Development of Al1070-Quasicrystal (Al\textsubscript{65}Cu\textsubscript{23}Fe\textsubscript{12}) composites using friction stir processing and its mechanical characterization

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Abstract
This study aims at analysing the microstructure and mechanical behaviour of quasicrystalline (Al\textsubscript{65}Cu\textsubscript{23}Fe\textsubscript{12}) strengthened Al1070 composites by Friction Stir Processing (FSP). The composites with various volume fractions of quasicrystal are fabricated by a multipass (3 passes) Friction Stir Processing with 1200 rpm speed, 30 mm min\textsuperscript{-1} feed rate and tilt angle of 2.5\degree. The hardness measurement and tensile test performed in the fabricated composites divulged an increasing trend in the hardness values and Ultimate tensile strength up to a volume fraction of 8\% of quasicrystals. The microstructural studies disclosed the increase in the hardness values are ascribed to the reduction in grain size due to the dynamic recrystallization and the strengthening of Al matrix by quasicrystals. Though the composites with higher volume fraction exhibited improved Ultimate tensile strength, the fractographic studies depicted there is transformation from ductile to brittle failure in those composites.

1. Introduction

The Aluminium and Magnesium alloys are predominantly used as structural members and critical components in the automotive and aerospace industries due to their high strength to weight ratio. However, they have inherent limitations owing to their soft nature. Hence, these alloys are susceptible to the failures due to wear and fatigue [1–5]. Therefore, many of the researchers are interested in improving their strength with variety of strengthening techniques [6–9].

During the past two decades, the more demanding and wider engineering applications in the harsh environment stimulated the development of materials with the tailor made properties to suit the requirements. One such technique is the strengthening of aluminium and magnesium alloys with quasicrystalline particles. These particles belong to the category of materials which possesses quasi periodicity with crystallographic symmetries which imbibe unique physical and mechanical properties such as high strength, hardness, high elastic modulus and low coefficient of friction [10, 11]. Though, the quasicrystals are invented long ago, its application as a potential reinforcement material is yet to be acclaimed.

The use of quasicrystal particles to improve the surface properties of aluminium and magnesium alloys are accomplished by wide range of techniques. Some of the findings of the researchers are reported here-in. Alok singh (2003) et al evinced superior mechanical properties by strengthening Mg–Zn–Y alloy with quasicrystals through extrusion. The enhancement in the properties are attributed to the icosahedral phased particles which acted as strong pinning centres for grain boundaries and dislocations [12].

Alok singh (2005) et al manifested remarkable improvement in the ultimate tensile strength and as well as in the elongation of magnesium based alloys at room temperature by stabilizing the grain size with the strong pinning effect of icosahedral phased particles [13]. Markoli (2012) et al investigated the behaviour of quasicrystal strengthened aluminium alloy during compression. It is stated that the presence of icosahedral quasicrystalline phase in aluminium rich solid solution possessed notable strength and ability for plastic deformation [14]. Hira Huang (2013) et al developed excellent mechanical properties in the ultrafine grained quasicrystalline...
2. Materials and methods

2.1. Base material and reinforcement particle

Al 1070 alloy finds a variety of application such as structural members, electrical bus bars, and containers in chemical and food industries due to its superior resistance to corrosion and chemical attacks. Hence, it is chosen as the base material. Its chemical composition is given in the table 1 below. The Al65Cu23Fe12 quasicrystal is non-toxic, cheaper and easily available. Further, the Al1070 alloys belongs to the category of food grade material. Hence, strengthening by Al65Cu23Fe12 particles may not be an issue. Therefore, Al65Cu23Fe12 is chosen as the reinforcement material. The size of the particle ranges from 55 - 75 μm and shape being spherical. The morphology of the quasicrystals which are used in this research is depicted in the SEM image (figure 1). It reveals those particles are homogenous in nature.

| Element | Fe  | Si  | Zn  | Mn  | Ti  | Cu  | Mg  | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| W(%)    | 0.25| 0.2 | 0.040| 0.030| 0.030| 0.030| 0.030| Remaining |

2.2. Fabrication of Al 1070- quasicrystal surface composites

A 3 axis hydraulically controlled fully automated friction stir processing machine (Make: Creative Automation, Model: 3 axis servo controlled) shown in figure 2 is used for manifesting surface composites with Al 1070 alloy as matrix material and Al65Cu23Fe12 particles as a reinforcement material. The tool material and FSP parameters used in the present work is given below in the table 2.

