An innovative industrial approach of SFSW technology on AA6061

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In the present study, an innovative industrial approach of submerged friction stir welding (SFSW) technology on AA6061 was investigated. This state-of-the-art nano-submerged FSW method is applied to advanced manufacturing and industrial sectors to enhance weld strength. The solid-state joining of aluminum alloy plates of AA6061 reinforced with titanium dioxide nanoparticles via SFSW butt welding was performed. Nano-SFSW meticulously considers the addition of TiO_2 nanoparticles into the abutting edges of the base material. The tool traversing speed played a predominant role in improving the mechanical properties of the joints. The tool rotational speed (ω) and transverse speed (ϑ) were varied from 1000 to 1200 rpm and 25–40 mm/min, respectively. Two different pitch welding conditions, nano SFSW and SFSW, were evaluated. Mechanical testing illustrated that hardness and tensile strength were enhanced, with the highest tensile strength reported as 284 MPa and hardness as 165 HV. Microstructural and metallurgical studies revealed that the weld nugget grain size diminished, and SEM and TEM microstructures showed very fine grains and uniform distribution of TiO_2 nanoparticles. This development in welding technology, particularly for clean energy processes, facilitates various joints, especially non-homogeneous joint nanocomposites.

KEYWORDS: SUBMERGED; FRICTION STIR WELDING; NANO-PARTICLES; TITANIUM-DIOXIDE

INTRODUCTION

Welding is the most widely used fabrication technique in the manufacturing industry, Rajak et al. briefly explaining their mechanisms to show a comparison between friction welding (FRW) and friction stir welding (FSW) [1]. FSW was invented by Thomas WM at TWI UK in 1991 to overcome the fusion welding problems. Shahabuddin et al. have been indicated that submerged friction stir welding is a latest technique which is widely acceptable in the industries like Aerospace and Shipbuilding for joining of different aluminum alloy series such as (6xxx,7xxx,8xxx) due to the light weight and high strength. It is very difficult to weld these alloys by using fusion method so, friction stir welding is introduced and it is widely taken into consideration for performing such welding process [2]. Sabry and El-Kassas have been illustrated that four stages during friction stir welding (FSW) have been carried out: the plunging stage, the dwelling stage, the welding stage, and the escape or retracting stage of the tool. The FSW procedure is essentially carried out by plunging a spinning FSW mechanism unit through the interface of two rigidly clamped sheets before the shoulder meets the surface of the material being welded [3]. Wahid et al. have been studied that the travel of the unit progresses

