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Microstructural Evolution and Mechanical Behaviour of Austenitic Stainless Steel Welded Joints: A Comparative Study of SMAW and MIG Welding

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Abstract- Austenitic stainless steels are very widely used engineering materials next to carbon steels. It can maintain its corrosive properties at normal as well as in severe conditions. It does not undergo ductile to brittle transition like plain carbon steels at cryogenic temperatures. It can retain its ductility and toughness at very low temperatures. Due to its high ductility and toughness it is very widely used in industries in fabricated conditions. Hence, its weldability should be investigated in different conditions. In this paper, weldability of austenitic stainless steel (304L) was investigated using SMAW and MIG welding processes. Stainless steel work-pieces were welded in butt joint position after preparing single V-groove. Different mechanical characteristics like, hardness, impact and ultimate tensile strength of the welded joints were measured after preparing suitable specimens. The mechanical properties of the welded joints prepared by both the welding processes were compared. The impact strength, UTS and hardness of MIG welded joints were found more than SMAW welded joints. Hence, superior mechanical properties can be obtained in case of MIG welding condition. Specimens for study of microstructures were also prepared to study the variation in microstructures in both of the processes. By using suitable etchant the variation in microstructure of welded joints was studied using metallurgical microscope. The photographs of microstructures of different zones were recorded and discussed.

Keywords*:* Weldability, Austenitic stainless steel, SMAW, MIG, Mechanical properties, Microstructure etc.

I. OVERVIEW

Stainless steels, or corrosion-resistant steels, are classified as alloy steels; a minimum of 11% chromium by weight is required in their formulation [1]. The inclusion of chromium produces a passive oxide layer that renders the steels rust-resistant and protects them from corrosion and chemical, gas, and liquid attacks. Most stainless steels provide good strength and resist scaling at elevated temperatures and, in addition, many of them retain good toughness and ductility at low temperatures [2]. Unlike substances that are classified purely by their chemical composition, stainless steels are characterized by their metallurgical phases (and/or combinations thereof) [3, 4].

Stainless steels can be categorized into the following five groups:

i. Austenitic Stainless Steel,
ii. Ferritic Stainless Steel,
iii. Martensitic Stainless Steel,
iv. Ferritic-Austenitic Steel,
v. Precipitation Hardening Stainless Steels.

1.1 Austenitic Stainless Steels (ASS)

ASS are defined as having a total Cr, Ni, and Mn content of 24% or greater. Cr content is generally > 16% and Ni content is > 7% in most cases. Table 1 shows the compositions of key stainless steel austenitic varieties. Chromium provides the material with a level of protection against oxidation and corrosion. Ni and Mn prevent the phase transition to a different structure when the steel is cooled rapidly to room temperature. At room temperature, austenitic stainless steel possesses an austenitic structure and the highest level of corrosion resistance when compared to other stainless steels [5]. It has the highest strength, scaling resistance, and temperature ductility near absolute zero. It is non-magnetic, and distinguishes from other steels and alloys by the presence of a magnet [2, 5]. These steels also provide a broad range of corrosion resistance, which is why they are most commonly used in extreme corrosion environments [5]. Their microstructure is either fully austenite or austenitic in a ferrite matrix. These steels cannot be hardened by heat treatment and maintain ductility at cryogenic temperatures.

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Table-1: Composition of different Grades of ASS [4].

AISI No.	Chemical Analyses of Austenitic Stainless Steel, per cent					
	C	Cr	Ni	Mn	Si	Other
201	0.15	16.0-18.0	3.5-5.5	5.5-7.5	1.0	N
202	0.15	17.0-19.0	4.0-6.0	7.5-10.0	1.0	N
301	0.15	16.0-18.0	6.0-8.0	2.0	1.0	
303	0.15	17.0-19.0	8.0-10.0	2.0	1.0	Mo
304	0.08	18.0-20.0	8.0-10.5	2.0	1.0	
304L	0.03	18.0-20.0	8.0-12.0	2.0	1.0	
309	0.20	22.0-24.0	12.0-15.0	2.0	1.0	
310	0.25	24.0-26.0	19.0-22.0	2.0	1.5	
316	0.08	16.0-18.0	10.0-14.0	2.0	1.0	Mo
316L	0.03	16.0-18.0	10.0-14.0	2.0	1.0	Mo
321	0.08	17.0-19.0	9.0-12.0	2.0	1.0	Ti
347	0.08	17.0-19.0	9.0-13.0	2.0	1.0	Nb

