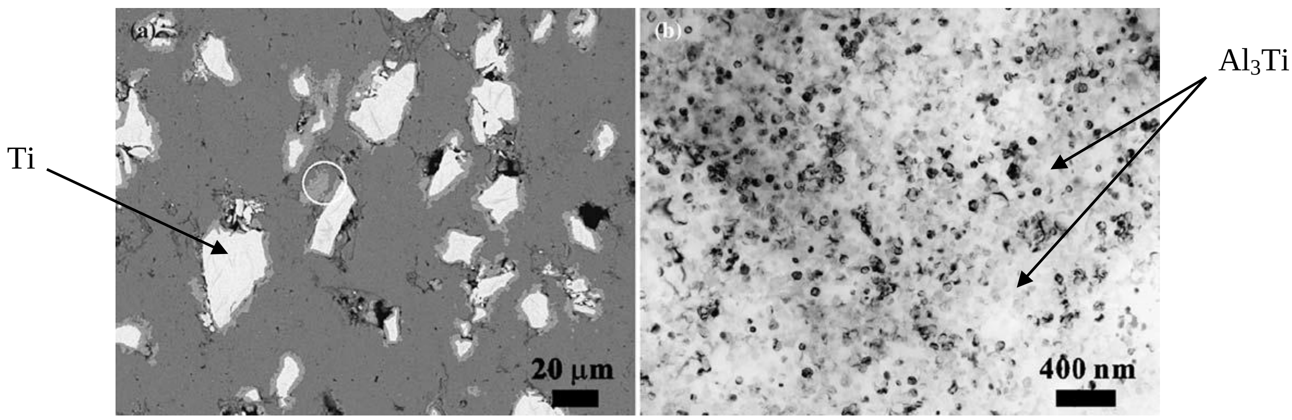

Figure 3. (**a**) BEI showing coarse unreacted Ti particles in Al-15 at. pct Ti sample sintered at 610 °C and (**b**) TEM bright-field image showing uniformly distributed nanosized Al_3Ti particles in four-pass FSP Al-10 at. pct Ti sample. **Hsu, et al., 2006**.

Table 1. Tensile Properties of Al-Al_3Ti Composites Prepared by Four-Pass FSP. **Hsu, et al., 2006**.

Materials	E (GPa)	YS (MPa)	UTS (MPa)	El. (Pct)
Al-5 at. pct Ti	82	277	313	18
Al-10 at. pct Ti	95	383	435	14
Al-15 at. pct Ti	108	471	518	1

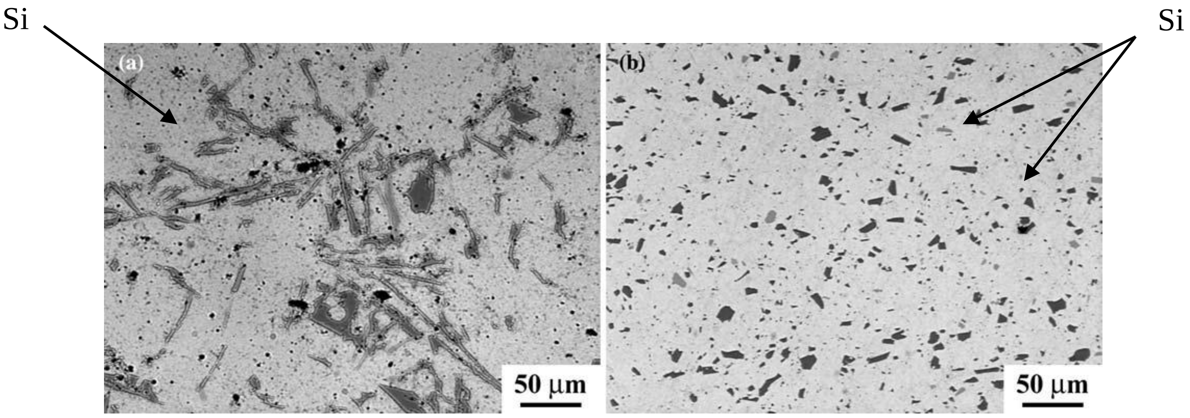

Figure 4. Optical micrographs showing morphology and distribution of Si particles in A356 samples: (a) as-cast and (b) FSP at 900 rpm and 203 mm/min. **Ma, et al. 2006**.

