Friction Stir Processing – A Review

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Abstract. Friction stir processing (FSP) is a solid state surface modification technique which is recently used to fabricate surface composites. Friction stir processing is an extension of friction stir welding which is developed by the welding institute of UK in 1991. In FSP a rotating tool consist of a pin and a shoulder is inserted into the material which is in the form of a sheet. The main advantages of FSP includes grain refinement and the uniform distribution of reinforcement particles that improves the mechanical and wear properties of the surface composites compared with the as cast alloys. In the review paper a detailed analysis was done on the mechanical and wear properties of the composites fabricated by FSP.

Keywords: FSP. Grain refinement. Mechanical properties.

1. Introduction
The friction stir processing unlike other processing techniques like laser melt treatment, electron beam irradiation and plasma spraying does not produce interfacial reaction which cause harmful phases. FSP is basically developed to prevent from various defects that occur during casting. In FSP, non-consumable tool rotating at desirable speed is inserted forcibly (shown in figure 1.) into the work piece causes fine grained microstructure, which improves the mechanical properties and wear resistance of the composites. In this paper a thorough review was performed on the mechanical and wear properties of composites that occur during FSP.
Saini et al. [1] fabricated of as cast Al-alloy surface composite via FSP. The surface composite has been developed by reinforcing MoS$_2$ and Zn powder in the matrix of cast Al-Si alloy and they performed observations on reinforced surfaces, microstructure, mechanical and tribological characterization. They found micro hardness value was higher in the case of composite fabricated using Zn as compare to composite fabricated using MoS$_2$ and Al-17Si alloy, The Ultimate Tensile Stress of FSPed modify with Zn and FSPed modify with MoS$_2$ has been decreased about 0.977 and 0.703 times of base metal respectively, so as that percentage elongation wasn’t affected considerably within the case of composite fabricated using Zn reinforcement with in the as-cast alloy. Don-Hyun et al. [3] performed Friction stir processing of AA6061-T4 alloy with SiC particles. They found that the micro hardness of the stir zone in the midst of SiC particles about HV80 was observed due to grain refinement and scattering of SiC particles. Arun Premnath [4] investigated studies on Aluminium silicon carbide nano composites prepared by FSP. The experiments were performed on commercially available aluminium 6061 plate of size 150 × 50 × 5 mm. Initially the groove was crammed with nano-SiC particles and a pin-less tool is employed to stop escaping of the nano-SiC particles. Then, pin-tool is allowed for the processing. So as to review the effect of process parameters on microstructure and mechanical properties, the workpieces are fabricated by varying the quantity of passes, rotational speed and transverse feed. The microstructure examination shows that nano SiC particles were distributed evenly throughout the matrix for 3 pass specimen, it is observed a better values of tensile strength, micro hardness and wear loss. Mazaheri et al. [5] disquisition FSP to manufacture A356/Al$_2$O$_3$ surface composites by blending A356 samples with Al$_2$O$_3$ powder particles. A substantial increase within the average micro hardness was obtained by this method. Alidokht et al. [6] investigated the hardness of A356 plates reinforced with SiC and MoS$_2$. Their results showed that the FSPed specimens, which were reinforced using the 2 varieties of powders, recorded higher micro-hardness values compared to the given sample. Mahmoud et al. [7] worked on different ratios of SiC and Al$_2$O$_3$ powders as reinforcements for 5-mm-thick Al-1050-H24 plates. In the FSPed stir zone the powder particles were uniformly scattered. The results pan out that the common micro-hardness values obtained employing a 100% SiC powder increased to approximately 60 HV. They found that whenever the relative ratio of the Al$_2$O$_3$ powder particles increases the micro hardness values decreased. Darras et al. [8] used CNC vertical milling machine to conduct friction stir processing of commercial magnesium alloy with H-13 alloy steel tool is employed as pin. FSP is performed with a one pass at various combinations of rotational (1200–2000 rpm) and translational (20–30 in./min) speeds and that they processed heating and cooling rates. The material incorporates a fine microstructure with a mean grain size of about 6µm and better hardness. Mohammad
Hasan Shojaeefard et al. [9] follow out research on fabrication of particle-reinforced aluminium matrix composites. The distribution of reinforcing particle on the pin profile in terms of microstructural, mechanical, and wear properties of A356 matrix composites reinforced by SiC, TiC, ZrO2, and B4C particles are scrutinized. Owing to the good binding between TiC and metal matrix the composites reinforced with TiC particle shows better hardness. Eftekharinia et al. [10] found that there is a remarkable increase in the hardness by increasing the passes number because of uniform distribution of reinforcement particles and finer grains size at the stir zone. It is concluded that by increasing the rotational speed from 1000 to 1500 rpm, the temperature in the stirring zone increased to a critical value which causes grain refinement there by decreasing the wear loss of the composites.

