Dissimilar Metal Gas Tungsten Arc Weldments of Maraging Steel and Medium Alloy Medium Carbon Steel – Effect of Post-weld Heat Treatments

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ABSTRACT

Maraging steel and medium alloy medium carbon steels exhibit their best mechanical properties such as tensile strength and toughness in their respective heat treatment conditions. Gas tungsten arc welding of maraging steel and medium alloy medium carbon steel was carried out taking both the steels in soft annealed condition. Later the weldments were subjected independently to two post-weld heat treatments, one corresponding to the maraging steel i.e. solutionising at 815°C/1 hr/air cooled & aging at 480°C/3 hrs/air cooled, and the other corresponding to medium alloy medium carbon steel i.e. quenching at 925°C/35 min/air cooled & tempering at 295°C/45 min/air cooled. The effect of post-weld heat treatments on the microstructure and mechanical properties such as hardness, tensile strength and impact toughness of the dissimilar metal welds of maraging steel and medium alloy medium carbon steel was investigated. The influence of filler materials was also studied by employing maraging steel and medium alloy medium carbon steel fillers. Maraging steel welds responded to the solutionising and aging treatment whereas the medium alloy medium carbon steel welds responded to quenching and tempering. Lowering of the hardness was observed at the interaction of maraging steel and medium alloy medium carbon steel due to the diffusion of manganese. Medium alloy medium carbon steel filler welds showed good strength and toughness properties.

Key words : Maraging steel, Medium alloy medium carbon steel, Gas tungsten arc welding and Post-weld heat treatment.

1.0 INTRODUCTION

Structural steels with very high strength levels are often referred to as ultrahigh-strength steels. These steels with ultrahigh strength coupled with fracture toughness, in order to meet the requirement of minimum weight while ensuring high reliability, are widely used in light weight high-performance structural applications [1-4]. Because of these properties these steels are extensively used in aerospace and defence applications. For many of the advanced applications, for both the technical and economic reasons, dissimilar combinations of ultrahigh strength steels are necessary. For such applications, maraging steel and medium alloy medium carbon steels are now being used.

Maraging steels are a class of very low carbon high alloy martensitic steels with ultra-high strength combined with good fracture toughness. These steels are iron-nickel alloys that gain strength through age hardening of low carbon martensite resulting in the precipitation of strengthening intermetallic phases in the martensitic matrix [5-13]. Medium alloy medium carbon steels are ultrahigh strength steels with reasonable ductility, considered to be inexpensive and attractive substitute for maraging steel [4]. These steels with good weldability are important candidate materials for critical applications such as rocket motor

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cases, submarine hulls etc [4, 14]. Though these steels are extensively used individually data are scarce about the dissimilar combination.

Dissimilar materials' welding is qualitatively different from that of similar materials welding because of many differences in physical, chemical and mechanical properties of parent materials [15-20]. These differences also complicate the selection of filler metals compatible to both base metals. Generally for better properties of the dissimilar weld, filler metal selection is often compromised between the two dissimilar metals [21-24]. One of the widely used fabrication process for ultrahigh strength steels is fusion welding in general and gas tungsten arc welding process in particular. Consistency in weld quality, process control, economy and weld joint efficiencies exceeding 90% are the features of gas tungsten arc welding with respect to these steels.

Mechanical properties such as tensile strength and impact toughness play an important role in the design of components. The adoption of dissimilar-metal combination provides possibilities for the flexible design of the component by using each material efficiently i.e., benefitting from the specific properties of each material to meet functional requirements.

Maraging steel and medium alloy medium carbon steels, used in this study, are generally supplied in soft condition. These steels attain their ultrahigh strength after respective heat treatments. When used in similar metal combination the materials will be subjected to their respective heat treatment schedules. But, when it comes to dissimilar combination it becomes important to choose between the one of the heat treatments. The aim of the present study is to investigate the influence of post-weld heat treatment and influence of filler materials on the microstructure and mechanical properties such as hardness, tensile strength and impact toughness of dissimilar metal welds of maraging steel and medium alloy medium carbon steel. The limited availability of the data on the dissimilar welds of these steels makes this study significant.

