A Study on the Effect of Sic and Ticn Reinforcements on Mechanical and Microstructural Properties of Friction Stirred Al 6061 Alloy

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Abstract: -

The friction stir processing (FSP), its pass counts, and the inclusion of hardened particles (SiC and TiCN) were studied for their effects on the micro hardness, wear characteristics, and tensile performance of the Al6061 aluminium alloy. To examine the microstructure of the alloy, FSPed composite samples, optical microscopy were used. After a single FSP pass, microscopic examinations showed that the SiC and TiCN particles were not evenly distributed throughout the matrix. However, a significant improvement in the distribution of the SiC and TiCN particles was seen when the pass number was increased. The use of FSP caused a general softening in comparison to the base metal. The coarsening of Mg_2Si was likely to blame for the Al6061 alloy softening. The FSPed samples' tensile strength was significantly lower than that of the basic metal. As the addition of TiCN particles increases the wear behaviour and hardness of composite compared to the inclusion of SiC particles, applying a higher pass number of the process and also adding the toughened particles increased the micro hardness and wear behavior of the samples.

Keywords: Friction stir processing, Al6061 alloy and mechanical properties

1. Introduction

Extremely optimised Materials that are needed for better engineering designs with high output efficiency now need to have mechanical qualities. Aerospace, automotive, defence, and other transportation-related industries call for these more efficient qualities, which calls for the use of aluminium alloys. One of the properties of aluminium alloys is their high thermal conductivity. They also have exceptional strength and durability, as well as high wear. Composites are used in place of conventional materials to improve wear resistance and other qualities. Unreinforced alloys cannot be used to improve certain penurious qualities, hence a specific form of composite has been designed. For the specific components utilised in various applications, these composites will provide greater and better qualities. Among the newest and oldest structural materials are composites. The more traditional definition of a composite is simply the blending of two or more monolithic materials to address some flaws in a specific usable component. Following this approach, bricks were constructed in the past using clay and straw. Similar to this, common steel that has been painted to prevent rust might be thought of as a composite. In general, composites of some type make up practically all engineering materials. The idea of merging two different types of materials has expanded in significance in modern technology. Traditional monolithic materials aren't always able to combine strength, stiffness, toughness, and density in a desirable way. Because of their low density to higher specific strength, wear resistance, good creep resistance, and high corrosion resistance, composite materials are preferred to traditional materials. Two or more different materials are combined to create composite materials, which have superior mechanical and thermal qualities.

The newest method of solid state fabrication, known as friction processing, is used to change the characteristics of the faces of metal matrix composites. A metal's characteristics can be altered via the friction stir processing

(PSP) method by undergoing significant, localised plastic deformation. This deformation is caused by forcing a non-consumable tool into the work piece and pushing the tool laterally through the work piece while rotating the tool in a stirring action. Friction stir welding, which is this method's predecessor, is used to fuse numerous pieces of metal together without producing the heat-affected zone typical of fusion welding. Ideally, this technique produces a microstructure with small, equidistant grains and mixes the material without altering the phase through melting. Some aluminium alloys can have superplastic characteristics due to the uniform grain structure and high angle separation. It refers to the metal's tensile and fatigue strengths. The micro hardness in the vicinity of the friction stir treated seam was practically tripled in experiments with continuously cooled magnesium alloy work pieces.

In friction stir processing (FSP), a rotating tool is attached to a single piece of material with a pin and a shoulder to enhance a specific property, such as increasing the material's toughness or flexibility, in a particular area of the microstructure of the material using fine grain of a second material with properties that enhance the first. Localized heating caused by friction between both the tool and the work piece causes the work piece to soften and plasticize. Material is moved from the front of pin to the back of the pin, producing a volume of processed material. The material goes through extensive plastic deformation during this process, which significantly refines the grain. FSP enables engineers to produce things like "high-strain-rate super plasticity" by altering physical properties without altering physical state. While combining with the second ingredient, the base material's characteristics are improved via the grain refining process. The qualities of the underlying material result from this. This makes it possible to swap out a range of materials for items that might need to meet additional challenging acquisition requirements. The technique is a subset of friction stir welding (FSW), which welds two pieces of various materials together using the same procedure without heating, melting, or altering the physical properties of the materials.

Yousef Mazaheri [1] et al studied about the effect of friction stir processing (FSP), its pass numbers and addition of nanoparticles on microhardness, wear behaviour and corrosion performance of the aluminium alloy. He used SiO2 as a nanoparticle and Al6061 as a foundation material to create a surface composite via friction stir processing. Investigated properties include microstructure, hardness, wear behaviour, and corrosion performance in comparison to base metal. Abhishek Sharma [2] et al studied about the Effect of exfoliated few-layered graphene on corrosion and mechanical behaviour of the graphitized Al–SiC surface composite fabricated by friction stir processing. Using friction stir processing, he created a hybrid composite using Al6061 with a plate thickness of 6mm. He discussed the effects of friction stir processing parameters on the development of the microstructures and corrosion behaviour of Al-SiC surface composites made with graphitic flakes present in his study. K.M. Mehta [3] et al studied about the wear behaviour of boron-carbide (B4C) reinforced aluminium surface composites fabricated using Friction Stir Processing (FSP). In this investigation, B4C particles (800 mesh) were employed as reinforcement media, while Al-6061-T6 was used as the base metal. The direction of subsequent processing passes (0° & 180°) was changed for different specimens, leading to the reversal of the processing passes' direction. N. Fatchurrohman [4] et al carried a research on surface Roughness and Wear Properties of Al–Al2O3 Metal Matrix Composites Fabricated Using Friction Stir Processing. The nugget zone of both samples had a micro-hardness that was highest between 85 and 88 Hv. Kshay B R [5] et al studied about the mechanical Properties of Friction Stir Processed Al6061-BN Surface Composite. In this study, the researcher examined the microstructure, hardness, and tensile behaviour of an FSPed Al6061 composite by altering the number of passes (1, 2, and 3), as well as the proportion of Boron Nitride used as reinforcement, which ranged from 0 to 6 wt% in increments of 3 wt%. Jun Qu[6] et al carried a research on Improving the tribological characteristics of aluminium 6061 alloy by surface compositing with sub-micro-size ceramic particles via friction stir processing. Al-6061-T651 was employed as the base metal in this investigation, and SiC and Al2O3 powders with nominal diameters of 200 nm and 300 nm each were used as reinforcements.

