Influence Of Welding Process And Weld Design On The Mechanical Properties Of Reduced Activation Ferritic-Matensitic Steel Weldments

P.Narsimha, L. Siva Rama Krishna, P.Venkata Ramana

Abstract : The demand for the employing nuclear energy for generation of power is ever increasing. In this regard constant efforts are being made to develop increased thermodynamic efficiency nuclear power reactors, which also help reducing the threat of global warming. These reactors require structural materials with acceptable high temperature mechanical properties and excellent irradiation resistance. Reduced Activation Ferritic-Martensitic (RAFM) steel is one such steel which can be used as structural material for fabricating the blanket module. Major route of fabrication employing these steels is welding. Researchers have already reported on welding of thick sheets of RAFM steel by employing welding processes such Narrow gap TIG, Electron Beam Welding etc. An attempt is made in the present work to weld thin sheets of RAFM steel by employing different welding processes such as TIG, Pulsed-TIG, and MIG to study the influence of the welding processes on the mechanical properties such as hardness, tensile strength and impact toughness. Attempt is also made to study the influence of weld design on the mechanical properties. It is observed that in all the weld joints the hardness of weld zone is high and is decreasing from weld zone to HAZ and parent material. The tensile and impact tests revealed that the TIG weld joints exhibited better tensile strength and impact toughness. It is also observed that higher the weld groove angle, higher the impact toughness. Among all the joints, TIG welded joint with 60^0 weld groove angle exhibited highest tensile strength and highest impact toughness.

Index Terms: Reduced Activation Ferritic-Matensitic Steel, Welding Process, Weld Design, Tensile Strength, Impact Toughness, Hardness

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1 INTRODUCTION

The biggest threat to the civilization of twenty-first century is the global warming. Reduction of CO_2 emission is an urgent task for power industries, especially for fossil power plants [1]. To reduce the CO_2 emission, one of the alternates of fossil power plants is realization of fusion power. Harnessing fusion power is the goal of fusion power plants. Fusion, the nuclear reaction that powers the Sun and the stars, is a potential source of safe, non-carbon emitting and virtually limitless energy. Power plants today rely either on fossil fuels, nuclear fission, or renewable sources like wind or water. Whatever the energy source, the plants generate electricity by converting mechanical power, such as the rotation of a turbine, into electrical power. In a coal-fired steam station, the combustion of coal turns water into steam and the steam in turn drives turbine generators to produce electricity. Just like a conventional power plant, a fusion power plant will use this heat to produce steam and then electricity by way of turbines and generators. Various approaches have been adopted for the development of steels and manufacturing technologies for fusion reactors [2-4]. Towards the realization of a viable fusion reactor technology to produce electricity, one of the key technological challenges has been the development of a suitable structural material for blanket module, which can retain adequate mechanical properties under intense neutron irradiation and high thermo-mechanical loads during reactor operation. The high dose of residual radioactivity, originating from the long-lived transmutation nuclides of Mo, Nb, Ni, N, B, Cu, Co, Ti, etc. W, Ta, Mn, V, etc. having relatively short-lived transmutations nuclides, to facilitate easy handling of the disposed blanket module at the end of service. The 9–12 wt.% Cr, tungsten and tantalum bearing steels are commonly classified as the Reduced Activation Ferritic–Martensitic (RAFM) steels. The ideally aimed decay time for residual radioactivity of this type of steels for shallow burial is reported to be around 100 years [3]. The RAFM steels developed internationally are mainly 9Cr–W–Ta based, with tungsten content in the range 1–2 wt.% and tantalum content in the range 0.02–0.18 wt.%. In India, an extensive research programme has also been initiated at Indira Gandhi Centre for Atomic Research, Kalpakkam, for the development of India-specific RAFM steel as one of the potential structural materials for Lead–Lithium Ceramic Breeder (LLCB) Test Blanket Module to be tested in ITER, France. One of the major routes for the fabrication nuclear power plant components is welding. Researchers have tried welding the RAFM steel with both fusion welding processes such tungsten inert gas welding (TIG), narrow gap TIG, laser beam welding, electron beam welding for joining thick plates and to obtain lesser weld metal volume and smaller heat affected zone. Studies also have been carried out by employing solid state welding process such as friction stir welding, in order to overcome the problems the associated with the fusion welding process. Though some work is reported on welding of the RAFM steel thick plates, there is scope for work on thin plates especially by employing welding processes such conventional welding processes such as TIG, pulsed TIG, and MIG.

