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Research Article

A Comparative Study on the Development of Friction Stir Processed AA6062-T6 Metal Foam

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Abstract

The porous aluminium is in high demand due to its low-density, high-energy absorption and high damping properties. A precursor method using friction stir processing (FSP) was used in the current study to develop metal foam on AA6061-T6 using $MgCO_3$ as a blowing agent. A composite parameter, i.e., unit stirring was used to study the combined effect of FSP parameters while developing the metal foam. The FSPed sample was heat treated at 650°C with a holding time of 15 minutes. It was found that the highest porosity 18.18% was obtained at the lowest unit stirring of 0.004960 mm/rev-shoulder diameter.

Keywords: Aluminium Foams; Pore Density; Unit Stirring; Light Weight; FSP

Introduction

Metal foam is light weight cellular foam structures which contain various advanced properties, like low specific weight [1], high stiffness [2], good energy absorption, high acoustics, high damping properties. These metal foams also possess high sound absorption capacity due to typical cellular structure that can absorb the high quantities of different forms of mechanical energy, which helps in reducing unpleasant sound effect [3]. In addition, it has low thermal conductivity and very high compressive strength [4]. Metal foam can be two types; one is closed-cell foam which have pore sealed and brittle in nature. Which can be used as a shock-absorbing structure, second one is interconnected type also known as metal sponge or open-cell foam, ductile in nature that can used as heat exchanger, heat pipe [5] and fuel cell. Metal foam also used in various component of automobile bodies, aerospace bodies, ship building bodies, lorry arm, motor bracket for car, transverse beam for different machine and biomedical implants etc. [6]. It is also used in heat pipes where capillary pumping performance occurred [7]. Metal foam is having high porosity than base metal. Conventionally metal foam is made by using various processes like Powder metallurgy, gas injection, by using foaming agent, electro deposition, sand ball and casting etc. [8,9]. Sintering and dissolution process was also used by some investigators to form uniform interconnected pores at relatively lower cost [10]. But all these processes have their own limitations, especially maximum are time taking process. The conventional processes are harmful to the human body and environment as hazardous blowing agent and gases are involved there. This problem can be eliminated using friction stir processing to mix the blowing agent in metal matrix followed by some heating process like welding, flame, furnace or induction heating [11].

Friction stir processing (FSP) technique is used for surface, micro structural modification and grain size refinement [12]. In a study aluminum alloy 5083 as base plate used and SiC particles are mixed by using a rotating tool and traversing and found approximately double micro hardness to base material as AA5083 [13]. Frictions stir processing also used for surface modification according to the required surface while other process very difficult to use for surface modification [14].

Friction Stir Processing also used for fabrication of aluminum metal foam and metal matrix composite [15]. Hangai., *et al*. was the first to actualize the idea of employing friction stir processing for the production of metal foam using precursors. Researchers focused on the foam's porosity, pore structure size and distribution, and relative density [16]. Azizieh., *et al*. developed metal foam by using friction stir processing on AA1100 rolled, 10mm thick plate and foaming agent and stabilizer as TiH_2 and nano-Al_2O_3 particles respectively. They found that with increasing the foaming temperature to 675°C and holding time 15 minute, the porosity also increased while by increasing the holding time 30 to 60 min, the porosity decreased at same temperature [17]. Alumina (Al_2O_3) particles also used as a reinforcement for improving the mechanical properties such as tensile strength and hardness by heat treatment of composite [18]. In this work aluminium metal foams are fabricated using friction stir processing because this process eliminates costly powders and gases which was earlier used in conventional methods. Friction stir processing is a solid-state process. In this process heat is generated by rotating tool and friction between tool and base material for process the material up to the plastics deformation [19], this is an eco-friendly and fast process take less time to complete the job [20]. While other process takes much more time than friction stir processing. Friction stirs processing having advantages over the other process is that there is no requirement of blowing agent and external heat source to produce the precursor foam without melting the base material [3,21]. The localized foaming was also performed using FSP [22]. Few researchers developed metal foam by filling foaming or blowing agent into a slot in the middle of base metal plate. The blowing agent can also be sandwiched between two plates, The plate is processed using FSP to make precursor, which used to be heat treated to form the metal foam [23]. In this type of process the rotational speed of tool, tool traverse speed [10], profile of pin, heating temperature and holding time plays very pivotal role in development of metal foam [24]. But individually these parameters give contradictory response. So, a composite derives component named "unit stirring" is used in this paper to study the combined effect of rotation and traverse speed of the tool along with the shoulder diameter. This factor in metal foaming is not discussed by researchers, so it may play an important role for future research works.