Elangovan et al. [11] comprehended the results of tool pin profile and tool shoulder diameter on FSP zone formation in 6061 AA and opted different tool pin profiles like straight cylindrical, tapered cylindrical and threaded out of that cylindrical, triangular and square with three different shoulder diameters are acquainted with process the joints. During this regard they found that the square pin profiled tool and irrespective of shoulder diameter produced mechanically sound and metallurgically defect free welds compared to other tool pin profiles. Ma et al. [12] investigated studies on applied five-pass FSP with 50% overlap on cast Al–Si–Mg A356 alloy and identified that overlapping FSP didn’t exert a major effect on the dimensions and distribution of the Si particles. The Si particles broken by FSP were uniformly scattered within the entire processed zones created by multiple-pass FSP. Wanchuck Woo et al. [13] measured the effect of the stirring pin and pressing tool shoulder on the microstructural softening occurring during FSP and ensuring natural aging behaviour of 6061-T6 AA and the microstructural softening has occurred mainly due the frictional heating from the tool shoulder during FSP. The reduction of the longitudinal residual strain outlined within the bead area was correlated to the microstructural softening. As a whole, the softening within the DRX and thermo-mechanically affected zones is expounded to the dissolution of fine needle-shape precipitates β on account of frictional heating, which reduced the micro hardness from the 110 to 70 HV. Softening has also occurred within the HAZ which was similarly related to the dissolution of β and so the expansion of coarse precipitate phase, which reduced the initial hardness to 60.

Karthikeyan, et al. [14] conducted experiments on the surfaces of cast A319 alloy plates for single stir FSP, tend to find effect on the grain size, porosity level and improving the mechanical properties. Establishing most of the combinations of traverse feed rates and tool rotational speeds, the friction stir processed material displays higher strength and micro-hardness compared with the base material. The ductility of the FSP material is additionally greater than that of the base material. For an exact rotational speed ductility increases were around 1.5–5 times that of the cast alloy. The increases in ductility might be due to grain refinement within the nugget zone. The specimens processed with a tool rotational speed of 1200 rpm were free from defects and with certain combinations of parameters the processed alloy displayed an approximate raise of 50% in tensile strength and 20% in micro-hardness compared to the as-cast alloy.

Manisha Dixit et al. [15] successfully deployed to disperse and immerse nitinol particles in Al 1100 matrix by FSP. Directional residual stresses were introduced with in the prepared material and micro hardness results are compiled the cold-rolled and annealed composites show significant improvement in micro hardness value, as compared with the average value of 26 VPN found for Al 1100. The hardness values for the annealed and cold-rolled composite samples were similar, with the cold-rolled samples showing slightly higher values. The strength values of the prepared composite are much higher as compared there with of the Al 1100 matrix. The anticipated yield stress values for the prepared composite were found to be 15–25% below the actually measured values, they predicted that tensile strength in the transverse direction will be expected to be less within the the longitudinal direction. The value of Young’s modulus modelled was found to be 109 GPa, which predicts the presence of improved elastic properties within the prepared composite.

