Aluminium Based Matrix Composites Fabricated by Friction Stir Processing

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Abstract: Aluminum alloys are used extensively in the manufacturing of automobiles and aircraft due to their low density, favorable mechanical characteristics relative to their weight, superior resistance to corrosion and wear, and low coefficient of expansion as compared to more conventional metals and alloys. In an effort to improve quality, lower weight, and increase structural material performance, researchers have recently switched from single to composite materials. The production of metal matrix composites (MMCs) and functional graded materials (FGMs) has been successfully studied using friction stir processing (FSP), which also uncovers new avenues for surface chemical modification. It has been demonstrated that the FSP approach holds great promise for alter the reinforced metal matrix composite materials' microstructure. Using FSP instead of conventional production techniques provides the advantage of reducing material distortion and flaws. The current work's objective is to provide an overview of FSP technology as a means of creating aluminum matrix composites, and the findings of this review will be illustrated.

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

1. Introduction

Composites made of a metal matrix reinforced by micro or nanoparticles are very useful materials that can be used for a variety of purposes. These metal-matrix composites enhanced with fibers or nanoparticles exhibit varying mechanical and physicochemical characteristics.
that are comparable to the base metal's. Metal matrix composites (MMCs) reinforced by nanoparticles, also known as Metal Matrix nano-Composites (MMnCs), are being researched all over the world these days due to their appealing qualities that make them appropriate for a wide range of structural and functional applications. The nano-scale strengthening phase, when combined with additional reinforced forces commonly found in conventional MMCs, results in an unusually enhanced mechanical property, making the interaction between reduced size particles and dislocations valuable.

Zhang, and Chen, 2008; Zhang, and Chen, 2006; Sanaty-Zadeh, 2012; Luo, et al. 2012. In addition to small engines and electronic packaging applications, metal matrix composites with micron-size reinforcements have shown to be extremely successful in the automotive and aerospace industries. For metal matrix nanocomposites, adding as little as one volume percentage of nanosize ceramics has significantly increased the strength of the basic composites made of magnesium and aluminum compared to using far higher loading levels of micron-sized additions.

Rohatgi, and Schultz, 2007. The cost of nanoscale reinforcements and the expense and difficulty of synthesizing and processing nanocomposites using existing techniques are the biggest obstacles to the development of MMnCs for widespread applications. The mechanical characteristics of an MMnC are largely determined by the characteristics of the reinforcements, their distribution, volume fraction, and interfacial strength between the matrix and the reinforcement, just like in traditional metal matrix composites with micron-scale reinforcements. It is challenging for most traditional processing techniques to achieve a uniform dispersion because of the high surface area of nanosize powders and nanotubes, which naturally tend to clump together to lower their total surface energy.

Saravanan, et al., 2010. Aluminum alloys are highly desirable for structural applications in the transportation, aerospace, and military sectors due to their exceptional corrosion resistance, high strength-to-weight ratio, and lightweight nature. However, aluminum alloys' low strength and hardness restrict their use, especially in tribological applications.

Deepak and associates (2013). According to Fig. 1, the rotating pin is specifically made for FSP. It moves along the predetermined pathways after first being placed into the metal to be processed at an appropriate tool tilt angle. Within the processing zone, the pin produces heat through plastic and frictional deformation. The material is forced to flow around the tool pin when it moves. After flowing to the back of the pin, the pushed material is consolidated and cooled under hydrostatic pressure conditions after being extruded and forged behind the tool.
This study provides an overview of the FSP process for fabricating the aluminum metal-matrix composite and can be regarded as a reference for FSP.