Sipokzi mabawa (2019) et al determined the usage of rotational speed of 1200 rpm, transverse speed of 40 mm min \(^{-1}\) and a tilt angle of 2\(^{0}\) resulted in better mechanical properties for both friction stir welding and friction stir process in AA1050-H14 alloy, a category of 1xxx series [27]. Sivanesh Prabhu (2019) et al employed a EN-31 steel as a tool material with a shoulder diameter of 21 mm and square pin of height 4.5 mm and diagonal of 7 mm for accomplishing a surface composite with AA6082 alloy as matrix and CaCo\(_3\) particles as reinforcement materials. It is reported the use of this geometry resulted in better tribological and mechanical characteristics of the fabricated composite [28]. Taking those FSP parameters as reference, trial experiments are performed and the aforementioned process parameters are identified as the optimal parameters, as it yielded the desired properties. Also, the use of quasicrystals with volume fraction above 8% and below 4% resulted in undesirable properties. Therefore 4%–8% is taken as the threshold range of the volume fraction while using Al65Cu23Fe12 quasicrystal as reinforcement material.

The step by step procedure involved in the accomplishment of surface composites are presented in the schematic of the methodology (figure 3)

1. V grooves of depth 1 mm and width 0.9, 1.3 and 1.7 mm respectively are made in the base material for filling the quasicrystal of 4%, 6% and 8% vol. fraction.
2. After filling the quasicrystal in the groove, a En-31 tool without pin having 1200 rpm rotation speed and 30 mm min$^{-1}$ transverse speed is employed to close the groove to prevent the escape of the reinforcement material.

3. A tool having square profiled pin with the above mentioned friction stir process parameters is applied to distribute the quasicrystalline particles homogenously in the Al1070 matrix at the surface to manifest a surface composite.

The number of passes determine the extent (depth) of the alloying. Here, a triple pass is adopted.

### 2.3. Scanning electron microscopy

To identify the microstructure of the fabricated Al1070—quasicrystal composites, following procedure have been adopted. The samples is cut across the section using wire cut-electrical discharge machining (WEDM) and mounted using bakelite. The mounted samples are polished using silicon carbide with various grit sizes of 400,
800, and 1200. It is then polished with 0.5 micron alumina slurry using velvet cloth to make the specimen extremely flat and free from scratches. The polished samples is etched using Keller’s reagent (1% HF, 1.5% HCl, 2.5 HNO₃) to reveal the grain boundaries. The microstructure of the friction stir processed (FSPed) Al1070 alloy and Al1070—quasicrystal composites is obtained by using Scanning Electron Microscope (Model: Hitachi S-3400N).

2.4. Phase structure
The phase structure of Al1070 alloy, Al₆₅Cu₂₃Fe₁₂ quasicrystal particle, FSPed Al1070 and Al1070—quasicrystal composites are analysed by x-ray Diffractometer (Make: PANalytical Pro MRD) using CuKα radiation with the wavelength of 1.54 Å in a step size of 0.02.

Figure 2. Fully Automated Friction stir processing machine used for processing Al1070-quasicrystal composites.

Figure 3. Schematic representation of FSP for the fabrication of Al1070-quasicrystal composites.
2.5. Micro-hardness
The measurement hardness of FSPed Al1070 and Al1070-quasicrystal composites are made with Micro Vickers hardness tester (Make: Economet, Model: VH–1D) with a load of 300 g and dwell time of 15 s. The hardness measurement is carried out at nugget zone and in steps of 2 mm away from nugget zone on either sides of the composites.

2.6. Tensile test
Tensile tests are carried out using the specimens prepared as per the E8/E8–11 standards from FSPed Al1070 alloy and Al1070-quasicrystal composites in a Electro-Mechanical universal testing machine (Make: Instron, Model:3369 K1550) at a cross head speed of 2.5 mm min\(^{-1}\). The images of the specimen before and after the tensile tests are shown in figure 4.