2 EXPERIMENTAL DETAILS

2.1 Material

The material employed in this study is a 6 mm thick Reduced Activation Ferritic- Martensitic Steel (9Cr 1.4W Grade, IN-RAFMS) whose chemical composition is given in the Table 1.

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TABLE 1

Chemical composition of parent material

Material	Element (wt %)								
RAFMS	C	Si	Mn	Cr	Ni	S	P	Ti	Co
	0.092	0.033	0.49	8.96	0.002	0.002	0.002	<0.005	0.002
	V	W	Ta	B	Al	Cu	Nb	Zr+As+ Sn+Sb	Fe
	0.24	1.33	0.06	<0.001	0.005	<0.002	<0.001	<0.03	Bal.

2.2 Welding Processes

In the present study, Gas Tungsten Arc Welding (GTAW) popularly known as Tungsten Inert Gas Welding (TIG), Pulsed Gas Tungsten Arc Welding (P-GTAW or P-TIG) and Gas Metal Arc Welding (GMAW) popularly known as Metal Inert Gas Welding (MIG) processes are employed. The details of weld coupon preparation and test plate assembly are shown in Fig.1. In all the welding processes, a matching filler material composition to that of the parent metal is used. The analyzed composition of the filler material is presented in Table 2.

TABLE 2

Chemical composition of filler material

Material	Element (wt %)								
RAFMS	C	Si	Mn	Cr	Ni	S	P	Ti	Co
	0.12	0.07	0.57	9.16	0.015	0.0017	0.003	0.001	0.004
	V	W	Ta	B	Al	Cu	Nb	Mo	Fe
	0.21	1.01	0.07	0.005	0.003	0.002	0.001	0.001	Bal.

The welding processes are employed independently to obtain similar metal welds of RAFMS. To study the effect of welding process and weld groove design on the mechanical properties, similar metal welding of plates was carried out independently with three different welding processes using three weld designs for each of the welding process. The details of all the weldments are given in Table 3 and the welding parameters are presented in Table 4. The weld coupons are prepared with 30, 45, 60 degrees included angle of weld groove, by special setup of fixers in the vertical milling machine with 1 mm root face and 1.5 mm root gap.

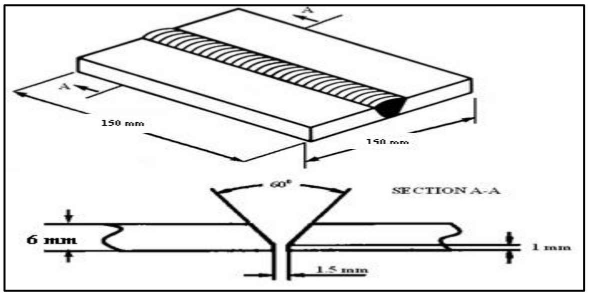

***Fig. 1**. Typical weld coupon design and test plate assembly.*

TABLE 3

Details of all the weldments

Weldments	Welding Process	Weld groove included angle	Weld Coupon Identification
RAFMS to RAFMS	TIG	30^0	T30
		45^0	T45
		60^0	T60
	Pulsed TIG	30^0	PT30
		45^0	PT45
		60^0	PT60
	MIG	30^0	M30
		45^0	M45
		60^0	M60