2.0 EXPERIMENTAL PROCEDURE

2.1 Parent materials, welding process and post-weld heat treatments

The materials investigated are 5.2 mm thick sheets of 18% Ni (250 grade) maraging steel and medium alloy medium carbon steel. Gas tungsten arc welding of maraging steel and medium alloy medium carbon steel was carried out taking both the steels in soft annealed condition. Later the weldments were subjected independently to two post-weld heat treatments, one corresponding to the maraging steel i.e. solutionising at 815°C/1 hr/air cooled & aging at 480°C/3 hrs/air cooled, and the other corresponding to medium alloy medium carbon steel i.e. austenising at 925°C/35 min/air cooled & tempering at 295°C/45 min/air cooled. The details of weld coupon preparation and test plate assembly are shown in **Fig.1**. The parameters used for welding are given in **Table 1**. Two fillers namely maraging

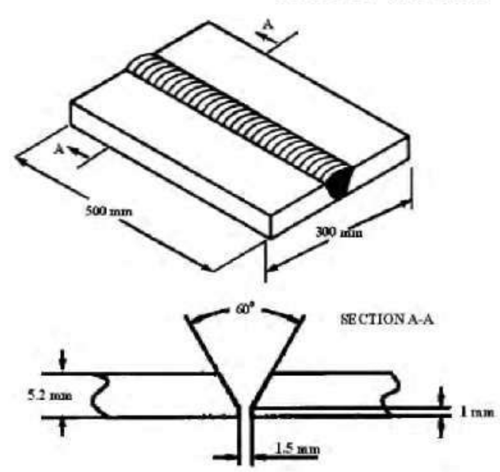

Fig. 1 : Weld coupon design and test place assembly

Table 1 : Gas tungsten arc welding parameters

Welding current	130 A
Welding speed	60mm/min
Electrode polarity	DCSP
Arc voltage	18-20 V
Filler wire diameter	1.6 mm
Electrode	2% Thoriated tungsten
No .of passes	2
Shielding gas	Argon, flow rate 35 CFH
Preheat	None

Table 2 : Composition of parent materials and filler materials

Material	Element (wt %)									
	C	Ni	Co	Mo	Ti	Al	Cr	Si	Mn	Fe
Maraging steel (parent material)	0.01	18.9	8.3	4.6	0.41	0.15	-	-	-	Bal.
Maraging steel filler	0.006	18.2	11.9	2.5	0.16	0.46	-	-	-	Bal.
Medium alloy medium carbon steel (both parent material & filler)	0.33	2.8	Max. 1.0	Max. 1.0	-	-	0.85	1.8	0.35	Bal.

steel filler, which was of similar composition of the parent material but with higher cobalt and aluminum and lower molybdenum and titanium contents and medium alloy medium carbon steel filler with matching composition of the parent material were used. Measured composition of the parent materials and filler materials is given in **Table 2**. The dissimilar metal welds of maraging steel and medium alloy medium carbon steels were subjected to post-weld heat treatments to study the influence of the same on microstructure and mechanical prope-rties such as hardness, tensile strength and impact toughness.

2.2 Metallography

The weldment macro-microstructures of dissimilar metal welds were studied by metallography of various regions using Leitz optical microscope. Modified Fry's reagent (50ml HCl, 25ml HNO_3, 1g $CuCl_2$ and 150ml water) was used to etch maraging steel weld and 2% nital (2ml HNO_3 and 98ml methanol) was used to etch medium alloy medium carbon steel weld. The respective etchants were also used to etch fusion zone, heat affected zone and parent material regions.

2.3 Hardness measurement

Micro-hardness survey was carried out across the cross section of the weld beads of all the weldments, with an interval of 0.5 mm, employing Knoop micro-hardness testing machine. All the hardness readings were obtained at a load of 300gf.

2.4 Mechanical testing

The flat tensile specimens with geometry as per ASTM E8 (25mm gauge length) and extracted from the transverse section of the weldment with weld at centre of the specimen were tested on Instron 1185 universal testing machine at a cross head of 0.5 mm/min.