1.2 Weldability of Austenitic Stainless Steel

Weldability, as defined by the American Welding Society, is the ease of successfully joining a particular type of material by welding along with the ease of the material performing satisfactually once it is in service. Austenitic stainless steels can be easily welded using several welding techniques like SMAW, GMAW, GTAW and FCAW. Compared with mild steels, austenitic stainless steels have approximately 45% greater thermal coeffecient of expansion, greater electrical resistance, and lower thermal conductivity. Because of these characteristics, it is suggested that welding be performed at a high speed. This will, in turn, lower the heat input and subsequent precipitation of carbides, as well as, minimize distortion [1, 2]. Due to the increased thermal expansion, the increased potential for warpage and distortion means special techniques should be employed. Among these techniques are back-step welding and skip welding.

1.3 Objective

The main objective of this research is to assess, using microstructure analysis, the effect of SMAW and MIG welding techniques on the microstructure as well as the mechanical characteristics of the welded joints. Microstructural investigation concentrated on the fusion zone, fusion boundary, heat-affected zone as well as the base metal in their original as welded state. In addition, the mechanical properties, hardness, toughness, tensile strength were evaluated and compared.

II. EXPERIMENTAL EVALUATION OF MECHANICAL PROPERTIES

A 12 mm thick plate of 304L austenitic stainless steel was cut to the required dimensions using a power hacksaw. A single 'V' butt joint configuration, as shown in Fig. 1, was prepared to fabricate joints using the SMAW and MIG welding processes. The welding parameters used in the study are listed in Table 2. Initially, the plates were secured in position by tack welding to obtain the required joint configuration. Proper precautions were taken to minimize joint distortion during welding. The chemical composition of the base metal and electrodes is presented in Table 3.

Table-2: Welding Conditions and Process Parameter

Particulars	SMAW	MIG Welding
Welding Machine	Castolin Eutectic	Inverter CO_2/MAG Arc Welding machine
Base Material	304L Austenitic Stainless Steel	
Plate Thickness (mm)	12	
Electrode	AWS A 5.4 :E-308L-16	AWS/SFA-5.9:ER308L
Electrode diameter (mm)	3.15	1.2
Welding Current (amps)	80	165-170
Welding voltage (volts)	23.2	22-24
Welding Speed	64.8 mm/min	67 mm/min
Polarity	DCEP	DCEP

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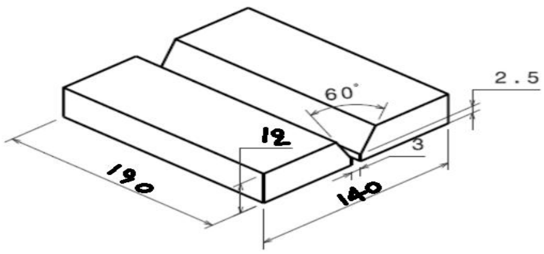

Fig-1: Dimensions of single 'V' butt joint configuration (mm)

Table-3: The Elemental Composition of Base Metal and Electrodes.

Elements	Base Metal	E-308L-16 Electrode	ER308L Electrode
C	0.032	0.04	0.03
Cr	18.83	18-21	19.5-22
Ni	8.234	9-11	9-11
Mn	1.46	0.5-2.5	1-2.5
Si	0.280	1.0	0.3-0.65
P	0.023	0.04	0.03
Cu	0.187	0.75	0.75
S	0.014	0.03	0.03
Mo	0.187	0.75	0.75

Fig 2 shows the dimensions of tensile test specimen. Fig 3a and 3b depicts the photographs of tensile test specimen of SMAW welded joint and fractured pieces respectively after tensile testing. Fig 4a and 4b show the photographs of tensile test specimen of MIG welded joint and fractured pieces respectively after tensile testing.