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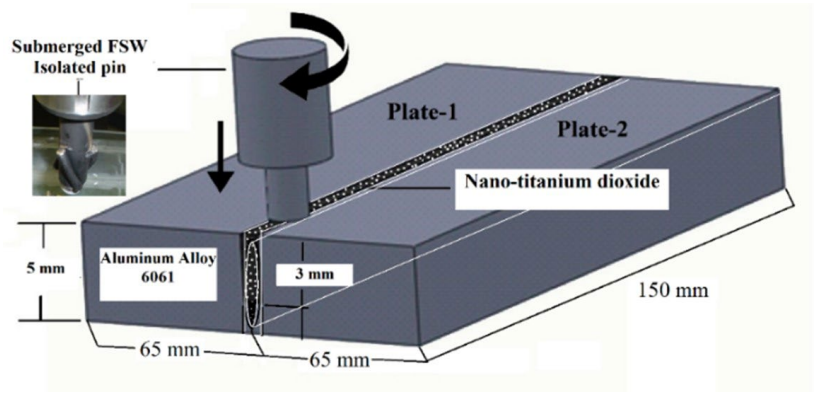
along the weld line allowing the material to displace from the advancing side to the retracting side. Meanwhile, the tool shoulder consolidates the material at the back of the pin, resulting in a stable state [4]. El-Kassas and Sabry, compared to other conventional welding processes, FSW process uses a significant amount of energy. The absence of flux or cover gas makes the process environmentally safe [5]. As well as Sabry et al. have been described that they are critical in producing heat generation, forging strain, the flow of material, welding appearance, and performance. As an outcome of dislocation density increase, the nugget area has high stiffness at higher speeds [6]. After this, Kucukomeroglu et al. and Imam et al. investigated the area of FSW research is broadening, and their excellent performance either in the joining of similar material or dissimilar material documented [7,8]. Magalhaes et al. and Meng et al. explored that FSW successfully used in various industries, including railway, automobile, defence, aerospace and renewable energy [9,10]. Kumar et al. have studied the parametric control of rotation speed, transverse speed, and pin length during underwater friction stir welding (UW-FSW) on aluminum AA6063 and indicates that the proposed optimization module efficiently controls the varying process parameters to achieve conflicting response values. It is highly efficient to manufacture high-efficiency welded joints and is recommended for optimum joint qualities [11]. Meikeerthy et al. observed the pure titanium welded joints produced by underwater FSW was evaluated and the mechanical properties such as yield strength, tensile strength, and hardness are improved in UW-FSW when compared with conventional FSW. As well as the effect of other prominent ceramic nanoparticles like Alumina (Al_2O_3), TiC, TiO_2 as reinforcement in the FSW process also has been reported by several researchers [12]. Singh et al. examined the effect of Al_2O_3 and TiO_2 nanoparticles reinforcement in the FSW of AA6061-T6. It can be observed that Al_2O_3 reinforced joints, nanoparticles distribution, are more uniform with no surface defect. While in the case of TiO_2 reinforced joints, agglomerated nanoparticles observed in the heat-affected zone on the advancing side, which is attributable to a reduction in heat transfer between the tool and deformed plasticized materials [13]. Fragmentation, in the case of TiO_2 reinforced joint is fewer than that of Al_2O_3 reinforced joints have been described by Derazkola and Simchi [14]. Vimalraj and Kah demonstrated that homogeneous distribution of carbide nanoparticles (i.e., SiC and TiC) in joints requires slow traverse speed and high rotation speed; however, in the case of oxide nanoparticles (TiO2), an increase in number of passes is required [15]. Manjunath et al. performed that double pass FSW-friction stir welding on 6061 T6 and 7075 T651 alloys of aluminium matrix reinforced with nano h-BN have been analyzed and deploying a range of welding parameters specifically tool spindle speed, tool traverse feed, and tool profile [16]. Singh and Singh et al. indicated that the solid-state joining of AA6061-T6 Al_2O_3 and TiO_2 nanoparticles via friction stir welding was done. Results reveal that the weld without nanoparticle welded at many FSW conditions, while in the case of weldments With Al_2O_3 Nanoparticle (WAL) and With TiO_2 Nanoparticle (WTI)), the working window was narrower [17,18]. The welds reinforced with Al_2O_3 and TiO_2 nanoparticles were inspected visually and at macroscale level for outward imperfections that depend on the flow behaviors, localized heat input intensity, and welding parameters Singh et al.[19]. The surface appearances of the TiO_2/FSW weld reveals the non-homogenous rough surface with the flash formation in the advancing side (AS) and retreating side (RS) of the weld. This was attributed to the inadequate heat generation and fast cooling rate occurred due to stiffer TiO_2 particles that provide more restriction against the movement of the FSW tool in the transverse direction Gangil et al. [20].While the surface appearance of Al_2O_3/FSW weld shows the smooth well forged surface appearance with no visually inspected particle agglomeration on either side of the weld zone (NZ) representing the perfect defect-free weld. Singh et al. are considered while the Al_2O_3 and TiO_2 nanoparticles agglomerations were observed when the tool rotational speed was further increased with the decrease in traverse speed. Despite the difference in nanoparticles, the particle distribution is not inherently sensitive to the particle type. Such that the type, size, volume fraction, and shape are all significant to determine the properties of nanocomposites or welds. [21,22]. Sufian et al. microhardness results reveal that appreciable enhancement in material strength for WTI weldment is ascribed due to a decrease in nanoparticle size according to the Hall-Petch relationship. [23]. No previous study on nano-submerged FSW processing of

AA6061/TiO_2 welds has been reported. This research fills that gap by evaluating the microstructure, metallurgical, and mechanical properties of nano-submerged FSWed AA6061/TiO_2 joints.