Materials and Methodology

In the present study, aluminium alloy (AA6061-T6) was used as the base metal. The chemical composition of as received AA6061-T6 plate is given in table 1. AA6061-T6 is a solid solution strengthened alloy, possessing high strength to weight ratio, high corrosion resistance and good ductility. AA6061-T6 is used in manufacturing of aircraft wings, fuselages, ship construction, automotive wheel, sports car rims and spacers, also used in marine industry [17]. The plates size of AA6061-T6 200 mm length, 50 mm width, 8 mm thick was used as base metal for fabrication of aluminium metal foam precursor.

Element	Al	Mg	Si	Fe	Cu
Wt%	Remaining	0.91	0.49	0.25	0.19
Element	Cr	Mn	Zn	Ti	-
Wt%	0.12	0.11	0.02	0.01	-

Table 1: Chemical Composition of AA6061-T6(weight %).

In this process first a groove with size 2 mm wide and 2.5 mm deep was engraved at the center of plate by using end milling cutter on vertical CNC machine. The milled groove was filled with a very fine $MgCO_3$, used as blowing agent to instigate the foaming phenomena. The filled groove was covered using a covering tool with shoulder diameter 12 mm, on a vertical milling. Now on groove covered plates, FSP was performed on using different parameters. FSP was carried out with a tool made of H13 tool steel with a cylindrical pin, having a shoulder diameter of 16 mm and 18 mm, a pin diameter of 7 mm, pin height of 4 mm, 20 tool tilt angle and plunge 4.2 mm. The FSPed plate is called precursor. The process flow chart is depicted in figure 1.

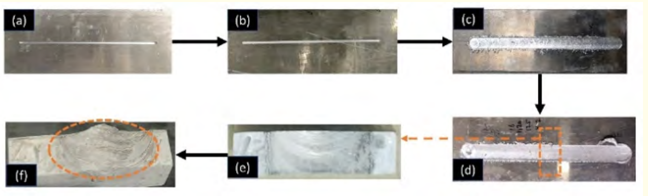

Figure 1: Steps of formation of a precursor using FSP followed by the development of metal foam.

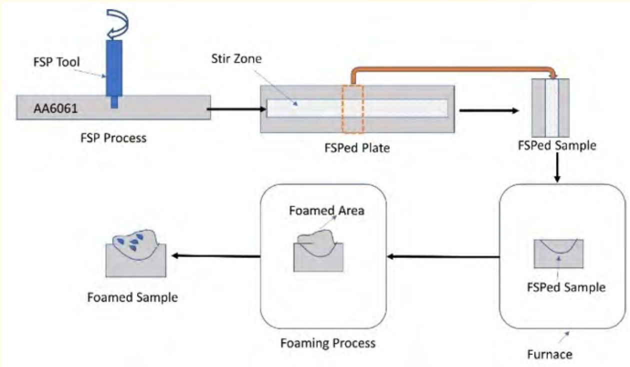

Figure 2: Schematic illustration of the development of metal foam using FSP.

Four experiments were performed using L-4 Taguchi Method with the given process parameters as shown in table 2.

Number of works has been reported on the formation of metal foam but many of them developed the metal foam by staking two plates and placing blowing and stabilizing powders in between those plates. In this study, the metal foam was developed on a single plate by placing blowing agent in a single groove, which was FSPed afterwards to make the precursor followed by controlled heating to form the metal foam as shown in figure 2.

Sample	Tool Shoulder Dia. (d_s; in mm)	Tool Rotation Speed (N; in rpm)	Traverse Speed (υ; in mm/min)	Foaming Temperature (°C)	Holding time (min.)
S1	16	900	100	650	15
S2	16	1120	125	650	15
S3	18	900	125	650	15
S4	18	1120	100	650	15

Table 2: Experimental parameters for FSP and heat treatment.