3. Result and discussion
3.1. Microstructural analysis
The sectional images of FSPed Al1070 and Al1070-quasicrystal composites obtained by using SEM are shown in figure 5. It reveals the reinforcement of grains in Al matrix effected by FSP process in both FSPed Al1070 and Al1070-quasicrystal composites. The figures 5(b)–(d) respectively portrays, the distribution of quasicrystal in the Al 1070 matrix in the composites containing 4, 6 and 8% volume fraction of quasicrystal. With the increase in the volume fraction of the quasicrystal, the density of the distributed quasicrystal in the Al1070 matrix is increased [29, 30]. With no cracks and pores are visible and lesser the agglomeration of quasicrystal, the fabricated composites are effective in terms of reinforcement and defect free. The effectiveness of the fabricate composites can be ascribed to the optimal process parameters selection during friction stir processing. It is in good agreement with findings of Sipokzimabawa (2019) et al and Sivanesh Prabhu (2019) et al that better mechanical properties are achieved with the selection of appropriate process parameters.

The measured grain size of the base metal, FSPed Al1070 and Al1070-quasicrystal composites with different volume fractions (4, 6 and 8%) of quasicrystal are 85 \(\mu\)m, 15 \(\mu\)m, 12 \(\mu\)m, 9 \(\mu\)m, and 3 \(\mu\)m respectively. A fivefold decrement is observed in the grain size of FSPed Al1070 with respect to the base material due to the dynamic recrystallization effected by the friction stir process [31]. Whereas, in the case of Al1070-quasicrystal composites, a trend of decrement in the grain size with an increase in the volume fraction of quasicrystals is observed. This may be attributed to the strong pinning effect of the icosahedral particles on the grain boundaries which prevents the grain growth at higher temperature during FSP process and hence stabilizes the grain size. This is in accordance with the zener pinning model proposed by kumar (2011) et al [32]. During Friction Stir Processing, the friction between the tool and work piece will result in the generation of heat in material which plays a critical role on recrystallization time. An enhanced heat generation is imperative with introduction of quasicrystal owing to the increased friction between tool and Al1070-quasicrystal composites which eventually will reduce the recrystallization temperature. As a direct consequence of reduction in the recrystallization time, the suppression of grain growth is imminent. Further, the additional heat as the result of increased friction will aid the formation of intermetallics in the composites. Therefore, the usage of higher volume fraction of quasicrystal in the composites will enhance the intermetallic formation. This subsequently will cause zener pinning [33] and reduction of recrystallization time. This could be the imputed cause for the enriched grain refinement in the Al1070—quasicrystal composites with 8% volume fraction of quasicrystal particles.
3.2. XRD analysis

XRD pattern of Al alloy, quasicrystal particles, FSPed Al1070 and Al1070-quasicrystal composites with different volume fractions of quasicrystal are presented in figure 6. Al alloy exhibited various peaks at angle $2\theta = 36^\circ$, $45^\circ$ and $65^\circ$ corresponding to the planes $(111)$, $(200)$, and $(220)$. The major peak of aluminium is obtained at angle $2\theta = 45$ in the plane $(200)$. The XRD pattern of quasi crystal particles displays the presence of both $i$ phase and $\tau$—Al(Cu, Fe) phase [10]. The elementary impurity phase of Fe, Cu and Al is depicted at angle $2\theta = 63^\circ$, $42^\circ$, $36^\circ$, corresponding to the planes of $(200)$, $(111)$, and $(111)$ for the quasicrystal particles. The existence of CuAl$_2$ phase in the quasi crystal particles is confirmed from the peak intensity at $2\theta = 39^\circ$. The aforementioned peaks affirm the quasicrystal particles consists a combination of various impurity phases and CuAl$_2$ phase [34]. An increase in the intensity at angle $2\theta = 36^\circ$ of FSPed alloy with respect to the base material may be due to the dynamic recrystallization process [35]. Al1070-quasicrystal composites exhibited various peaks at angle $2\theta = 42.5^\circ$ and $26.5^\circ$ corresponding to the planes of $(110)$, $(220)$ which is very much similar to the FSPed Al alloy. However, the addition of quasicrystal particles (4%) increased the intensity of the major plane $(111)$ at angle $2\theta = 36^\circ$. This is due to the increase in the dynamic recrystallization process. On increasing the volume percentage of quasicrystal particles to 6% and 8%, there is a gradual increase in the intensity of the major peak and peak corresponding to the CuAl$_2$ phase. From this results, it is evident that the reinforcement with a higher volume percentage of quasicrystal particles could have resulted in higher recrystallization process. The maximum intensity is obtained for Al1070-quasicrystal composites with volume percentage of 8%. Since, the intermetallic compounds are present in the form of impurities, it is not possible to detect in the XRD pattern of Al1070-quasicrystal composites.