MATERIALS AND EXPERIMENTAL PROCEDURES

Thin sheets of AA6061 aluminum alloy were selected as the parent material. TiO_2 nanoparticles (rutile-reinforced) with 99.9% purity and an average particle size of 30 nm were used as reinforcement. Rutile is a low-cost, readily available mineral with superior mechanical properties, corrosion resistance, wear resistance, and higher thermomechanical properties. The schematic of SFSW Al 6061 with TiO_2 reinforcement and the isolated pin tool location are shown in Fig. 1.



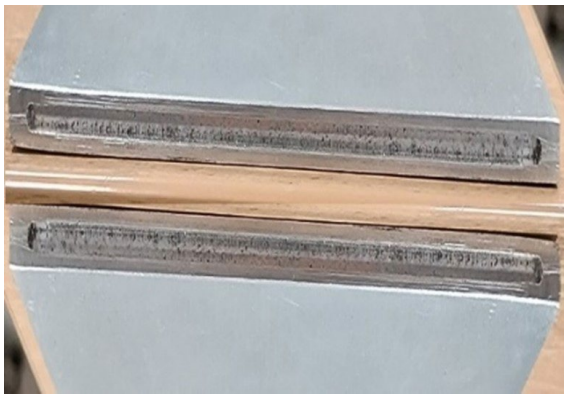


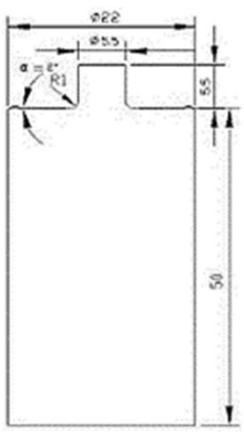
Fig.1 - (a) Schematic of the Nano-SFSW (b) The location of TiO_2 nano-particles.

The quality of FS welded joints is influenced by several factors, including rotational speed, tool traverse speed, axial force, tool geometry, material, tilt angle, backplate material, and workpiece material. This work identified three process variables: rotational speed, tool traverse speed, and welding condition (Nano-SFSW and SFSW).

Process Steps:

1. Simulate a seawater environment
2. Design special tools for SFSW
3. Improve tool properties via heat treatment for water environment use
4. Add TiO_2 nanoparticles to abutting edges of the base material
5. Cut weld samples for mechanical testing
6. Observe weld microstructure using optical microscopy and SEM

Fig. 2 illustrates the aluminum alloy joint welded simulation and pin tools.



(a) (b)

Fig.2 -The SFSW and dimensions (a) The nano SFSW(b) Tool pin

Tools made of H13 low-alloyed carbon tool steel were heat treated to improve properties. The novel technique was applied to Al 6061 strips (150×65×5 mm³) in butt welding positions, with the chemical composition shown in Table 1. For the first time, 0.2% TiO_2 (30nm) reinforcement particles were used in submerged FSW. The tool rotational speed (ω) and transverse speed (ϑ) were varied, with different welding conditions given in Table 2.

Tab. 1 – Chemical composition of AA6061 (Wt.%)

element	AL	Mg	Si	Fe	Cu	Cr	Zn	Ti	Mn
%	97.6	1.0	0.5	0.3	0.2	0.15	0.10	0.10	0.05

Tab. 2 – Welding conditions for different samples

ω /ϑ	ω (rpm)	ϑ (mm/min)	Welding Condition	No.
30	1200	40	SFSW	1
40	1000	25	SFSW	2
30	1200	40	Nano- SFSW	3
40	1000	25	Nano- SFSW	4

Figs. 3 scheme of mechanical and microscopy samples and the tensile specimens after wire cut from the weld joints.