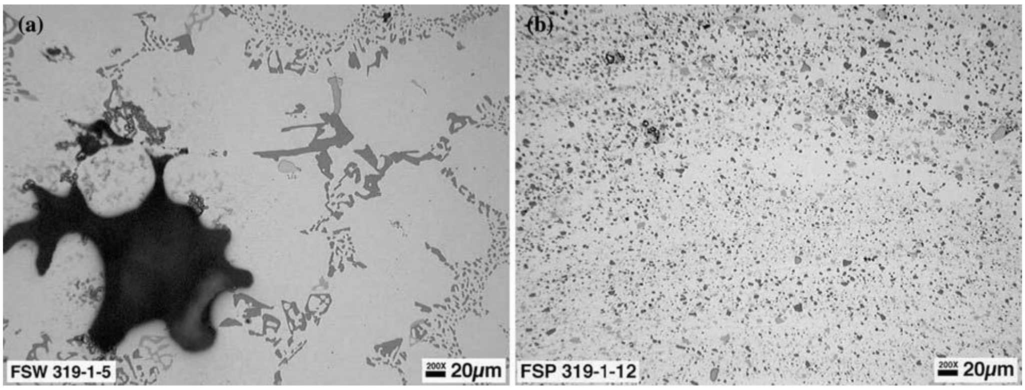

Figure 5. Optical micrographs showing (a) as-cast microstructure and (b) SZ of A319 (1000 rpm, 102 mm/min). **Ma, et al. 2006**.

Table 3. Size and Aspect Ratio of Si Particles and Porosity Volume Fraction in FSP and As-Cast A356 **Ma, et al. 2006**.

Materials	Particle Size (lm)	Aspect Ratio	Porosity Volume Fraction (Pct)
As-cast	16.75	5.92	0.95
FSP, 300 rpm, 51 mm/min	2.70	2.30	0.087
FSP, 900 rpm, 203 mm/min	2.50	1.99	0.032
FSP, 900 rpm, 203 mm/min, 2 pass	2.43	1.86	0.020

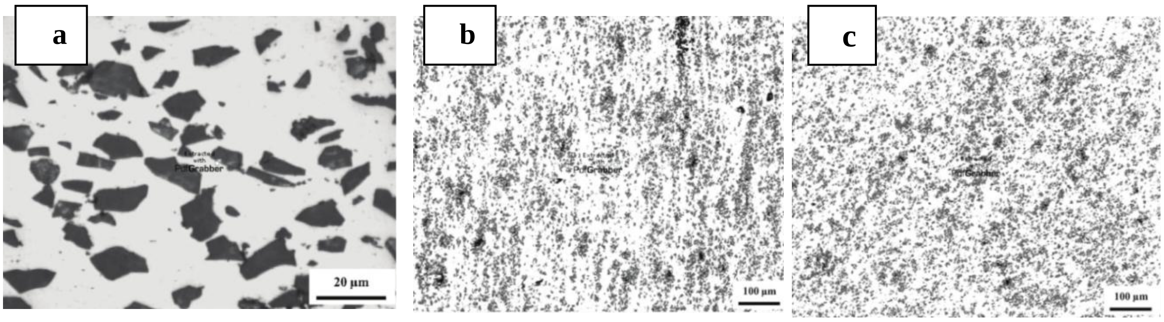

Figure 6. Microstructure change in SiC particle reinforced A6061 due to FSP (after Tewari et al. **Lakshminarayanan, and Balasubramanian, 2008)**: (**a**) scanning electron microscopic image of the composite showing the anisotropic shape of SiC particles; (**b**) as-extruded SiC/Al; (**c**) after FSP.

