



IMPACT OF FRICTION STIR PROCESSING ON THE FUSION-WELDED AISI 304 STAINLESS STEEL JOINTS: MICROSTRUCTURE, MECHANICAL AND FRACTURE BEHAVIOURS

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Abstract

This work investigated the microstructure, mechanical properties, as well as fracture behaviour of the friction stir-processed fusion-welded AISI304 alloy. The AISI304 alloy plates were conventionally welded by a shielded metal arc welding (SMAW) technique in a regular butt geometry by using stainless electrode (AWS E308-16). Three rotational speeds of 710 rpm, 900 rpm, and 1120 rpm were utilised to perform the friction stir processing on the AISI304 weld zone using a cylindrical pinless tungsten carbide tool. The weld metals of the AISI304 austenitic stainless alloy plate were subjected to multiple surface FSP tool passes with lesser bulk plasticization. The results show that the non-uniform weld bead of the as-fusion-welded AISI304 joint was smoothed through the synergy of friction-induced metal shearing and plasticization effects. The inherent dendritic structures at the near-surface zones of the fusion welds were refined via tool-aided plasticization and dynamic recrystallization of the weld paths. The pinless tungsten carbide tool leaves a partially deformed zone (PDZ) and undeformed regions in the FSW-processed AISI304 joints. The increment in the tool speed (700 – 1120 rpm) improved the tensile strength of the FSW-processed AISI304 joints from 193 to 393 MPa. However, the highest tool rotational speed is better suited for the secondary processing of the hard as-fusion welded AISI304 joints due to the sufficient heat input required for plasticization.

Keywords: friction stir processing, AISI304 alloy, microstructure, mechanical property, fracture.

Introduction

High temperature/thermal gradient of fusion welding processes often leads to weld challenges such as pores, oxidation, solidification-induced micro/macro-cracks (or hot cracking), and coarsened columnar grain structures (Roeen *et al.*, 2021; Sabry *et al.*, 2025; You *et al.*, 2025). These defects reduce the weld strength of the weld zone by up to half of the base metal (Mehdi and Mishra, 2019). Mehdi and Mishra (2020) reported that the brittle inter-dendritic structure in the weld's fusion zone is accountable for the low tensile strength, hardness, and ductility of the joints. Xue *et al.* (2016) revealed that coarse martensitic and bainitic phases are formed in the fusion-welded steel. These brittle microstructures deteriorated the mechanical properties of the welds. Ferritic structure is, thus, the most desired phase in steel weld metal owing to its excellent toughness, but it exhibits lower strength compared to the martensitic and bainitic structures

(Xue *et al.*, 2016). The refinement of the ferrite phase is an ideal method for simultaneously improving the strength and toughness of high-strength low-alloy steel (HSLA) joints. To achieve grain refinement and circumvent the inherent weld challenges, the top surface of the fusion-welded steel joints can be processed using friction stir processing (FSP) up to 90% of the workpiece's thickness or penetration depth. Friction stir welding/processing (FSW/P) is a solid-state joining/processing technique for ferrous and non-ferrous materials (Kumar *et al.*, 2025; Ojo, 2019). It employs a rotating and non-consumable tool to induce frictional heat, plastic deformation, inter-material flow, and bonding at a temperature below the solidus temperatures or melting points of the parent materials (Ojo *et al.*, 2018; Heydari *et al.*, 2019; Ojo and Taban, 2018). The low heat input from this process implies that energy efficiency, minimal residual stresses, and distortion are attainable