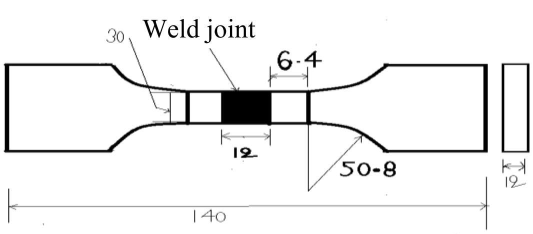

Fig-2: Dimensions of tensile test specimen (mm).

Width of weld bead = 30 mm
Thickness of the plate = 12 mm
Area of weld bead = 30 × 12 = 360 mm^2

Fig-3a: Tensile Test Specimen of 304L Austenitic Stainless Steel SMAW welded joint.

Fig 3b: Fracture Tensile piece of 304L ASS SMAW welded joint.

Fig 4a: Tensile Test Specimen of 304L ASS MIG welded joint.

Fig-4b: Fracture Tensile Piece of 304L ASS MIG welded joint.

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2.1 Charpy Impact Test

The test specimens for impact testing were prepared according to ASTM standards. Six specimens (three for SMAW and three for MIG welding) were prepared to evaluate and compare the toughness property of welded joints. Fig 5a and 5b show all dimensions of test specimens. Fig 6 shows the photograph of Charpy test specimens which were used for the experiment. Impact test were carried out on impact testing (Charpy test) machine of capacity 30 kg-m. Fig 7 shows the impact testing machine. The specimens were positioned in simply-supported manner. The specimens were broken and corresponding readings were recorded on the scale of machine.

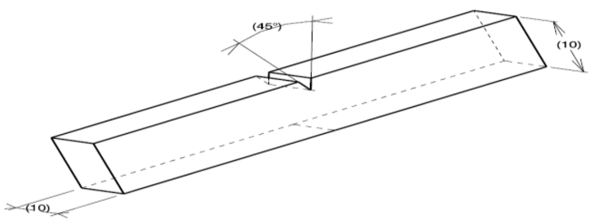

Fig-5a: Dimensions of specimen for impact test (Charpy test).

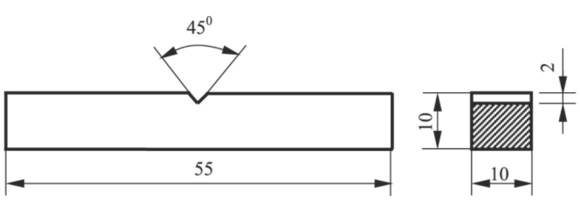

Fig-5b: Front view and cross-sectional view of specimen.

Fig-6: Specimens for impact test.

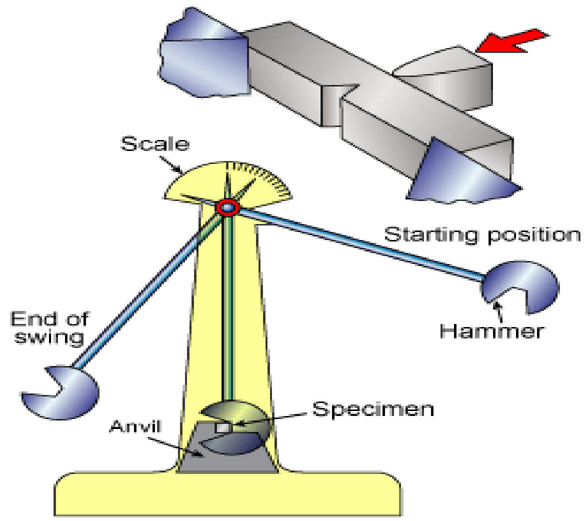

Fig-7: Charpy Impact Test Machine

2.2 Micro-Structural Investigation

Before going for micro-structural investigation the sample surface was prepared as per standard procedure. The finished surface is shown in Fig 8. The microstructures were investigated under the metallurgical microscope. For the etching of stainless steel, mixture of HCl, HNO_3 and H_2O in 1:1:1 was used. The purpose of etching was to enable the surface for investigations of its microstructure.

