Influences of pinprofile and transverse speed on microstructure, mechanical properties, and wear behavior of nanocomposite AA6082/WC and fabricated via friction stir processing

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ABSTRACT
Friction stir processing (FSP) was successfully employed to produce AA6082/WC composite material. This research uses nano-sized WC particles of 50 nm average diameter as a reinforcement material. In order to identify the best condition for producing AA6082/WC composite material, two-pin profiles and four feed rates at 1200-rpm tool rotational velocity were used. The microstructure of the AA6082/WC obtained composites was investigated using a light optical microscope (LOM), Scanning Electron Microscope (SEM), and Transmission Electron Microscope (TEM). Results showed a homogenous distribution and excellent interfacial bonding between WC nanoparticles and the base matrix. The mechanical tests result showed significant improvement in obtained composite mechanical properties using different pin profiles and transverse speed. The composite processed by a cylindrical left pin tool had the highest ultimate tensile strength (UTS) strength, yield strength (YS), and microhardness compared to the hexagonal pin tool. The well-distributed nano-WC particles within the matrix improved the wear resistance by preventing the peeling of the AA6082 grains during the sliding wear test.

1. Introduction

The attractive properties of the AA6082 alloy have inspired researchers to reinforce them with ceramic dispersoids to obtain advanced engineering materials. AA6082 is an aluminum alloy hardening precipitation with the alloying elements being magnesium, silicon, and manganese. This alloy is suitable for various structural applications in the construction, marine aerospace and shipbuilding, industrial applications, transport, automotive, and aircraft sectors (The aluminum association, Inc., 2004). The key disadvantages of aluminum alloys are their poor mechanical properties and wear resistance, thus affecting their performance lifetime (Tjong et al., 1996). Recently, to enhance the mechanical characteristics and wear resistance of aluminum alloys, great efforts were made, such as incorporating ceramic particles into the aluminum matrix, and the results were promising (Fadavi Boostani et al., 2015; Harris, 1988; Khanna et al., 2021; Khodabakhshi et al., 2018; Madhan Kumar & Govindaraj, 2021; Prof et al., 2019; Stojanovic et al., 2018). Many researchers successfully fabricated AMMCs. The most common ways of AMMCs fabrication include liquid state and solid-state processing techniques such as stir casting (Tahezdah Mousavian et al., 2016), squeeze casting (Agarwal et al., 2019), and molten metal infiltration (Sasaki et al., 2010). Liquid-state composite fabrication techniques have certain advantages, such as faster processing rate and near-net shapes obtained compared to solid-state processes such as extrusion and diffusion bonding (Chawla & Chawla, 2006; Kohara, 1990). However, liquid state techniques generally lead to unwanted reactions and deleterious phases between reinforcement and base matrix. In addition, solidification-related defects are more severe in these methods. Because of these shortcomings, researchers are increasingly focusing their work on solid-state composite fabrication techniques. Solid-state methods can be used to achieve the high mechanical properties of MMCs. Powder metallurgical (Kandil et al., 2011), diffusion bonded and deformation-based techniques (Yazdani et al., 2018) constitute prominent solid-state techniques to develop AMMCs. Friction stir processing (FSP) is a newly developed solid-state process, which offers an excellent choice for the development of MMCs.

Using FSP, composites can be developed via two routes, i.e. ex-situ and in-situ. Ex-situ composite fabrication is attained by the external addition of reinforcement particles to the base matrix and subsequently performing FSP. On the other hand, reinforcement is inherent during in-situ composite synthesis necessitating the completion of specific reactions. The process of ex-situ composite fabrication
fabrication via FSP involves two steps. The first step is the pre-placement of reinforcement particles into the base matrix and the second step is the FSP of the reinforced packed substrate. The pre-placement of reinforcement particles (termed reinforcement strategies) can be done in several ways. These mainly include direct pasting of reinforcement particles, groove technique, spray techniques, etc. (Gamil & Ahmed, 2020; Hoziea et al., 2016; Sandeep Rathee et al., 2015).

