Mechanical properties and microstructural characteristics of rotating arc gas metal arc welded carbon steel joints

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KEYWORDS

Carbon Steel,
Rotating Arc Welding,
Tensile Properties,
Impact Toughness
and Microstructural
Characteristics.

ABSTRACT

Low carbon steels are widely used in the manufacturing sectors due to their easy weldability than other carbon steels. Usually, the welding processes like shielded metal arc welding (SMAW), and gas metal arc welding (GMAW) are used for welding thick low carbon steel plates. Recently, a novel "rotary arc" or "spin arc" technique is developed with a rotary motion of filler wire that can change the flow of the weld puddle. In this investigation, an attempt has been made to join 12mm thick carbon steel plates made by stationary arc gas metal arc welding (SA-GMAW) and rotating arc gas metal arc welding (RA-GMAW) processes. The objective of present paper is to study the influence of rotating arc on mechanical properties and microstructural characteristics of GMA welded carbon steel joints. The results indicated that the arc rotation of GMAW process yielded 15% improvement in joint efficiency than the conventional stationary arc process.

1. Introduction

IS2062 Gr-B steel is the most widely used form of carbon steel. This is the most preferred steel for carburized components. These steels are comparable soft and have good strength. They do, however, have high ductility, making it better for machining, forming, welding at a low cost. These steels are usually welded by shielded metal arc welding (SMAW), and gas metal arc welding (GMAW) processes. Defects like weld porosity, lack of sidewall fusion and wide heat affected zone softening are unavoidable during welding of high thickness steel plates. These defects affect the welded joints of mechanical properties. Additionally in the conventional welding processes, each plate is to be edge prepared before welding. This requires more time and leads to reduction in productivity. Hence the fabricators in the manufacturing industry are looking out for technologies to reduce the time required for joint preparation and welding. Also searching for technologies to limit distortion and using a low volume of filler metal addition without compromising mechanical properties [1].

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The above mentioned problems could be overthrown by a new emerging welding technique called "Spin Arc" or "Rotating Arc" welding. In this process, the filler wire is rotated at middle of weld plates (Fig. 1). This filler wire generates an arc after touching work piece and the rotation of arc creates the centrifugal force in the weld pool.

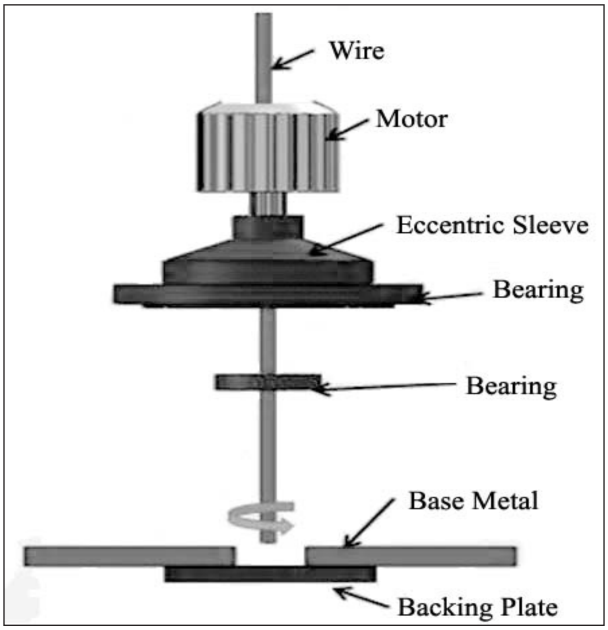


Fig. 1. Schematic diagram of Rotary arc welding set up.

This phenomenon decreases the heat input supplied to base metal and also increasing sidewall fusion. A customized torch is used for rotating the arc. The torch works with both constant voltage GMAW and pulsed GMAW power sources [2]. The main parameters affecting the process in the rotation arc welding technique are: (i) Arc rotational speed, (ii) Diameter of arc rotational, and (iii) Arc rotating direction. All these parameters can be precisely controlled using a control box included with the welding power source as shown in Fig. 2.

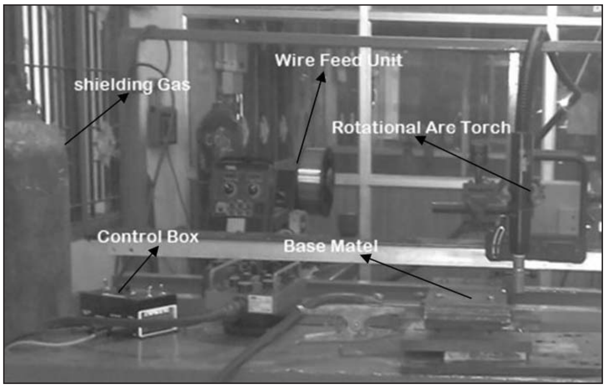


Fig. 2. Rotary arc welding machine set up.