Result and Discussion

The precursor samples were heat treated in muffle furnace at 650°C for 15 minutes of holding time. A bump formation on the surface of the heat-treated samples were observed as shown in figure 3(b). The samples were cut through their cross sections to observe the formation of porosity in the metal matrix. Figure 3(a)-(c) depicted the FSPed sample, metal foamed sample and the magnified image of cross sectional cut of the metal foamed portion. Many pores of different sizes can be observed in figure 3(c). Larger pores are assumed to be formed due to improper mixing or agglomeration of blowing agent, i.e., $MgCO_3$ caused due to insufficient stirring action.

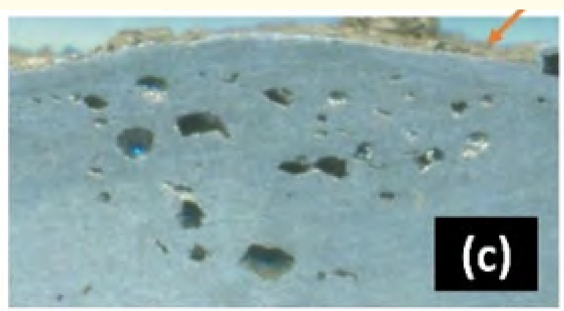

Figure 3: Sample of Precursor (a) After FSP (b) After heat treatment; and (c) magnified cross-sectional image of metal foam.

The researchers found that the individual FSP parameters may give contradictory results. So, to make the responses more reliable and non-contradictory, a composite parameter "unit stirring" was floated by some researchers [25]. Unit Stirring is the combination of tool traverse speed (), tool rotational speed (N) and the shoulder diameter (d_s) of the tool. It is presented as the traverse speed per unit rotational speed-shoulder diameter as shown in Eq. 1.

$$\omega = v/(N * d_s) \text{-------}(1)$$

The unit stirring of each sample is tabulated in table 3. In sample S3 the processing rate is highest as the unit stirring of the sample is 0.0077 mm/rev-shoulder diameter.

The formation of pores after the heat treatment of FSPed sample, i.e., precursor was analyzed to know about the formation of metal foam. The percentage of the porosity (p) in the foamed AA 6061-T6 was calculated for each sample on the basis of the Eq. 2, where is the density of the sample before the heat treatment and is the density of the heat-treated sample. The densities were calculated on the basis of Archimedes' principle [2].

$$p = (\rho_i - \rho_f) * 100/\rho_i \text{-----------}(2)$$

The calculated unit stirring and porosity is tabulated in table 3.

S. No.	Unit Stirring (ω mm/rev.-shoulder dia.)	Porosity %ge (p)
S1	0.006944	16.67
S2	0.006975	15.00
S3	0.007716	10.00
S4	0.004960	18.18

Table 3: Unit Stirring and Porosity of different samples.

FSP was performed on the AA6061-T6 plate to prepare the precursor for the formation of metal foam. The microstructure of the stir zone of all the four samples (S1, S2, S3 and S4) observed after polishing and etching is shown in figure 4. The average grain size of S1, S2, S3 and S4 was observed as 7.139, 10.854, 7.415 and 22.416 μm respectively. Under the combination of traverse movement and rotation of tool, the material in the vicinity of the tool pin undergone the repeated stirring, that resulted in spreading, mixing and dispersion of particles in the metal matrix. The stirring action resulted severe plastic deformation and the redistribution of grains in the stir zone. At lowest unit stirring, the average grain size was highest whereas for two higher unit stirring, the observed grain sizes are lower. In sample S3, the mixing of material is not uniform as shown in figure 4(c). The blowing agent was not uniformly distributed in metal matrix where as in sample S1 and S4, the distribution is more uniform, which can be seen in figure 4(a) and (d) respectively.

All the FSPed samples were heat treated at 650 °C to form the metal foam. Heat treatment caused formation of pores in the stir zone due to the decomposition of $MgCO_3$ and formation of CO_2. The CO_2 try to escape from the metal matrix which in turn form the aluminium metal foam. Foaming of the metal caused due to the nucleation of the pores, their growth and coalescence. While heating, the material gets soften at holding temperature and smaller pores got collapsed into each other to form bigger pores which tried to move towards the surface where the gasses released. Some non-uniformity in pore distribution was observed that may be developed due to inhomogeneous distribution of reinforcement in metal matrix. During FSP of S4, the unit stirring is the lowest amongst all. During FSP of S4 the $MgCO_3$ distributed uniformly in the metal matrix. Due to stirring action and crushing of $MgCO_3$, the number of Al/$MgCO_3$ increased which enhances the decomposition mechanism.

