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EXPERIMENTAL STUDY ON MAG WELDED E350 HSLA STEEL JOINTS

EKSPERIMENTALNA ŠTUDIJA ZVARNIH SPOJEV IZ JEKLA Z VISOKO TRDNOSTJO VRSTE 350, VARJENIH S POSTOPKOM MAG

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Activated flux has been used successfully to improve the penetration of Tungsten Inert-Gas (TIG) welding, which is normally a welding process with low penetration. But the same activated flux when used for Metal Active Gas (MAG) welding showed a moderate improvement in penetration. Hence only a few research articles reported on activated flux MAG welding. TIG dressing is a post-weld treatment intended to improve the fatigue life of welded joints. The use of activated flux along with TIG dressing were not yet reported. In this work, an experimental study was conducted on the metallurgical changes and their effects on fatigue life in E350 steel welded by MAG welding with activated flux coating as well as toe TIG dressing. The metallurgical changes induced by various weld conditions and the effect on the fatigue life of welded joints were discussed. Welding conditions were categorised as: as weld (AW), weld with flux coating (FW), weld with TIG dressing (AWT), and flux weld with TIG dressing (FWT). Fatigue tests at stress ranges closer to the yield stress (80 % to 90 % of yield) were studied. In comparison with AW joints, the AWT and FWT showed a fatigue-life improvement of 60 % to 80 %, and 69 % to 103 % respectively. Whereas the FW joints showed 10 % to 17 % deterioration in fatigue life. Upon investigation with electron microscopy it was found that the variation in grain sizes and phase changes induced by the usage of flux and TIG dressing, as well as the changes in weld toe radius by TIG dressing and root strengthening due to extra penetration induced by the use of flux were the reasons behind these fatigue behaviours. In this work a novel effort is made to find a way to improve the fatigue life of a welded joint with a combination of two techniques. The activated flux is used to improve the penetration, whereas TIG dressing is performed to reduce the stress concentration. This new combination of techniques has improved the fatigue life of the weld significantly, which can lead to reduced maintenance costs of welded joints and a longer life.

Keywords: E350 Steel, microstructure, activated flux, fatigue, TIG dressing

Aktivno talilo se uspešno uporablja za izboljšanje penetracije (prodiranja) taline med postopkom elektro-obločnega varjenja z volframovo elektrodo v zaščitni atmosferi (TIG; angl.: Tungsten Inert Gas welding). Podobno se je pri postopku elektro-obločnega varjenja v prisotnosti aktivnega plina (MAG; angl.: Metal Active Gas Welding) pokazalo določeno izboljšanje zaradi uporabe aktivnega talila. Avtorji tega članka so v strokovni in znanstveni literaturi našli le nekaj poročil o MAG postopku varjenja z uporabo aktivnega talila, usmerjenih v postopek naknadnega avtogenega varjenja (pretaljevanje kapic oz. vrhov zvarov), ali tako imenovano TIG »dresiranje«, ki izboljša trajno trdnost zvarnih spojev. Vendar pa v raziskovalnih člankih niso našli poročil o uporabi aktiviranga talila z nadaljnim postopkom TIG dresiranja. Avtorji v tem članku zato obravnavajo eksperimentalno študijo metalurških sprememb in njenih vplivov MAG postopka varjenja z aktivnim talilom in naknadnim TIG dresiranjem na trajno trdnost zvarnih spojev malo legiranega jekla z visoko trdnostjo (HSLAS; angl.: High Strength Low Alloyed Steel). Avtorji v članku obravnavajo metalurške spremembe mikrostrukture med različnimi pogoji varjenja, ki vplivajo na trajno trdnost varjenih spojev. Pogoje varjenja so razdelili na običajno varjenje (AW), varjenje s prevleko iz aktivnega talila (FW), varjenje z naknadnim TIG dresingom (AWT) ter varjenje z aktivnim talilom in TIG dresingom (FWT). Nato so zvajali in študirali preizkuse dinamičnega utrujanja zvarov v bližini njihove meje tečenja (od 80 % do 90 %). Primerjava dinamičnih trajnih trdnosti oziroma njihove dinamične dobe trajanja je pokazala, da so imeli AWT v primerjavi z AW zvari od 60 do 80 %-no izboljšanje in FWT od 69 do 103 %-no izboljšanje oziroma podaljšanje dinamične dobe trajanja. Medtem, ko so imeli FW zvari celo 10 do 17 %-no poslabšanje trajne trdnosti. Preiskave s pomočjo vrstične elektronske mikroskopije (SEM) so pokazale, da je sprememmba velikosti kristalnih zrn posledica uporabe talila in TIG dresinga, kakor tudi sprememba velikosti premera kapic zvarov. Pri uporabi talila je prišlo tudi do ojačitve korena zvarov zaradi boljše penetracije taline. V tem članku avtorji opisujejo nov prispevek k izboljšanju dinamične trajne trdnosti zvarov s kombinacijo dveh tehnik. Aktivno talilo prispeva k izboljšanju penetracije, medtem ko TIG dressing zmanjša koncentracijo notranjih napetosti. Uporaba kombinacije dveh tehnik varjenja močno izboljša odpornost zvarov proti dinamičnim obremenitvam in posledično zmanjša stroške vzdrževanja oziroma obnove ali kontrole zvarov.