(Ramakanth *et al.*, 2025). The severe plastic deformation and complex thermomechanical processes of FSP within the stir zone of the weld will aid dynamic crystallization and substantial microstructural modification, thereby enhancing the overall mechanical properties of the fusion-welded joints. Existing literature has shown extensive application of FSP on fusion-welded aluminium alloys. For instance, the gas tungsten arc welded AA5052 (Roen *et al.*, 2021), AA7075 (Shamanian *et al.*, 2017), AA7075/AA6061 (Mehdi and Mishra, 2021), AA5083 (Tandel and Menghani, 2022), and 5083-H111 (Mabuwa and Msomi, 2019) aluminium alloys have been friction stir-processed to improve the structure and mechanical properties of the resultant welds. The tensile strength of the GTAW'ed AA7075 joints was improved from about 228 MPa to about 320 MPa due to the dynamic recrystallization-assisted fine equiaxed structure and the increased fraction of high-angle grain boundaries (Shamanian *et al.*, 2017). The FSP process facilitated the refinement of the inherent as-cast dendritic structure in the as-welded joints and composites, as observed in the studies by Ma *et al.* (2023), Li *et al.* (2023), and Liu *et al.* (2023).

Limited studies have been carried out on the improvement of the fusion-welded steel joints with a secondary FSP processing technique in the literature. This may be due to the requirement for a harder processing tool and the mitigation of tool wear. Xue *et al.* (2016) subjected the submerged arc-welded high-strength low-alloy (HSLA) steel joints to friction stir processing under a low rotational speed (80 rpm). The processing of the welds transformed the coarsened bainite structure to ultrafine-grained (UFG) ferrite structure and enforced significant grain refinements at the upper (500 nm) and lower (300 nm) regions of the FSP'ed zone. There is a need to investigate the role of FSP on steel alloys welded with different fusion processes, as defects, heat-affected zone, and properties of welds change with the choice of fusion welding processes. Also, the subsection of fusion-welded steel joints to multiple surface FSP tool passes with lesser bulk plasticization remains a research area that is yet to be given detailed clarification in the literature. The FSP-induced lesser bulk plasticization of the fusion weld metal is expected to reduce the amount of tool wear and cut

back the inclusion of worn tool debris in the structure of the joint.

The present study examined the fusion welding of the AISI304 austenitic stainless alloy, and subjected the weld metal to multiple surface FSP tool passes with lesser bulk plasticization. The microstructure, tensile strength, and fracture behaviours of the FSP'ed AISI304 welds were investigated and compared with the as-fusion welded counterparts.

Materials and Experimental Procedures

A 2 mm thick AISI304 austenitic stainless alloy sheet (containing up to 67.85% Fe as shown in Table 1) was used as a base metal for this investigation. The plate was cut into dimensions of 50 mm x 100 mm with the aid of a guillotine machine. Thereafter, the surfaces of the cut plates were cleaned with the aid of acetone solution. The cut metal pairs were arranged in butt geometry and held with clamps to prevent distortion during the shielded metal arc welding process.

A stainless-steel filler metal (AWS E308-16) was employed for the fusion welding process. The chemical composition of the filler metal is also provided in Table 1. The friction stir processing of the obtained weld metal was carried out by employing three near-surface tool passes with minimal bulk plasticization along the plate thickness. The travel speed of the tungsten tool was kept constant at 45 mm/min while the level of the rotational speed was varied between 710 rpm to 1120 rpm for each sample under study. Multiple travel of the FSP tool along the paths of the weld bead was carried at minimal tool penetrations for the post-processing of the as-fusion-welded joints. This is to lessen the susceptibility of the tool to wear and minimize possible wear debris in the stir zone of the alloy. For the friction stir processing of the joint, a pinless tungsten carbide tool (10 mm diameter) was utilized.

The FSP'ed weld samples were cut, mounted in resin, ground, polished with grit papers to a mirror-like surface, and etched in a solution containing ferric chloride (8.5gm) + Alcohol (122 ml) + nitric acid (6 ml). The samples were then viewed under an Accuscope optical microscope. The dog-bone shaped tensile samples were fabricated from the FSP'ed samples with the FSP path falling within the

Table 1: Chemical compositions of base and filler metals in wt.%

Materials	C	Cr	Ni	Mo	Mn	Si	P	S	Cu	N	Fe
AISI304	0.08	19.00	10.00	-	1.00	0.01	0.05	0.03	-	0.10	67.80
AWS E308	0.08	18.12	9.10	0.75	1.50	0.90	0.04	0.03	0.25	-	Bal.