TABLE 4

Welding parameters

Parameters	TIG	Pulsed TIG	MIG
Welding current (A)	100-120	90-110	180-200
Welding speed (mm/min)	100	100	100
Electrode polarity	Direct Current Straight Polarity	Direct Current Straight Polarity	Direct Current Straight Polarity
Arc voltage (V)	26-30	24-28	22-24
Filler wire diameter (mm)	1.2	1.2	1.2
Electrode	2% Thoriated tungsten	2% Thoriated tungsten	-
No .of passes	3	3	2
Shielding gas	Argon, flow rate 35 CFH	Argon, flow rate 35 CFH	Argon, flow rate 35 CFH

2.3

Hardness, Tensile Strength and Charpy V notch impact properties of welds and parent metal were evaluated. ASTM Standard specimen configurations were employed for tensile and impact testing.

2.3.1 Hardness

Hardness survey was conducted across the weld beads of all the welded coupons employing Vickers hardness testing machine. All the hardness readings were obtained at a load of 300 gf applied for 10 seconds.

2.3.2 Tensile test

Tensile tests were carried out using universal testing machine at a cross head of 0.5 mm/min on flat tensile specimens extracted from the transverse section of the weldment with weld as centre of the specimen. The specimen geometry is as per ASTM E8 (25mm gauge length). The average tensile properties obtained from three test specimens for each experimental condition are reported.

2.3.3 Impact Test

Impact tests were carried out on weld samples using Impact testing machine, at room temperature. Standard sub-size specimens were sectioned from the weldment with specimen axis transverse to the weld joint, with notch location at the weld centre as per specifications ASTM E23-28 (ASTM standards, 1970). Impact tests were also carried out on the parent metal as per the specifications mentioned above. The average impact toughness values obtained from three test specimens for each experimental condition are reported.

2.4 Scanning Electron Microscopy (SEM)

The fractured surfaces of weldments and parent metal after tensile and impact tests were cleaned ultrasonically in acetone and examined under HITACHI scanning electron microscope (SEM) at an accelerating voltage of 15 kV.

3 RESULTS AND DISCUSSION

3.1 Hardness

Vickers hardness profiles on transverse cross-section of weld joints in the mid thickness region for TIG, pulsed TIG and MIG are shown in Fig.2. From the hardness profiles it is clearly evident that the weld zone exhibited high hardness. There is a decline of hardness from weld centre to the parent metal. The temperature experienced decreases with increasing distance away from the weld zone. This thermal gradient will contribute to the varied microstructure in the weld zone, HAZ and parent material. The trend of higher hardness in the weld metal and HAZ could be associated with the formation of martensite. Coarse grain HAZ region close to fusion boundary has high hardness due to the occurrence of high carbon martensite. The intercritical zone close to the parent material exhibits hardness which is lower than that of the parent metal and this is due to fine $M_{23}C_6$ carbide precipitates which result microstructure at room temperature would be low carbon martensite [12, 13].

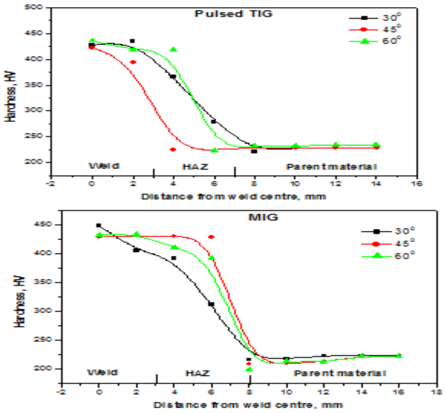

***Fig.2**. Hardness profile across the weld joint*

3.2 Tensile Strength

The transverse tensile properties of various joints of RAFM steel welded with TIG, pulsed TIG and MIG were evaluated. In each of the welding process joints with weld groove angles 30^0, 45^0 and 60^0 are considered as weld design. The parent material properties are given Table 5 and the results of transverse tensile test of weldments are presented in Table 6.