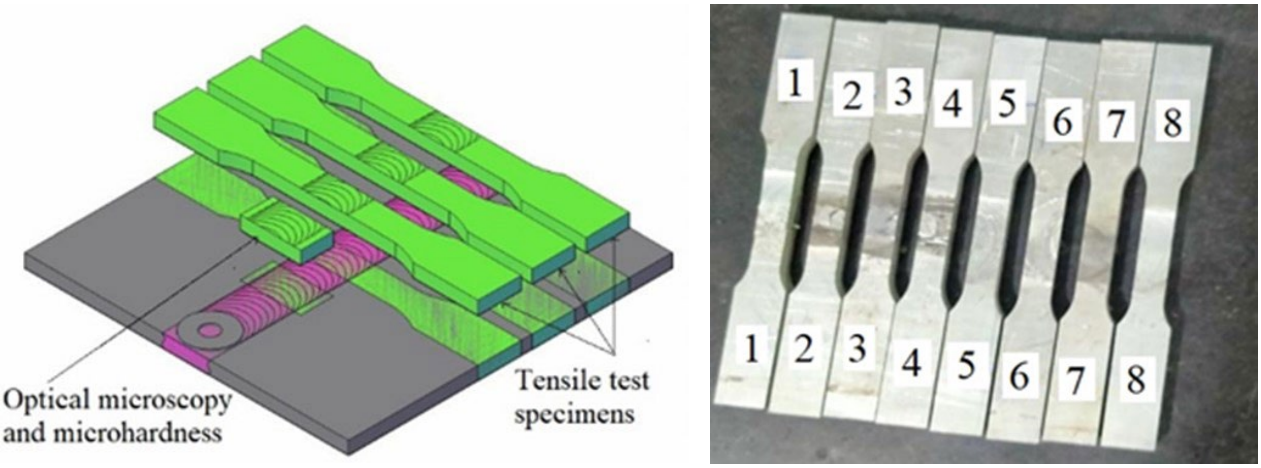
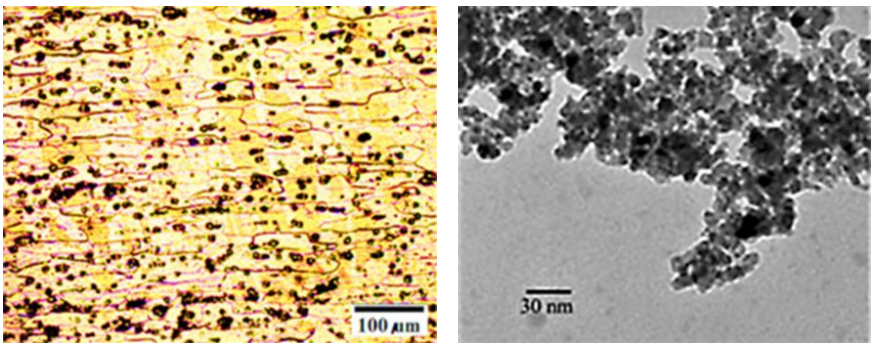


Fig.3 -(a) Scheme of mechanical and microscopy samples(b) The tensile specimens.

Mechanical tests, including hardness and tensile strength, were conducted on different samples. The tensile tests followed ASTM-E8M-11 at ambient temperature with a cross-head velocity of 2 mm/min. Microhardness profiles were evaluated using a Vickers microhardness tester (OMNITECH). Weld zone microstructures were analyzed using optical microscopy and scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS).

RESULTS AND DISCUSSION

The microstructure and mechanical properties of the base material were examined before SFSW. The volume fraction of nanoparticles was determined using Clemex image analyzer which comes out to be 0.2%. The microstructure of Al 6061 base material was shown in Figs.4 The characterization of the base material was depicted in optical microstructure of Al 6061 base material reveals and Transmission electron microscopy (TEM) images of TiO_2 nanoparticle have similar morphology of spherically shape irregular patterns, and mean grain size of 30 nm was evaluated using the William- Son-Hall method.