Fig-8: 304L Austenitic Stainless Steel sample for study of microstructure.

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2.3 Hardness

Quality control of a weldment involves multiple factors, of

	Sample No.	A	B	C	D	E
Base metal	1	44	25	19	0.76	0.79
	2	45	25	20	0.80	
	3	45.5	25	20.5	0.82	
SMA W	1	27	25	2	0.08	0.10
	2	27.5	25	2.5	0.10	
	3	28	25	3	0.12	
MIG	1	31	25	6	0.24	0.27
	2	32	25	7	0.28	
	3	33	25	8	0.32	

which hardness is a key consideration. The strength/hardness inconsistency across different micro-structural regions is a major factor influencing the fracture response of a weldment. Hardness testing was conducted using a Rockwell hardness testing machine, the principle of which is illustrated in fig. 9.

HR == E - e
F0 = preliminary minor load (usually 10 kgf)
F1 = additional major load (kgf)
F = total load (kgf)
e = permanent increase in depth of penetration due to major load F1 measured in units of 0.002 mm
E = a constant depending on the form of indenter: 130 units for the steel ball indenter
HR = Rockwell hardness number
D = diameter of steel ball

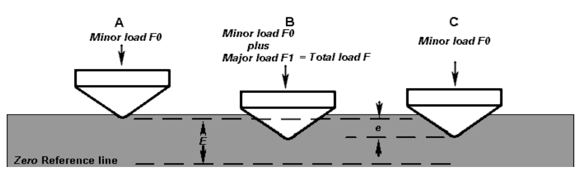

Fig-9: Rockwell Principle

III. RESULTS AND DISCUSSIONS

3.1 Strain Calculation

The experimental values obtained from tensile testing of base metal, welded joint prepared by SMAW and MIG welding have be given in table 4. The average value of strain was calculated in each case and compared.
It was found that value of strains obtained for welded joints was found to be less than the base metal. Hence, ductility of the stainless steel reduces due to welding. Further

ductility of MIG welding welded joints were found more than the ductility of SMAW welded joints.

Table-4: Calculation of Strain

A - Length after breaking (mm)
B - Original length taken (mm)
C – Difference (A - B) (mm)
D - Strain ($\frac{C}{B}$)
E - Average strain

3.2 Tensile Strength Calculation

Experimental data and calculation of UTS were recorded in table 5. The average value of UTS of base metal, SMAW welded joints, MIG welding welded joints were found 617.68 MPa, 247.03 MPa and 573.42 MPa respectively.

Table-5: Calculation of UTS
Area of cross section 360 mm^2

	Sl No	**Load**			**UTS**	**Avg UTS**
		Ton	**Kg (10^3)**	**N (10^4)**	**(MPa)**	
Base Metal	1	22	22.36	21.91	608.61	617.68
	2	22.3	22.66	22.20	616.66	
	3	22.7	23.07	22.60	627.77	
SMAW	1	8.2	8.33	8.16	226.66	247.03
	2	9.1	9.25	9.06	251.66	
	3	9.5	9.65	9.46	262.77	
MIG	1	22	22.36	21.91	608.61	573.42
	2	21	21.34	20.91	580.83	
	3	19.2	19.51	19.11	530.83	

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The experimental results show that UTS of MIG welded joints reaches near to the UTS of base metal. In both the welding conditions the breaking of specimens took place at the welded joints. Hence, efficiency of the joints was less than 100%. The UTS of SMAW welded joints were found much below the UTS of base metal due to presence of welding defect. The SMAW was completed in three passes and slag cover on the weld metal could not be cleaned properly after each pass.

Due to the presence of entrapped slag the strength was reduced. The presence of slag can be seen in Fig 3b. Fig 10 compares the values of UTS of base metal, MIG welding welded joint and SMAW welded joint.