Sub-size Charpy specimens (5mm x 10mm, notch depth-2mm) as per ASTM E23-28 specifications, sectioned from the weldment with specimen axis transverse to the weld joint and 'V' notch at the weld centre were tested on Tinius Oslon impact testing machine at room temperature.

Both the above tests were also carried out on the parent materials with the same standard specifications. Scanning electron microscopy was done to make the fractographic analysis of both tensile and impact specimens. A minimum of three tensile and impact tests were carried out in each condition.

3.0 RESULTS AND DISCUSSION

3.1 Microstructure

The weld zone microstructures of dissimilar metal welds of maraging steel and medium alloy medium carbon steel with maraging steel filler and medium alloy medium carbon steel filler, in the as-welded and post-weld heat treated conditions are shown in the **Fig.2**. From the figure it is evident that in the as-welded (AW) condition of maraging steel filler welds, the microstructure consists of dendritic structure with well developed primary arms and clearly distinguishable short secondary arms. With the post-weld solutionising and aging (PWSTA) treatment, the dendritic features disappeared and the marten-site microstructure experienced coar-sening. Post-weld quenching and tempering (PWQT) treatment did not eliminate the light etching segregation features.

The as-welded (AW) microstructure of medium alloy medium carbon steel filler weld consist fully dendritic structure in addition to acicular product in the transgranular location (**Fig.2**). Post-weld solutionising and aging (PWSTA) treat-ment at 815°C resulted in development of acicular product and fine precipitates while transgranular product and light etching phase persist. When subjected to post-weld quenching and tempering (PWQT) treatment the dendritic features disappeared and martensitic microstructure experienced coarsening.