***TABLE 5** Parent material mechanical properties*

Material	YS (MPa)	UTS (MPa)	% El.	Impact Toughness (J)	Hardness (HV)
RAFM Steel	495	650	20	250	192

TABLE 6

Tensile strength of similar metal weldments

Material	Welding Process	Weld groove included angle (degrees)	YS (MPa)	UTS (MPa)	El. (%)	Location of Failure
RAFM Steel	TIG	30	511	645	22	In the parent material near HAZ
		45	553	645	22	
		60	562	663	22	
	Pulsed TIG	30	510	659	21	
		45	548	646	22	
		60	546	662	23	
	MIG	30	468	643	21	
		45	544	635	12	
		60	572	653	18	

From the Table 6 it is evident that among the TIG welded joints, the joint with weld groove angle of 60^0 exhibited better tensile strength compared to that of the other joints. Among the pulsed TIG joints and MIG joints, the joints with 60^0 weld groove angle have exhibited better tensile strength compared to that of the joints with 30^0 and 45^0 weld groove angles. All the joints with 60^0 weld groove angle also exhibited better elongation compared to that of the other joints.The tensile strength when compared among the joints obtained by various welding processes viz. TIG, pulsed TIG and MIG there is a marginal difference in the magnitude of tensile strength. But among all the joints the joint obtained by TIG welding with 60^0 weld groove angle exhibited highest tensile strength. As the cooling rate of the fusion zone is relatively fast in pulsed TIG and MIG weld zones compared to the cooling rate in TIG welds, the grains are coarser in pulsed TIG and MIG welds. The lesser tensile strength in pulsed TIG and MIG joints compared to that of TIG joints may be attributed to the coarser grain size in pulsed TIG and MIG welds.All the welds with 60^0 weld groove angle exhibited better joint strength compared to that of the other joints. This may also be attributed to relatively lower cooling rate in 60^0 weld groove angle compared to 30^0 and 45^0 groove angle joints.From Table 6 it is also evident that all the joints irrespective of weld groove angle and welding process failed in the parent material near heat affected zone. The weld zone of consists of equiaxed martensite lath structure with hardness close to 450 HV. In the HAZ grain structure is fine, but the fine $M_{23}C_6$ carbide precipitates are observed which lead to a hardness reduction (210 – 220 HV) [13]. This hardness reduction is near the parent material. Thus the failure location of all the joints in parent material close to the HAZ may be attributed to the low hardness at the boundary of HAZ and parent material. This low hardness is clearly evident the hardness profiles of all the weld joints (Fig. 2). The typical fractured tensile samples with failure locations are given in Fig. 3.

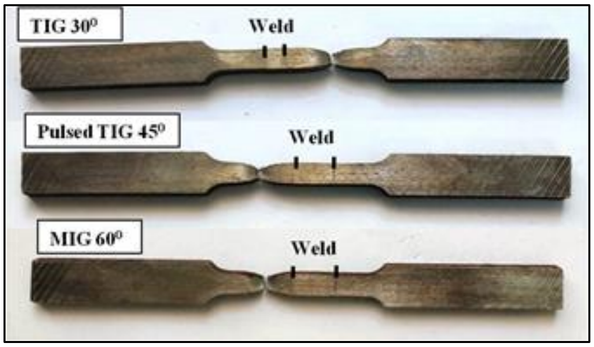

Fig. 3. *Fractured tensile samples with failure locations*

From the study on the tensile strength of various joints it can be concluded that the TIG welded joint with 60^0 weld groove exhibited highest tensile strength. The fractograph of the TIG welded joint with 60^0 weld groove revealed ductile fracture with dimple structure as shown in Fig.4.