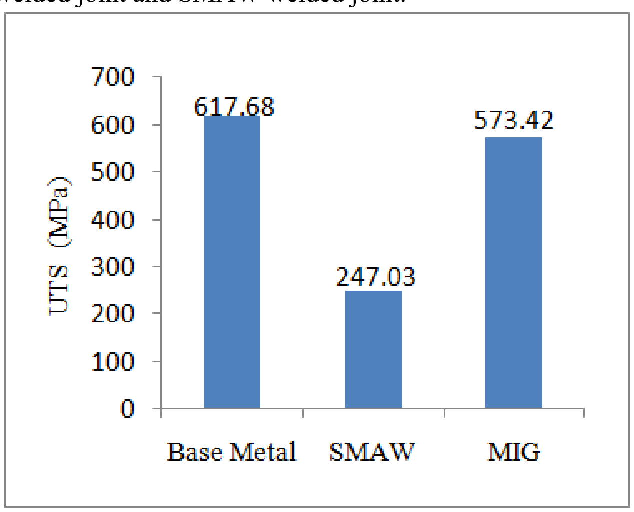

Fig-10: Comparison of UTS of Base Metal, SMAW and MIG welding welded joint.

3.3 Impact Test Results

The notch impact strength (I) is calculated by using the formula:
$I = K/A$
Where, I = Impact strength (N/mm^2)
K = Impact energy absorbed by the specimen during rupture (joules).
A= Area of cross section of specimen below the notch before test (mm^2).
The notch impact strength, to a great extent depends on the shape of the specimen and accuracy of the notch. The values determined with other specimens, therefore, may not be exactly same even if the specimens are derived from the same stock.

The impact test results are depicted in table 6. Fig 11 correlates the impact strength of SMAW welded joint and MIG welding welded joints. It is evident that the toughness value of MIG welded joint is much more than the SMAW welded joint. The slag entrapment may be the cause of lower value of impact strength in case of SMAW.

Table-6: Notch Impact Strength of Samples
A = Area of cross section 80 mm^2

	S No.	K (Kg-m)	K (joules)	I =K/A (N/mm^2)	Avg. I
SMAW	1	10.0	10×9.8 = 98.0	1.23	1.12
	2	9.2	9.2× 9.8 = 90.2	1.15	
	3	8.1	8.1×9.8 = 79.4	0.99	
MIG	1	12.2	12.2×9.8 =119.6	1.49	1.30
	2	10.2	10.2×9.8 = 99.9	1.25	
	3	9.6	9.6 ×9.8 = 94.1	1.17	

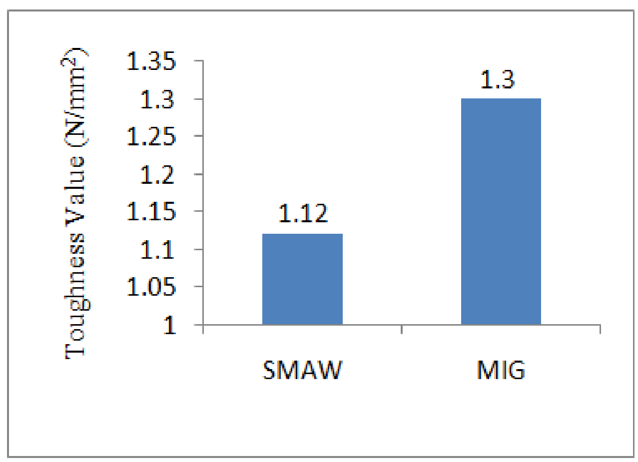

Fig-11 Comparison of toughness value of SMAW welded joint and MIG welding welded joint.

3.4 Hardness Test Results

The hardness of base metal, heat affected, and fusion zone were measured at five points in each zone. The average value of hardness were calculated in each case and recorded in table 7. Table 7 shows that the hardness value of the fusion zone in the MIG welded joint is higher than that of the SMAW welded joint. Additionally, the hardness of both the heat-affected zone (HAZ) and the fusion zone in the MIG welded joint is higher than that of the base metal.

In contrast, for the SMAW welded joint, the hardness values of the fusion zone and HAZ are lower than those of the base metal.

The carbon percentage in the SMAW rod was higher than the carbon percentage of MIG filler wire. Carbon is an austenite stabilizing element; hence more austenite will be formed in case of SMAW. The presence of more austenite may be the cause of reduced value of hardness in case of SMAW. Fig 12 compares the Rockwell Hardness Number in different zones of welded joint.