(a) (b)

Fig.4 -(a) Optical microstructure of Al 6061(b) TEM images of TiO2.

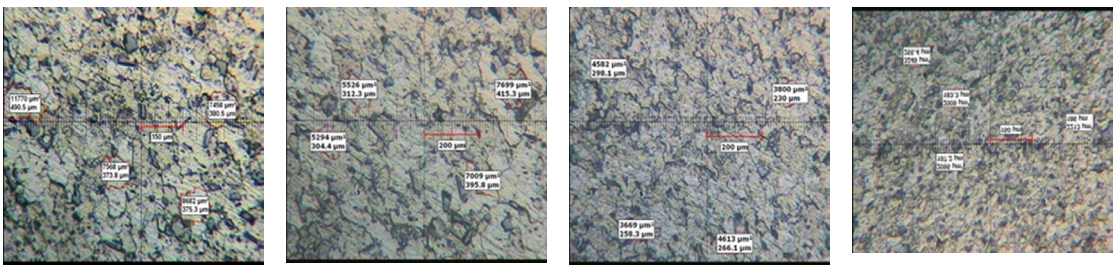
When the Nano-SFSW samples are compared with SFSW sample, the Nano-SFSW sample is without cracks and defects, and the quality of the welding surface is similar to each other.

The Nano-SFSW sample are free of cracks and defects and surface quality specimens similar as another sample that welded in SFSW. Table 3 Given the mechanical test of different samples. It can be seen that by increasing the pitch welding (ω /ϑ), the hardness, yield and tensile strength of weld metal in SFSW and Nano-SFSW condition increased. In addition, the hardness, yield strength and tensile strength of weld metal in Nano-SFSW as higher than the SFSW condition. The tensile strength of joints formed in Nano-SFSW is higher than those of SFSW and the highest tensile strength was reported as 284 MPa.Microhardness of the friction stir welded aluminum alloy joints was directly related to the amount of reinforcing TiO_2 nano-particles and grain size. The highest microhardness of nugget in the absence of TiO_2 nano-particles was HV110, which significantly increased to HV165 in the presence of TiO_2 nano-particles, for the 1000-1200 rpm specimen.

Tab. 3 – Mechanical test result SFSW and Nano-SFSW.

ω /ϑ	welding Condition	NO.	Hardness (HV)	Strength (Mpa)	Tensile Strength (Mpa)
1	SFSW	30	110	167	263
2	SFSW	40	125	175	273
3	Nano- SFSW	30	148	184	280
4	Nano- SFSW	40	165	190	284

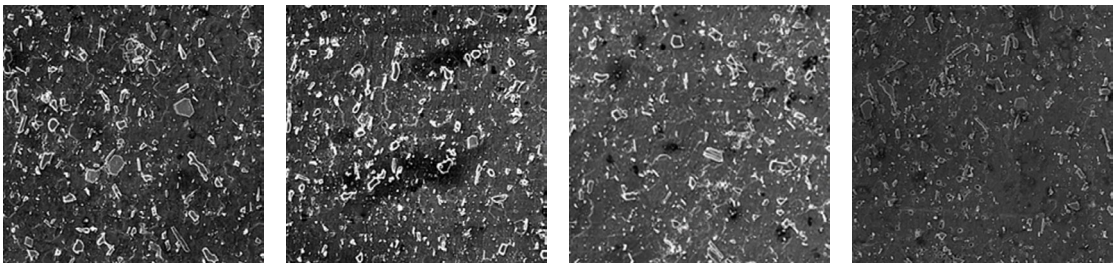
The microstructure weld metal by optic microscopy (OP) shown in Figs. 5. In SFSW condition with 30 and 40 grain size 82µ and 60µ were gained when two microstructure nuggets compared in Nano-SFSW condition with 30 and 40 pitch welding grain size 63µ and 47µ therefore grain size in Nano-SFSW condition has been decreased.