Mishra et al. (1999) reported initial work on FSP in 1999. Both FSP and friction stir welding (FSW) work an almost similar principle apart from the fact that while FSP utilizes to process single plate, FSW involves the joining of two plates/work pieces. During FSP, a non-consumable tool (in rotating state) with tailored pin and shoulder design is plunged into base material/workpiece. The stirring action of the tool leads to the generation of heat of friction between tool and workpiece, which in turn results in softening, and plasticization of workpiece material. Work material is deformed plastically and reinforcing particles mix with base matrix owing to the intense stirring of the tool, thereby amounting to the development of desired composites by FSP (Rathee, Maheshwari, Noor Siddiquee et al., 2018).

Wide ranges of ceramic materials (oxides, borides, carbides, and nitrides) are commonly used as reinforcement particles for different aluminum alloys and are produced AMCs (Al-Salih et al., 2019; Chen et al., 2020; Rathee, Maheshwari, Siddiquee et al., 2018; Shagbard et al., 2018). Tungsten carbide is approximately twice as stiff as steel and is double the density of steel (Mourad et al., 2020), so it can be excellent among the various reinforcements.

In this work, FSP was carried out to fabricate AA6082/WC surface composites with nano-sized WC particles. The effect of tool geometry and transverse speed were carried out for investigating its impact upon microstructural evolution, mechanical properties, and wear resistance behavior.

2. Experimental work

2.1. Base matrix

Extruded aluminum alloy plates AA6082-T6 used as a matrix, and their chemical composition has been analyzed and presented in Table 1.

Ten millimeter plate thickness were cut perpendicularly in extrusion direction into samples with dimensions of 100 ×170 mm. The groove for packing the WC particles is machined in the middle along the length direction using the wire-cut EDM process. The groove’s length, depth, and width were 170, 5, and 0.7 mm, respectively.

2.2. Reinforcement material

The selected reinforcement is a high purity (99.8%) WC with an average particle size of 50 nm. SEM and TEM micrographs of WC nanoparticles are shown in Figure 1.

2.3. FSP tools

The FSP tools are made from heat-treated tool steel H13, which has subsequently been hardened to 58 HRC. The tools are fabricated in three different profiles; the first profile is made without a pin. The other two tools have a pin (cylindrical left-hand threaded and hexagonal), as illustrated in Figure 2. The shoulder diameter was 18 mm; the pin diameter and length were 6 and 5 mm, respectively. The cylindrical left hand has a threaded pin pitch of 1 mm.

Table 1. Chemical composition of AA6082 aluminum alloy.

| Element | Si   | Mg  | Fe  | Mn  | Cu  | Zn  | Ti  | Each | Total | Al  |
|---------|------|-----|-----|-----|-----|-----|-----|------|-------|-----|
| Wt.%    | 0.90 | 1   | 0.35| 0.65| 0.04| 0.001| 0.020| 0.05 | 0.15  | Balance |

Figure 1. SEM (a) and TEM (b) of WC particles.
2.4. FSP process

FSP was performed using a powerful computer numerical controlled vertical milling machine, as shown in Figure 3.

The fixture was first fixed with clamps on the machine bed, and then the plates were held correctly in the fixture for FSP. Upon clamping, the plates on the machine vice, the powder packed in the groove. At first, a pinless tool crossed along a groove with a rotational speed of 1000 rpm and a feed of 25 mm/min to compact particles and close the groove opening to avoid the spattering of WC nano-size particles during FSP as schematically illustrated in Figure 4.

2.5. Experimental procedure

The series of FSP runs were carried out according to the condition and parameters tabular in Table 2 and shown in Figure 5.

2.6. Specimens sampling and testing

The samples were cut from the stir zone (SZ), as schematically illustrated in Figure 6, using wire electric discharge machining (WEDM).