Ključne besede: jeklo z visoko trdnostjo vrste E350, mikrostruktura, aktivno talilo, utrujanje, TIG postopek dresiranja

1 INTRODUCTION

GMAW (Gas Metal Arc Welding) is the most frequently used arc-welding technique. It is divided into MAG and MIG. MAG is for ferrous materials and MIG is for non-ferrous material.[1] MAG welding is simple with low costs and high productivity.[2–4] In MAG welding, active gases like oxygen (O_2), carbon dioxide (CO_2), etc., along with argon (Ar), were used as shielding gases. E-350 steel is a structural steel used in onshore and offshore structures for its good weldability, strength and corrosion resistance.[5] It is used in girders, piers, landing gears, engine pylons, slat tracks, etc.

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Table 1: Chemical composition of base metal and electrode.

Elements	C %	Mn	P	S	Si	Ni	Cr	Mo	V	Cu
Base metal	0.162%	1.24%	0.004%	0.025%	0.04%	–	–	–	–	–
Electrode	0.06–0.15	1.4–1.85	0.025Max	0.035Max	0.80–1.15	0.15Max	0.15Max	0.15Max	0.03Max	0.5Max

Table 2: MAG welding conditions

Process Parameters	Arc Voltage	Welding current	Traverse speed	Gas flow rate	Shielding gas	MAG torch angle	Electrode feed rate	Stick - out
Values	26 V	180 A	70 mm/min	7 lpm	90% Ar& 10% CO_2	90°	5.7 m/min	2 mm

Table 3: TIG dressing parameters

Process Parameters	Arc Voltage	Dressing current	Traverse speed	Gas flow rate	Shielding gas
Values	18 V	130 A	100 mm/min	7 lpm	Ar

Activated flux is commonly used to improve weld penetration in TIG welding, which normally is a low-penetration process. In MIG/MAG welding, the usage of activated flux has little effect on weld penetration and the effect was not as high as it was for TIG welding.[7] Dynamic loading can cause fatigue failure of materials even with load magnitudes below the yield point.[6,8] Post-weld treatment techniques minimize welding defects, improve fusion, reduce thermal stress and thereby improve its quality and fatigue life. Weld toe grinding and toe defect rectification are common post-weld toe treatments. Weld toe grinding eliminates fatigue crack growth zones by grinding off the defected weld-toe region into a fillet depression.[9,10] In defect rectification, the defect is removed by re-melting the toe,[11] mostly with a TIG arc called TIG dressing. In TIG dressing, the weld-toe region is re-melted resulting in improved fusion and formation of a fillet depression by melting off a portion of the weld reinforcement along the weld toe. This creates a smooth cross-sectional transition from the base metal to the weld reinforcement and reduces the chance of crack growth.[12] The usage of the flux and TIG dressing causes a change in energy supplied in different zones and affects the formation of different phases and grain sizes.[13]

The fatigue behaviour of MIG/MAG weldments with the combination of activated flux coating and TIG dressing was not reported. In this study, an effort is made to study the impact of activated flux and TIG dressing on the fatigue life of MAG-welded E350 steel joints.

2 EXPERIMENTAL PART

E350 steel plates were purchased from M/s.MatRICS, Nagercoil and subjected to welding. The chemical composition of the base metal and the electrode spool were tested and listed in **Table 1**.