2. Experimentation and Methodology:

The main objective of this study was to create Hybrid Aluminium Metal Matrix Composites (HAMMCs) using the Friction Stir Processing method, as well as to examine the impact of SiC and TiCN particulates with a size of less than 30 m on the microstructure and mechanical characteristics of Al 6061-based HAMMCs under different passes (1 and 3), and compositions of SiC (100% vol.), SiC (70% vol.)+TiCN (30% vol.), and TiCN(100% vol.).

Consideration has been given to wear behaviour as well as changes in the physical and mechanical qualities. An experimental setup has been built to make it easier to prepare the necessary HAMMCs in order to meet the goals mentioned. It has been designed to investigate how changes in the percentage composition and the number of passes affect predictions of tensile strength, wear rate, and micro hardness. The Vickers micro hardness tester, computerised pin-on-disc wear testing machine, and universal testing machine have all been used in experiments after samples of various percentage compositions were prepared using the FSP process. To make sure the distribution of reinforcement in the matrix, an optical microscope has done a quick investigation of microstructure.

Firstly, Al6061 plates of 250*60*6.35 mm3 size were cut as the base materials and in order to insert SiC and TiCN reinforcements in the matrix, holes of 2 mm diameter and 3mm depth were created in a zig-zag way on the base metal as shown in figure.2.1, and then SiC and TiCN powders were filled into the holes. To perform FSP, H13 tool with required dimension is used.

Figure 2.1 Al6061 Plate

By adding reinforcements, we can increase the mechanical properties of Al6061. By changing the tool materials and tool pin profiles we can also increase the mechanical properties of Al606. There is no melting taking place during Friction Stir Processing and the surface produced is in the solid state itself due to the heat generated by the friction and flow of metal by the stirring action. In order to obtain the desired fine grain size, certain process parameters, like rotational and translation speeds, tool geometry etc., are to be controlled. Several investigations are being carried out in order to study the effects of these process parameters on the grain structure.

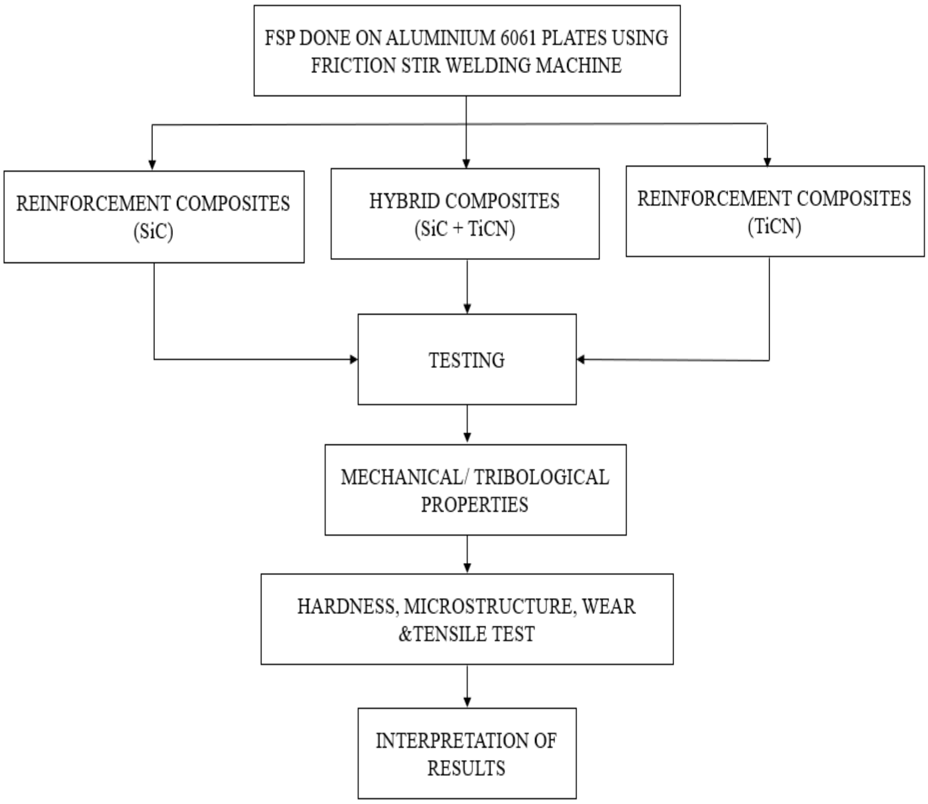

Figure 2.2 FSP Process Flow-Chart

The main objective of the present study is to increase the mechanical properties of Al6061 aluminium alloy, to get fine grained microstructure, to investigate the mechanical behaviour of Al6061 alloy using Friction Stir Processing (FSP). FSP is carried out using the Al6061 alloy by adding reinforcements as SiC (100% vol.), SiC (70% vol.) +TiCN (30% vol.) and TiCN (100% vol.) of particle size less than 30μm at different passes (1 and 3) by using process parameters such as traverse speed 70mm/min and rotational speed 1500rpm by using H13 tool. The experimental procedure has been summarized in the form of flow-chart in Figure 2.2 and the equipment used to develop the Hybrid Aluminium Metal Matrix Composites by using Friction Stir Processing is shown in fig 2.3.

Figure 2.3 Friction Stir Processing machine

The schematic experimental set-up with tool and Friction Stir Processed (FSPed) zone is shown in Figure 2.4 (a&b). From the rolled plates of 6.35 mm thickness, Al6061 Al alloy were cut into the required sizes of 250×60 mm and holes of 2mm diameter and 3mm depth with uniform spacing of 3mm in zig-zag way was made by using portable drilling machine.