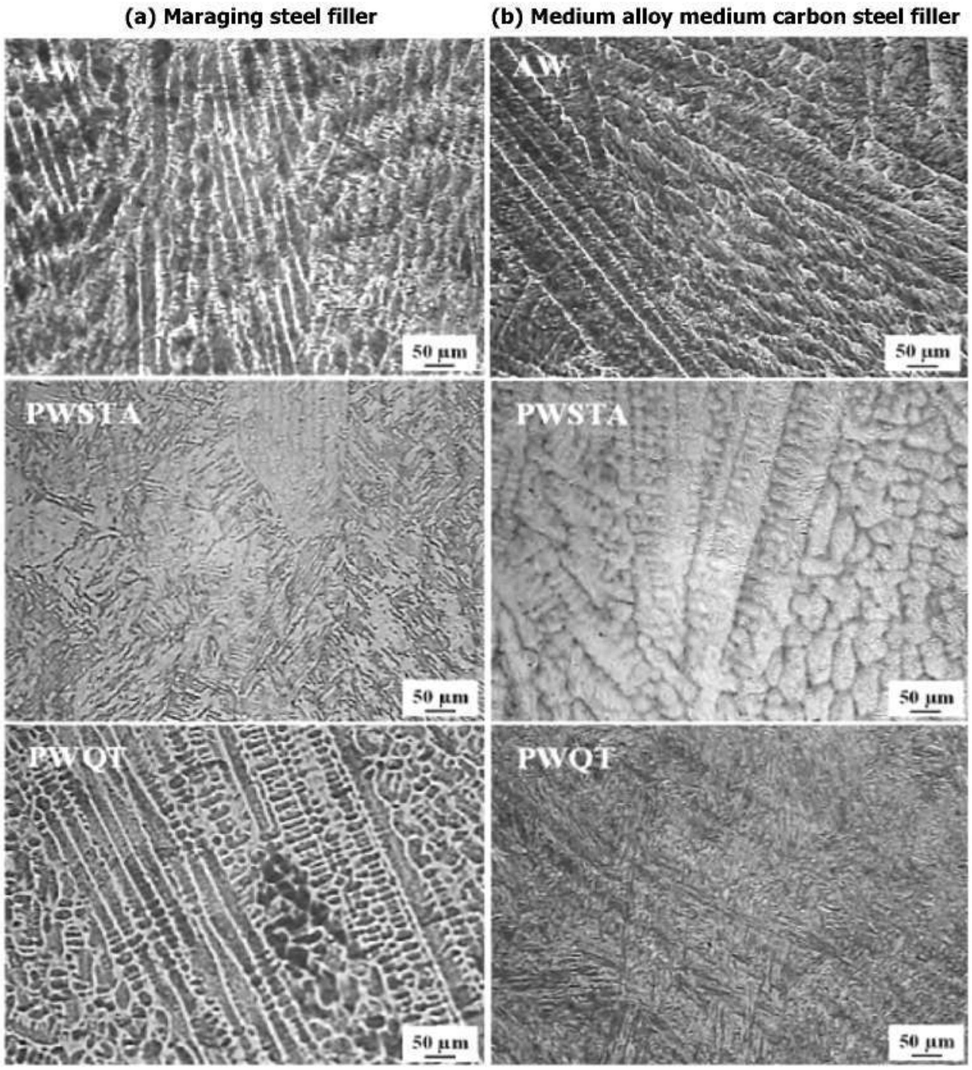

Fig.2 : Optical microstructure of weld centre of dissimilar metal gas tungsten arc weldment of maraging steel and medium alloy medium carbon steel with (a) maraging steel filler (b) medium alloy medium carbon steel filler, in various post-weld heat treated conditions

3.2 Hardness

3.2.1 Dissimilar metal welds of maraging steel to medium alloy medium carbon steel with maraging steel filler

The hardness survey across the transverse section of the dissimilar metal weld of maraging steel and medium alloy medium carbon steel in the AW condition is shown in the **Fig.3a**. The hardness in the fusion zone is mostly same as that of the maraging steel parent material except a decreasing trend near the fusion boundary of medium alloy medium carbon steel. The reason for this being the presence of austenite formed due to diffusion of manganese [25].

Fig.3b shows the hardness survey across the PWSTA dissimilar weldment of maraging steel and medium alloy medium carbon steel. It is known that the maraging steel gains its strength due to precipitation of intermetallic compounds during aging treatment. This made the hardness of the maraging steel parent material and weld to rise to 550 HK from 350 HK in the as-welded condition. There is marginal decrease in the hardness of medium alloy medium carbon steel (Compare **Fig. 3a** and **Fig. 3b**) due to solutionising and aging temperatures being more than the quenching and tempering temperatures. There is a dip in the hardness value in the weld very close to the fusion boundary of medium alloy medium carbon steel as the austenite present due to the diffusion of manganese did not respond to the solutionising and