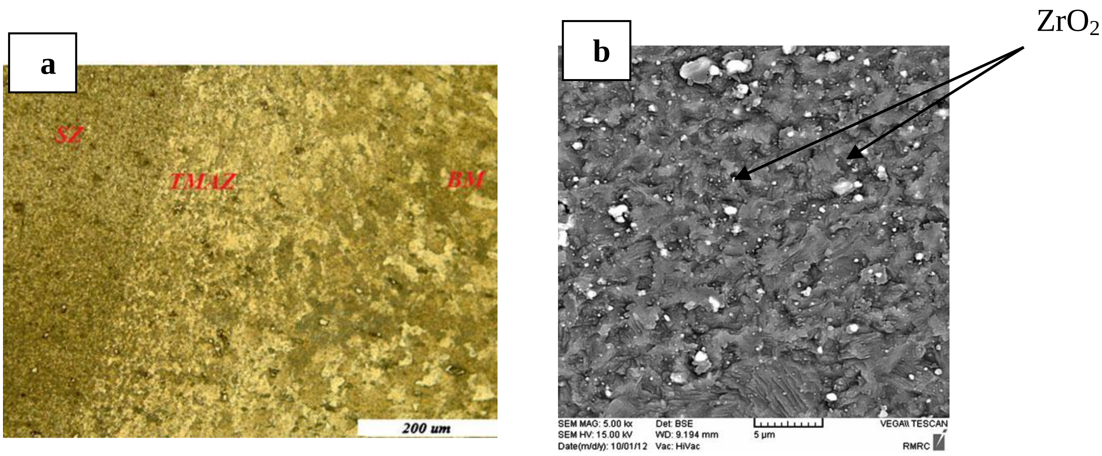

Figure 7. a) Micrograph of various zones with high magnification of Al/ZrO_2, process parameters: 1250 rpm, 80 mm/min **b**) distribution of ZrO_2 particles in the SZ. **Shahraki et al., 2013.**

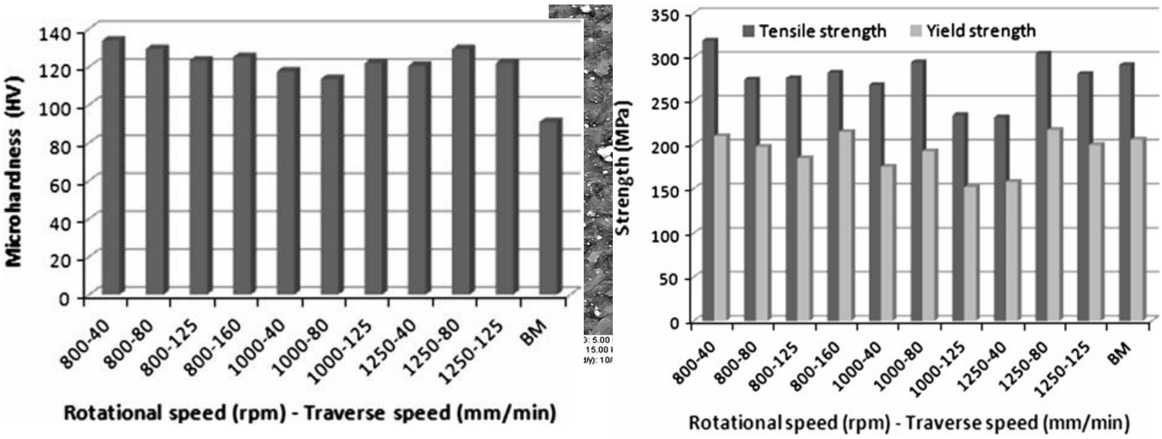

Figure 8. a) Hardness values of BM and SZ. b) Mechanical properties of BM and FSP samples **Shahraki et al., 2013.**