Table-7: Hardness Value in Different Zones

		Rockwell Hardness Number (RHB)					
SI. No.		1	2	3	4	5	Avg.
Across BM		40	34	33	33	34	34.8
Across HAZ	SMAW	30	33	33	33	33	32.4
	MIG	45	41	39	37	36	39.6
Across FZ	SMAW	36	33	34	35	33	34.2
	MIG	42	40	37	36	37	38.4

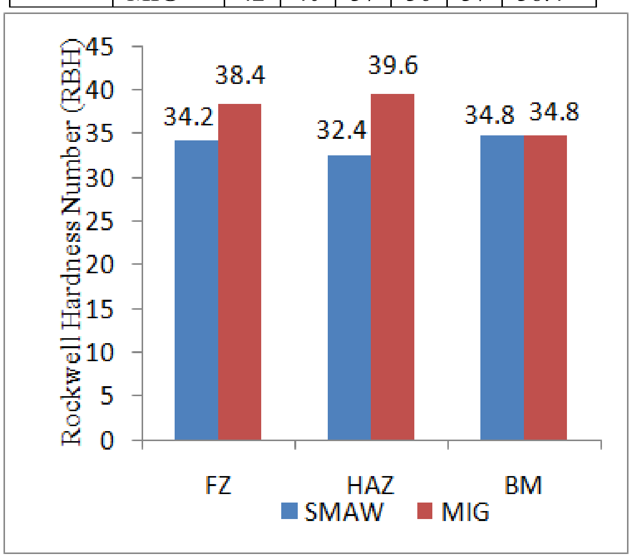

Fig-12: Comparison of Rockwell Hardness Number in different welded region

3.5 Microstructure

Microstructure of different zones was studied under metallurgical microscope and photographs were taken. Fig 13 demonstrates that FZ (fusion zone) microstructure of SMAW welded joints. It consists of mainly an austenitic matrix.

Figure 14 presents the microstructure of the weld metal zone, heat-affected zone (HAZ), and base metal. The figure also shows the fusion boundary line Figure 15 shows the base metal microstructure, consisting of austenite within a ferrite matrix.

Figure 16 shows the weld metal zone microstructure under MIG welding conditions. The microstructure contents fully austenite structure. This happens due to rapid cooling after welding. Figure 17 presents the weld metal zone, fusion boundary, heat-affected zone, and base metal for MIG welding. It shows that the HAZ width in MIG welding exceeds that of SMAW. The higher rate of heat input may be the cause of wider HAZ in MIG welding.

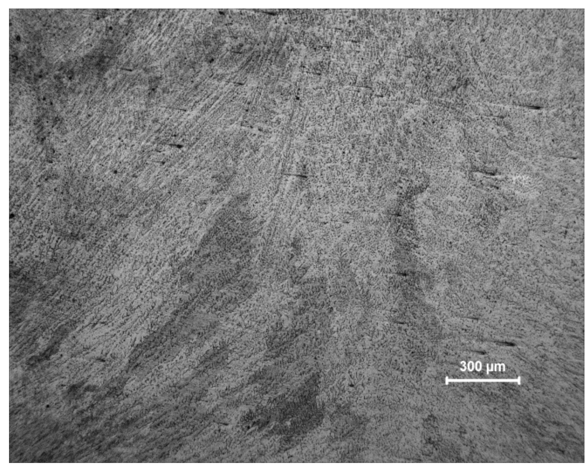

Fig-13: Weld metal zone microstructure - SMAW welded joint.

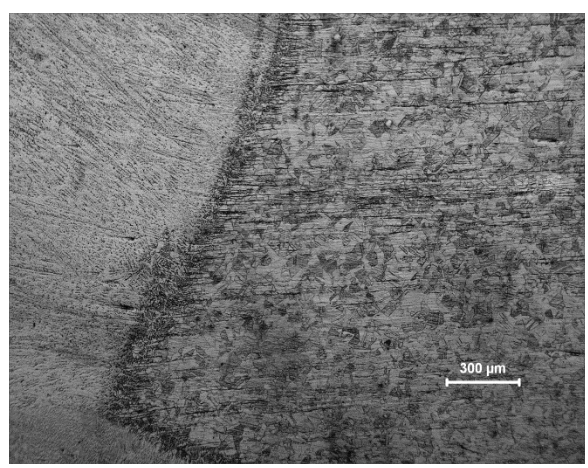

Fig-14: Weld metal zone and HAZ microstructure - SMAW welded joint.