Generally, the process of rotating arc welding is developed to reduce the heat input, improve sidewall fusion, increase productivity by eliminating edge preparation and reduce the number of passes without any compromise on strength properties in weld joints. In this process, the filler wire was rotated by a special type of rotating motor within itself. This rotating filler wire will rotate the arc between the welding plates. During welding, the rotation arc should be rotated in a circular motion, so it creates the centrifugal force on the arc. This force action on molten metal droplet transfer during welding and also due to arc rotation the heat will be distributed from the weld joint, so the cooling rate will increase. Fig. 3 shows the arc rotation during welding.

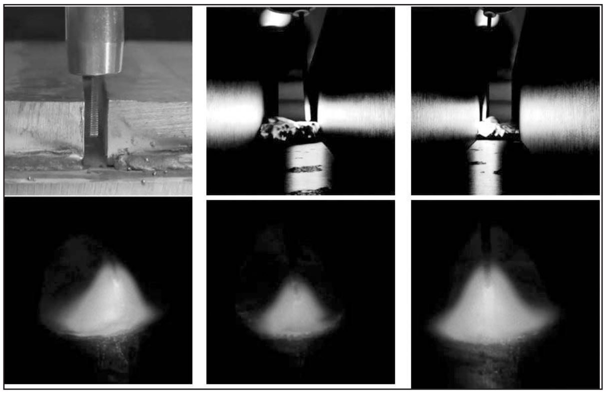


Fig. 3. Rotating Arc technology; operation at rotating arc welding high speed video frame.

Most of the research works on carbon steels have been focused on the effect of various parameters of the GMAW and SMAW processes. However, the effect of stationary arc (SA) and rotating arc (RA) on mechanical properties and microstructural characteristics of carbon steel joints is not yet fully understood. Therefore, the present work aims to study the effect of arc rotation on tensile and impact toughness properties of GMA welded carbon steel joints and correlate with corresponding microstructural features.

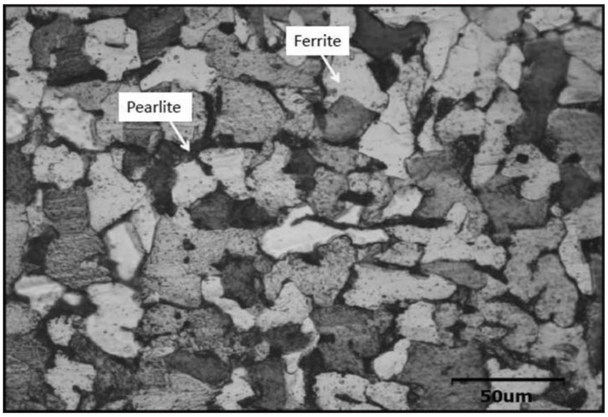


Fig. 4. Optical micrograph of base metal.

2. Experimental Work

2.1 Base material and welding processes

The base metal used in this study was IS2062 Gr-B, carbon steel of 12 mm thickness. The base metal contains large volume fraction of elongated ferrite and small volume fraction of pearlite microstructure as shown in Fig. 4. The filler wire ER70S-6 with a diameter of 1.2 mm was used to fabricate the joints. The base metal and filler metal chemical composition and mechanical properties are presented in Table 1 and Table 2, respectively. The rolled plates were sliced into ($300x150x12mm^3$) dimensions by abrasives cutting machine. The plates were edge prepared in "V" groove configuration for welding using SA-GMAW process. Square butt configuration was prepared for welding using the RA-GMAW process (Fig. 5). The GMAW-1G with multi-pass welding technique was applied for both SA-GMAW and RA-GMAW processes. For the SA-GMAW process, arc voltage (V), welding current (A), travel speed (mm/min), wire feed rate (mm/min) are considered to be significant process parameters. However, for the RA-GMAW process, along with the above

Table 1
Chemical composition of base metal (BM) and filler metal (FM).

Material	Specification	C	Si	Mn	P	S	Cr	Mo	Ni	Fe
BM	IS2062 Gr.B	0.25	0.07	0.65	0.028	0.038	0.08	0.005	0.013	Bal
FM	ER 70S-6	0.07	0.86	1.44	0.014	0.008	0.025	0.002	0.014	Bal

Table 2
Mechanical properties of base metal (BM) and filler metal (FM).

Material	Yield Tensile Strength (MPa) at 0.2% strain	Ultimate Tensile Strength (MPa)	Elongation (%) at 50 mm GL	Impact Toughness @ RT (J)
BM	437±5	547±7	28±3	170±6
FM	424±6	518±4	28±2	163±3
GL : Gauge Length; RT : Room Temperature.				

Table 3
Optimized welding parameters used to fabricate the weld joints.