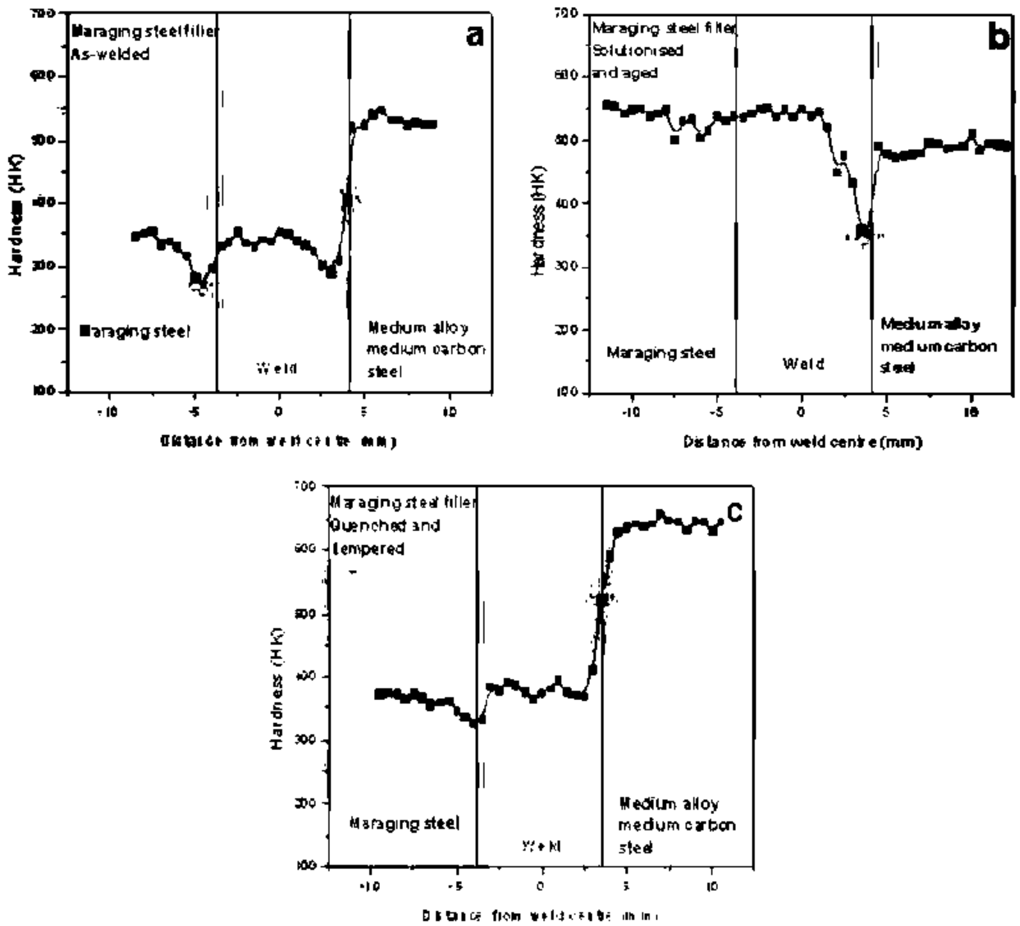

Fig.3 : Hardness traverse across the dissimilar metal gas tungsten arc weldment of maraging steel and medium alloy medium carbon steel with maraging steel filler in various post-weld heat treated conditions (a) As-welded (b) Solutionised and Aged (c) Quenched and tempered

aging heat treatment.

The hardness survey across the PWQT dissimilar weldment of maraging steel and medium alloy medium carbon steel is shown in the **Fig. 3c**. It is clear from the figure that the maraging steel parent material and maraging steel weld did not respond to the quenching and tempering, whereas the hardness of medium alloy medium carbon steel increased as compared to that in as-welded condition(**Fig. 3a**) as it responded to the quenching and tempering treatment.

3.2.2 Dissimilar metal welds of maraging steel to medium alloy medium carbon steel with medium alloy medium carbon steel filler

Fig. 4a shows the dissimilar weld of maraging steel and medium alloy medium carbon steel in the AW condition. The hardness of the fusion zone is high compared to that of the heat affected zone of maraging steel whereas it is low compared to that of the heat affected zone of medium alloy medium carbon steel. It is noticed that the hardness showed considerable decrease, partially along the fusion boundary of maraging steel and adjacent region, in the heat affected zone of maraging steel. This decrease in the hardness can be attributed to the dilution medium alloy medium carbon steel weld with low carbon martensite from the maraging steel, diffusion of manganese from medium alloy medium carbon steel weld to the heat affected zone of maraging steel and also may be due to the coarse grain structure formed near the fusion boundary of maraging steel as it is exposed to high temperature during the welding process.

Fig. 4b shows the hardness of the dissimilar weld of maraging steel and medium alloy medium carbon steel, in the PWSTA condition. From the figure it is observed that the hardness of maraging steel is higher than that of the weld and medium alloy medium carbon steel. The increase in the hardness of the maraging steel is due precipitation hardening of maraging steel. The medium alloy medium carbon steel weld and parent material show low hardness due to the over tempering due to solutionising and aging temperatures. In the fusion zone very close to the fusion boundary of maraging steel is observed to the presence of austenite formed due to the diffusion phenomenon as mentioned earlier.

The hardness survey across the dissimilar weld of maraging steel and medium alloy medium carbon steel, in the PWQT condition is shown in the **Fig. 4c**. It is clear from the figure that the medium alloy medium carbon steel filler weld and medium alloy medium carbon steel parent material have responded to the quenching and tempering, with increase in the hardness as compared to the as-welded condition (**Fig. 4a**). The maraging steel did not respond to the quenching and tempering temperatures. In the fusion zone it is observed that the hardness decreased close to the fusion boundary of maraging steel. This is due to the dilution of low carbon martensite and presence of austenite.