Microstructure and microhardness specimens were cut perpendicular to the feed direction in the SZ, polished, and etched following standard metallography. The microhardness was measured at several locations at an interval of 3 mm, at both sides of the centerline of the FSP region, from the processed zone to the base metal at 10 different points with a load of 200 g by the Vickers Hardness tester at a distance of 2 mm from its top surface.

Mini tensile specimens measuring 25 mm in gauge length, 6 mm in width, and 4 mm in thickness as per ASTM E8 standards have been prepared from the FSP zone, parallel to the composite direction shown in Figure 7.
A computer-controlled universal test machine performed the tensile test. The wear rate test was conducted at room temperature by the pin-on-disk wear system (DUCOM TR20-LE) according to the ASTM G99 04 standard. The wear test specimen’s dimensions were 40 \times 6 \times 5 \text{ mm}, where its polished surface is placed against the rotating disk made of hardened chromium steel (HRC 62). It was carried out at a constant speed of 1.66 \text{ m/sec}, a sliding load of 5 \text{ kg}, and a total sliding distance of 3000 \text{ m} for 30 minutes. An electron weighing scale with an accuracy of 0.001 \text{ mg} was used to determine the weight sample losses.

### Table 2. Friction stir processing parameter used for final experimentation.

| Exp. No. | Pin Profile | Feed (F) \text{ mm/min} | Volume fraction WC % | Rotational speed \text{ rpm} | Tilt angle | Axial force \text{ KN} |
|----------|-------------|--------------------------|----------------------|-------------------------------|------------|-----------------------|
| FSP-1    | TC          | 20                       | 10                   | 1200                          | 2^\circ    | 10                    |
| FSP-2    | Cylindrical left hand threaded | 40 |                      |                               |            |                       |
| FSP-3    | HE          | 60                       |                      |                               |            |                       |
| FSP-4    | Hexagonal tool pin | 80 |                      |                               |            |                       |
| FSP-5    | HE          | 20                       |                      |                               |            |                       |
| FSP-6    | HE          | 40                       |                      |                               |            |                       |
| FSP-7    | HE          | 60                       |                      |                               |            |                       |
| FSP-8    | HE          | 80                       |                      |                               |            |                       |

### Figure 5. Friction stir processed plates.

### Figure 6. Schematic illustration of the procedure for cutting.

3. Results and discussion

#### 3.1. Analysis of AA6082/WC AMCs microstructure

The obtained composites microstructures were analyzed to check the effect of the FSP technique applying different processing parameters.

Figure 8 shows different micrographs of AA6082/WC composites. All sample micrographs contain aluminum base metal. Figure 8(a) shows the unreinforced aluminum alloy base matrix, while Figure 8(b, c) shows the microstructure of AA6082/WC composite applying 20 mm/min. The effect of travel speed on WC distribution within matrix base metal shows
some particle clustering and ununiformed distribution of WC particles with low travel speed Figure 8 (b). While a uniform distribution of WC reinforcement particles in a stirred zone was found with increasing travel speed to 80 mm/min, as shown in Figure 8(d). WC uniform particle distribution was present using different pin profiles with the same travel speed (Figure 8(e,f)). The intense and high temperature during FSP causes dynamic crystallization (DRX), which refines the grains responsible for higher hardness and low ductility (Hamdollahzadeh et al., 2015).

Figure 8 presents the SEM micrographs of the prepared AA6082/WC composite prepared using HE (Figure 8(a-c)) and TC (Figure 8(d-f)) pin profiles. The distribution of WC particles is homogeneous in the obtained composite as shown in Figure 9(e). During the initial stages of the AA6082/WC composite formation, the plasticized aluminum alloy flowed into the groove and was forged at the back of the tool. The rotating action of the tool provides a vigorous stirring, which causes the packed WC particles in the groove to be uniformly distributed in the aluminum matrix. Segregation reduces the mechanical and tribological
properties of the AMC. Due to the density gradient, there was an agglomeration of WC particles in just a few places.

### 3.2. Mechanical properties

#### 3.2.1. Tensile behavior of AA6082/WC AMCs

The mechanical properties such as ultimate tensile strength UTS, yield strength YS, and elongation percentage El %, were evaluated and presented in Table 3.