Parameters	Unit	SA-GMAW						RA-GMAW		
Number of Pass		1	2	3	4	5	6	1	2	3
Welding current	A	133	135	134	136	135	133	130	135	132
Arc voltage	V	25	25	25	25	25	25	25	25	25
Welding speed	mm /min	250	250	250	250	250	250	250	250	250
Wire feed rate	mm /min	165	165	165	165	160	160	165	165	165
Filler wire diameter	mm	1.2						1.2		
Arc rotational speed	rpm	-						1500		
Arc rotating diameter	mm	-						3		
Root gab	mm	3						8		
CTWD	mm	15						20		
Gas flow rate	lit/min	18						15		
Heat input	kJ/min	0.80	0.81	0.80	0.81	0.81	0.80	0.78	0.81	0.79

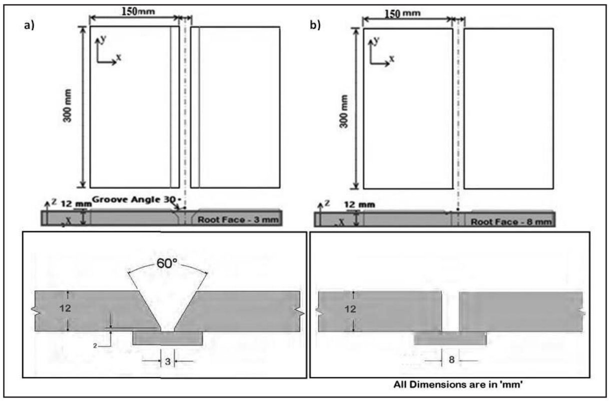


Fig. 5. Configuration of welded joints
a) SA- GMAW joint b) RA- GMAW joint.

parameters, arc rotating diameter (mm) and arc rotating speed (rpm) are considered to be significant process parameters. During welding, using SA-GMAW and RA-GMAW processes, the shielding gas flow rate was kept constant. The optimized welding processes parameters used to fabricate the joints are presented in Table. 3.

2.2 Mechanical properties evaluation

The welded joints were cut and then machined to the necessary dimensions. The smooth (unnotched) tensile specimens were prepared to calculate the tensile strength, yield strength, elongation, and joint efficiency. The notched tensile specimens were prepared to evaluate the notch tensile strength and notch strength ratio (NSR) of the joints. The impact toughness specimens were prepared to estimate the impact toughness of welded joints. The scheme of extraction of the specimen from the welded joints and dimensions of the specimen are shown in Fig. 6 and 7, respectively. The tensile test and notch tensile test were carried out in a 100 kN electromechanical controlled universal testing machine (UTM). The specimens were loaded at 1.5 kN/min as per ASTM E8-04 guidelines [3]. The Charpy impact toughness test was conducted using a pendulum-type impact testing machine. At each condition, three specimens were tested and the average of three samples was used to calculate tensile and impact toughness properties. A Vickers microhardness testing machine was used for measuring the microhardness across weld metal and heat affected zone regions, with a load of 0.5 kg and a dwell time of 15s.

2.3 Metallurgical characterisation

Microstructural analysis of the weldments was carried out following the procedure prescribed by ASTM E354 standard using a light optical microscope (OM). The cross sectional weld surfaces were etched with 2 % nital reagent to reveal the microstructure of weld metal (WM), interface (IF), coarse grain heat-affected zone (CGHAZ), and fine grain heat-affected zone (FGHAZ) regions of the welded joints. Moreover after testing the fracture surface of tensile, notch tensile, and impact toughness test specimens were analised by scanning electron microscopy (SEM). The chemical composition of the weld metal region of SA-GMA and RA-GMA welded joints were quantified by optical emission spectroscopy (OES) analysis.

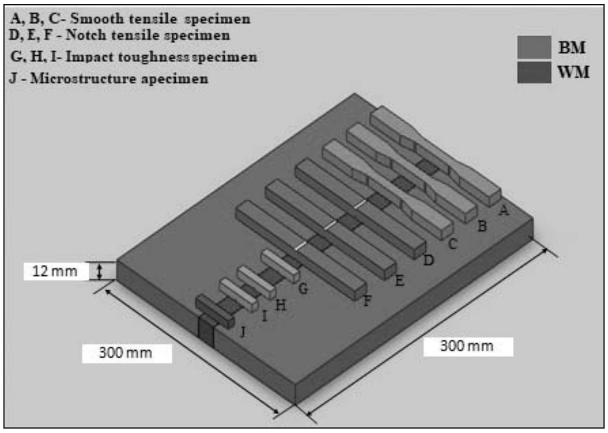


Fig. 6. Scheme of extraction of specimens from the welded joints.

3. Results

3.1 Tensile and impact toughness properties

The transverse tensile properties of BM, SA – GMAW and RA - GMAW joints are reported in Table 4. The SA-GMAW joint failed in the WM region and the RA-GMAW joint failed in the BM region during tensile test. It is inferred that the WM strength of RA-GMAW joint is higher than BM and SA-GMAW joint. The tensile and notch tensile specimens are displayed in Fig. 8. The stress -strain curves were recorded during tensile test and displayed in Fig 9. The results indicated that the ultimate

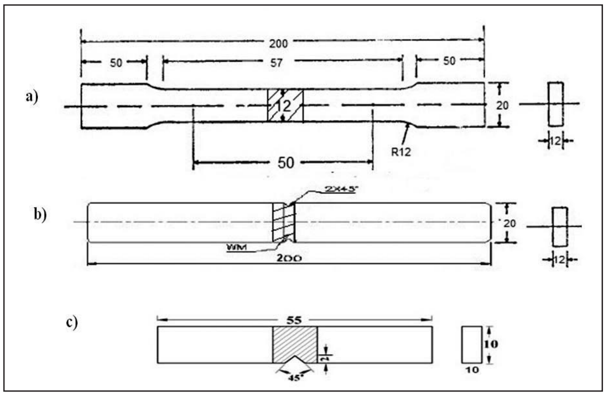


Fig. 7. Dimensions of the specimens
a) Smooth tensile specimen, b) Notch tensile specimen
c) Impact toughness specimen

Table 4
Transverse tensile properties of welded joints.