3.3. Hardness analysis

The hardness values measured at the nugget zone and in the steps of 2 mm from nugget zone on either sides of FSPed Al1070 and FSPed Al1070-quasicrystal composites are presented in a plot of hardness (in HV) Vs the distance from the stirred zone (figure 7). In all the specimens the peak hardness is observed in the nugget zone. This is because of the more uniform distribution of the quasicrystalline particles within nugget zone accomplished by dynamic stirring of rotating tool while performing FSP. The shear and circumferential forces administered by tool make the reinforcement particles to be finer in size [31]. The synergistic effect of the both instilled the peak hardness at the nugget zone.

The average hardness values of the base material, FSPed Al1070 and FSPed Al1070-quasicrystal (4%, 6% and 8%) composites are respectively 50 HV0.3, 72 HV0.3, 79 HV0.3, 86 HV0.3 and 91 HV0.3. The increase in the hardness values of the base material after friction stir processing is due to the presence of fine grains emanated.
from the dynamic recrystallization process. However, the increased hardness imparted in Al1070-quasicrystal composites can be accredited to the combined effect of (1) The pinning of the grain boundaries by quasicrystalline particles and the resultant stabilization of the grain size. (2) The suppression of grain growth effected by reduction in the recrystallization time due to increased friction between tool, reinforcement and base material and (3) The formation of intermetallics ensued by augmentation of heat due to increased friction [36].

It is noteworthy that the increase in the volume fraction of quasicrystal beyond 10% resulted in severe agglomeration which abets anisotropy. Therefore, it leads to hardness variations in the surface of the composites. Eventually, it will cause reduction in the average hardness value.

3.4. Tensile strength
The Ultimate tensile strength value and percentage elongation of base material, FSPed Al1070, Al1070-quasicrystal (4%, 6% and 8%) composites are given in the table 3. The increment in the Ultimate tensile strength of
FSPed Al1070 alloy relative to that the base material is due to the dynamic recrystallization and grain refinement effect by FSP [37].

In the case of Al1070–quasicrystalline composites (4%, 6% and 8%), the increase in the volume fraction of quasicrystalline resulted in increased density of the distribution of particle in the Al matrix. This in turn, augmented the Ultimate tensile strength of the composites by pinning of grain boundaries and formation of intermetallics [28]. However, the percentage elongation exhibited a decreasing trend with an increase on the volume fraction of quasicrystal. This is attributed to the restriction of dislocations movements by intermetallics and quasicrystals.

This is in good agreement with the findings of a previous literature where-in, it is reported that the ultimate tensile strength (UTS) is influenced by the factors such as grain refinement, porosities, extent of distribution of reinforcement particles and strong interfacial bonding between base material and reinforcement particles [32]. However, the increase in the volume fraction beyond 10% resulted in the agglomeration of particles which provides the site for crack initiation, which in turn decreases the ductility. The inhomogeneous distribution of reinforcement material reduces the effective strength and hence, failed in a brittle manner at a lower stress.