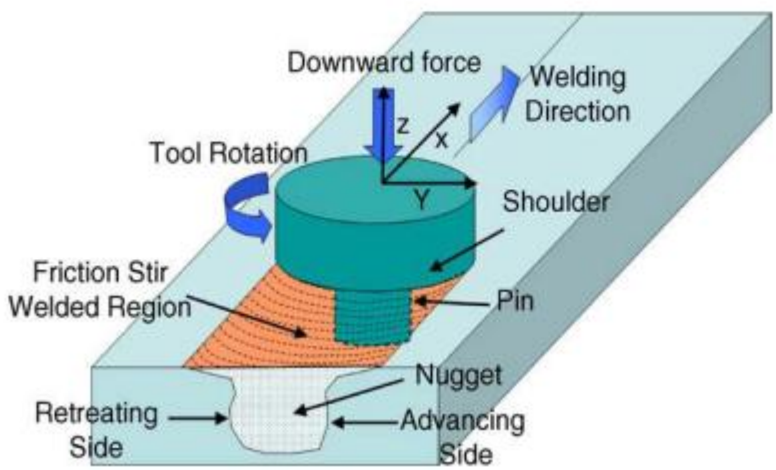

Figure. 1 . Schematic drawing of friction stir processing. Mishra, et al., 2003.

2. Fabrication of MMCS Using FSP

It is commonly known that the mechanical properties of MMCs are controlled by the size and volume fraction of reinforcing phases as well as the properties of the base metal-reinforcement interface **(Shafiei-Zarghani et al., 2009).** The primary methods for creating particle-reinforced metal matrix composites have been the powder metallurgy (P/M) method or the processing of molten metal. However, using P/M processing or traditional casting makes it particularly difficult to achieve a uniform dispersion of small reinforcing particles within the matrix. It is mostly caused by the fine particles' innate tendency to aggregate when the matrix and reinforcement powders are blended. It has been demonstrated that aluminum matrix composites can be made in-situ using FSP without the need for an additional consolidation procedure. According to Yang et al. (2010), there are the following benefits to using FSP to create MMCs:

(a) In order to further mix and refine the material's constituent phases, severe plastic deformation is induced. (b) Raise the temperature to facilitate the in-situ reaction and create reinforcing fragments. (c) Creating a totally thick solid by causing hot consolidation.

However, brittleness, which is often undesirable, results from the reinforcing particles' presence in the metallic matrix. Thus, adding particles to the surface in place of bulk reinforcement improves wear characteristics, a surface-dependent degradation mechanism, without compromising bulk characteristics **(Dixit et al., 2007).** However, using traditional surface treatments to evenly distribute ceramic particles on a metallic surface is difficult. Processing in the liquid phase at high temperatures is the foundation of the methods currently used to create surface composites. It is difficult to stop the base metal and reinforcement from reacting at the contact and developing some dangerous phases, though. Additionally, it appears that monitoring the processing parameter is essential to achieving a flawless cemented microstructure in the surface layer. It appears that these issues can be avoided by treating surface composites at low temperatures, below the melting point **(Lim et al., 2009).** In this instance, surface composites can be effectively created using FSP, a solid state processing method.

3. Friction Stir Processing to Create Aluminium Matrix Composites
3.1 Fabrication Micro-Composites
3.1.1 Modified and Fine-Grained Aluminum Matrix Composite

Dynamic recrystallization takes place in the stirred zone (SZ) as a result of significant friction heating and extreme plastic deformation during FSP, producing fine, equiaxed recrystallized grain of perfectly uniform size. **Mishra and associates (2003).** Hsu et al. (2005) noted that following FSP, the Al-No. 7 Volume 23 July 2017 Journal of Engineering 881 Al_2Cu composite made in-situ turned into an ultra-fine-grained composite. The Al-Cu reaction was not accomplished for 20 minutes at the sintering temperature of 500 °C for the Al-Cu sintered billet. When the sintering temperature reached 530 °C, the process was greatly accelerated. Nevertheless, as seen in Fig. 2(a), the original coarse Cu or resulting Al_2Cu particles were unevenly distributed throughout the aluminum matrix. This demonstrated that while the interaction between aluminum and copper can be carried out over a longer period of time and at a higher sintering temperature, the heterogeneity distribution and coarseness of the resulting Al_2Cu particles are distinct characteristics. Due to the full Al-Cu reaction and uniform dispersion of the resulting Al_2Cu particles in the aluminum matrix, an ultra-fine-grained Al-Al_2Cu composite was produced during two-pass FSP on billets sintered at both 500 °C and 530 °C, as shown in Fig.