In summary, it is observed that the in the as-welded condition the medium alloy medium carbon steel displayed high hardness compared to that of maraging steel in the same condition. Both the steels responded to their respective heat treatments with high hardness (Maraging steel - nearly 550 H_K and Medium alloy medium carbon steel - nearly 650 H_K). Maraging steel showed slight decrease in the hardness due to the quenching but did not respond to the tempering temperature. Medium alloy medium carbon steel showed lower hardness, when subjected to solutionising and aging due to over tempering. In all the heat treatment conditions, always there is a considerable decrease in the hardness along the interface of maraging steel medium alloy medium carbon steel due to dilution and diffusion effects.

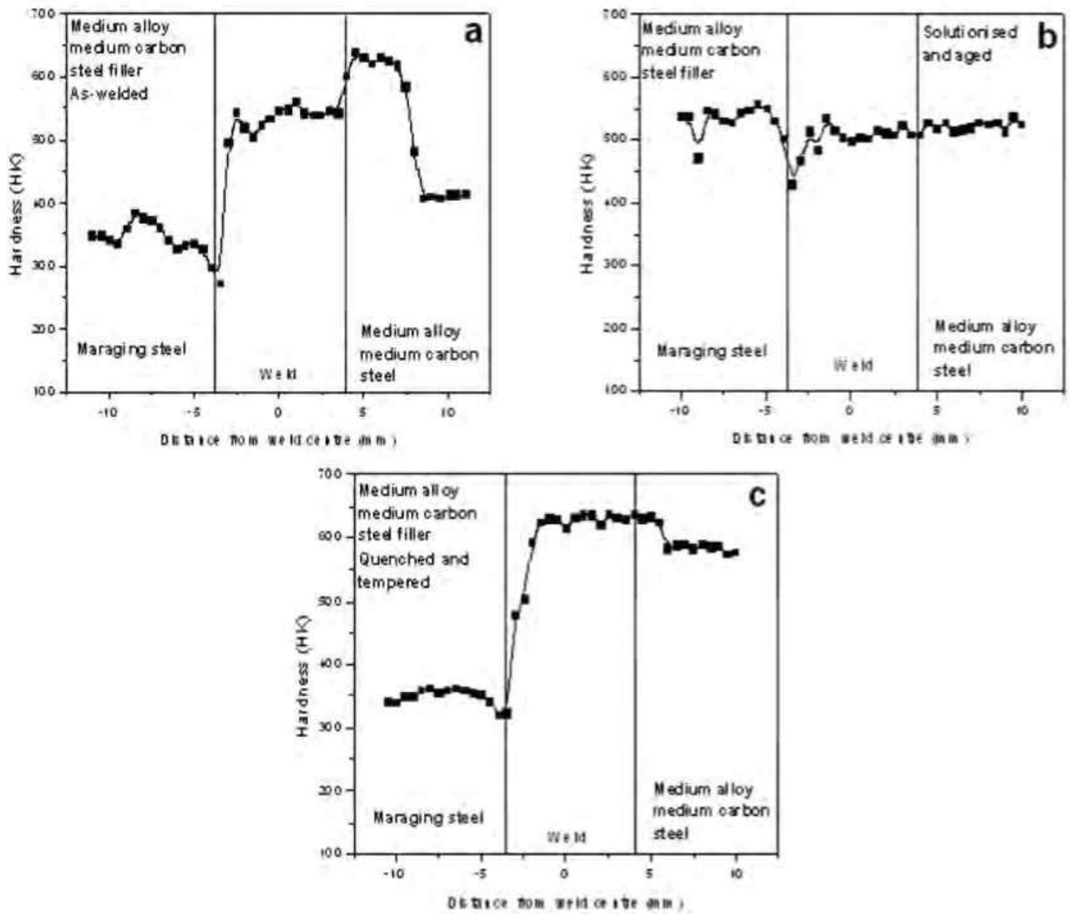

Fig.4 : Hardness traverse across the dissimilar metal gas tungsten arc weldment of maraging steel and medium alloy medium carbon steel with medium alloy medium carbon steel filler in various heat treated conditions (a) As-welded (b) Solutionised and Aged (c) Quenched and tempered

3.3 Tensile properties

The tensile properties of dissimilar metal welds with maraging steel filler and medium alloy medium carbon steel fillers, in different heat treatment conditions, are shown in **Table 3**. Parent material properties are given **Table 4** for ready reference.