The inversely proportional between feed and the heat input; at low feed, the greatest heat input obtained, which causes the growth of grains forming the coarse grains in the SZ. (Thangarasu, Murugan, Dinaharan, Vijay et al., 2015). As well known that the grain size has a direct effect on the mechanical properties, so coarse grains have good elongation and a lower UTS and yield strength as compared with fine grains, as indicated in Figure 10(a–c).

Also, the mechanical mixing at the SZ has a significant effect on the fabricated composite's mechanical properties (Abdullah & Beithou, 2014).

![Figure 9. SEM micrograph of AA6082/WC AMCs containing WC: 10 vol.% (a–e).](image)

| Specimen no. | Feed (mm/min) | Tool used | UTS (MPa) | YS (MPa) | El % |
|--------------|---------------|-----------|-----------|----------|------|
| FSP 1        | 20            | TC        | 305       | 276      | 11.85|
| FSP 2        | 40            | TC        | 312       | 281      | 10.78|
| FSP 3        | 60            | TC        | 318       | 285      | 7.50 |
| FSP 4        | 80            | TC        | 322       | 291      | 5.20 |
| FSP 5        | 20            | HE        | 297       | 270      | 9.75 |
| FSP 6        | 40            | HE        | 304       | 278      | 7.45 |
| FSP 7        | 60            | HE        | 309       | 283      | 5.85 |
| FSP 8        | 80            | HE        | 313       | 287      | 3.90 |
| AA6082/T6    |               |           | 246       | 216      |      |

AA6082 plates processed with a threaded cylindrical pin tool (TC) have the greatest UTS and yield strength. This has been attributed to the proper material movement between the threads. That makes it easier to blend well mechanically. The material flow is both horizontal and vertical, inclined from top to bottom, filling the bottom cavity at the bottom of the pin. The mechanical mixing was very low for a hexagonal pin tool due to a deficient pulsating action.

The higher value of UTS was observed with increase of speed and reinforcement. This may due to higher the heat input with the higher speed which cause more softening effect in the SZ because of stirring action of the tool pin. The similar observations were drawn by researchers (Kurt et al., 2011; Thangarasu, Murugan, Dinaharan, Vijay et al., 2015). This might be due to strengthening mechanisms such as Orowan and enhanced dislocation density (Lim et al., 2009).

It also observed that elongation of composites was less than the base metal due to presence of reinforcement particles which may leads to increase of slip distance of dislocations during deformation of material during processing of composites. The tensile fracture surface of the base metal and friction stir processed composites of the tensile test specimens were characterized by using scanning electron microscope (SEM) to understand the failure pattern.

#### 3.2.2. Fracture surface analysis

The fracture surface morphology of obtained samples consists of dimples, shown in Figure 11(a–f) for base metal, Exp. 1, Exp. 4, and Exp. 6, respectively. The deeper and lower dimples were observed for Exp. 1,
which indicates lower UTS and high ductility, whereas shallow and larger dimples for Exp. 6 indicate higher UTS and low ductility.

The fracture surface analysis of tensile-tested specimens was carried out using a SEM. The microscopic examination was performed on the fracture surface for friction stirring-processed tensile specimens and the base metal. There was a fracture shape in the base metal AA6082, and the tensile sample appearance showed a 45° angle with the tensile axis. Moreover, there was a shear fracture pattern. The SEM micrographs of fractured surfaces of a single-pass FSP sample processed at 1200 rpm with 40 mm/min traverse speed are shown. The fracture surface of FSP specimens reveals the formation of dimples, which demonstrates a ductile fracture can be observed on the fracture surfaces of the FSP specimens. A straight fracture is noticed on the friction stir processed specimens, as shown in Figure 12(a,b). The analysis represents the two types of brittle fracture, intergranular or, transgranular fracture, by using SEM analysis. The fracture analysis revealed that most of the friction stir processed samples are characterized as brittle fractures. The presence of ceramic particles in the matrix causes a brittle fracture. The results are in accordance with many previous work (Besharati-Givi & Asadi, 2014; Dinaharan, 2016).