Joint	0.2% Yield strength (MPa)	Ultimate Tensile strength (MPa)	Elongation in 50 mm gauge length (%)	Notch Tensile Strength (MPa)	Notch Strength Ratio (NSR)	Joint Efficiency (%)	Location of Failure
BM	437±10	547±12	26±6	671±15	1.22	-	-
SA-GMAW	426±9	525±5	28±2	685±12	1.28	95	WM
RA-GMAW	467±11	598±4	23±3	727±8	1.15	110	BM

tensile strength and yield strength of the BM are 547 MPa and 437 MPa respectively. The RA-GMAW joints exhibited a maximum ultimate tensile strength and yield strength of 598 MPa and 467 MPa. The elongation of BM, SA-GMAW, and RA-GMAW joints is 26% 28%, and 23% respectively. It indicates that there is a 12% reduction in ductility in RA - GMAW joint and an 8% increase in the SA-GMAW joint compared to BM.

The notch tensile strength of the BM is 671 MPa but the notch tensile strength of SA – GMAW and RA-GMAW joints are 685 MPa, 727 MPa respectively. Thus there is an 11% increase in notch tensile strength. There is a 10% increase in SA-GAMW joint compared to BM. Another notch tensile parameter, NSR is greater than one (>1) for all the joints. This shows the BM is insensitive to notches and they fall into the notch ductile martial's category. The joint efficiency calculated with the above equation is presented in table 4. From the results, it is found that joint efficiency of SA-GMAW and RA-GMAW are 95 % and 110%. The RA-GMAW joint is showing 15% higher joint efficiency compared to the SA-GMAW joint.

The Charpy impact toughness values of BM and the welded joints are shown in Table 5 and the photographs of test samples are displayed in Fig. 10. From the results, it is found that the SA-GMAW joints are having greater impact toughness than RA-GMAW joints. The RA-GMAW joints showed a 20 % reduction in impact toughness compared to BM.

3.2 Microhardness

Fig. 11 illustrates the microhardness distribution in various regions of SA- GMAW, and RA - GMAW joints. Lowest hardness was recorded in the weld metal (WM) of the SA-GMAW joint and the maximum hardness was recorded in the fine grain heat affected zone (FGHAZ) region of the RA-GMAW joint. The hardness of unwelded BM is 185 HV, however, the WM region of SA-GMAW joint shows an average hardness of 197 HV, and 220 HV is recorded in WM region of RA - GMAW joint. The CGHAZ region of the SA-GMAW joint recorded lower (170 HV) hardness. The hardness of the FGHAZ region of SA- GMAW and RA- GMAW joints are 214 HV and 224 HV respectively.

The CGHAZ region of the RA - GMAW joint shows 17% higher hardness compared to SA-GMAW joints. The variation in hardness of WM

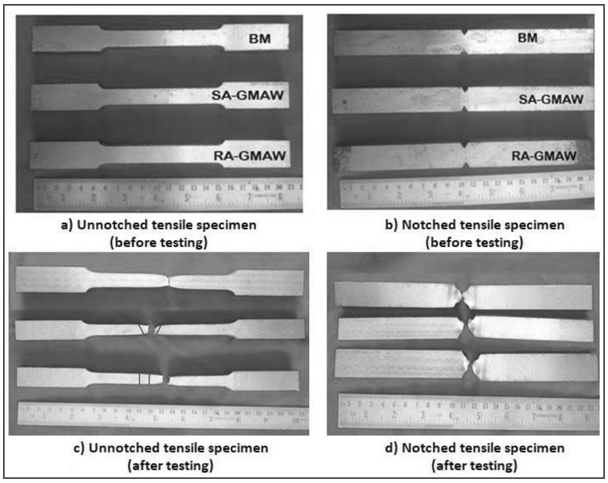


Fig. 8. Photographs of tensile test specimen.

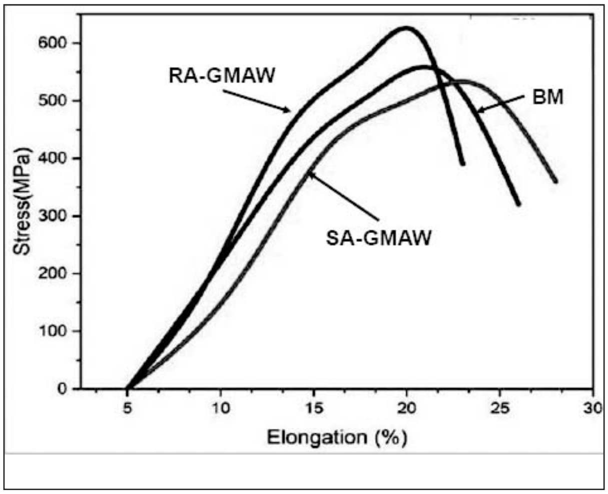


Fig. 9. Stress – Strain curves for the base metal and welded joints.