3.3.1 Dissimilar metal welds of maraging steel to medium alloy medium carbon steel with maraging steel filler

From the **Table 3**, it is evident that the dissimilar metal welds of maraging steel and medium alloy medium carbon steel in PWSTA condition has high strength and very low ductility compared to that of the weld joints in AW and PWQT conditions.

Fig.5 shows the fracture location of the tensile samples. In the AW condition the fracture occurred in heat affected zone of maraging steel close to the fusion boundary. This due to the low hardness of the maraging steel (**Fig. 3a**).

In the weld joint in PWSTA condition the fracture occurred in the weld close to the fusion boundary of medium alloy medium carbon steel. This is may be attributed to the presence of low hardness region in fusion zone (**Fig. 3b**).

In the PWQT weld joint the fracture occurred in the maraging steel. This may be attributed to the following: due to quenching and tempering the medium alloy medium carbon steel gains strength whereas the maraging steel remains unaffected with low strength. Moreover the as the maraging steel is exposed to higher temperatures during the welding process the heat affected zone close to the fusion boundary inherits the low hardness coarse grain structure.

The fractographs of the tensile samples of dissimilar metal welds in AW, PWSTA and PWQT shown in **Fig.6** reveal that the dimpled structure is in tune with

Table 3 : Tensile properties of dissimilar metal welds of maraging steel to medium alloy medium carbon steel

Material	Maraging Steel Filler				Medium alloy medium carbon steel filler			
	YS (MPa)	UTS (MPa)	El.(%)	Loction of Failure	YS (MPa)	UTS (MPa)	El.(%)	Loction of Failure
As-welded	970	1045	11.4	Maraging steel	942	1007	11.8	Close to FB of Maraging Steel
Wolutionised and Aged	1307	1337	0.4	Weld (close to FB of MAMCS)	0	719	0.02	Weld

Table 4 : Parent material properties in various heat treated conditions

Material	Condition	YS (MPa)	UTS (MPa)	El. (%)	Impact Toughness (J)
Maraging steel	Solutionised	950	1000	12	110
	Solutionised and aged	1600	1750	7.5	40
	Quenched and tempered	844	1015	18.6	156
Medium alloy medium carbon steel	Annealed	779	977	22.3	31
	Solutionised and aged	1564	1790	11	26
	Quenched and tempered	1458	1815	12	24

ductility of weld joints in AW and PWQT conditions, whereas the brittle features of facets with cleavages are in tune with the very low ductility of the weld joint in PWSTA condition.

3.3.2 Dissimilar metal welds of maraging steel to medium alloy medium carbon steel with medium alloy medium carbon steel filler

Table 3 shows that the strength of dissimilar metal weld joint in PWQT condition is marginally higher than that of the joint in AW condition, whereas the ductility of the AW condition joint is marginally higher than that of the joint in PWQT condition. It is observed that the weld joint in PWSTA condition failed without any yielding.

Fig.7 shows the fracture location of the dissimilar metal weld joints. In the AW condition dissimilar metal weld joint, the fracture occurred close to the fusion boundary of maraging steel. This may be due the low hardness region at the fusion boundary of maraging steel (**Fig. 4a**). In the PWSTA dissimilar metal weld joint the fracture occurred in the fusion zone though there is a low hardness region along the fusion boundary of maraging steel (**Fig. 4b**). This may be attributed to the temper embrittlement of the medium alloy medium carbon steel weld. The fracture in the dissimilar metal weld in PWQT condition occurred in the maraging steel. The weld and medium alloy medium carbon steel respond to the quenching and tempering treatment and gain strength and hardness where as the maraging steel remain in the solutionised condition with low hard-ness. This makes the joint to fail in the maraging steel (**Fig. 4c**).

Fig.8 shows the fractographs of the tensile samples of dissimilar metal weld joints. The fine dimpled structure of the fracture surfaces in the weld joints in AW and PWQT conditions are in tune with high ductility values compared to that of the PWSTA condition weld joint. The brittle morphology with cleavages sub-stantiates the failure of the weld joint, in PWSTA condition, before yielding.