3.2.3. Microhardness of AA6082/WC AMCs

The microhardness values of the base metal and the fabricated composites are tabulated in Table 4 and presented in Figure 13.

The microhardness of the fabricated composite is usually affected by heat generation and grain refinement. As a result, the increase in heat input increases grain growth and reduces the processed plates’ microhardness. It has been shown that the micro-hardness value is more remarkable with 80 mm/min, compared to 20 mm/min feed at a rotational speed of 1200 rpm with TC pin profile (Figure 12). Low feed is correlated with high heat, which further decreases the cooling

Figure 10. The relation between feed and tool pin profile on, tensile strength (a), yield strength (b), and (c) elongation.
The microhardness is also dependent on the grain size, i.e. the smaller the grain size, the higher the microhardness value will be. The grain boundary is a practical obstacle to dislocation slipping so that the fine-grain material would have a higher microhardness and UTS.

Microhardness is more with a cylindrical left-hand threaded tool than a hexagonal tool pin. This may be attributed to the whirling effect of the TC threads missing from the Hexagonal tool. In the Hexagonal pin tool, more area covered and high heat production resulted in coarse grains and, therefore, a coarse grain size resulting in less microhardness (Yadav et al., 2014). The base metal has a hardness value of 95 Hv, while this value increases with the addition of WC particles. Including WC particles split the base metal grain and precipitate grain boundaries, stopping grain from increasing, achieving finer grain size,

| Specimen no. | Transverse speed (mm/min) | Tool used | Microhardness (HV) |
|--------------|---------------------------|-----------|--------------------|
| FSP 1        | 20                        | TC        | 115                |
| FSP 2        | 40                        | TC        | 122                |
| FSP 3        | 60                        | TC        | 129                |
| FSP 4        | 80                        | TC        | 137                |
| FSP 5        | 20                        | HE        | 111                |
| FSP 6        | 40                        | HE        | 119                |
| FSP 7        | 60                        | HE        | 124                |
| FSP 8        | 80                        | HE        | 130                |
| AA6082/T6    |                           |           | 95                 |

Figure 11. SEM fractography of the tensile specimens, (a) base metal, (b–c) Exp. 1, (d–e) Exp. 4 and (f) Exp. 6.

Figure 12. Photograph of the fractured (a) as-received and (b) friction stir-processed tensile specimens.
and, therefore, more hardness (Hari Prasada Rao Pydi, 2013). It will be noticed that, 137 Hv microhardness value was obtained with TC at 80 mm/min.

3.2.4. Sliding wear behavior of AA6082/WC AMCs

As shown in Figure 14, the wear rate values of the AA6082/WC composite reduced with increasing the traverse speed from 20 mm/min to 80 mm/min. The obtained wear rate values were $5.2 \times 10^5$ mg/m and $3.6 \times 10^5$ mg/m, respectively.

The wear rate and the traverse speed have a linear relationship. This shows that grain refinement, distribution, and fragmentation of WC nanoparticles improving wear rate at reduced travel velocity for AA6082 alloy. When using the TC profile, the mean wear rate value was $4.7 \times 10^5$ mg/m, the mean wear rate was $4.4 \times 10^5$ mg/m, with a HE pin profile. The results showed that the wear rates were affected by the tool pin profile. In addition, it can be concluded that the hexagonal pin profile proved better than the other one.

Figure 15 shows the effect of pin geometry on worn surface with one FSP pass, the wear rate in FSPed specimen by straight cylindrical pin is more than that by square pin. This can be attributed to homogenized distribution of WC particles. It is also observed that the worn debris at straight cylindrical pin is more than that at the square, which can be attributed to their hardness in surface of composite. These results indicate that the wear rate is significantly affected by different parameters including pin geometry, rotational speed, travel speed and FSP pass number. Additionally, it can be inferred that suitable distribution, finer WC particles and finer grain size are the main reasons affecting wear surface of FSPed specimens.