Table 3. Ultimate tensile strength and elongation percentage of processed samples.

| S. no. | Samples                          | UTS (MPa) | Elongation (%) |
|-------|----------------------------------|-----------|----------------|
| 1     | Base material (Al1070)           | 111       | 35.8           |
| 2     | FSPed Al1070                     | 164       | 39.44          |
| 3     | Al1070–quasicrystal (4%) composite | 173       | 32.89          |
| 4     | Al1070–quasicrystal (6%) composite | 189       | 30.36          |
| 5     | Al1070–quasicrystal (8%) composite | 206       | 25.02          |

Figure 8. Fractured SEM image of (a) FSPed Al1070, (b) Al1070–quasicrystal (4%) composite, (c) Al1070–quasicrystal (6%) composite and (d) Al1070–quasicrystal (8%) composite.
3.5. Fractographic analysis
Fractographic studies are performed with SEM images of fractured surface of FSPed Al1070 and Al1070—quasicrystal composites (4, 6 and 8%). It is observed from the figures 8(b), (c) and (d) that the size of the dimples is decreased considerably with the addition of quasicrystal particles (4, 6 and 8%) in the Al matrix. No cracks are observed in the FSPed Al1070—quasicrystal composites with quasicrystal of volume fraction 4% (figure 8(b)), whereas with increase in the volume percentage of quasicrystal to 6% and 8%, brittle cracks are observed in the fractured surface (figures 8(c) and (d)). The formation of brittle cracks are clear indication of the transformation of failure mechanism from ductile failure to brittle failure [37].

Hosseinzadeh et al reported the improved Ultimate tensile strength is due to the grain refinement. However, the high grain boundary density and pinning of the grain boundary by the reinforcement particles offers greater resistance to dislocation movement which eventually causes inter granular fracture upon stirring. This explains the transformation from ductile to brittle failure and reduction in the elongation. The base material and FSPed Al1070 are fractured by coalescence of micro voids which is evident from the presence of large dimples the characteristics of ductile failures [38].

4. Conclusion
The following conclusions are drawn based on the analysis of mechanical properties and microstructure of Al1070—quasicrystal composites with various volume fractions by friction stir processing.

1. The average hardness value of Al 1070—quasicrystal composite having 8% volume fraction of quasicrystal is 91 HV0.3 which is about 2 fold increases in hardness value of the base material.
2. The Ultimate tensile strength of Al 1070—quasicrystal (8%) composite exhibited a twofold increase relative to the base material with a reduction in the percentage elongation on Al1070—quasicrystal (8%) composite.
3. XRD study confirms the presence of both i phase and τ-Al(Cu, Fe) phase and CuAl2 phase in the Al1070—quasicrystal composite.
4. The strengthening in the Al1070—quasicrystal composite are attributed to the strong pinning effect of the quasicrystalline particles in the grain boundaries, suppression of grain growth, formation of intermetallic and dynamic recrystallization during FSP process. This ascribes the enhancement in the mechanical properties of the composites.
5. The fractographic studies revealed the increased grain boundary densities and pinning effect created intergranular fracture under high strains which discloses the transformation from ductile to brittle fracture and the ductility loss.

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References
[1] Thirumavalavan K, Karunamoorthy L and Padmanabhan K A 2019 Mechanical properties of AA6061 aluminium alloy subjected to severe surface mechanical treatment Mater. Res. Express 6 11656
[2] Abeens M, Muruganandhan R and Thirumavalavan K 2019 Comparative analysis of different surface modification processes on AA 7075 T651 IOP Conf. Series: Materials Science and Engineering 574 IOP Publishing
[3] Abeens M, Meikandan, Jaffer Sheriff and R Muruganandhan 2018 Experimental analysis of convective heat transfer on tubes using twisted tape inserts, louvered strip inserts and surface treated tube Int. J. Ambient Energy 57 1–7
[4] Thirumavalavan K, Sastry C Chandrasekhar, Abeens M, R Muruganandhan and M A Muthu Manickam 2019 Study on the influence of process parameters of severe surface mechanical treatment process on the surface properties of AA7075 T651 using TOPSIS and Taguchi analysis Mater. Res. Express 6 11656
[5] Abeens M, Muruganatham R and Arulvel S 2019 Friction–wear behavior of shot peened aluminium 7075-T651 alloy Indian Journal of Engineering & Materials Sciences 26 20–6 http://nopr.niscair.res.in/bitstream/123456789/47332/1/iJEMS%2026%20-%202020-26.pdf