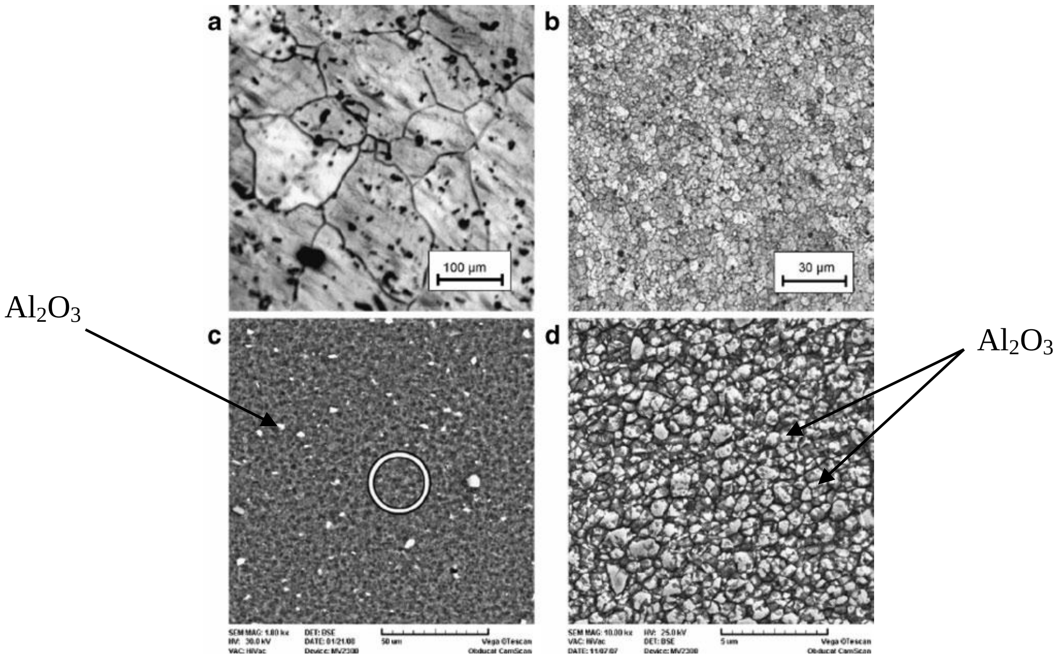

Figure 9. Optical micrographs showing the grain size of as-received 6082 Al (a) and Al 6082 before FSP (b) after four FSP passes. (c and d) SEM images showing the microstructure of the Al/Al_2O_3 surface composite layer produced by four FSP passes. Panel (d) is enlargement inside a circle for panel (c). **Zarghani, et al., 2009**.

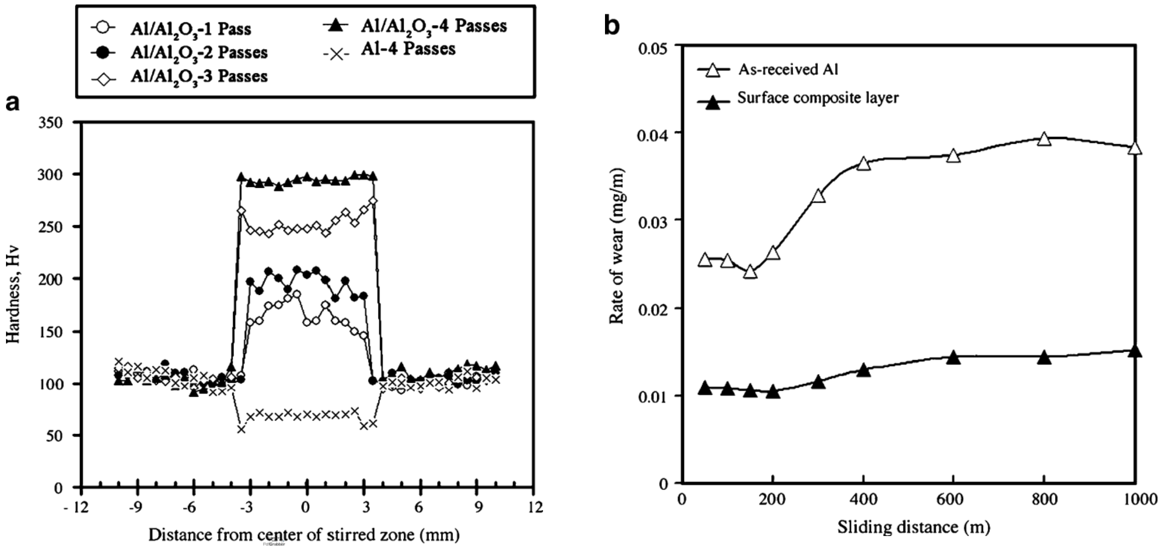

Figure 10. (**a**) Typical variation of the microhardness HV distributions of the FSPed 6082 Al alloy (no Al_2O_3) and surface composite layers. (**b**) Change in the reduction in pin weight with sliding distance for as received Al and surface nanocomposite layer produced by four FSP passes. **Zarghani, et al., 2009**.

Table 4. Processing parameters used in the FSP operations with 3-pass technique; travel speeds were 30 mm/min. **Sahraeinejad, 2014**.

Pass Number		Groove Depth (mm)	Shoulder Diameter D1 (mm)	Pin Diameter D2 (mm)	Pin Length L1 (mm)
0	Capping	N/A	15	N/A	N/A
1	Spiral Pin		10, 15	5	2.2, 4.0
2	3-flat	2 and 4	12, 15	5	2.2, 4.0
3	3-flat		12, 15	5	2.0, 3.8

Table 5. Summary of FSP Parameters applied**. Sahraeinejad, 2014**.