Since the thickness of the plate is only 6 mm, it was decided to perform MAG welding on top and bottom sides without edge preparation. After cleaning the surface, tack welding was applied on both ends of the plate, with a gap of 1.5 mm between them. Butt welding was applied by using a FRONIUS welding machine on the steel plates. Welding was performed with ER70S-6 weld wire of 1.2-mm diameter. The parameters were initially selected from the welding machine's user manual and then fine tuned after several trials of welding and listed in **Table 2**.

For the current investigation, a set of samples were welded under the following conditions: weld without flux (AW), weld with TIG dressing (AWT), TiO_2 flux welded (FW), TiO_2 flux welded with TIG dressing (FWT). Recent research has reported an improvement in weld penetration and quality due to the application of flux materials like TiO, TiO_2, Fe_2O_3, MnO_2, $MgCl_2$, ZnO, TiO_3, and Cr_2O_3. Even three times higher penetration was recorded with A-TIG welding.[23] Among various fluxes, TiO_2 provides an increase in hardness as well as the depth of penetration.[19–21] Even though the use of many oxide-containing activated fluxes increase the weld penetration, it is found that optimum amount of flux coating is necessary for improved penetration. If not, the increased penetration effect is nullified. TiO_2 has better stability among most of the fluxes and it is recommended for the welding of steel.[22] Hence, TiO_2 was selected for this work. For making FW joints, The TiO_2 powder is mixed with acetone to form slurry and is coated over the surface to be welded with a brush and dried at room temperature for 30 min. The TIG dressing is performed by using standard TIG welding equipment following the recommendations of IIW[14] and the parameters are listed in **Table 3**. The fatigue-test results are presented in **Table 4**.

After a visual inspection, the defect-free specimens were machined per the ASTM standards for mechanical and metallurgical characterization. The macrographic and microstructural analyses were carried out using an OLYMPUS optical microscope. The tensile samples were machined on a wire EDM as per the ASTM E8M-04 standard and tested on an INSTRON 8801 machine with a constant strain rate of 0.5 mm/min. Fatigue samples were machined as per the ISO/TR 14345 standards and tested with a MTS servo hydraulic fatigue test-

Table 4: Fatigue testing results

S. No	Weld condition	Stress Range (Mpa)	Number of cycles to failure		
			Trial 1	Trial 2	Trial 3
1	PM	350	40335	40108	39863
2	PM	330	70635	70118	69545
3	PM	315	137920	133103	125018
4	AW	350	19261	20275	20682
5	AW	330	32322	33193	33892
6	AW	315	60131	54005	50036
7	AWT	350	32031	32507	32889
8	AWT	330	60420	59604	59236
9	AWT	315	91408	97591	103542
10	FW	350	15790	11305	11511
11	FW	330	30105	28938	30156
12	FW	315	42302	50400	43360
13	FWT	350	33080	34139	34571
14	FWT	330	65274	66383	67309
15	FWT	315	107304	112291	113075

ing machine (Model 370.02) at a frequency of 15 Hz and a stress ratio of 0.1. Using an SEM (JOELJSM 5610LV), different locations on the transverse section of the weld and fatigue fractured surface were analysed to understand the nature and mechanism of the failure.

3 RESULTS AND DISCUSSION

This study examined heat-induced microstructural changes for all the weld conditions. The microstructure of the base metal showed equiaxed ferrite and lamellar pearlite phases with a grain size of about 10 ± 3 μm.[15–17] The different regions formed by welding are the weld bead (WB), weld centre (WC), heat-affected zone (HAZ), and intermediate heat-affected zone (IHAZ) and TIG zone (TZ) when TIG dressing is used. The flux-coated specimens before welding, the welding setup and a schematic of the different zones in a weldment are shown in **Figure 1a** to **1c**.

The weld bead (WB) is the region where a weld seam is deposited by melting filler material and parent material to be welded. Since the WB is open to the atmosphere, the solidification was quick. Due to melting and solidification, the base metal's ferrite and pearlite phases collapse and form feathery ferrite. Moreover, the formed lamellar pearlite phase collapses and transforms into tiny phases. The WB of the AW and FW specimens were similar. In the WB, nearer to the TIG zone of AWT and FWT specimens, fine α-ferrite and pearlite were observed. The effect was found much deeper in the WB of the FWT than the AWT.