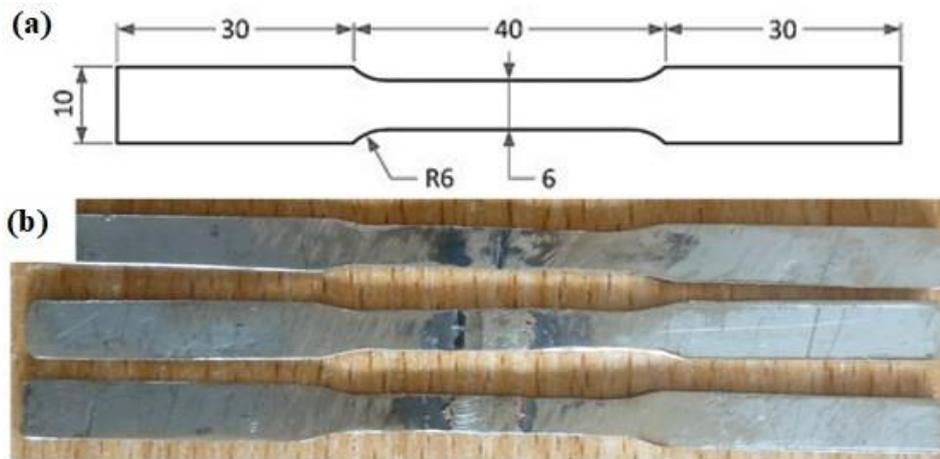


Figure 1: Tensile specimen (a) geometry and dimensions in millimetres, (b) fabricated samples

centre of the gauge length. Figure 1(a) provides the dimensions of the tensile sample utilized in this study while the actual samples are shown in Figure 1(b). The tensile test was conducted at ambient conditions and with a 5 mm/min load rate using an Instron tensile testing machine. The fracture surfaces of the welds were examined in a scanning electron microscope after the tensile test to understand the fracture behaviour of the FSP'ed welds.

Results and Discussion

As-welded and Friction Stir-Processed Appearances

Figure 2 shows the surface appearances of the as-

fusion welded process but no palpable melting or liquation occurs at this region. The multiple travel of the FSP tool along the paths of the weld bead establishes somewhat smoother surfaces (see Figure 2(b-d)) relative to the as-fusion-welded counterpart in Figure 2(a). The pinless tool performs two functions during the FSP of the as-fusion-welded joints. Friction-induced metal shearing and plasticization of the weld bead were achieved by the rotating pinless tool to obtain the surface appearances shown in Figure 2(b-d). The flash produced on the surfaces of the FSP'ed welds was minimal owing to the lesser bulk plasticization effect in an attempt to reduce the level of tool wear and debris inclusion in the stirred zone of the processed

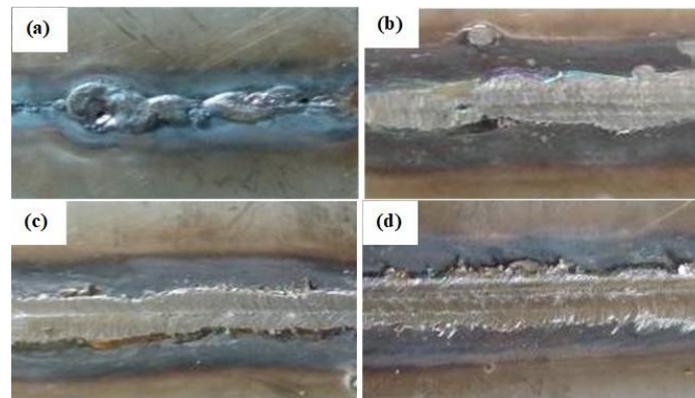


Figure 2: Surface appearance of the as-welded and FSP'ed AISI304 samples (a) as-fusion welded joint, and FSP'ed at (b) 710 rpm, (c) 900 rpm, and (d) 1120 rpm