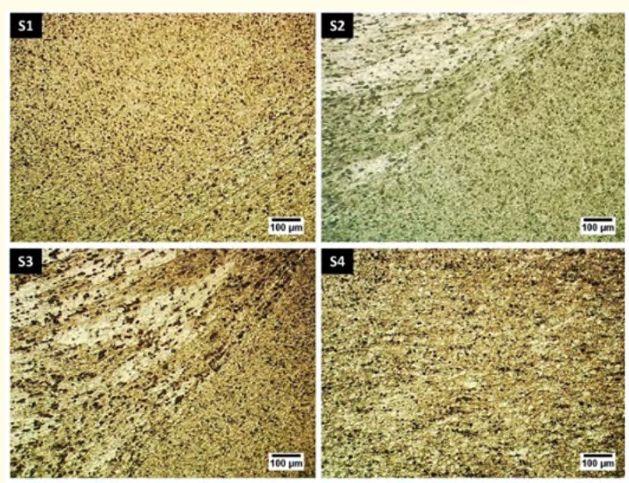

Figure 4: Microstructure of the FSPed sample at different parameters.

The macro and micro-morphology of metal foams are shown in figure 5. The closed cell porous metal matrix of sample S1, S2, S3 and S4 is depicted in figure 5(a), (d), (e) and (h) respectively. The pores are in darker color and distributed in the metal matrix.

The pores are also visible in cross section of sample S1, S2, S3 and S4 as shown in figure 5(b), (c), (f) and (g) respectively. Highest porosity, 18.18%, was observed in S4. In S4 the tool rotational speed was 1120 rpm with shoulder diameter 18 mm. The higher rotational speed generates enough frictional heat to distribute the blowing agent in efficient manner over the metal matrix. The better distribution of $MgCO_3$ provides higher number of nucleation site for the foam evolution which in turn gives higher porosity. The higher flow of material over and around pin increases the stored energy of the metal matrix. This energy accelerates the rate of decomposition reaction. These are the major factors responsible for the higher porosity in S4.

The increase in the nucleation sites promotes formation of small pockets of pores with lower diameters. The coalescence of pores can be evident where the stiffness of base metal is higher which impedes the phenomena of nucleation and growth of pores. In that case the pores collapsed in each other to promote the formation of larger pores. The range of the pores size (in micro meter) in S1, S2, S3 and S4 are (82.765, 354.515), (84.984, 368.932), (221.064, 659.227) and (67.987, 559.668) respectively. In figure 5(a), (d) and (h), long narrow channels can be observed, which was formed due to thermal expansion. The pores experience high thermal gradient so the elongation occurred towards higher temperature zone. The pores on the surface acts as thermal barrier so the pores below them experienced higher pressure due to which they collapsed and form larger pores.

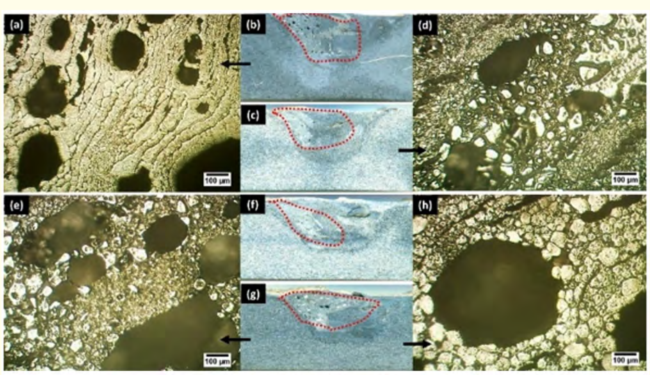

Figure 5: Micrograph of the heat-treated precursors of sample (a) S1, (d) S2, (e) S3 and (h) S4 and Macrograph of the heat-treated precursors of sample (b) S1, (c) S2, (f) S3 and (g) S4.

It is evident from figure 6 that the higher porosity percentage can be obtained by keeping unit stirring lower. The porosity decreases with the increase of unit stirring. At higher unit stirring, material flow rate is lower which is responsible for the lower mixing of blowing agent in metal matrix and it also promotes the agglomeration of the powder. Due to which, the distribution of pores is not homogeneous and the pores coalescence took place. By the virtue of which the larger pores formed and local accumulation of pores can be observed. The formation of pores can be largely evident near the surface, from which CO_2 try to escape, as shown in figure 5(b), (c), (f) and (g).