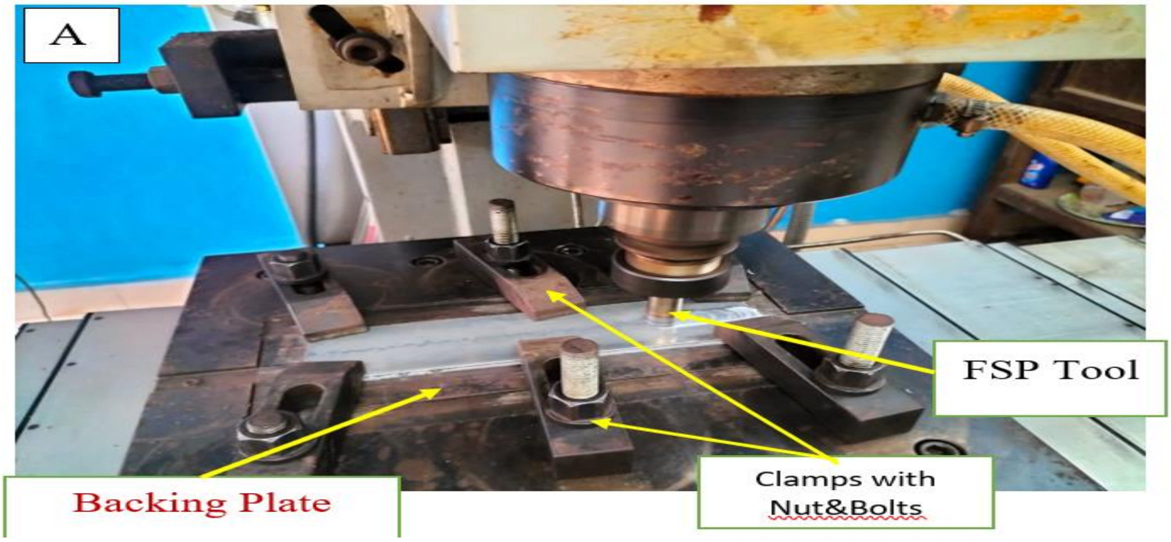

Figure 2.4 Macrograph showing the FSP on the Al6061 plate (a) Fixed on a chuck (b) FSP processed zone

After making the hole, the work piece is filled with reinforcements and the work-piece was clamped to the fixture of the Friction stir welding machine and the FSP is carried out with reinforcement by using the H13 tool with threaded tapered cylindrical probe of mm diameter pin, shank diameter of 15 mm and shoulder diameter of 18.5 mm.

The reinforcement of different volume percentages SiC (100% vol.), SiC (70% vol.) +TiCN (30% vol.) and TiCN (100% vol.) were filled in the holes as shown in fig 2.4 a. Then, the work piece was clamped to the fixture and the FSP is carried by using H13 tool. As tool descends to the work-piece, the rotating pin contacts the surface and friction was produced rapidly between tool pin and metal surface in turn heats and softens a small column of metal. The rotating tool with pin provides continuous heating of work-piece, plasticizing metal and transporting metal from the leading face of the pin to its trailing edge. During FSP, work-piece and the tool are moved relative to each other to process the required area. The processed zone cools, without solidification, as there is no liquid, thus forming a defect free metal matrix composite with fine grain microstructure. In the same way the experimental work of the remaining MMC's as shown in table 1 was carried out and the friction stir processed Hybrid Aluminium Metal Matrix Composites are shown in figure 3.8. Then the mechanical and metallurgical properties were found.

Table 1: Samples with their process parameters

specimen	composition	speed	feed	No. of passes
1	SiC(100% vol.)	1500 rpm	70mm/min	1 pass
2	SiC(100% vol.)	1500 rpm	70mm/min	3 passes
3	SiC+TiCN (70% vol.+30% vol.)	1500 rpm	70mm/min	1 pass
4	SiC+TiCN (70% vol.+30% vol.)	1500 rpm	70mm/min	3 passes
5	TiCN (100% vol.)	1500 rpm	70mm/min	1 pass
6	TiCN (100% vol.)	1500 rpm	70mm/min	3 passes

3. Results and discussions

In this chapter, the results and interpretations of tensile strength, hardness, wear behaviour and microstructural properties will be discussed at length. The effect of friction stir processing on the microstructure and strength in terms of hardness of Al 6061 MMCs are discussed here below.

3.1 Surface Roughness Evaluation

The value of the arithmetic average roughness, Ra, presented in Fig.3.1, shows the surface roughness of the Friction Stir Processed specimens. According to the average roughness overall result, the attributes of the average roughness decrease as the number of substrate passes increases. The figure's orange bar depicts the average roughness of single pass specimens of various reinforcements, while the blue bar in the figure depicts the average roughness of three pass specimens.

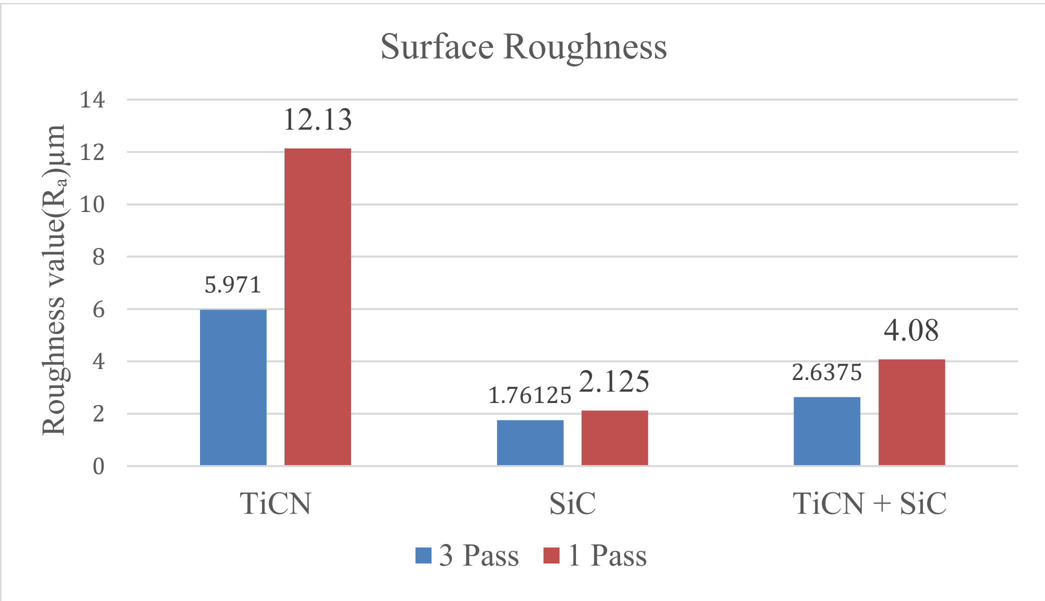

Figure 3.1 Surface roughness with various reinforcement compositions and number of passes

In comparison to single pass reinforced FSPed specimens, three pass reinforced FSPed specimens had a reduced average roughness. The three pass SiC reinforced specimen had an average roughness of 1.76 µm, while the single pass TiCN reinforced specimen had an average roughness of 12 µm. Due to the fact that TiCN particles are harder than SiC particles and the inclusion of toughened particles, the FSP method was able to produce surfaces with a higher degree of surface roughness. Because the composite's particle combination was evenly spread utilising the FSP method, the surface becomes smoother with a higher number of passes.