[6] Abeens M, R Muruganandhan, K Thirumavalavan and S Kalainathan 2019 Surface modification of AA7075 T651 by laser shock peening to improve the wear characteristics Mater. Res. Express 6 066519

[7] Shendur G S, M Abeens, R Muruganandhan, M Arivandan, M Premnath and E Rajasekaran 2019 Investigation of nano ceramics added bismuth antimony telluride for energy harvesting applications Materials Today: Proceedings In (Press) [https://doi.org/10.1016/j.matpr.2019.11.050]

[8] Thirumavalavan K, Karunamoorthy L and Padmanabhan K A 2014 Optimization of process parameters using Taguchi technique in severe surface mechanical treatment of AA6061 International Journal of Engineering and Technology (IJET) 6 1026–32

[9] Muruganandhan R, Mugilvalavan M, Thirumavalavan K and Yuvaraj N 2017 Investigation of water jet peening process parameters on AL6061-T6 Surf. Eng. 34 330–40

[10] Litynska-Dobrzynska L, Dutkiewicz J, Stan-Głowinska K, Wajda W, Dembinski L, Langlade C and Coddet C 2015 Characterization of aluminium matrix composites reinforced by Al-Cu–Fe quasicrystalline particles J. Alloys Compd. 643 S114–8

[11] Dubois F-M 2012 Properties– and applications of quasicrystals and complex metallic alloys Chem. Soc. Rev. 41 6760–77

[12] Alok Singh M, Nakamura M, Watanabe A and Kato A P T 2003 Quasicrystal strengthened Mg–Zn–Y alloys by extrusion Scripta Materialia 49 17–22

[13] Alok Singh M, Watanabe A and Kato A P T 2005 Strengthening in magnesium alloys by icosahedral phase Sci. Technol. Adv. Mater. 6 895–901

[14] Markoli B, Boncina T and Zupanic F 2012 Behaviour of a quasicrystalline strengthened Al-alloy during compression testing Mat.-wiss. u. Werkstofftech. 43 340–9

[15] Huang H, Yuan G, Chen C, Ding W and Wang Z 2013 Excellent mechanical properties of an ultrafine quasicrystalline strengthened magnesium alloy with multi-model microstructure Mater. Lett. 107 181–4

[16] Pedrazzini S, Galano M, Audebert F, Collins D M, Hofmann F, Abbey B, Korsunsky A M, Lieblich M, GarciaEscorial A and Smith C D W 2016 Strengthening mechanisms in an Al–Fe–Cr–Ti nano-quasicrystal alloy and composites Mater. Science & Engineering A 672 175–83

[17] Rajabi M, Miresmaeili R and Alifiohkhazraki M 2019 Hardness and wear behavior of surface mechanical attrition treated titanium Mater. Res. Express 6 066503

[18] Zhao K, Yong Liu, Tianhang Yao, Bin Liu and Yuehua He 2016 Surface nanocrystallization of Ti–45Al–7Nb–0.3 W intermetallics induced by surface mechanical grinding treatment Mater. Lett. 166 59–62

[19] Ye Y, Song-Zhu Kure-Chu, Zhiyan Sun, Xiaopei Li, Haibo Wang and Guoqiang Tang 2018 Nanocrystallization and enhanced surface mechanical properties of commercial pure titanium by electropulsing assisted ultrasonic surface rolling Mater. Des. 149 214–27

[20] Zhang L, Yuan Zou, Hongtao Wang, Liang Meng, Jiahun Li and Zhongwei Zhang 2016 Surface nanocrystallization of Mg–3 wt% Li–6 wt% Al alloy by surface mechanical attrition treatment Mater. Charact. 120 124–8

[21] Zhang Z, Yaozi Li, Jinhua Peng, Peng Guo, Juan Huang, Pengyu Yang, Shan Wang, Chang Chen, Wei Zhou and Yucheng Wu 2019 Combining surface mechanical attrition treatment with friction stir processing to optimize the mechanical properties of a magnesium alloy Materials Science and Engineering: A756 184–9