fusion-welded AISI304 austenitic stainless alloy with its friction stir-processed counterparts at different rotational speeds. Uneven/non-uniform weld bead is found in the as-fusion welded joint in Figure 2(a). The inherent heat input changed the appearance of the heat affected zone in the fusion-welded joint (see Figure 2(a)). The darker region head-to-head to the weld bead in Fig.2a is the region exposed to the intense local heat input from the

sample. Meanwhile, the increment in the level of the rotating speed to 1120 rpm improves material flow and plasticization, leading to a relatively rather more flash in Figure 2(d) as compared to the lower rotating speed levels in Figure 2(b and c). This is attributable to the direct relationship between the rotational speed and induced heat input. At elevated temperature, the materials' flow behaviour is

enhanced, leading to the formation of plasticized lateral flash along the boundary of the stirred zone.

Microstructure

Figure 3(a-f) reveals the microstructure appearances of the as-fusion-welded and friction stir-processed AISI304 samples. The as-fusion-welded microstructure is characterized by a dendritic structure (see Figure 3(a and b)), which is attributable to the directional solidification of the fused/molten metal. The dendrite sizes or arms in the as-fusion-welded joints are short owing to the rapid cooling rate associated with the fusion welding process. The FSP process causes refinement of the dendritic

structure in the as-fusion-welded AISI304 joints irrespective of the level of the tool rotational speed. The multiple FSP of the as-fusion welded joints performs microstructural modification through the tool-aided plasticization and dynamic recrystallization of the weld paths, consequently, leading to refinement or elimination of the inherent dendrites in the FSP'ed weld samples (see Figure 3(c and d)). This result is in tandem with literature results when softer metals, such as Al alloys, are FSP'ed (Ojo et al., 2019). Shamanian et al. (2017) revealed that the FSP process caused the complete disappearance and refinement of the as-cast