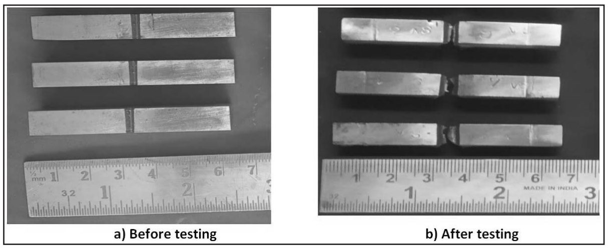


Fig. 10. Photographs of impact test specimen.

Table 5
Impact toughness of welded joints.

Joint	Impact toughness @ RT (J)
Base metal	170±6
SA-GMAW	153±9
RA-GMAW	137±5

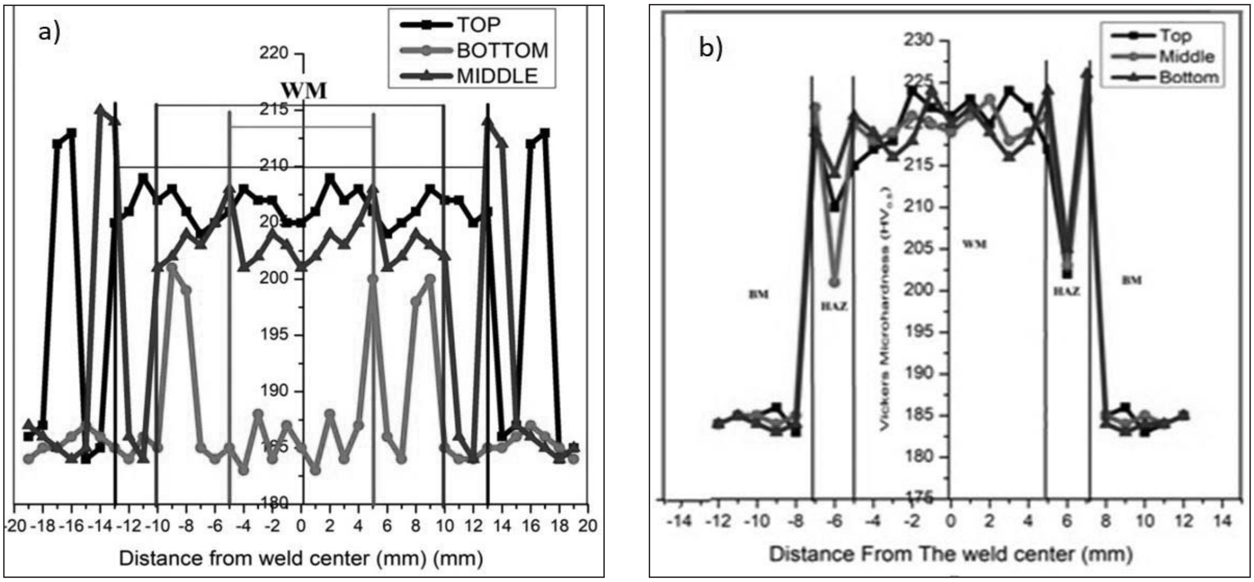


Fig. 11. Microhardness variation across the welded joints. a) SA- GMAW joint b) RA- GMAW joint.

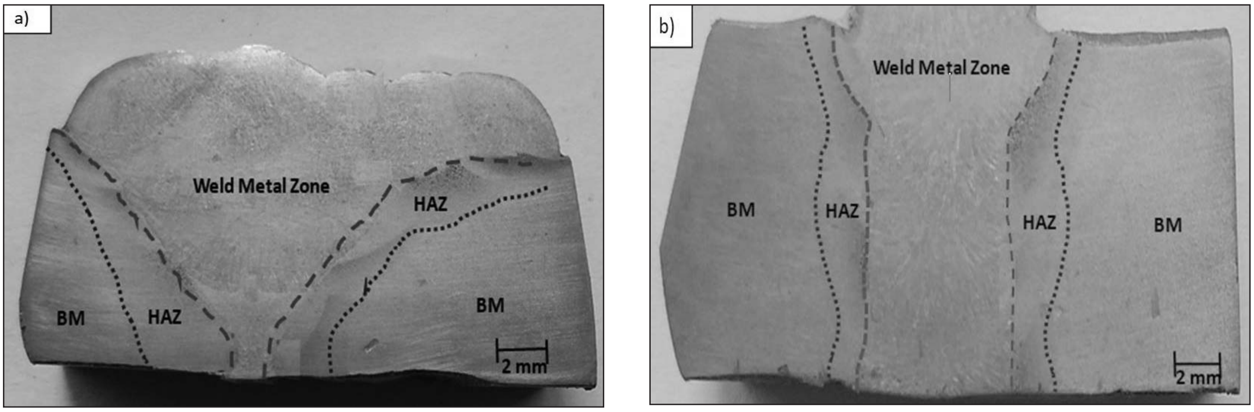


Fig. 12. Cross- sectional macrostructure of welded joint. a) SA- GMAW joint b) RA- GMAW joint.

