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Effect of Stirring Efficiency on Fatigue Behavior of Graphene Nanoplatelets-Reinforced Friction Stir Spot Welded Aluminum Sheets

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INTRODUCTION & AIM

Friction Stir Spot Welding (FSSW) is a Novel variant of Friction Stir Welding (FSW), developed by Mazda Motors Corporation and Kawasaki Heavy Industries to join similar and dissimilar metals and alloys in a solid state. It is an economic feasible and environmentally friendly alternative to Resistance Spot Welding (RSW).

Mechanical properties and microstructure of the FSSW joints are mainly controlled by welding parameters and welding tool design through controlling frictional heat generation and material flow induced during the welding process. The most dominant welding parameters are tool rotational speed, dwell time, plunge depth and plunge rate. The welding process consists of three distinct steps: plunging, stirring, and retracting, as depicted in schematic Figure 1.

The FSSW is commonly used in a wide range of industrial applications in Joining similar and dissimilar materials in structural, electrical and transportation industries in cars and vehicles structures and Bodies, aircraft, aerospace, trains, ship building, and many other industrial applications. Figure 2. shows cars production line employing the FSSW welding technique.

Despite the advantages of the FSSW technique compared to traditional fusion welding methods, this technique includes some structural defects imbedded within the weld joint, challenging the joint quality and strength, such as keyhole formation, hook crack, and bond line oxidation, as depicted in schematic Figure 3. Therefore, further research is necessary to improve the FSSW joint quality and durability.

This work aims to demonstrate the role of the welding pin geometry on the distribution of the GNPs within the joint matrix and thus prevent the formation of brittle phases resulting from nano-agglomerations that deteriorate the fatigue strength of the FSSW joints.

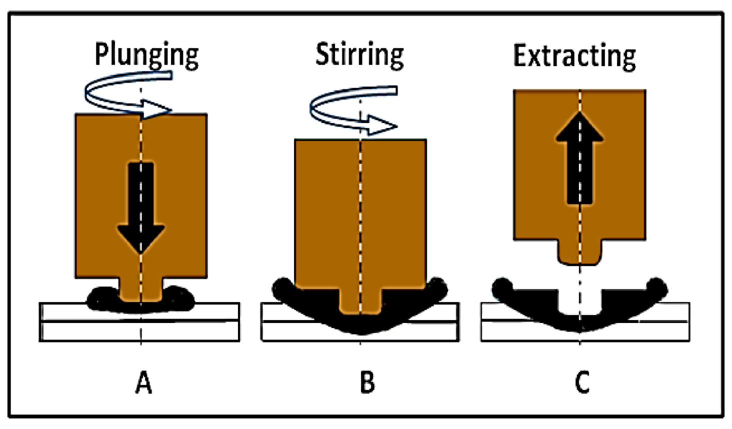


Figure 1. Schematic of the FSSW welding process.

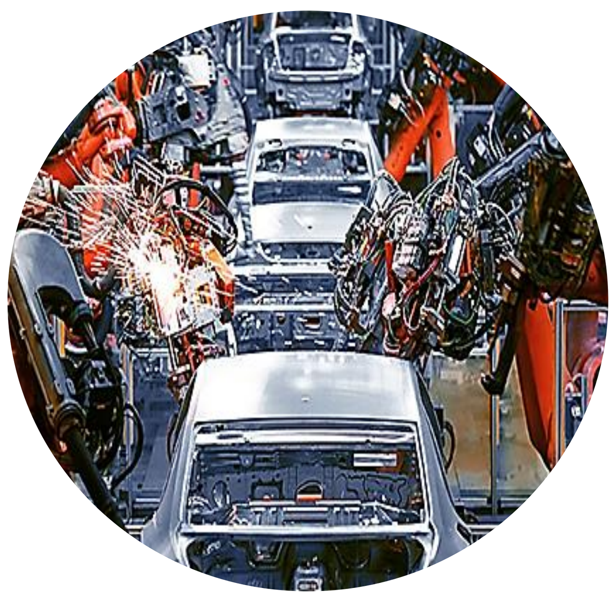


Figure 2. Industrial applications of the FSSW.