3.2 Optical Micrograph Analysis

The distribution of different phases and inclusions, which have a bigger impact on the mechanical and tribological properties, can be determined using the micro-structural research. In order to verify the outcomes, microstructural characteristics have been investigated using an optical microscope.

Microstructural characterization of Al6061

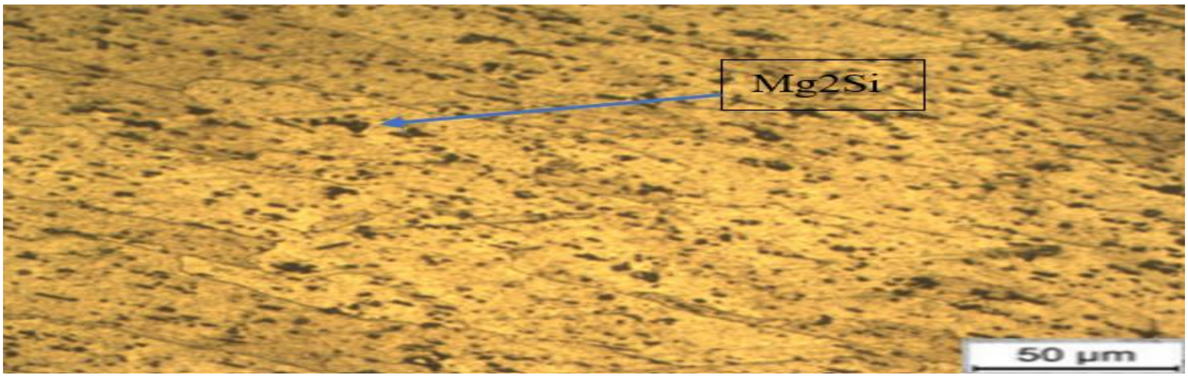

Figure 3.2 Optical micrograph of Al 6061

Figure 3.2 depicts the cross-section of an unreinforced treated Al 6061 sample. Due of the rolling to that the plate has been subjected, the cross-section's grains show some elongation. Mg_2Si Second-phase particles are evenly dispersed throughout the matrix and are orientated in the direction of rolling according to the Al6061 microstructure. Some of these particles are spherical, while others have a more rectangular shape.

Microstructural characterization of Al6061 with SiC particles

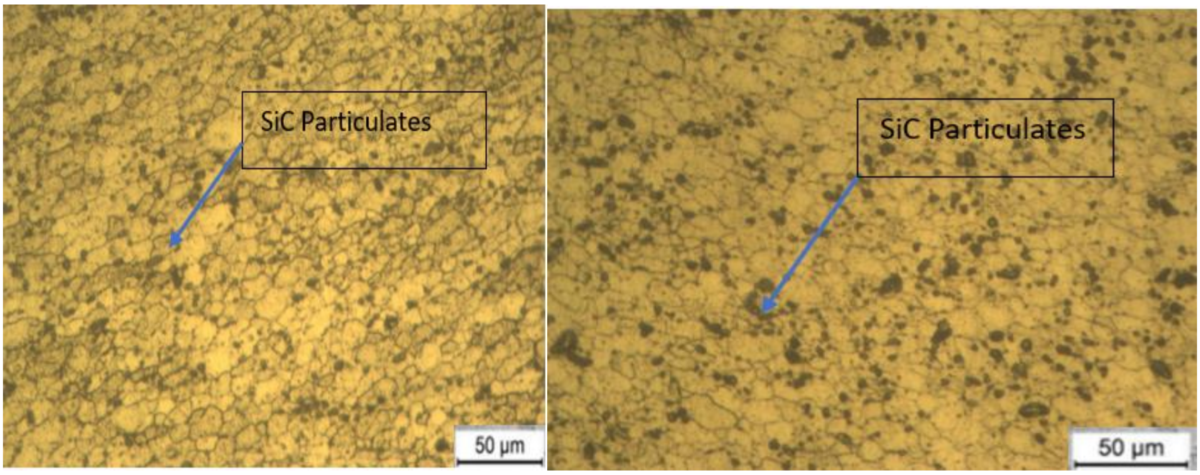

Figure 3.3 Optical micrographs of FSP Al6061-SiC single pass & three pass MMCs

Surfaces of metal matrix composites were visually examined for typical FSP flaws and material behaviour in response to applied stresses and heat input. All of the SiC-MMCs exhibit good aesthetics, are expertly forged, and have macroscopic flaws near the bottom of the cross section. There is no evidence of particle build up on their surface. Prior to sample preparation for microstructural investigation, the high-thickness burrs produced on three passing SiC-MMCs were easily automated.

Transversely sliced cross sections of MMCs were used to collect specimens for optical microscopy observations of particle distribution. From the two processing conditions that were used (single pass and three pass), it can be shown that more FSP passes lead to a less amount of reinforcing particles being incorporated in the matrix. This is explained by the fact that throughout processing, reinforcing particles are lost because they stay enmeshed in the burrs produced during each pass. In every instance, the majority of the SiC particles are seen to be moved to the advancing side and only partially centred in the FSPed zone, while the retreating side is devoid of embedded powder. Since surface characteristics determine tribological qualities, the near-surface layer is scrutinised for the existence of reinforcement.

Just below the surface, a transient particle aggregation is seen, which explains why wear behaviour has improved. The swirling action of the tool causes the SiC particles to break apart. This process causes a higher concentration of small, rounded particles to be present in the nugget region.