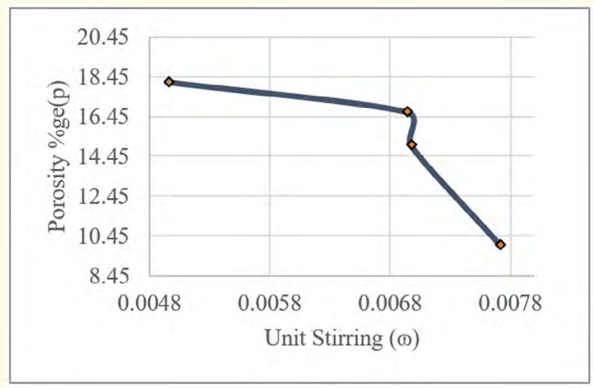

Figure 6: Graph between Unit stirring and Porosity.

Due to heat treatment, the thermal expansion of grains occurred, so the average size of grains of foamed AA6061-T6 metal matrix increased manyfold. The average grain size of the foamed metal matrix was observed as 52.032, 59.85, 54.81 and 61.8 μm. The comparison of FSPed sample (precursor) and metal foam is depicted in figure 7.

This investigation shows that the stirring parameters plays important role in development of metal foam and its characteristics. The unit stirring can be an important derived combined factor to decide the development of metal foam as the individual factors may give some contradictory response. The uniform distribution of blowing agent can give higher porosity which is a major requirement of metal foam.

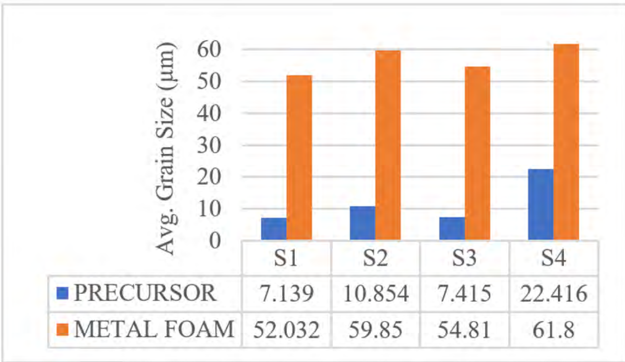

Figure 7: Comparison of average grain size of precursors and metal foams of samples S1, S2, S3 and S4.

Conclusions

The present study was carried out to study the feasibility of MgCO3 as blowing agent with AA6061-T6 base metal for the development of metal foam using single pass FSP. The FSPed sample acts as precursor for the heat treatment in which the decomposition of MgCO3 took place which in turn foam the aluminium metal matrix. The characterization of metal foam was performed and evaluated on the basis of FSP parameters. The major finding of the study can be summarized as follows:

- The individual FSP parameter may give contradictory response. So, a composite parameter "unit stirring" was used. Unit Stirring is the combination of tool traverse speed, tool rotational speed and the shoulder diameter of the tool.
- The unit stirring of sample S1, S2, S3 and S4 are 0.006944, 0.006975, 0.007716, 0.004960 mm/rev-tool shoulder diameter respectively. The lower unit stirring gives better distribution of metal flow over and around the tool pin.
- The FSPed sample S3 evident non uniform distribution of blowing agent in metal matrix whereas the sample S1 and S4 evident uniform distribution.
- Development of metal foam occurred after the heat treatment of FSPed sample at 650°C for 15 minutes in muffle furnace.
- Elongated pores were witnessed in S3 due to non-uniform distribution and accumulation of blowing agent in metal matrix. The elongated pores experienced the high thermal gradients, so they moved towards the surface.
- Formation of pores are maximum near the surface. The porosity was calculated as 16.67, 15.00, 10.00 and 18.18% in S1, S2, S3 and S4 respectively. Lower porosity in S3 was due to the non-uniform material flow during the FSP.