The weld centre (WC) is the region where weld roots from both sides join. In the weld centre, solidification was slower; hence coarse grains were found. Here, the filler and base material mix to form a coarse feathery structure. In comparison with the AW joints, the FW joints have a much smaller and delicate microstructure at the WC. This may be due to the fact that since the penetration is deeper in the FW joints, the heat is transferred to a larger area along the depth causing relatively quicker solidification, resulting in a reduced grain size. Since the heat input in TIG dressing is less there were no microstructural changes in the WC. Hence the WC of the AWT and AW as well as WC of FW and FWT were similar.

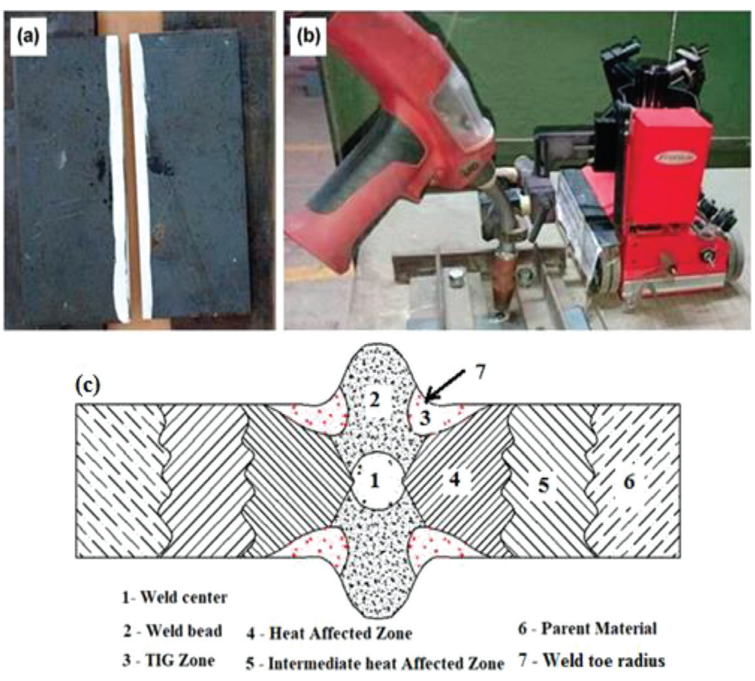

Figure 1: Pre-arrangement for welding with schematic of weld joint a) Flux-coated plates before welding b) MAG welding machine c) Schematic sketch of weld zones

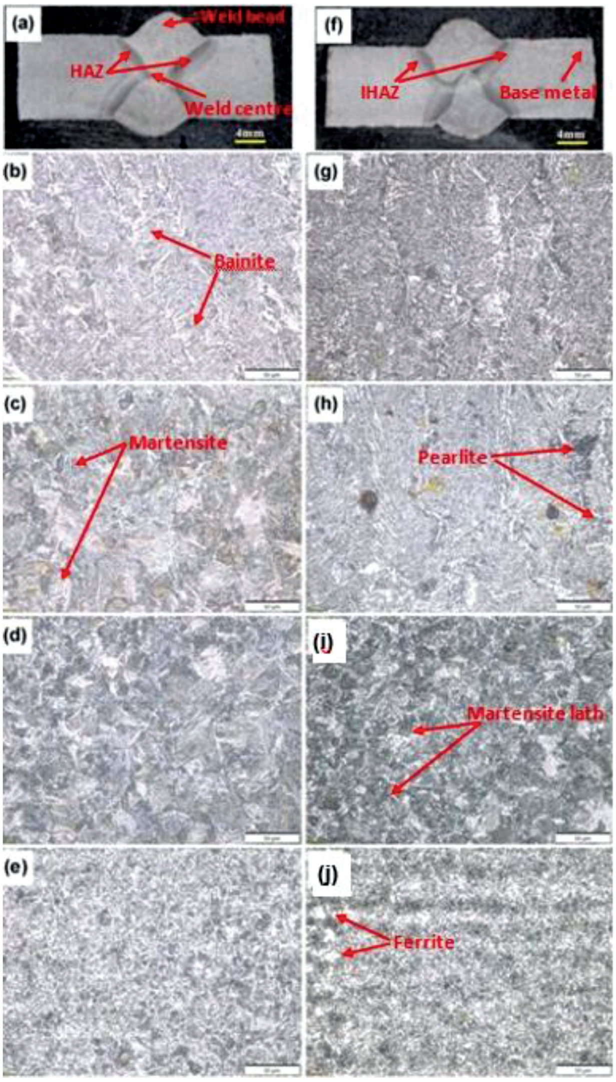

Figure 2: Images of AW and FW joints: a) Macrograph of AW, b) weld bead of AW, c) weld center of AW, d) HAZ of AW, e) IHAZ of AW, f) macrograph of FW, g) weld bead of FW, h) weld center of FW, i) HAZ of FW, j) IHAZ of FW