3.3 Impact Toughness

The impact toughness properties of various joints of RAFM steel welded with TIG, pulsed TIG and MIG were evaluated and are presented in Table 7. From Table 7 it is clearly evident that the impact toughness is in the increasing order of TIG > Pulsed TIG > MIG welding processes. The TIG welds exhibited highest impact toughness compared to that of the welds of pulsed TIG and MIG. It is also evident that the impact toughness increased as the welding groove angle increased in all the welds of TIG, pulsed TIG and MIG.

TABLE 7

Impact toughness of similar metal weldments

Material	Welding Process	Weld groove included angle (degrees)	Impact Toughness (Joules)
RAFM Steel	TIG	30	89
		45	105
		60	129
	Pulsed TIG	30	31
		45	52
		60	69
	MIG	30	9
		45	5
		60	16

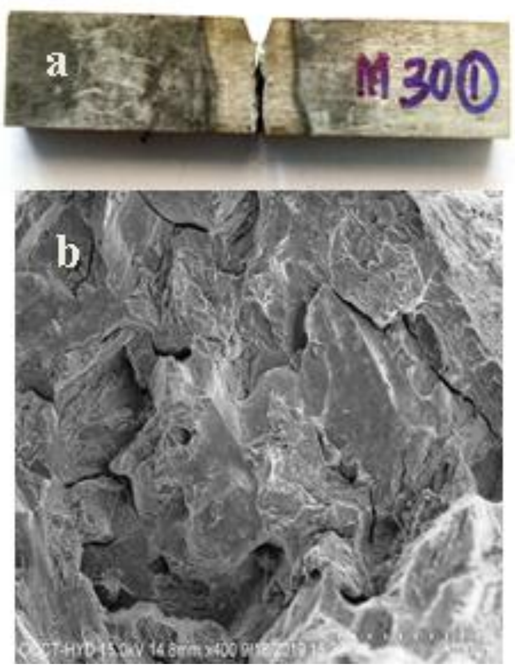

Fig. 5 *(a). Impact sample (b) Fractograph*

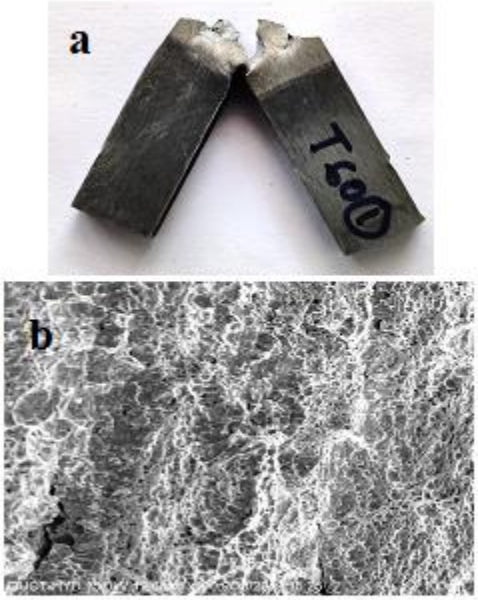

Fig. 6 *(a). Impact sample (b) Fractograph*

From the study on the impact toughness properties it can be concluded that the TIG welded joints exhibited the highest impact toughness. The higher weld groove angle also contributed to the increase in the toughness in each of the welding process.

4 CONCLUSIONS

Following are the conclusions drawn from the present work:

a) The hardness trend was same in the all the welds irrespective of welding process. The hardness is high in the weld zone and there on decreasing from HAZ to parent material.
b) Welding processes as well as weld design influence the tensile strength and impact toughness of the welds.
c) TIG weld joints exhibited better tensile strength compared to that of the weld joints of pulsed TIG and MIG welding processes.
d) All the joints failed in the similar location in parent material near to HAZ due to lower hardness in that region.
e) TIG weld joints exhibited better impact toughness compared to that of the weld joints of pulsed TIG and MIG welding processes.
f) In all the welds, the impact toughness increased with the increased weld groove angle.
g) Among all the joints, TIG weld with 60^0 weld groove angle exhibited a good combination of tensile strength and impact toughness.

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