Yuvuraja, et al. [16] found that the number of passes increases the hardness due to the refinement of grains and uniformity in particle distribution that occurs during FSP of Al5083/B4C composites. S.Soleymani et al. [16] fabricated the composites using FSP and analysed the tribological behaviour. Hybrid composites (AA5083/(SiC + MoS2)) exhibited higher wear resistance compared to AA5083/100% SiC or AA5083/100% MoS2. MoS2 particles assisted in the formation and retention of a solid lubricating film which enhanced the
wear resistance of hybrid composites. Summary of investigation on Mechanical and wear properties of composite fabricated by FSP is shown in Table 1.

**Table 1. Summary of investigation on Mechanical and Wear properties of composite fabricated by FSP**

| Investigator name       | Material investigated                  | Characteristic studied                                      | Prominent results                                                                                                                                 |
|-------------------------|----------------------------------------|-------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| saini et al. [2]        | Al-17Si alloy and Zn/MoS$_2$ powders.  | studied on sliding wear using pin-on-disk Tribometer and UTS.| Ultimate tensile strengths for MoS$_2$ which is greater than Zn which are reinforced with Al-Si alloys. Wear resistance is higher in MoS$_2$ when compared with Zn are Reinforced with Al-17Si alloy. |
| Arun premnath [4]       | Al-6061 alloy and SiC nano-particles.   | Optimization of Process parameters Was done by using Taguchi orthogonal Array coupled with Durability approach | Achieved combination of optimum process parameters such as 3passes, 1500 rpm rotational speed and 70 mm/min transverse feed. Noticed better results in mechanical properties and wear loss |
| Mazaheri et al.[5]      | A356/Al$_2$O$_3$ surface-Nano composites using FSP. | sample tests conducted to analyse the characteristics of composite. | Microstructural studies shows Al$_2$O$_3$ particles were uniformly-Distributed in Al-matrix. Improved micro- hardness and elastic-modulus were noticed when Al$_2$O$_3$ particles used as reinforcement for Al matrix. |
| Alidokht et al. [6]     | A356 alloy and SiC/MoS$_2$ particles   | micro structure, hardness and Tribological behaviour Was studied. | SiC and MoS$_2$ particles were uniformly distributed on the top of stir zone without any defects after one pass FSP. |
| Investigator name            | Material investigated                  | Characteristic studied                  | Prominent results                                                                                                                                                                                                 |
|-----------------------------|---------------------------------------|----------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Mahmoud et al. [7]          | Al-1050-H24 base-material and SiC/Al2O3 particles as reinforcements. | Micro structure and hardness distribution. | Reinforcement particles SiC/Al2O3 were uniformly distributed equally on top of nugget zone using FSP. Hardness of composite get increased due to adding of SiC and decreased due to increased proportions of Al2O3 particles. |
| Woo et al.[13]              | 6061-T6 Al alloy                       | effects of stirring pin and pressing tool shoulder on microstructural softening. | Tool shoulder creates the friction heating which causes reduction in the longitudinal residual strain profiles in nugget zone which generates microstructural softening                                                                                       |
| Karthikeyan et al.[14]      | cast A319 grade Aluminium alloy.       | micro structure and mechanical properties. | Mechanical properties were improved at 1200- rpm rotational speed and ductility improved to 1.5 to 5 times for A319 cast alloy.                                                                                     |
| Solemani et al.[16]         | Al5083/(SiC+MoS2)                      | tribological behaviour                 | For SiC sample composite hardness increased to 102HB and also having high friction coefficient, MoS2 has lowest friction coefficient.                                                                                 |

2. Conclusions
The major conclusions obtained from comprehensive review of FSP in terms of mechanical properties and wear resistance is summarized below.

1. The mechanical properties and wear resistance of composites fabricated by FSP shows higher values when compared with other processing techniques
2. FSP has unique advantages compared with traditional composites in terms of surface composite fabrication which can be explored in the near future.
3. The major drawback that limits industrial application of FSP is the wear of stir tools. Modification in the tool design was required for effective usage.

3. References
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