Pass Number		Tool	RPM	Rotation Direction	Inclination (°)	Travel Speed (mm/min)
0	Capping	Capping	1800	CW		
1	Pass 1	Spiral pin	1120	CCW	2.5	30
2	Pass 1	3 flat	450	CCW	2.5	
3	Pass 1	3 flat	450	CW	2.5	

Table 6. Chemical composition (wt %) of the base metal 6061 Aluminum alloy. **Samiee et al., 2011.**

Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti	Al
1.05	**0.36**	**0.41**	**0.23**	**0.05**	**0.07**	**0.12**	**0.01**	**Base**

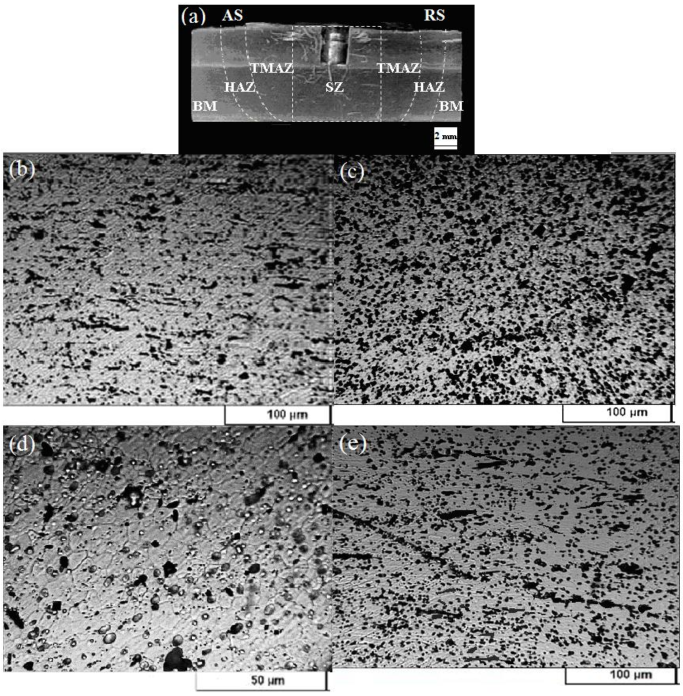

Figure 11. Cross section of the F1800: (a) the stirred zone, the TMAZ and the base metal interface, (b) the base metal, (c) the stirred zone, (d) the TMAZ and (d) the HAZ. **Samiee et al., 2011**.

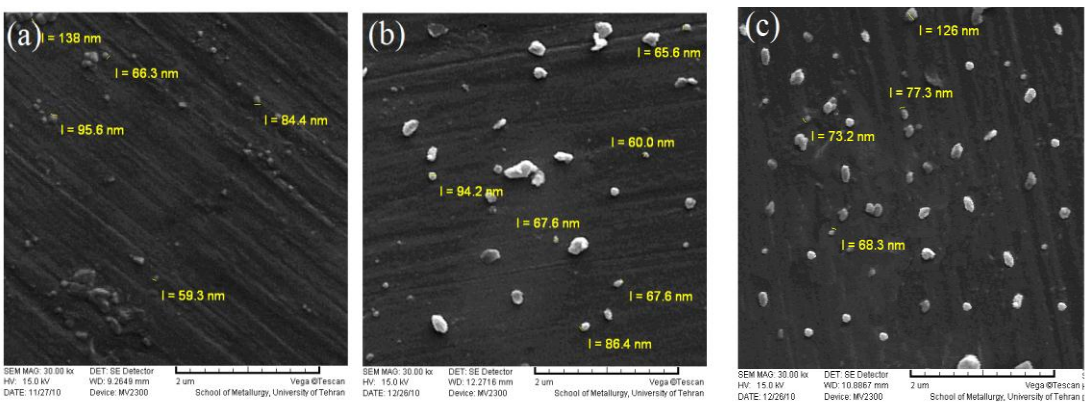

Figure 12. Effect of the rotary speed on the nano-sized AlN powder distribution and aluminum nitride cluster size in the surface Al/AlN nano-composite of the: (a) F900, (b) F1120 and (c) F1800 at a magnification of 30.00 kx. **Samiee et al., 2011**.