2(b). Higher compressive strength and hardness were demonstrated by this ultra-examined how FSP affected the in-situ interaction between Ti and Al in a sintered billet of Al-Ti. They found that a small quantity of Al-Ti reaction may be produced surrounding the Ti particles by sintering at 610 °C, as shown in Fig. 3(a). The FSP significantly accelerated the in-situ reaction. The reaction between titanium and aluminum was fundamentally completed when a four-pass FSP took place, and the dispersion of the Al-Ti nanoparticles that had generated in situ in the ultra-fine-grained aluminum matrix was clearly visible, as shown in Fig. 3(b). based on tensile test results

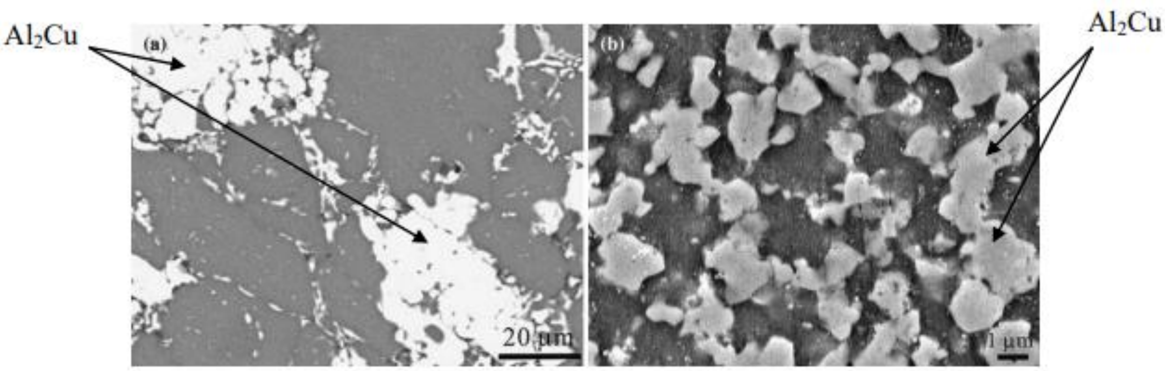

Figure 2. Backscattered electron imaging (BEI) of Al-15 at. pct Cu samples sintered at 530 °C, showing (a) coarse Al2Cu/Cu particles under as-sintered condition and (b) fine and uniformly distributed Al2Cu particles after a subsequent two-pass FSP. Hsu, et al. 2005.

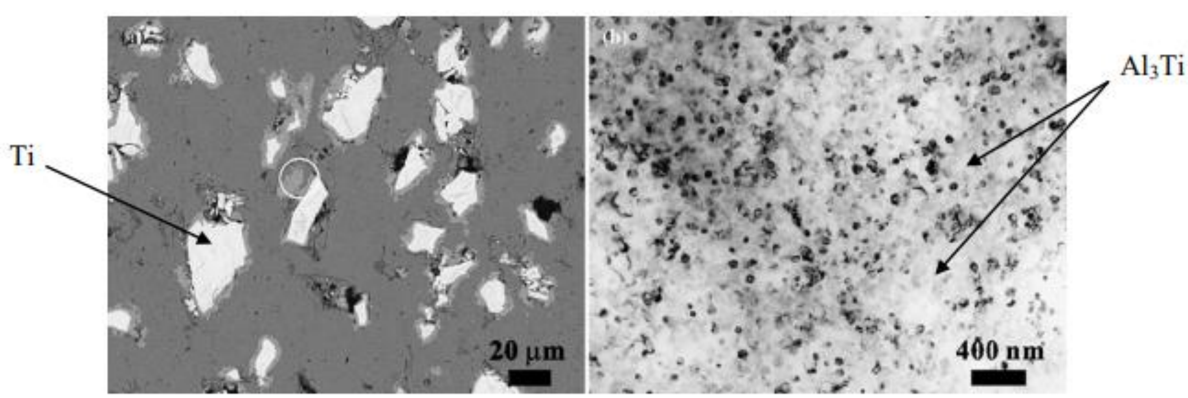

Figure 3(a). BEI showing coarse unreacted Ti particles in Al-15 at. pct Ti sample sintered at 610 °C and (b) TEM bright-field image showing uniformly distributed nanosized Al3Ti particles in four-pass FSP Al-10 at. pct Ti sample. Hsu, et al., 2006.