(a) (b) (c) (d)

Fig.5 -Optical microstructure nugget weld (a) SFSW 30 pitch welding, grain size 82µ(b) SFSW 40 pitch welding, grain size 60µ(c) Nano- SFSW 30 pitch welding, grain size 63µ(d) Nano- SFSW 40 pitch welding, grain size 47µ.

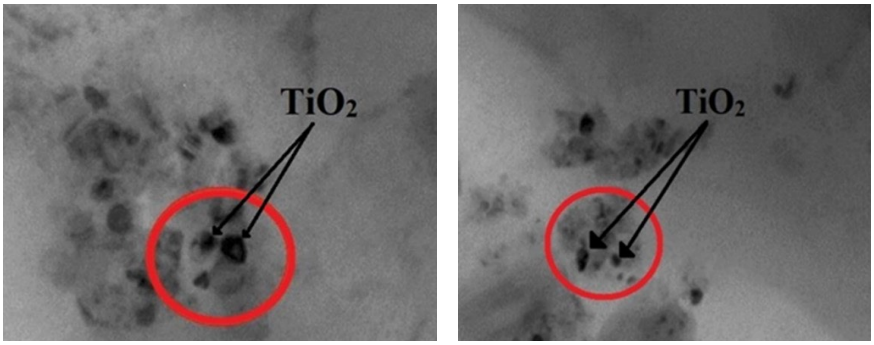
In figs. 6 the microstructure of weld metal result illustrated that scanning electron microscopy (SEM) microstructure approved that very fine grains and nano-TiO2 particles uniformly mix between the base materials.



(a) (b) (c)

Fig.6 -Scanning electron microscopy (SEM) nugget weld (a) SFSW 30 pitch welding, grain size 82μ(b) SFSW 40 pitch welding, grain size 60μ(c) Nano- SFSW 30 pitch welding, grain size 63μ(d) Nano- SFSW 40 pitch welding, grain size 47μ.

When considering microstructural formation, nanoparticles reinforcement in Al joints tends to reduce the grain size. With TiO_2 nanoparticles, the grain size in the joint has been reduced compared with grain sizes in joints without nanoparticles. By using TiO_2 nanoparticles with a single pass, the grain size has been slightly reduced compared to the grain size attained without nanoparticles. However, the grain size was further reduced by increasing the number of passes on the joints with TiO_2 nanoparticles. Nano-SFSW the grain sizes in the weld nugget with the TiO_2 nanoparticles further grain size reduction (50μ) when compared to SFSW the TiO_2 nanoparticles (88μ). This could be due to the size of the TiO_2 nanoparticles in SFSW (20–25 nm) and the size of the TiO_2 nanoparticles in Nano-SFSW (5–10 nm). Moreover, no agglomeration of TiO_2 nanoparticles was found in the joints, as shown in (Fig. 7).



(a) (b)

Fig.7 -TEM microstructure (a) size of the TiO_2 in SFSW (20–25 nm) (b) size of the TiO_2 in Nano-SFSW (5–10 nm)

Nano-SFSWed samples exhibited better tensile properties than SFSWed joints due to enhanced grain refinement and uniform TiO_2 distribution. The highest tensile strength and hardness were observed at a higher tool rotational speed (ω=1200 rpm) and traverse speed (ϑ=40 mm/min).

CONCLUSIONS

This study explored an innovative industrial approach of SFSW technology on AA6061. The incorporation of TiO_2 nanoparticles led to significant improvements in mechanical properties. The following conclusions can be drawn:

- Nano-SFSWed AA6061 joints exhibited enhanced mechanical properties compared to conventional SFSWed joints.
- Uniform distribution of TiO_2 nanoparticles contributed

to increased hardness and tensile strength.

• Optimal welding conditions for the highest mechanical properties were identified as ω=1200 rpm and ϑ=40 mm/min.

The findings suggest that Nano-SFSW is a promising technique for improving the mechanical properties of aluminum alloy joints in various industrial applications.

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