Figure 13. Effect of transverse speed and tool pin profile on the microhardness.

Figure 14. Effect of tool traverse speed on the wear rate of AA6082 AMCs.
4. Conclusions

We can summarize the conclusions derived from this study as follows:

- The AA6082/WC metal matrix composites were fabricated successfully by friction stir processing.
- Microstructure observations showed homogeneous WC particle distribution and strong interfacial bonding between WC and aluminum matrix AA6082.
- During FSP, reinforced particles break grains of base metal and prevent grain growth by precipitating on the outer boundary of base metal grains, and hence fine grains are obtained.
- The mechanical properties and wear resistance are significantly affected by transverse tool speed and tool pin profile.
- By increasing transverse speed from 20 up to 80 mm/min. Tensile strength, yield strength, microhardness, and wear resistance increased.
- The tool geometry plays a critical role in the material flow, generating heat and mechanical properties, the optimal results obtained when using cylindrical pin profile.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Abdullah, R., & Beithou, N. (2014). Burnishing effects on friction stir welding of Al alloy 7075-T6. Global Journal of Researches in Engineering, 14(3), 13–20. https://www.researchgate.net/publication/263010683_Burnishing_Effects_on_Friction_Stir_Welding_of_Al-Alloy_7075_T6

Agarwal, P., Kishore, A., Kumar, V., Soni, S. K., & Thomas, B. (2019). Sourabh Kumar Soni and Benedict Thomas, fabrication and machinability analysis of squeeze cast Al 7075/h-BN/graphene hybrid nanocomposite. Engineering Research Express, 1(1), 15004. https://doi.org/10.1088/2631-8695/ab26f5

xAl-Salhi, H. A., Mahmood, A. A., & Alalkawi, H. J. (2019). Mechanical and wear behavior of AA7075 aluminum matrix composites reinforced by Al2O3 nanoparticles. NANOCOMPOSITES, 5(5), 67–73. https://doi.org/10.1080/20550324.2019.1637576

The aluminum association, Inc. (2004). Aluminum now. 6(3). https://www.aluminum.org/about-association

Besharati-Givi, M. K., & Asadi, P. (2014). Advances in friction-stir welding and processing. Woodhead.

Chawla, N., & Chawla, K. K. (2006). Metal matrix composites. In Metal matrix composites. (pp. 164-211). Springer. DOI: 10.1007/978-1-4757-2966-5

Chen, B., Zhou, X. Y., Zhang, B., Kondoh, K., Li, J. S., & Qian, M. (2020). Microstructure, tensile properties and deformation behaviors of aluminum metal matrix composites co-reinforced by ex-situ carbon nanotubes and in situ aluminia nanoparticles. Materials Science & Engineering A, 795 (23), 139930. https://doi.org/10.1016/j.msea.2020.139930

Dinaharan, I. (2016). Influence of ceramic particulate type on microstructure and tensile strength of aluminum matrix composites produced using friction stir processing. J. Asian Ceram. Soc, 4(4), 209–218. https://doi.org/10.1016/j.jascer.2016.04.002

Fadavi Boostani, A., Yazdani, S., Mousavian, R. T., Tahamtan, S., Khorosshahi, R. A., Wei, D., Brabazon, D., Xu, J. Z., Zhang, X. M., & Jiang, Z. Y. (2015). Strengthening mechanisms of graphene sheets in aluminum matrix nanocomposites. Materials & Design, 88(25), 983–989. https://doi.org/10.1016/j.matdes.2015.09.063

Gamil, M., & Ahmed, M. M. Z. (2020). Investigating the thermo-mechanical properties of aluminum/graphene nano-platelets composites developed by friction stir processing. International Journal of Precision Engineering and Manufacturing, 21(21), 1539–1546. https://doi.org/10.1007/s12541-020-00355-3