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

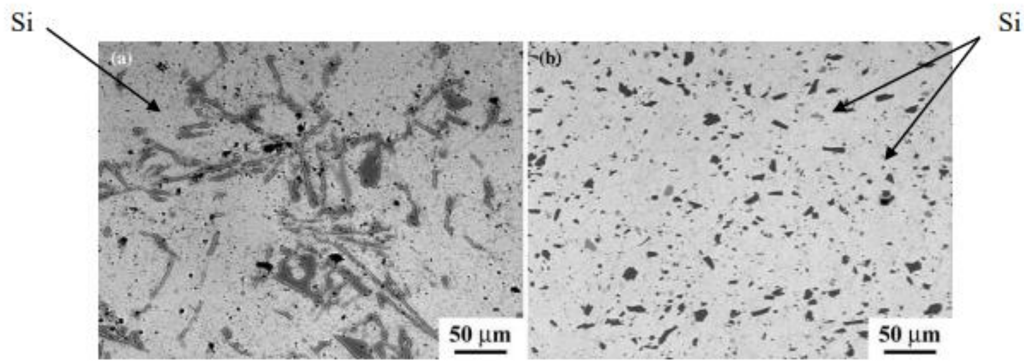

Figure 4. Optical micrographs showing morphology and distribution of Si particles in A356 samples: (a) as-cast and (b) FSP at 900 rpm and 203 mm/min. Ma, et al. 2006.

fine-grained AlAl2Cu composite. More recently, **Hsu et al. (2006).** It is evident that the resulting Al-Al_3Ti composite exhibits high modulus and strength. Table 1. As the Ti concentration rose, the modulus and strength rose as well, but the ductility fell. High strength/modulus and strong ductility were interconnected in the Al-10 at.pct Ti composite. **Ma et al. (2006)** looked at how common FSP parameters affected A356 sand-cast plates. As seen in Fig. 4(b), the results demonstrated that the action of FSP caused the coarse primary aluminum dendrites and coarse acicular Si particles to break up. Additionally, the casting porosities were closed, and the broken Si particles were uniformly distributed throughout the aluminum matrix.

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 It encompassed the range at a distance of 1.5 mm from the pin edge at the advancing side and might flow upward of the thermomechanical impacted zone (TMAZ) beneath the tool's shoulder. However, the width shrank and the MMC dispersion was roughly 2.5 mm in the deeper place. at a depth of 2 mm, which was within the advancing side's pin range. The microhardness of the matrix was about 88 HV. Because of the integrally dispersed SiC, the microhardness was consistent and 10% greater than the matrix at depths of 0.5 and 1.0 mm below the surface.

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/ZrO2 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 ZrO2 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 ZrO2 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 ZrO2. 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/ZrO2, 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 ZrO2 particles distribution in the SZ. Depending on the parameter of Zener-Holoman, the grain size decreases with increasing the volume fraction of ZrO2 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 ZrO2 showed that microstructures refined to a much smaller scale than the base metal alloy. 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/ZrO2 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 ZrO2 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 Al2O3 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 Al2O3, a groove was machined with a width of 1mm and depth of 4 mm, in which the required amount of Al2O3 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 Al2O3 particles in the surface composite layer was better when three FSP passes than that one FSP pass.

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 Al2O3, 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 ϖ the stir zone when the number of FSP passes increased.

(a) 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.

(b) Composites reinforced by B4C particles showed the highest tensile yield strength;ϖ however, their ductility drastically declined to 2.5% elongation in comparison to the parent considered.

© When using 4.3-µm Al2O3 particles, the FSP technique lead to a 10 multiply refinementϖ in the particle, whilst 1.1-µm Al2O3 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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