Microstructural characterization of Al6061 with TiCN particles

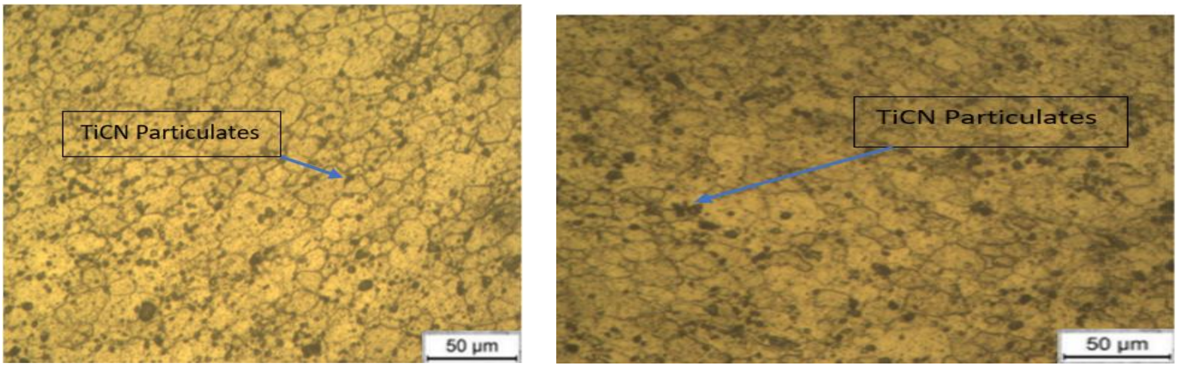

Figure 3.4 Optical micrographs of FSP Al6061-TiCN single pass & three pass MMCs

The TiCN-MMCs' produced surfaces are well-forged and free of flaws, according to visual assessment. TiCN-MMC cross sections on the FSPed zone have been observed, and they reveal that both the single-pass and three-pass particle distributions are uniform and symmetric with regard to the FSPed zone. For all the conditions examined with this kind of powder, the density of reinforcing particles is high at the near-surface zone. Although the three pass TiCN-MMCs exhibit a uniform particle distribution along the FSPed zone, the reinforce density is low, similar to earlier SiC-MMCs, due to the loss of powder embedded in burrs. It is seen that the intermetallic and reinforcement particles have undergone a fracture process, same like with FSPed-SiC. The fragmentation process is, however, less vigorous since the TiCN particles are tougher than SiC.

Microstructural characterization of Al6061 with SiC-TiCN hybrid composite

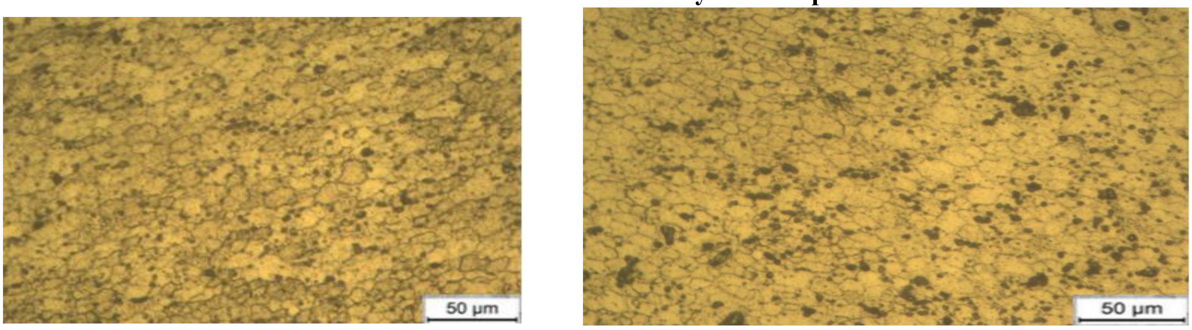

Figure 3.5 Optical micrographs of FSP Al6061-SiC+TiCN single pass & three pass

The SiC+TiCN-MMCs' produced surfaces are well-forged and free of flaws, according to visual inspection. Particle dispersion is homogeneous and symmetric with regard to the FSPed zone for single and three passes, according to observations of cross sections of SiC+TiCN-hybrid composite on the zone.

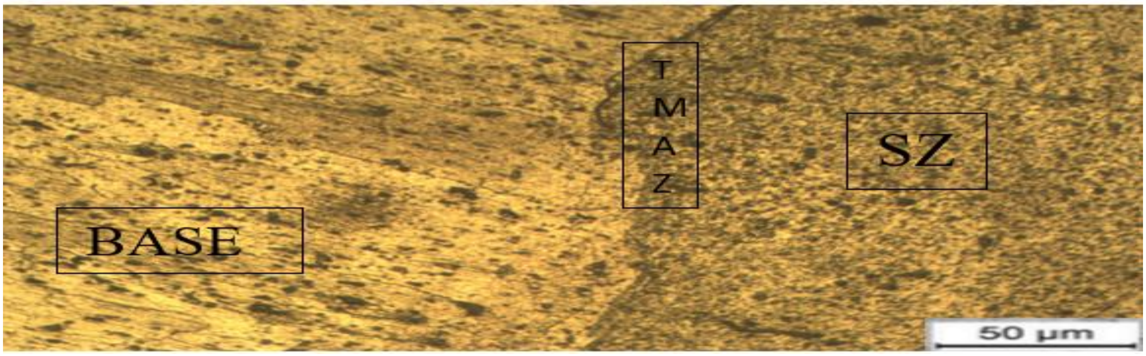

Figure 3.6 Optical micrographs FSP Al6061-MMC of various zones

The base substance has lengthy grains that are made up of a space encircled by a regular crystal lattice. The grains are as far away from the black lines as is physically possible. When considering the mechanical and metallurgical qualities, the grain's normal size is a crucial factor. A larger grain size prolongs creep, the endless winding that grows over time under a constant load. However, under the revised conditions, dynamic recrystallization resulted in the discovery of a fine and equiaxed grain structure in the stir zone (SZ). Multiple passes during friction stir processing may be responsible for the smaller grain size and even particle dispersion as a result of the increased number of passes.

As the mechanism of intermixing and complex material flow restricts this phenomenon to only one pass, several researchers [10,11] have also noted that it is exceedingly difficult to disperse the particles equally with just one pass. Therefore, for better particle distribution during FSP, several studies advised performing numerous passes. Particulates in the FSZ pin down the grain boundaries during recrystallization post-FSP, which prevents the grain boundaries from migrating. Particles prevent grain development, which leads to finer grains.

3.3 Micro-Hardness Evaluation

The hardness distribution of various samples fabricated by friction stir processing by changing the composition with different parameters are tabulated as below. This test was conducted by applying a load of 500gf for 8 seconds to indent on the various samples as given in the table 2. The test was repeated at three different places at the stirred zone of each sample and took average to obtain the hardness value accurately.