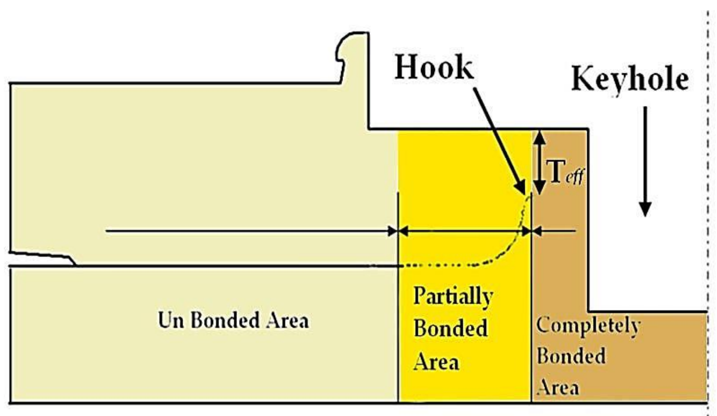


Figure 3. A cross-sectioned FSSW joint illustrating the structural defects included within the joint.

METHOD

FSSW lap-shear specimens were prepared in lap configuration from AA6061-T6 aluminum alloy sheets with a thickness of 1.8 mm. A guide hole of 1.5mm in diameter and 2.5mm in depth was made at the center of the lap area of each lap shear specimen, as shown in Figure 4. As-received GNPs with lateral sizes of 1–10 µm and thicknesses of 3–9 nm were prepared, as shown in the FE-SEM micrograph in Figure 5. The guide holes were fully filled with the GNPs.

Two welding tools made of H13 tool steel were prepared and hardened to 48–50 HRC. The tools were machined to an identical shoulder diameter of 12 mm and different pin profiles, cylindrical and threaded pins, as shown in schematic Figure 6.

The FSSW process was carried out for two sets of specimens using the two prepared welding tools using The MAHO MH 400T, CNC milling machine (Germany, Bavaria).

Tensile test was conducted and the average of three specimens was used to evaluate the tensile shear fracture load (TSFL).

A standard fatigue test was conducted at different load levels and the average of three specimens was used to evaluate the number of cycles to failure at each load level. The test was conducted on an MST 809 Axial/Torsional Test System (USA, Eden Prairie, Minnesota) at a sinusoidal stress ratio of R = 0.1 and a frequency controlled from 10 to 30 Hz, depending on the test load ranges. A fatigue life of 10^4 is considered as a dividing limit between low and high-cycle fatigue conditions. This categorization is specific to this study and is intended to facilitate understanding of fatigue behavior at different load levels of the fatigue test.

As welded joints from both welding conditions were cross-sectioned, wet grinded, polished, and etched depending on the standard metallurgical procedures.

OM and FE-SEM facilities were utilized to characterize the morphology of the welded joints.

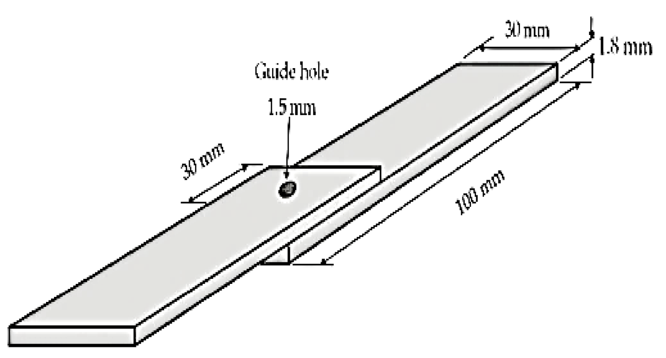


Figure 4. Lap-shear specimen with guide hole.

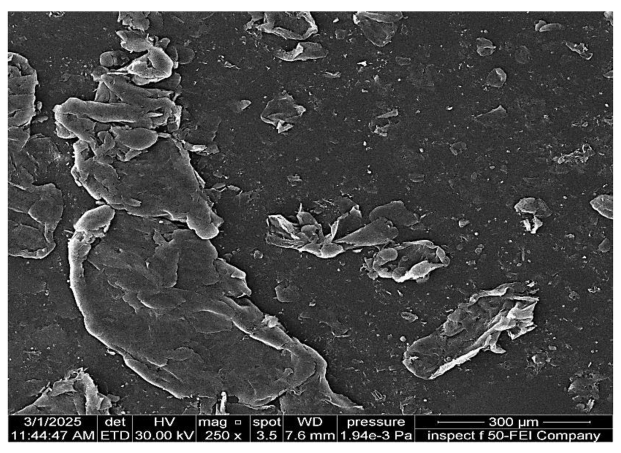


Figure 5. FE-SEM micrograph of as-received GNPs.