The heat-affected zone (HAZ) is the region adjacent to the weld zone, where the heating melts the base metal to its semi-solid state. Heat from the WB and WC keeps this zone hotter with cooling rate resembling an annealing heat treatment. This transforms a part of α-ferrite and cementite into austenite and bainite. The HAZ of the AW and FW were similar. The micrograph of various weld zones of the AW and FW are shown in **Figure 2a** to **2i**. Whereas in the HAZ closer to the TIG zone (AWT, FWT) joints, grains were nearly half the size of grains in HAZ. This smaller grain effect is found much deeper in the FWT.

The region between the HAZ and the base material is named the intermediate heat-affected zone (IHAZ). Here the temperature was raised just above the recrystallization temperature and cools quickly, causing coarse α- ferrite and cementite phases to evolve into finer phases. The microstructure of the IHAZ was more or less similar in all the weld categories, but in the AWT and FWT the grains were slightly smaller. TIG dressing reduces possible flaws on the weld toe.[18,27] The additional heat during the TIG dressing causes grain re-crystallization and the grains were coarsened in the TIG zone (TZ). The TZ is much more pronounced and deeper in the FWT than the AWT. The prominent phase changes identified in comparison with the AW and FW joints is observed is in the WC where the WC of the AW **Figure 2c** has martensite phase as the prominent phase where the WC of the FW **Figure 2h** has more pearlite phase.

The weld bead profiles of the AW and FW joints are shown in **Figures 3a** and **3b** respectively. The AW has a bead width of 5.59 mm and depth of 2.89 mm. whereas the bead width and depth of FW joint are 4.22 mm and 3.26 mm respectively. There is an around 12.8% increase in penetration due to the use of flux. The percentage of improvement is closer to the reported work where the penetration increase was around 20 %[7] The macrographs of all the weld conditions are shown in **Figures 4a** to **4d**. FW joints show deeper penetration than the AW **Figures 4c** & **4a**. The WC is near the central plane in the AW. Due to the deeper penetration in the FW, the root formed previously was overlapped by the later root shifting WC away from the central plane.[19] Marangoni forces or surface-tension forces in a weld pool is one of the major forces determining the penetration into the weld. Normally, surface tension decreases with an increase in the temperature. As a result, the edges of the weld pool, which have a relatively lower temperature, have a higher surface tension compared with the center of the weld pool. Since fluid flow from a region of lower surface to a region of higher surface tension, the movement of the