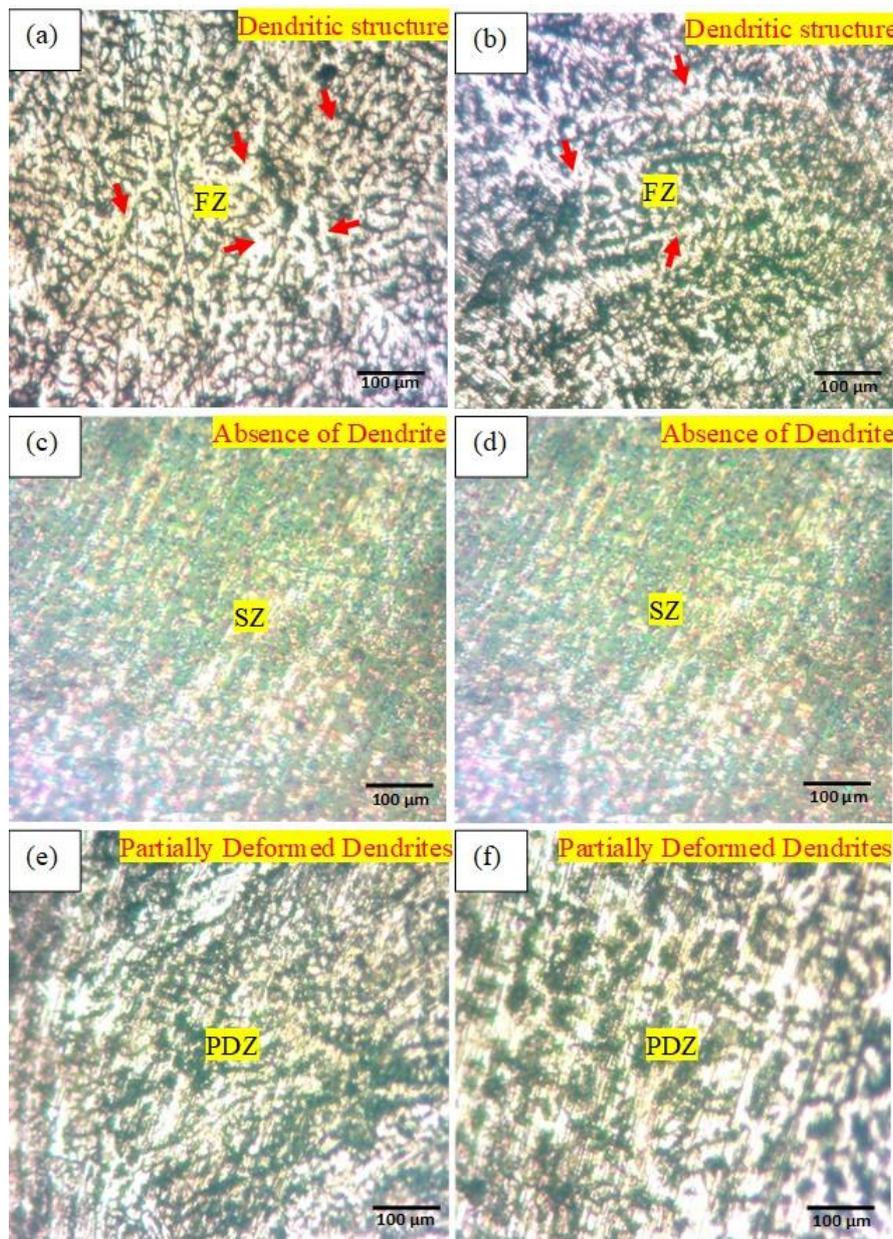


Figure 3: Optical images of as-fusion-welded and FSP'ed joints: (a) and (b) fusion zones (FZ) of as-fusion welded joints, (c) and (d) stirred zones (SZ) of FSP'ed joints, (e) and (f) partially deformed zone (PDZ) of the FZs after FSP

dendritic microstructure found in the gas tungsten arc-welded joints. Owing to the profile of the tungsten carbide tool (pinless), the entire fusion zone (FZ) of the AISI304 joint could not be completely refined (see Figure 3(e and f)). The compressive and vortex-aided deformation effects beneath the rotating tool are reckoned to have caused the formation of a partially deformed zone (PDZ) in the joint after the FSP processing. The partial deformation at the PDZs could not entirely refine the dendritic structure (see Figure 3(e and f)) in the FSP-processed AISI304 joints. In the recent studies of Gupta *et al.* (2024), it was reported that the weld metal of the FSP'ed AISI 409L plates was refined compared to the other regions owing to the significant presence of austenite and martensite, which hindered the growth of ferritic phases in the weld metal zone of the joint.

Tensile

The plot of the tensile strength versus the tool rotational speed for the FSW-processed AISI304 joints is revealed in Figure 4. A direct relationship is found to exist between the increment in the level of the rotational speed and the resultant tensile strength of the joint. The tensile strength increased from 193

input is reckoned to have facilitated a better bulk plasticization/deformation, material flow, and refinement of the as-welded fusion zone of the FSP-processed AISI304 joints (Paidar *et al.*, 2021).

However, the correlation of the FSW-processed AISI304 joints with the as-welded counterpart shows that lower tool speeds (700 and 900 rpm) impair the tensile strength of the joints (Figure 4). The as-welded AISI304 joint had a tensile strength of 226 MPa, which was higher than the FSW-processed samples at 700 and 900 rpm while the sample processed at 1120 rpm demonstrated a significant strength improvement compared to the as-welded counterpart. Although surface and near-surface microstructural modifications are caused by the change in the tool rotational speeds, a favorable structure is reckoned to have been established at the highest tool rotational speed. This is owing to the hardness of the weld metal of the AISI304 joint. It is adjudged that sufficient heat input to sufficiently plasticize and refine the weld metal of the AISI304 joint was only possible at the highest level of the rotational speed. Lower tool rotational speeds were unable to form a suitable microstructure for the FSW processing of the hard AISI304 joint. Thus, a high