Bibliography

1. IG Papantoniou., *et al.* "Manufacturing process of AA5083/nano-γAl2O3 localized composite metal foam fabricated by friction stir processing route (FSP) and microstructural characterization". *Journal of Materials Science* 53.5 (2018): 3817-3835.
2. SU Nisa., *et al.* "Formation and characterization of 6063 aluminum metal foam using friction stir processing route". *Materials Today: Proceedings* 26.40 (2019): 3223-3227.
3. R Shandley., *et al.* "Foaming of friction stir processed Al/MgCO3 precursor via flame heating". *Materials Research Express* 7.2 (2020).
4. R Dyga and S Witczak. "Investigation of effective thermal conductivity aluminum foams". 42 (2012): 1088-1099.
5. H Yang., *et al.* "Effective thermal conductivity of high porosity open-cell metal foams". *International Journal of Heat and Mass Transfer* 147 (2020): 118974.
6. J Banhart. "Manufacture, characterisation and application of cellular metals and metal foams". *Progress in Materials Science* 46.6 (2001): 559-632.
7. S Supriadi., *et al.* "Fabrication of a Lotus-type Porous Material to be Applied in Heat Pipe Wick". *Evergreen* 8.4 (2021): 855-860.
8. TK Tatt., *et al.* "Review on Manufacturing of Metal Foams". *ASM Science Journal* 16 (2021): 1-8.
9. V Pamidi and M Mukherjee. "Melt injection - A novel method to produce metal foams". *Materialia* 4 (2018): 500-509.
10. VM Sharma., *et al.* "Effect of tool traverse speed on fabrication of open-cell copper foam using friction processing". *The International Journal of Advanced Manufacturing Technology* 116.7-8 (2021): 2137-2147.
11. N Ali., *et al.* "A novel hybrid approach to develop bioresorbable material". *Journal of Orthopaedics* 34 (2022): 61-66.

12. VK Jain., *et al.* "Effect of tool rotational speed on microstructure and mechanical properties of friction stir processed AA5083/ Fe-Al in-situ composite". *Materials Today: Proceedings* (2021).

13. RS Mishra., *et al.* "Friction stir processing: A novel technique for fabrication of surface composite". *Materials Science and Engineering A* 341.1-2 (2003): 307-310.

14. MZ Rahman., *et al.* "Mechanical and microstructural characterization of Ti-SiC reinforced AA5083 surface composites fabricated via friction stir process". *Materials Research Express* 8.12 (2021).

15. S Rathore., *et al.* "Effect of Process Parameters on Mechanical Properties of Aluminum Composite Foam Developed by Friction Stir Processing". *The Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 235.12 (2021): 1892-1903.

16. Y Hangai., *et al.* "Fabrication of functionally graded aluminum foam using aluminum alloy die castings by friction stir processing". *Materials Science and EngineeringA* 534 (2012): 716-719.

17. M Azizieh., *et al.* "Influence of Friction Stir Processing Parameters on the Microstructure of Aluminum Foams". *Transactions of the Indian Institute of Metals* 71.2 (2018): 483-491.

18. AZ Syahrial., *et al.* "Effect of Nano Al2O3 Addition and T6 Heat Treatment on Characteristics of AA 7075/Al2O3 Composite Fabricated by Squeeze Casting Method for Ballistic Application". *EVERGREEN. Joint Journal of Novel Carbon Resource Sciences and Green Asia Strategy* 9.2 (2022): 531-537.

19. MM Shahin Arshadi Rastabi. "Effect of multi-pass friction stir processing and Mg addition on microstructure and tensile properties of Al-1050 alloy Shahin". *International Journal of Minerals, Metallurgy and Materials* 29 (2020): 97-101.

20. N Gangil., *et al.* "Aluminium based in-situ composite fabrication through friction stir processing: A review". *Journal of Alloys and Compounds* 715 (2017): 91-104.

21. Y Hangai., *et al.* "Foaming behavior of blowing- and stabilization-agent-free aluminum foam precursor during spot friction stir welding". *Journal of Materials Processing Technology* 265 (2019): 185-190.

22. K Yamamura and T Nishihara. "Development of local reinforcement and local metallic foam using FSP". *Materials Science Forum* 638.642 (2010): 1267-1272.

23. Y Hangai., *et al.* "Effect of tool rotating rate on foaming properties of porous aluminum fabricated by using friction stir processing". *Journal of Materials Processing Technology* 210.2 (2010): 288-292.

24. IG Papantoniou., *et al.* "Fabrication of MWCNT-reinforced Al composite local foams using friction stir processing route". *The International Journal of Advanced Manufacturing Technology* 97.1-4 (2018): 675-686.

25. N Gangil., *et al.* "Another approach to characterize particle distribution during surface composite fabrication using friction stir processing". *Metals (Basel)* 8.8 (2018).