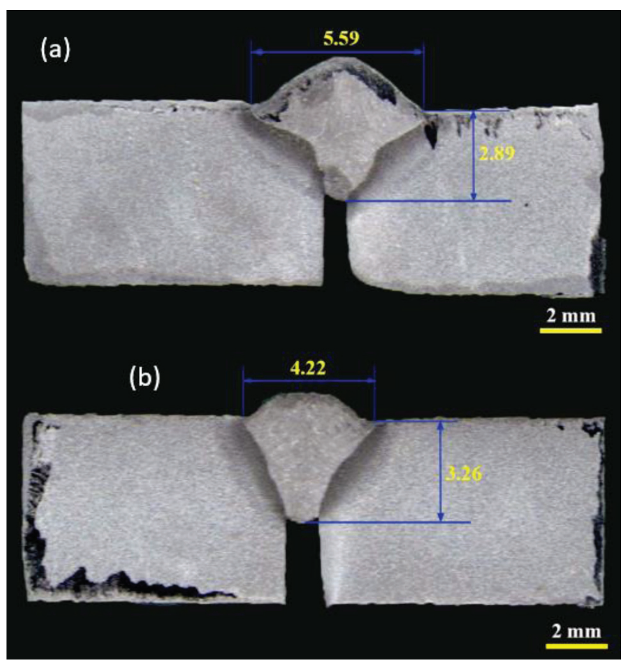

Figure 3: Weld bead profile of: a) AW, b)FW

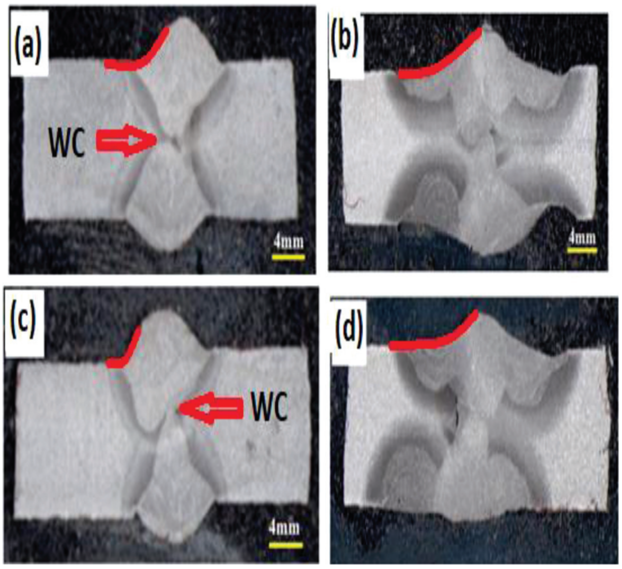

Figure 4: Macrograph of weld joints: a) AW, b) AWT, c) FW, d) FWT

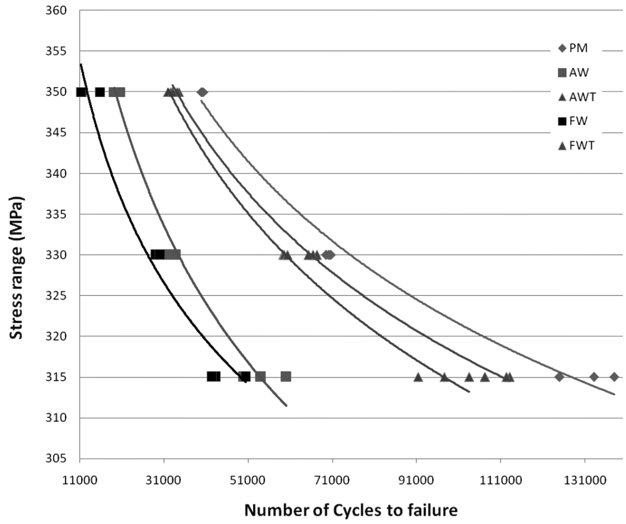

Figure 5: SN curve of welded joint

molten metal in the weld pool is directed towards the edges, causing a wider and shallow weld bead. In activated flux welding the oxides result in the presence of oxygen content in the weld pool. This active element causes a reversal of marangoni forces directing the molten metal more towards the center of the weld pool, resulting in deeper penetration of the weld bead.[22] The ionized flux particles around the arc create a constricted path, resulting in a smaller bead width.[23,24] The reason for this deep penetration is the Marongani effect and arc constriction.

The weld-toe radius is made visibly larger due to TIG dressing **Figure 4b** & **4d**. The weld-toe radius was smaller in the FW and it is the largest in the FWT, making it nearly a straight line, enabling a smooth transition from parent material to WB in the FWT.

All the tensile specimens ruptured away from the weld zone with ultimate stress values not less than 90% of that of parent material ,which is recorded as 500 MPa. The fatigue testing was conducted on three stress levels, at 80 % to 90 % of yield, and the results are shown in **Table 4**.

The fatigue tests show an increase in the fatigue life of the AWT and FWT in comparison with the AW specimens. AWT has a fatigue-life improvement of 60 % to 80 %, whereas FWT shows improvement of 69 % to 103 %. The SN curve indicating fatigue life at different stress levels is shown in **Figure 5**. The trend in the results is comparable with published work[12] where the improvement in fatigue life was greater at lower stress levels and it is lower at higher stress levels. The TIG treatment on the weld toe may have eliminated any weld defects and reduced the stress concentration by increasing the weld-toe radius, resulting in an improved fatigue performance. The superior performance of the FWT may be due to additional root strengthening due to improved penetration with the use of flux. The FW joints showed a reduction in fatigue life of 10 % to 17 %, but it was expected to show better performance in view of its improved root penetration. The reduction in weld-toe radius increased the stress concentration and thereby reduced the fatigue life. A fatigue fractograph was made to verify the above claims.