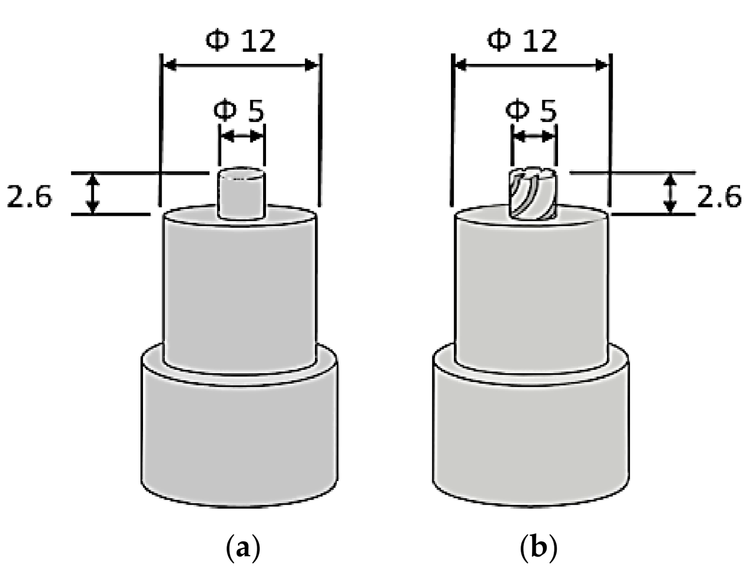


Figure 6. Schematic of the FSSW welding tools: (a) simple cylindrical pin tool; (b) threaded pin tool.

RESULTS & DISCUSSION

Micrograph

Employing the cylindrical pin tool during welding resulted in continuous GNPs agglomerations in the welded joints' SZs due to decreased stirring effect away from the welding tool pin, as shown in the OM and FE-SEM micrographs of Figures 8a and 9a, respectively. On the other hand, micrographs of Figures 8b and 9b show a significant improvement in the GNPs distribution within the SZ, lower inclusion of scattered agglomerations achieved by the more efficient stirring effect of the threaded tool pin compared to the cylindrical one.

Figure 7. OM micrograph of a GNP-reinforced FSSW joint.

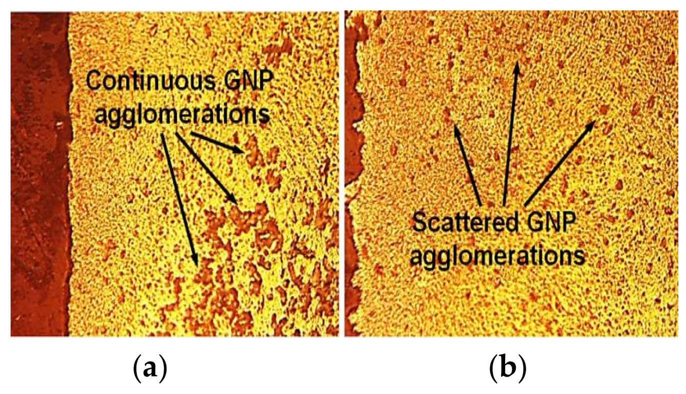


Figure 8. OM micrographs of SZs of FSSW joints performed by: (a) simple cylindrical pin tool; (b) threaded pin tool.

Tensile Strength

Using the threaded pin tool resulted in a tensile strength improved by nearly 32% compared to the cylindrical pin tool. This improvement is achieved by the uniform distribution of the GNPs within the SZ, and the consequent low content of scattered agglomerations associated with the higher stirring efficiency induced by the threaded pin. Therefore, tensile strength is related to morphological purity in the SZ and lower content of voids, which are typical sites for stress concentration and potential sources for developing and propagating shear cracks.

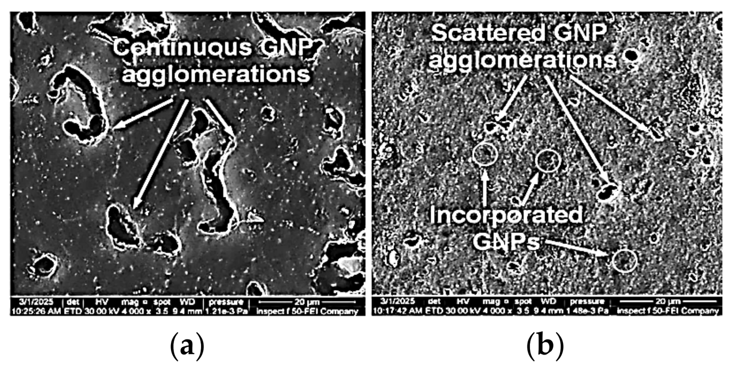


Figure 9. FE-ESM micrographs of SZs of FSSW joints performed by: (a) simple cylindrical pin tool; (b) threaded pin tool.