Table 6

Weld bead geometry (macrostructure analysis).

Joint	Width of bead (mm)	Depth of penetration (mm)	Weld metal area (mm^2)	HAZ area (mm^2)	Width of the HAZ (mm)	Number of passes	Cumulative heat input (kJ*min^{-1})
SA-GMAW	26	12.4	158	64	4	6	4.83
RA-GMAW	10	12.6	98	32	2	3	2.38

and HAZ regions are mostly due to the variations in microstructural characteristics, caused by thermal cycles during welding and formation of the different chemical composition in weld metal region.

3.3 Macrostructure

The cross sectional macrostructure of SA-GMA and RA-GMA welded joints is depicted in Fig 12. From the macrographs, it is undershoot that WM region reveals very sound joints without any sagging defect, porosity, and cracks. Fig. 12a) shows the macrograph of SA-GMAW joint with 'V' groove edge preparation. Fig. 12b) shows the macrograph of RA-GMAW square butt joint (without edge preparation). This type of straight bead profile with very good sidewall fusion is difficult to attain in the SA-GMAW process. The bead geometry such as the width of the bead, HAZ area, WM area, HAZ width, and penetration were measured using Image J analysis software

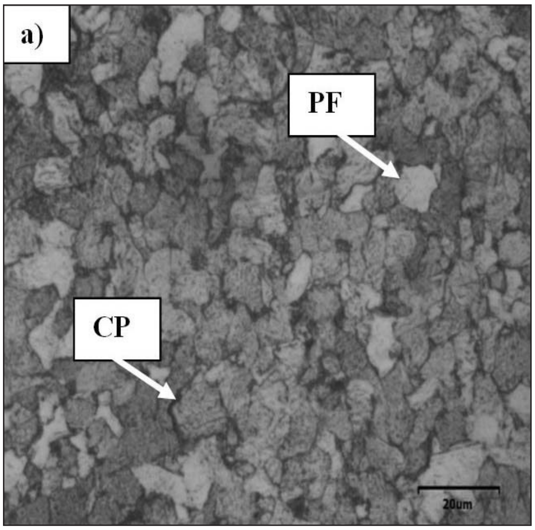
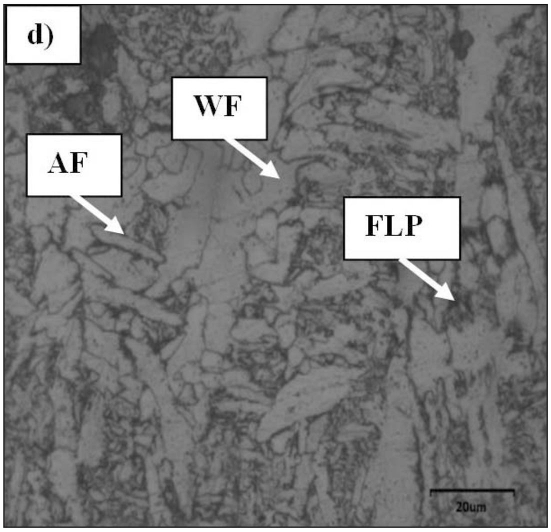
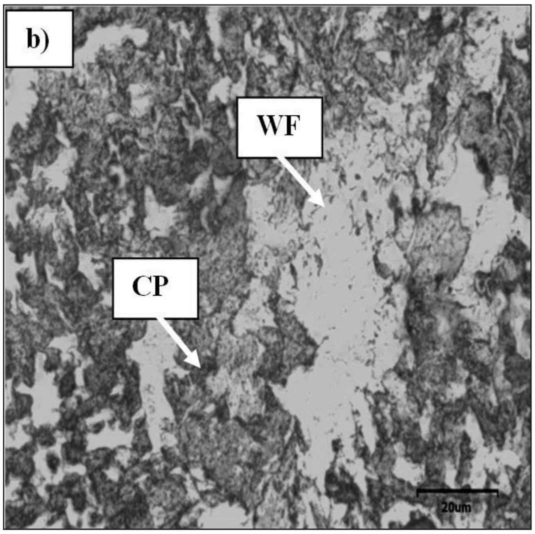
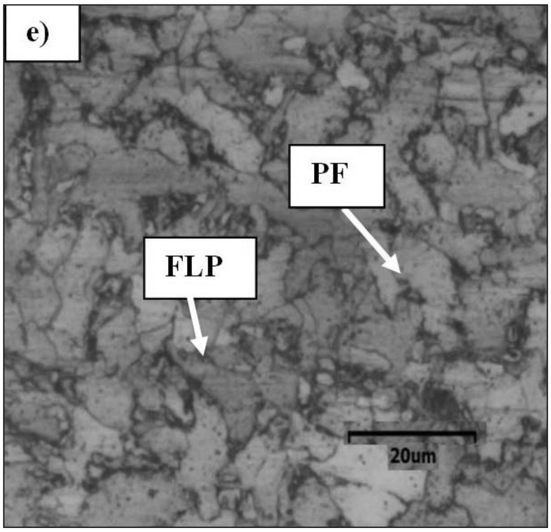
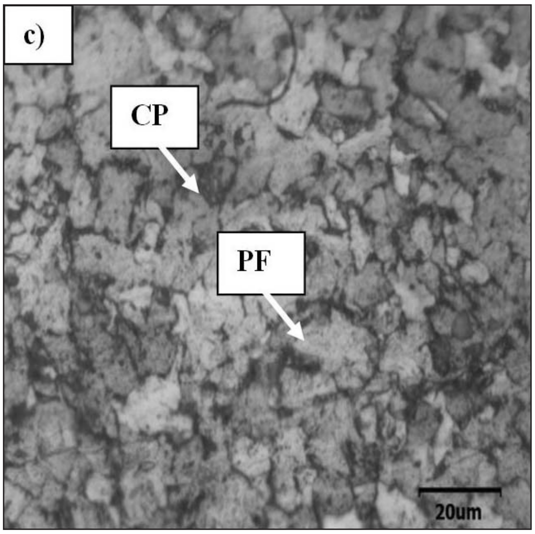
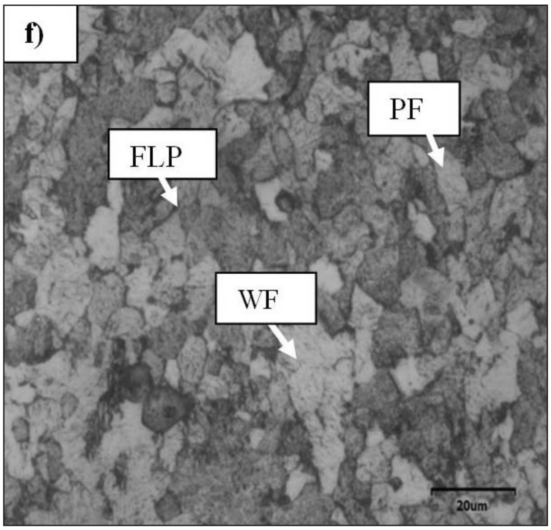
Location	SA-GMAW Joint	RA-GMAW Joint
Top Region (3mm from top)		
Middle Region (6 mm from top)		
Bottom Region (9 mm from top)		