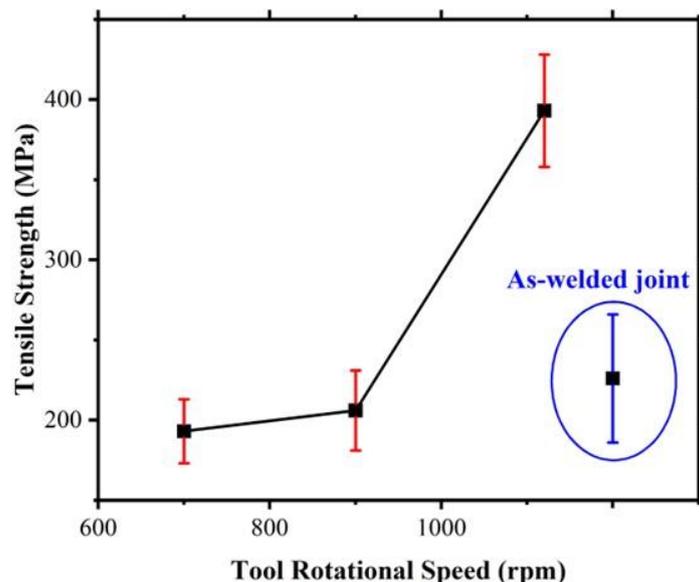


Figure 4: Tensile strength vs. tool rotational speed of the FSW'ed joints

MPa to 393 MPa as the speed was increased from 700 rpm to 1120 rpm. This outcome can be attributed to the improvement in the level of the tool rotational speed-induced dynamic crystallisation at the weld metal zone (fusion zone) (Ojo *et al.*, 2018; Ojo, 2024). This behaviour refines the dendritic morphology present in the fusion zone of the AISI304 joints. It has been reported in numerous studies that an increase in the tool rotational speed leads to a rise in friction-induced heat generation (Ojo and Oboro, 2024; Tong *et al.*, 2020; Oladimeji *et al.*, 2016; Ojo and Oluwale, 2024). Higher heat

level of tool rotational speed is recommended for the refinement of the coarse dendritic structure of AISI304 joints (weld metal) to improve the load-bearing performance of the joints.

Figure 5 presents different fracture magnifications of the AISI304 joints (as-welded and FSW-processed). Mixed fracture behaviours, predominated by brittle appearances, are the characteristic features of all the SEM images displayed in Figure 5, despite the FSW processing of the joint's weld metal.

The inherent partial deformation zone (PDZ) and the region beneath the PDZ could not be significantly modified due to the profile of the FSW tool during the FSW processing of AISI304 joints. The microstructures of these regions and those of the as-welded counterpart are relatively similar. The similar structural appearances in the joints (as-welded and FSW-processed) are considered to have influenced the somewhat comparable fracture appearances in Figure 5(a-f).

The studies of Raja *et al.* (2024) revealed the presence of fine lamellae (pearlites) in the FSP-processed IS2062 steel plates. In the fracture analysis of Sajadifar *et al.* (2022), it was reported that the refinement or plastic deformation of the 316L stainless steel aided the transformation of

through the synergy of friction-induced metal shearing and plasticization effects

- ii. The increment in the level of the rotating speed (700 - 1120 rpm) improves material flow and plasticization leading to a relatively rather more flash at higher rotating speed.
- iii. The dendritic structures (sizes and arms) of the as-fusion welded AISI304 were refined by the friction stir processing irrespective of the level of the rotational speed at the surface and near-surface zones of the weld due to tool-aided plasticization and dynamic recrystallization of the weld paths.