Table 2 Observations of Vickers hardness of various samples

S.No.	Sample	No. of Observations			Hardness (H_v)
1	Al 6061	103.5	107.63	105.96	105.7
2	TiCN 3 PASS	116.86	120.32	126.43	121.2
3	TiCN 1 PASS	115.83	118.96	108.28	114.35
4	SiC 3 PASS	102.7	110	110.37	107.69
5	SiC 1 PASS	109.56	106.56	103.98	106.7
6	SiC+TiCN 3 PASS	106.3	108.46	111.03	108.59
7	SiC+TiCN 1 PASS	110.23	109.5	102.54	107.42

Fig. 3.6 shows the microhardness characteristics of the FSPed samples and depicts the development of the Al6061 base metal's microhardness after one and three FSP passes with varying compositions. For all of the

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examples examined, micro-Vickers's tests demonstrate that the hardness value increases at the FSPed zone at material surface measurements.

The microhardness value of the Al6061 and FSPed surface composites of Al6061- SiC, Al6061-TiCN and Al6061-SiC+TiCN hybrid composites after single pass and three pass is shown in Fig.5.7. The mean hardness value of Al6061 base material was found to be 105.7 HV.

It is clear from Fig.3.7 that the normal hardness of Al6061-TiCN three pass FSPed was almost 121.2 HV, which is higher as compared to base Al6061 composite and other reinforced composites. As the increased number of passes increases the hardness value and also by varying different reinforcements affects the grain refinement which indirectly varies the hardness value of the composite.

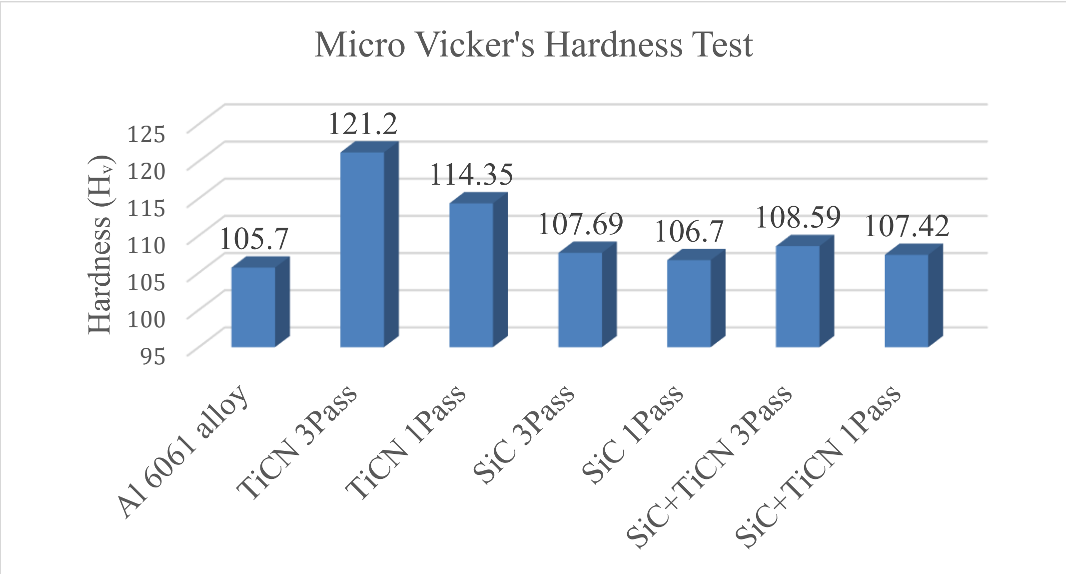

Figure 3.7 Micro Vickers hardness values with various reinforcement compositions and number of passes

Grain modification and re-precipitation of helper phase are the two fundamental contemplations which are liable for this expanded hardness of FSPed Al6061 compound. At first, base Al6061 compound has extended grains and tremendous intricate formed discretionary phase particles Mg_2Si which are then substituted by fine equiaxed grain structure and re-scattering of accelerates all through the mix zone by the thermo-mechanical method of FSP. Nevertheless, these secondary phase elements don't melt in the mix zone. Al6061 alloy strengthened with SiC and TiCN either uninhibitedly or in total structure displays an enhancement in the hardness multifaceted nature to FSPed Al6061 compound and baseAl6061 composite. The improved hardness is, all things considered, inferable from uniform movement of SiC and TiCN particulates brings about separations staying and quelling grain growth, extraordinary interfacial holding between the matrix and particles. Increase in hardness value in FSP is mainly due to the following factors

- Extensive grain reinforcement induced by dynamic recrystallization during FSP.
- Orowan strengthening due to addition of TiCN particles.
- Owing to uniform particle dispersion, grain size of the matrix drastically decreases.
- Restricted grain growth due to the pinning effect of TiCN and SiC particles on the grain boundaries.

3.4 Wear Test Evaluation

A "Pin-on-disk" testing equipment was used to conduct a dry sliding wear test. Before the test, all of the specimens were polished using SiC paper up to 1000 grading to have a comparable degree of roughness. The disc in use was a 140 mm diameter EN31 hardened steel disc. Radius of wear track was 50 mm. The sliding tests were performed at 3.4 m/s (650 rpm), for 10 minutes, with a normal force of 20 N and a sliding distance of 2042 m.

Table 3 Co-efficient of friction, Specific wear rate, Wear for base metal and different FSPed samples (TiCN-MMCs, SiC-MMCs, and SiC+TiCN-MMCs)

S.No	**Material**	**Co-efficient of friction (µ)**	**Specific wear rate (mm^3/N-M) x 10^{-3}**	**Wear (mm^3)**
1	Al6061 alloy	0.76	4.46	182.162
2	Al6061-TiCN MMC 1 PASS	0.524	2.813	114.89
3	Al6061-TiCN MMC 3 PASS	0.385	2.652	108.3
4	Al6061-SiC MMC 1 PASS	0.75	4.419	180.47
5	Al6061-SiC MMC 3 PASS	0.66	4.609	188.25
6	Al6061-SiC+TiCN MMC 1 PASS	0.42	3.512	143.43
7	Al6061-SiC+TiCN MMC 3 PASS	0.73	4.583	187.263

Wear = specific wear rate (SWR)*sliding distance*applied load

Friction coefficient

For base metal, the friction coefficient was measured (0.76 average value). Measurements of the friction coefficients between base metal and MMCs and sliding distance were plotted, and their curves were compared. It can be seen in Fig (3.8, 3.9, 3.10) that FSPed samples consistently display a lower friction coefficient than basic metal. For single and triple passes, TiCN powder produces the best results.