Fig. 13. Optical micrograph of weld metal (WM) region.

attached with an optical microscope. The measured values are presented in Table 6. From the results, it is inferred that the width of the bead reduced from 26 mm to 10 mm in RA-GMAW joint. Another very interesting note is that the WM area of the SA-GMAW joint is 158 mm^2 and the RA-GMAW joint is 68 mm^2. The WM area is greatly reduced (48%) in RA-GMAW joint compared to the SA-GMAW joint. It is very useful to improve efficiency of the process and reduce filler metal (fabrication) cost. Further, HAZ width is reduced from 4 mm to 2 mm, which is a great advantage RA-GMAW process. This may be due to lower heat input supplied during welding. Another very interesting note is the number of passes reduced from 6 to 3 in RA-GMAW process, and have the arcing time and heating and cooling cycles will be reduced. In this way, the rotation arc welding processes reduced heat input, edge preparation time, labor cost, machine cost, and filler metal cost and welding time by 50 %. Thus, the overall productivity has enhanced due to the use of arc rotation arc in GMAW process.

3.4 Microstructure

The base metal microstructure mainly consists of dark pearlite strips mixed with white ferrite matrix. The ferrite grains appear slightly elongated. Fig. 13 displayed the OM images of weld metal (WM) regions of both the welded joints. The WM region of SA-GMAW joint contains coarse pearlite (CP) mixed with polygonal ferrite (PF) matrix (Fig. 13a-c). The WM region of RA-GMAW joint revels the high volume fraction of acicular ferrite (AF) and PF matrix mixed fine lamellar pearlite (FLP) microstructure (Figs.13d-f) [4].