Fatigue Strength

Fatigue test results revealed an improved fatigue strength of 40% – 24% exhibited by the threaded pin tool over the cylindrical pin tool at the low and high-cycle fatigue conditions, respectively, as shown in Figure 10.

This improvement is attributed to the higher stirring effect induced by the threaded pin tool compared to the cylindrical one, which significantly reduced the GNP agglomeration, thereby minimizing the formation of voids and brittle phases that typically shift the joint failure from ductile to brittle nature.

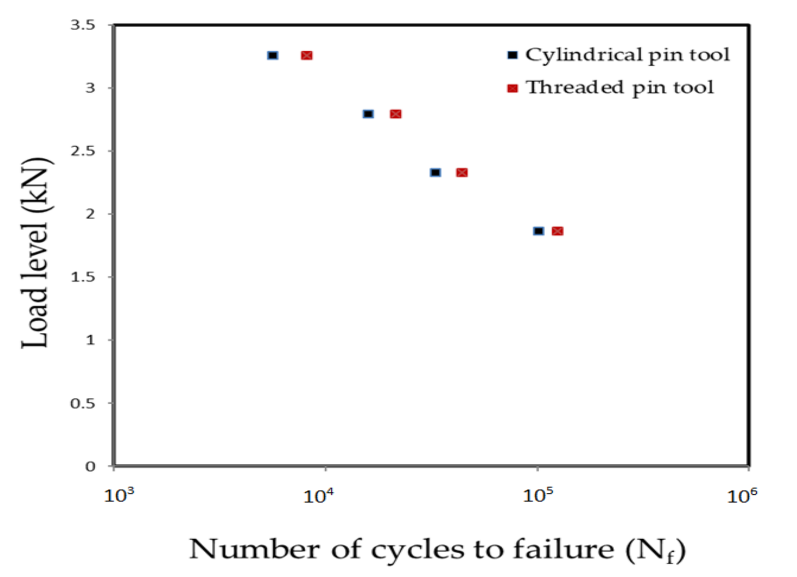


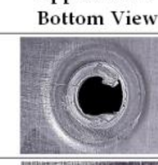
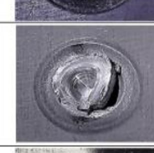
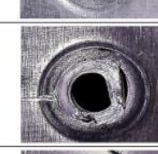
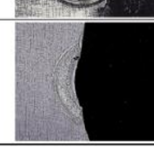
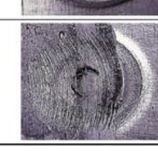
Figure 10. Experimental results of fatigue test.

Failure Modes

Shear fracture mode is observed in both welding conditions at low-cycle fatigue conditions. However, the nugget pull-out mode is observed at the end of the fatigue test for joints performed by the threaded pin tool. Whereas, at high-cycle fatigue conditions, specimens from both welding conditions exhibited a circumferential failure mode, and a lower sheet transverse fracture was observed while testing joints welded by the threaded pin tool, as shown in Table 1.

Worth noting that shear fracture mode is associated with lower strength joints, while joints of higher strength usually exhibit circumferential failure mode and lower sheet transverse fracture.

Table 1. Summary of failure modes observed during the fatigue test of FSSW joints performed with a cylindrical and threaded pin tools.

Failure Mode	Lower Sheet Top View	Upper Sheet Bottom View	Welding Condition
Shear Fracture			Cylindrical pin Tool Low-cycle Ftigue
Nugget Pull-out			Threaded Pin Tool Low-Cycle Fatigue
Circumferential			Threaded Pin Tool High-Cycle Fatigue
Lower Sheet Transverse Fracture			Threaded Pin Tool High-Cycle Fatigue

CONCLUSION

- GNPs were successfully incorporated within the SZs of the FSSW welded joints by utilizing both cylindrical and threaded pin tools.
- The FSSW joints performed by the threaded pin tool exhibited tensile strength improved by nearly 32% compared with the cylindrical pin tool.
- An improvement varying between 40% – 24% was achieved in fatigue strength by using the threaded pin tool at low and high-cycle fatigue conditions over that of the joints performed by the cylindrical pin tool.

FUTURE WORK

There is still a need for further research to enhance the static and fatigue properties of friction stir spot weld joints. In this context, it is important to study the effect of the volumetric ratio, type of nanoreinforcement material, and welding parameters on the feasibility of nanoreinforcement of friction stir spot weld joints.