Hamdollahzadeh, A., Bahrami, M., Farahmand Nikoo, M., Yusefi, A., Besharati Givi, M. K., & Parvin, N. (2015). Microstructure evolutions and mechanical properties of nano-SiC fortified AA7075 friction stir weldment: The role

Figure 15. SEM images of worn surface as a function of pin geometry: (a) Threaded cylindrical pin, and (b) Hexagonal pin.
of second pass processing. Journal of Manufacturing Processes, 20(1), 367–373. https://doi.org/10.1016/j.jmatpro.2015.06.017

Hari Prasada Rao Pydi, B. (2013). Adhithan, microstructure exploration of aluminium-tungsten carbide composite with different manufacturing circumstances. International Journal of Soft Computing and Engineering, 2(6), 33–45. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.301.996&rep=rep1&type=pdf

Harris, S. J. (1988). Cast metal matrix composites. Materials Science and Technology, 4(3), 231. https://doi.org/10.1179/mst.1988.4.3.231

Hozieta, W., Toschi, S., Ahmed, M. M. Z., Morri, A., Mahdy, A. Y., El-Sayed Selem, M. M., El-Mahallawi, I., Cescini, L., & Atlam, A. (2016). Influence of friction stir processing on the microstructure and mechanical properties of a compocast AA2024-Al2O3 nanocomposite. Materials & Design, 106, 273–284. https://doi.org/10.1016/j.matdes.2016.05.114

Kandil, A., Amer, A., Abdul Fattah, H., & Salem, H. G. (2011). Effect of TiC particulates reinforcement on mechanical properties and aging behavior of micro and nanostructured matrices of AA1224, metal 65. Jahrgang, 6(55), 393–397.

Khanna, V., Kumar, V., & Bansal, S. A. (2021). Mechanical properties of aluminium-graphene/carbon nanotubes (CNTs) metal matrix composites: Advancement, opportunities and perspective. Materials Research Bulletin, 138, 111224. https://doi.org/10.1016/j.materresbull.2021.111224

Khodabakhshi, F., Gerlich, A. P., & Worswick, M. (2018). Fabrication and characterization of a high strength ultra-fine grained metal-matrix Al8006 B, C layered nano-composite by a novel accumulative fold-forging (AFF process. Materials & Design, 157(11), 211–226. https://doi.org/10.1016/j.matdes.2018.07.047

Kohara, S. (1990). FABRICATION OF SiCp-Al COMPOSITE MATERIALS. Mater Manuf Process, 5, 51–62. https://doi.org/10.1080/10426919008953228

Kurt, A., Uygur, I., Cete, El. (2011). Surface modification of aluminum alloys by friction stir processing. Journal of Material Processing Technology, 211(3), 313–331. https://doi.org/10.1016/j.jmatprotec.2010.09.020

Lim, D. K., Shibayanagi, T., & Gerlich, P. A. (2009). Synthesis of multi-walled CNT reinforced aluminium alloy composite via friction stir processing. Materials Science and Engineering A, 507(1-2), 194–199. https://doi.org/10.1016/j.msea.2008.11.067

Madhan Kumar, S., & Govindaraj, E. (2021, January). Surisetty Sri Sai Girish, Chandolu Yaswanth, Garre Sai Bharath, fabrication and characterization of aluminum metal matrix composite reinforced with graphite. Materials Today: Proceedings, 45, 6708-6711. https://doi.org/10.1016/j.matpr.2020.12.237

Mishra, R. S., Mahoney, M. W., McFadden, S. X., Marx, N. A., & Mukherjee, A. K. (1999). High strain rate superplasticity in a friction stir processed 7075 Al alloy. Scripta Materialia, 42 (2), 163–168. https://doi.org/10.1016/S1359-6462(99)00329-2

Mourad, A., Mahdy, A. A., Mosa, E. S., & Kandil, A. (2020). Fabrication of AA6082/WC nanocomposite by friction stir processing and optimization using TAGUCHI approach. Journal of Al Azhar University Engineering Sector, 15(57), 971–980. https://doi.org/10.21608/auje.2020.120375