The fatigue fractograph was studied for the parent material as well as different weld specimens. In the AW and FW specimens the crack-initiation and crack-growth

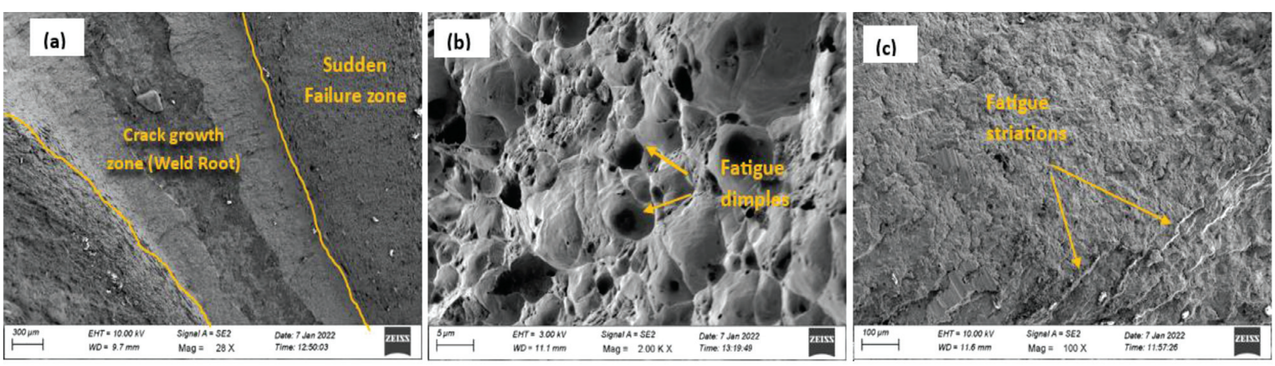

Figure 6: Fatigue fractograph of FWT: a) fatigue zones, b) magnified sudden failure zone, c) magnified crack growth zone

zones were found in the weld-toe region, which is common in earlier work.[26] Whereas in the AWT and FWT specimens the crack-initiation and crack-growth zones were seen in the weld root **Figure 6a** and **6c**. When TIG dressed, (AWT, FWT) the crack initiation shifts from the weld toe to the weld root, indicating reduction in possible weld defects by remelting and the reduction of stress concentration by the formation of a larger weld toe radius, which is in line with reported work.[25] The fatigue factograph of the FWT is shown in **Figure 6a** to **6c**. The improved penetration makes the second root to re-melt the first formed root leading to better fusion at the WC.

4 CONCLUSION

An extensive study was conducted on E350-HSLA MAG welded structural steel plates. The welding was made with four conditions, AW, AWT, FW, and FWT, with TiO_2 as the activated flux. The effect of activated flux and TIG dressing on the fatigue life of the welded joints were analyzed by conducting fatigue tests at stress levels around 80 % to 90 % of yield stress. The conclusions are as follows.

All the tensile specimens failed away from the weld zone with ultimate stress values not less than 90 % of parent material, indicating the weld is sound and the use of flux has not deteriorated the strength of weld.

In comparison with AW specimens the AWT specimens showed an improvement of 60 % to 80 %. A reduction in stress concentration by increased weld-toe radius and reduction of toe defects by remelting in TIG dressing were the reasons behind fatigue-life improvement.

The FWT specimens showed the best fatigue life with improvement of 69 % to 103 % in comparison with the AW joints. The reasons being (i) positive effects of TIG dressing as in AWT and (ii) greater weld-root strength due to improved penetration by flux.

The FW joints showed the least fatigue performance with reduction in fatigue life by 10 % to 17 % in comparison with the AW. The improvement in weld-root strength by activated flux usage was negated by the formation of a small toe radius, resulting in increased stress concentration and early failure.

The fractographic study revealed shifting of the crack-initiation zone from the weld toe to the weld root upon TIG dressing, and improved strength of weld root with the use of flux.

The phase transformation due to TIG dressing causing the formation of much ductile fine α-ferrite phase might have also reduced the crack growth near the toe and shifted the crack initiation zone to the weld root.

The reduction of grain size at weld centre upon the use of flux was found and this might have improved the strength of the root. The formation of α-ferrite phase improved the ductility and slowed down the fatigue-crack propagation near the weld toe. The combined effect of these two phenomena of slowing crack propagation at the weld toe and the improved strength of weld root resulted in the superior performance of FWT joints.

From this study it is inferred that using activated flux in conjunction with adequate TIG dressing can improve the fatigue life of MAG welded joints.

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Conflicts of interest

The authors declare that they have no conflicts of interest. All the original data are available from the corresponding author.

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