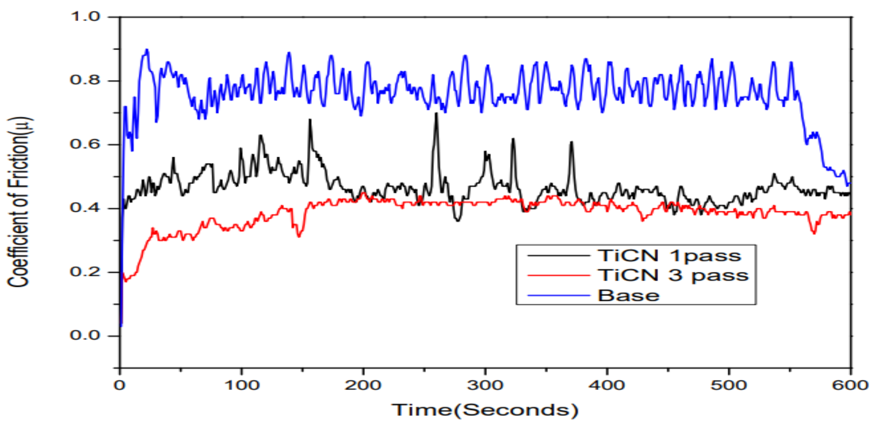

Figure 3.8 Variation of the friction coefficient with time for the TiCN-MMCs FSPed sample and comparison with base metal. Note: FSPed, friction stir processed; MMCs, metal matrix composites.

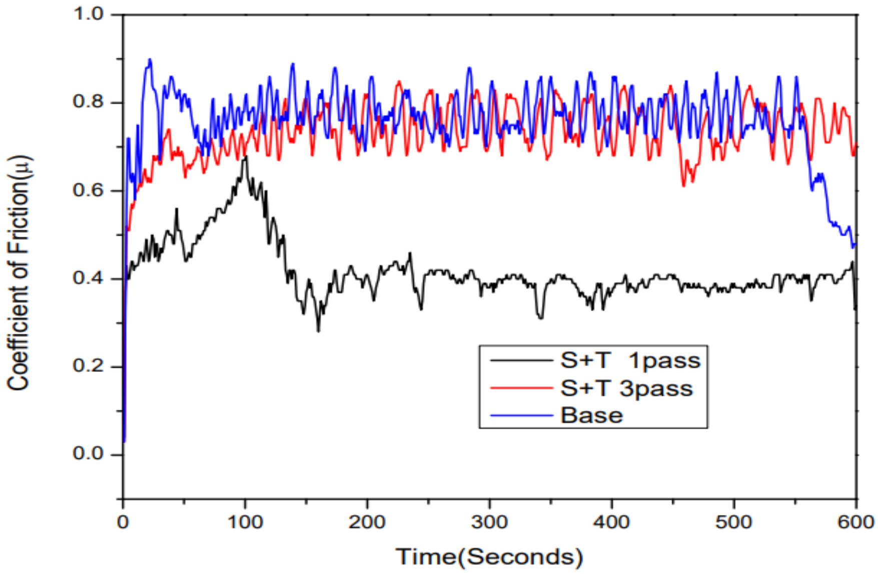

Figure 3.9 Variation of the friction coefficient with time for the SiC+TiCN-MMCs FSPed sample and comparison with base metal. Note: FSPed, friction stir processed; MMCs, metal matrix composites.

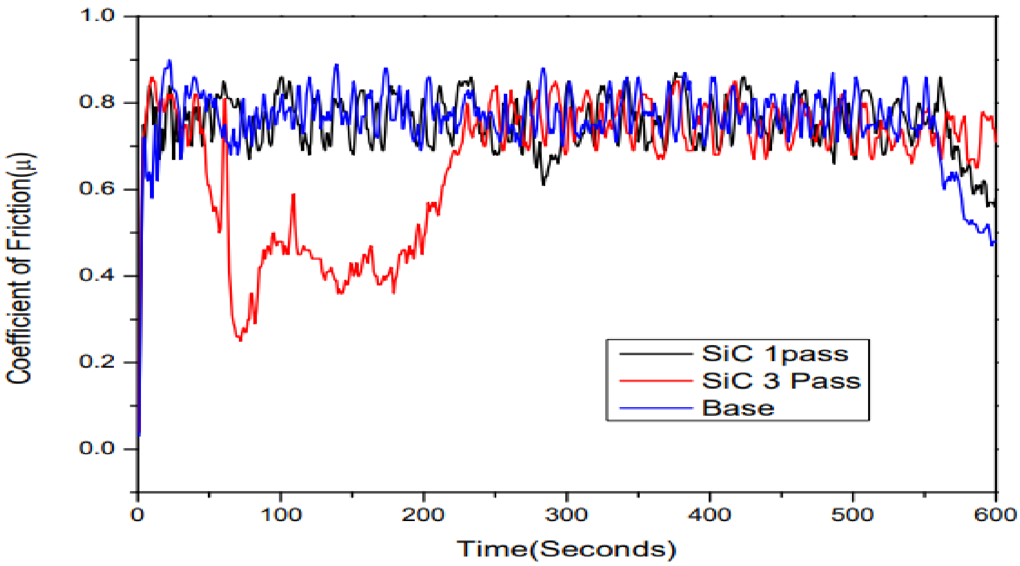

Figure 3.10 Variation of the friction coefficient with time for the SiC-MMCs FSPed sample and comparison with base metal. Note: FSPed, friction stir processed; MMCs, metal matrix composites.

Specific wear rate

The calculated base metal specific wear rate (SWR) was $4.46*10^{-3}$ mm^3/Nm. SWR was determined for each reinforced metal matrix composite, for both single pass and three pass construction, and the results were compared to the value of base metal. Table 2 depicts the difference in value compared to base metal, giving a visual means of assessing wear rate improvement or loss in comparison to the unprocessed alloy. However, with the exception of the Al6061-SiC three pass FSPed sample ($4.61*10^{-3}$ mm^3/Nm), FSPed samples always show a lower specific wear rate than the base metal.