[22] Wang Y, Li Y and Sun K 2018 Effect of process duration on the microstructures of fast multiple rotation rolling-induced nanocrystalline layer and its wear properties J. Mater. Process. Technol. 252 159–66

[23] Wang H, Zhiming Xia, Xinba Yaer, Zheng Tong and Zhaoxin Du 2019 High mechanical performance of AlSi304 stainless steel plate by surface nanocrystallization and microstructural evolution during the explosive impact treatment Journal of Materials Research and Technology 8 679–94

[24] Thirumavalavan K, Karunamoorthy L and Padmanabhan K A 2014 Optimization of process parameters using taguchi technique in severe surface mechanical treatment of AA 6061 International Journal of Engineering and Technology 6 1026–32

[25] Laine S, Knowles K M, Doorbar P J, Cutts R D and Rugg D 2017 Microstructural characterisation of metallic shot peened and laser shock peened Ti–6Al–4V Acta Mater. 123 350–61

[26] Mordyk B N, Prokopenko G I, Milman Y V, Iefimov M O, Grinkevych K E, Sameljuk A V and Tkachenko I V 2014 Wear assessment of composite surface layers in Al–6Mg alloy reinforced with AlCeFe quasicrystalline particles: effects of particle size, microstructure and hardness Wear 319 84–95

[27] Mabuwa Sand Msoomi V 2019 The effect of friction stir processing on the friction stir welded AA1050-H14 and AA6082-T6 joints Materials Today: Proceedings (In Press) [https://doi.org/10.1016/j.matpr.2019.10.039]

[28] Sivanesh Prabhu M, Elaya Perumal A, Arulvel S and Franklin Issac R 2019 Friction and wear measurements of friction stir processed aluminium 6082 Al2O3 composite, grinding process Measurement 142 10–20

[29] Lee C J, Huang J C and Hsieh P J 2006 Mg based nano-composites fabricated by friction stir processing Scripta Materialia 54 1415–20

[30] Mishra R S, Ma Z Y and Charit I 2003 Friction stir processing: a novel technique for fabrication of surface composite Material Science and Engineering A341 307–10

[31] Sathishkumar R, Murugan N, Dinaharan J and Vijay S 2013 characterization of boron carbide particulate reinforced in situ copper surface composites synthesized using friction stir processing Mater. Charact. 84 16–27

[32] Kumar N, Mishra R S, Huskamp C S and Sankaran K K 2011 Microstructure and mechanical behavior of friction stir processed ultrafine grained Al–Mg–Si alloy Materials Science and Engineering A 528 5883–7

[33] Yuvaraj N and Sivananand Aravindhan V 2015 Fabrication of Al5083/B4C surface composite by friction stir processing and its tribological characterization Journal of materials research and technology 4 398–410

[34] Ali F, Scadino S, Liu G, Srivastava V C, Mukhopadhyay N K, Samadi Khoshkhoi M, Prashanth G K, Uhlenwinkel V, Calin M and Eckert J 2012 Modelling the strengthening effect of Al–Cu–Fe quasicrystalline particles in Al-based metal matrix composites J. Alloys Compd. 536 S130–5

[35] Travessa D N, Cardosoa K R, Wolf W, Jorge A M Jr and Botta W J 2012 The formation of quasicrystal phase in Al–Cu–Fe system by mechanical alloying Mater. Res. 15 749–52

[36] Devaraju A K and Kotiveerachari B 2013 Influence of addition of Grp./Al2O3 p with SiCp on wear properties of aluminum alloy 6061-T6 hybrid composites via friction stir processing Trans. Nonferrous Met. Soc. China 23 1275–80

[37] Pineau A A B and Parodo T 2016 Failure of metals I: brittle and ductile fracture Acta Mater. 107 424–83

[38] Hosseinzadeh A and Yapici G G 2018 High temperature characteristics of Al2024/SiC metal matrix composite fabricated by friction stir processing Materials Science & Engineering A 731 487–94