Prof, P. P., Awate, P., & Barve, S. B. (2019). Study on fabrication and characterization of aluminium metal matrix composites. Journal of Applied Science and Computations, VI, 6(5), 2620–2629. https://www.researchgate.net/publication/339948307_STUDY_ON_FABRICATION_AND_CHARACTERIZATION_OF_ALUMINIUM_METAL_MATRIX_COMPOSITES_AND_NANOCOMPOSITES

Rathe, S., Maheshwari, S., & Noor Siddiquee, A. (2018). Issues and strategies in composite fabrication via friction stir processing: A review. Mater Manuf Process, 33(3), 239–261. https://doi.org/10.1080/10426914.2017.1303162

Rathe, S., Maheshwari, S., Siddiquee, A. N., & Srivastava, M. (2018). Distribution of reinforcement particles in surface composite fabrication via friction stir processing: suitable strategy. Materials and Manufacturing Processes, 33(3), 262–269. https://doi.org/10.1080/10426914.2017.1303147

Rathe, S., Maheshwari, S., Siddiquee, A. N., & Srivastava, M. (2015). A review of recent progress in solid state fabrication of composites and functionally graded systems via friction stir processing. Critical Reviews in Solid State and Materials Sciences, 43(4), 334–366. https://doi.org/10.1080/10408436.2017.1358146

Sasaki, G., Haray, Y., Zhefang, X., Sugio, K., Fukushima, H., Choi, Y. B., & Matsugi, K. (2010). Fabrication of carbon nano-fiber/aluminum composites by low-pressure infiltration method. Materials Science Forum, 654-656, 2692–2695. https://doi.org/10.4028/www.scientific.net/MSF.654-656.2692

Shabgard, M. R., Gorji, H., & Nouroozi, S., & Hadi Eivazi bagheri. (2018). Improving the surface wear resistance of aluminum by electrical discharge process. Journal of Advanced Materials and Processing, 6(2), 24–33. http://jmat.pro.jaun.ac.ir/article_623134.html

Stojanovic, B., Bukvic, M., & Euler, I. (2018, October). Application of aluminum and aluminum alloys in engineering. Applied Engineering Letters Journal of Engineering and Applied Sciences, 3(2), 52–62. https://doi.org/10.18485/aletters.2018.3.2.2

Taherzadeh Mousavian, R., Azari Khosroshahi, R., Yazdani, S., Brabazon, D., & Boostani, A. F. (2016). Fabrication of aluminum matrix composites reinforced with nano-tomicro-meter-sized SiC particles. Materials & Design, 89, 58–70. https://doi.org/10.1016/j.matdes.2015.09.130

Thangarasu, A., Murugan, N., Dinaharan, I., & Vijay., S. J (2015). Synthesis and characterization of titanium carbide particulate reinforced AA6082 aluminum alloy composites via friction stir processing. Archives of Civil and Mechanical Engineering, 15, 324–334. https://doi.org/10.1016/j.jacme.2014.05.010

Tjong, S. C., Wang, H. Z., & Wu, S. Q. (1996). Wear behavior of aluminum-based metal matrix composites reinforced with a preform of aluminosilicate fiber. Metallurgical and Materials Transactions A, 27, 2385–2389. https://doi.org/10.1007/BF02651894

Yadav, V., Kumar, V., & Tiwari, V. (2014). Effect of tool pin profile on mechanical properties of AL6082 and AL6082-Cu composite by friction stir processing. Journal of Mechanical and Civil Engineering, 11(3), 7–11. DOI:10.9790/1684-11340711

Yazdani, Z., Toroghinejad, M. R., Edris., H., & Ngan, A. H. W. (2018). A novel method for the fabrication of Al-matrix nanocomposites reinforced by mono-dispersed TiAl3 intermetallic via a three-step process of cold-roll bonding, heat-treatment and accumulative roll bonding. Journal of Alloys and Compounds, 747, 217–226. https://doi.org/10.1016/j.jallcom.2018.03.017