4. Discussion

The RA-GMAW joint showed higher tensile strength (598 MPa) than SA-GMAW joint. This is mostly due to two factors: weld metal hardness and microstructure. The hardness of the weld metal of RA-GMAW joint recorded 223 HV and the SA-GMAW joint recorded 185 HV. This hardness variation on WM is due to the difference in grain size, microstructural changes and chemical composition. The microstructure of the WM region of SA-GMAW joint contains coarse PF and a small amount of LP morphology. The RA-GMAW joint contains a FLP phase in the AF matrix. The FLP structure has higher hardness compared to coarse PF and pearlite phases [5]. The formation of these microstructures is because of the different cooling rates of weld metal. The RA-GMA welding process provides very low heat input (2.38 kJ/mm) compared to the SA-GMA welding process (6.48 kJ mm). These heat inputs affect the cooling rate of the weld joint. The higher heat input leads to grain growth in the weld pool [6]. The heat input is lower, there is no time for grain growth, so the grains solidified faster, and it is formed FLP mixed with AF matrix microstructure in RA-GMA weld metal. The heat input is higher in SA-GMAW process compared to RA- GMAW process, because of this, the SA-GMAW joint showed coarse PF mixed with pearlite in the weld metal. The AF microstructure shows a significant effect on the tensile strength of weld metal, due to its fine-grained size and interlocking structure with high angle grain boundaries, which act as a hindrance to crack propagations.

Table 5 presents the impact toughness of base metal and welded joints. It inferred that the impact toughness of SA-GMAW joints was higher (157 J) than RA-GMAW joints (137 J) and BM. From the hardness survey, it is understood that RA-GMAW joints show higher hardness (223 HV) in the weld metal and this is due to lower heat input and different ferrite phases formed in the WM. The effect of arc rotation on impact toughness lies on the influence of heat input of the microstructure in WM. Due to less solidification time; it is observed that the formation of fine AF in WM, and it is leading to the higher hardness and lower toughness of the RA-GMAW joint. It is not easy to propagate micro-cracks along the CPF structure, when the heat input is high takes more time for solidification leads to growth in grains resulted in CPF formed in weld metal [7]. Due to these reasons, SA-GMAW joint showed higher impact toughness compared to RA-GMAW joints.

Smaller grains will hinder the dislocations more than the larger grains, due to a large number of grain boundaries per unit area [8]. Consequently, dislocation pile up at the grain boundaries and generate internal stress due to this a large sudden force has applied to the maternal i.e. to overcome dislocation pile-up stress [9]. Hence SA-GMAW joint exhibited higher impact toughness than RA-GMAW joint. Fig. 13a-c) shows CLP formed in PF grain boundaries. It has been the best feature to stop a propagating crack. From this study RA-GMAW joint showed better tensile and hardness properties. However, the SA-GMAW joint exhibited better impact properties.

5. Conclusions

In the present investigation, the effect of rotating arc on mechanical properties of gas metal arc welded carbon steel was analysed and the following important conclusions are derived.

(i) Carbon steel plates of 12 mm thickness where successfully welded with square butt join configuration by rotating arc GMAW process without any macro-level defects.

(ii) Because of square butt joint configuration, the volume of weld metal deposition and number of passes to complete the fabrication were greatly reduced in rotating arc GMAW process.

(iii) The weld metal area is reduced to 98 mm^2 square (158 mm^2 for SA-GMAW joint) and adjusted with also reduced to 2 mm (4 mm in SA-GMAW joint) and number of passes is reduced to 3 (6 passes in SA-GMAW process) in RA-GMAW process.

(iv) Tensile strength (598 MPa) and weld metal hardness (223 HV) of RA-GMAW joint are superior compared to SA-GMAW joint. Moreover, RA-GMAW joint exhibited 15% higher joint efficiency than SA-GMAW joint. This is due to the presence of higher volume fraction of acicular ferrite mixed with fine lamellar pearlite in the weld metal region.

(v) The ductility (percentage of elongation and notch strength ratio) of the weld metal and impact toughness of the weld metal is 10 % higher in SA-GMAW joint compared to RA-GMAW joint. This is due to presence of coarse pearlite mixed with polygonal ferrite matrix in weld metal region.

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References

1. World Pipelines, Magazine (2017). 71-75.

2. World-Pipelines, Article. January (2015). 67-75.

3. Designation ASTM, (2014). Standard test methods for notched bar impact testing of metallic materials.

4. Mehran, R., Mahya, G., Alireza,V., Nasiri, A. (2019). Microstructural evolution and mechanical properties of a low-carbon low-alloy steel produced by wire arc additive manufacturing. *International Journal of Advance Manufacturing and Technology*, 2, 01-14.

5. Kumar, R., Arya, H.K., & Saxena, R. K. (2014). Effect of cooling rate on microstructure of saw welded mild steel plate (Grade C 25 as per IS 1570). *International Journal of Modern Engineering Research*, 4(1), 222–228.

6. Mohammad, S., Hosseini, K., Zarei-Hanzaki, A. (2015). Effects of ferrite phase characteristics on microstructure and mechanical properties of thermo mechanically-processed low-silicon content TRIP-assisted steels. *Material Science Engineering. A,* 626, 229-236.

7. Elwazri, A.M., Wanjara, P. (2002). The effect of microstructural characteristics of pearlite on the mechanical properties of hypereutectoid steels. *Material Science Engineering. A*, 404.

8. Morris, J. W. (2001). *The influence of grain size on the mechanical properties of steel*. UK.01.

9. Armstrong, R. W. (2017). Dislocation pile-ups, strength properties and fracturing. *Advanced Materials Science,* 48, 1-12.

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