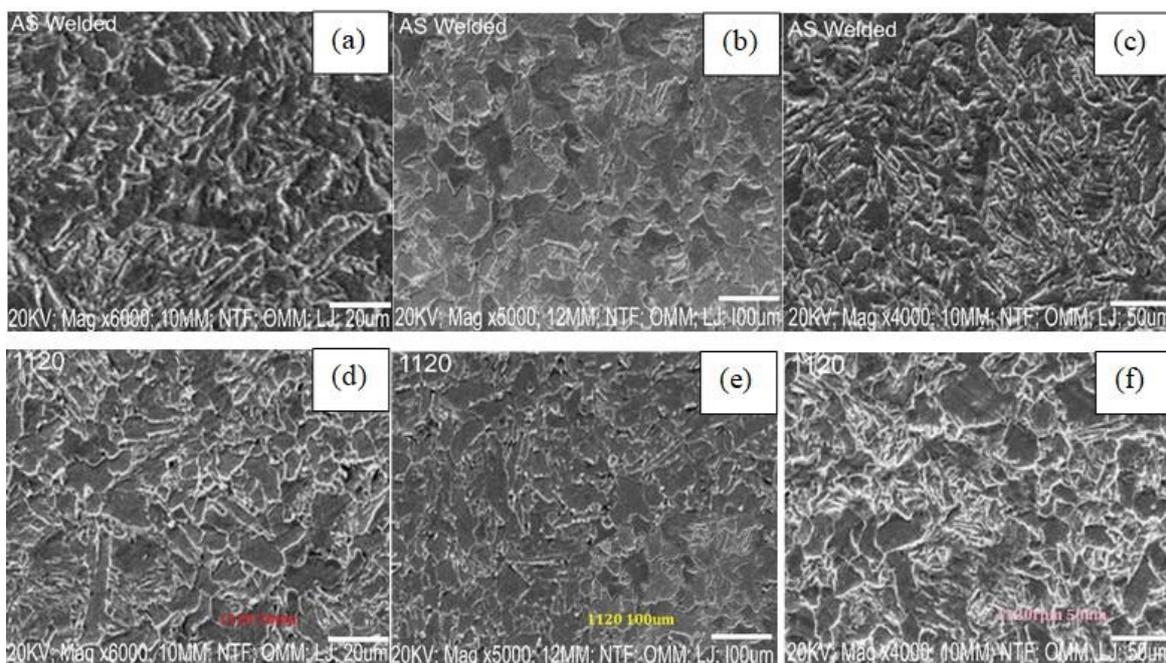


Figure 5: Fracture images (a-c) as-welded AISI304 joint, and (d-f) FSW-processed AISI304 joint at 1120 rpm

coarse voids to fine voids. This improves densification and the mechanical properties of the sample.

Conclusion

In this research, an attempt has been made to mitigate the inherent fusion-line defects in the fusion-welded austenitic stainless-steel joints (hard metal) by employing the friction stir processing method as a secondary processing route. The resultant processed welds were then characterised in terms of surface appearance, microstructure, and mechanical properties. The following findings were obtained:

- i. Uneven/non-uniform weld bead of the as-fusion-welded AISI304 joint is smoothed by friction stir processing
- ii. Partially deformed zone (PDZ) and undeformed regions are characteristic features of the FSW-processed AISI304 joints owing to the profile of the tungsten carbide tool (pinless).
- iii. Increment in the tool speed (700 – 1120 rpm) improved the tensile strength of the FSW-processed AISI304 joints from 193 to 393 MPa. However, the highest tool rotational speed is better suited for the secondary processing of the hard as-fusion welded AISI304 joints due to the sufficient heat input required for plasticization.
- iv. The as-fusion welded and the FSW-processed AISI304 joints failed via a mixed fracture behaviour owing to the presence of

partial deformation and undeformed zones in FSW-processed joints.

A high level of tool rotational speed is recommended for the refinement of the coarse dendritic structure of AISI304 joints (weld metal) to improve the load-bearing performance of the joints.

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