From table 3, Al6061-TiCN three pass and Al6061-TiCN single pass FSPed samples are shown to significantly enhance wear resistance in the FSPed zone, with respective values of 2.652*10^{-3} mm^3 /Nm and 2.813*10^{-3} mm^3 /Nm. This is a result of the fact that under certain circumstances, a small particle aggregation can be seen just below the surface. Despite these findings, this behaviour is not seen when SiC particles are present. On single pass MMC, SiC reinforcement appears to have little impact on wear rate, while on three pass FSPed, it looks to be becoming worse. Since SiC powder results are inconsistent and it is challenging to spot patterns, it has been determined that TiCN and SiC+TiCN particles have a more predictable effect on wear rate. The general trend appears to be that, in the presence of TiCN particles, SWR improves for SiC reinforced MMCs with fewer passes and diminishes for those with more passes. This is due to the fact that SiC is less hard than TiCN particles, and the matrix softens as a result of the heat generated by subsequent passes, which affects wear rate.

3.5 Tensile Test Evaluation

According to the ASTM-E8 standard testing protocol, the tests were carried out using a computerised universal testing equipment. Table 4 lists the tensile parameters, including ultimate tensile strength and yield strength for all hybrid composites made of Al6061-SiC, Al6061-TiCN, and Al6061-SiC+TiCN at 1500 rpm and 70 mm/min surface rotation. Figure 3.11 depicts the Stress-Strain curves of Al6061-MMCs and the original Al6061 alloy.

Table.4 Tensile properties of Aluminum alloy surface composites.

S.no	Surface composite	Ultimate Tensile Strength(N/mm^2)	Yield Strength(N/mm^2)
1	Al6061-TiCN 1 pass	211.768	158.791
2	Al6061-TiCN 3 pass	213.859	131.402
3	Al6061-SiC 1 pass	202.858	127.314
4	Al6061-SiC 3 pass	201.025	119.22
5	Al6061-SiC+TiCN 1 pass	199.895	122.485
6	Al6061-SiC+TiCN 3 pass	215.679	148.244
7	Al 6061	216	205

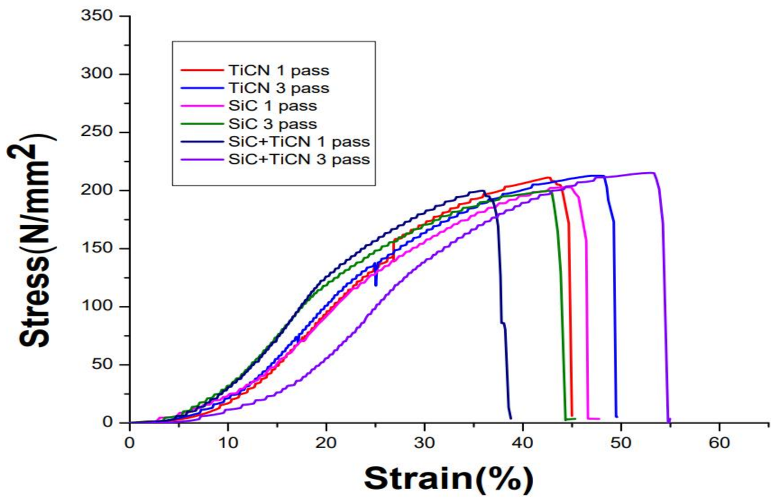

Figure 3.11. The Stress-Strain curves of the different FSPed samples (TiCN-MMCs, SiC-MMCs, and SiC+TiCN-MMCs) and comparison with base metal. Note: FSPed, friction stir processed; MMCs, metal matrix composites.

It was discovered that the use of friction stir processing causes a loss in ultimate tensile strength and yield strength when compared to the as-received Al6061 alloy. In addition, as was already indicated, matrix softening is caused by the FSP, and as the number of passes grows, so does the heat input. It would be assumed that the material's softening would increase elongation.

The grain boundary slipping and dislocation motion may be impeded by reinforcing particles like SiC and TiCN. Additionally, a loss of tensile characteristics is eventually caused by a poor interfacial interaction between the reinforcing particles and matrix [12]. In other words, a composite material has incompatible distortion between its stiff reinforcing particles and plastically deformed matrix, which results in the creation of dislocations that are geometrically required. Additionally, the addition of reinforcing particles enhances the effective slip distance of dislocation motion during deformation, resulting in less elongation.

4. Conclusion

The Al6061 aluminium alloy underwent FSP in several passes in this investigation. In order to create the surface composite, SiC and TiCN particles were also added to the alloy during FSP. The following are the study's primary conclusions:

1. Friction stir processing is an appropriate method for creating surface composite materials in alloys based on aluminium. Our findings demonstrate that the distribution of SiC and TiCN particles in the treated zone is remarkably uniform for three successive passes.
2. The FSPed Al6061 alloy has a harder surface than base metal, and three pass TiCN reinforced FSPed composite has a harder surface than single pass TiCN reinforced FSPed composite, three pass SiC reinforced FSPed composite, and single pass SiC reinforced FSPed composite.
3. Increase in hardness value in FSP is mainly due to the following factors

- Extensive grain reinforcement induced by dynamic recrystallization during FSP.
- Orowan strengthening due to addition of TiCN particles.
- Owing to uniform particle dispersion, grain size of the matrix drastically decreases.
- Restricted grain growth due to the pinning effect of TiCN and SiC particles on the grain boundaries.

4. With respect to the value of base metal, friction coefficient is decreased in all situations. As known the hardness and frictional coefficient plays an important role on wear resistance.
5. When TiCN reinforcing particles are employed in comparison to SiC reinforced composite and base alloy, the specific wear rate is lowered for the conditions of three pass FSP.
6. It was found that friction stir processing reduces the ultimate tensile strength and yield strength of Al6061 alloy when compared to the alloy as supplied.
7. The grain boundary slipping and dislocation motion may be impeded by reinforcing particles like SiC and TiCN. Additionally, a loss of tensile characteristics is eventually caused by a poor interfacial interaction between the reinforcing particles and matrix. An overall softening in comparison to the base metal was brought on by the use of FSP.

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