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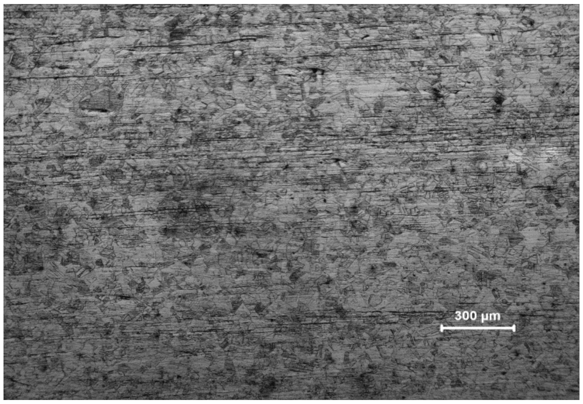

Fig-15: Base metal microstructure of 304L ASS.

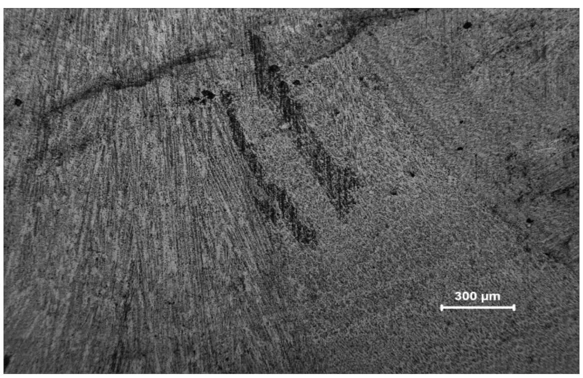

Fig-16: Weld metal zone microstructure - MIG welded joint.

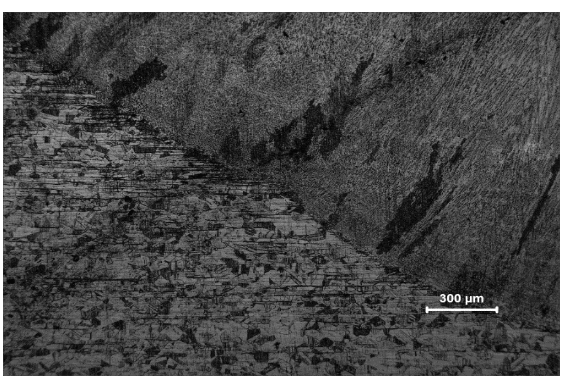

Fig-17: Weld metal zone and HAZ microstructure - MIG welded joint

IV. CONCLUSIONS

MIG welded joints exhibited a substantially greater ultimate tensile strength as compared to those produced by SMAW. Most probably due to the slag entrapment the strength of the SMAW welded joint was reduced. From Fig 3b, it is clear that slag was entrapped in the weld bead which didn't allow the filler metal to fuse completely with base metal. Both types of welded joint ruptured at the weld joint, it shows that the efficiency of welded joints were less than 100%. However, the UTS of MIG welding welded joint was found near to the base metal. Toughness value of welded joint of MIG welding was found more than SMAW. It is clear that MIG welded joint absorbs more energy during impact. SMAW welded joint's average Rockwell hardness was found less than MIG welded joint in fusion zone and HAZ. Hardness of SMAW welded joint was also found less than the hardness of base metal. In case of MIG welded joint, hardness value of fusion zone and HAZ were found more than the primary metal. The carbon percentage in the SMAW rod was higher than the carbon percentage of MIG filler wire. Carbon is an austenite stabilizer element; hence more austenite will be formed in case of SMAW. The presence of more austenite may be the cause of reduced value of hardness. In MIG welding wider zone of HAZ was found than SMAW. It may be the result of higher heat input rate in MIG welding than SMAW.

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