To summarize, in dissimilar metal welds, if the strength is the criterion dissimilar metal weld of maraging steel and medium alloy medium carbon steel with maraging steel filler in PWSTA condition may be used. If the ductility is the criterion dissimilar metal weld of maraging steel and medium alloy medium carbon steel either with maraging steel filler or medium alloy medium carbon steel filler may be used. If both strength and ductility are the criterion dissimilar metal weld of maraging steel and medium alloy medium carbon steel with medium alloy medium carbon steel filler in PWQT condition may be preferred.

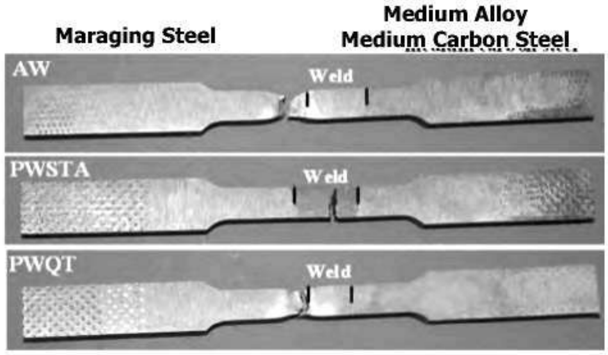

Fig.5 : Fracture location of tensile samples of dissimilar metal gas tungsten arc weldment of maraging steel and medium alloy medium carbon steel with maraging steel filler in various heat treated conditions

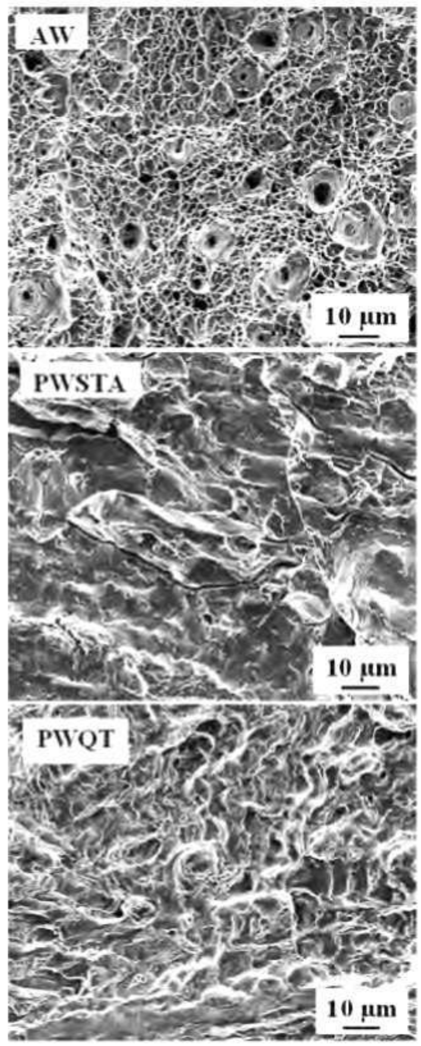

Fig.6 : Fractographs of tensile samples of dissimilar metal gas tungsten arc weldment of maraging steel and medium alloy medium carbon steel with maraging steel filler in various heat treated conditions

3.4 Impact toughness

Table 5 presents the Impact toughness of the dissimilar metal weld joints, with maraging steel filler as well as medium alloy medium carbon steel filler, in as-welded (AW), post-weld solution treated and aged (PWSTA) and Post-weld quenched and tempered (PWQT) conditions. Parent material impact toughness properties are presented in Table 4.

3.4.1 Dissimilar metal welds of maraging steel and medium alloy medium carbon steel with maraging steel filler

From **Table 5** it is clear that the order of toughness in dissimilar metal welds is that the impact toughness of weld joint in PWQT condition is high compared to that of the weld joint in AW condition which in turn is higher than that of the weld joint in the PWSTA condition.

From Fig.9 which shows the impact samples, it is observed that the crack path is in tune with the toughness values with longer curved path for ductile welds and shorter straight path for brittle weld.

Fig.10 shows the fracture features of the weldments. Fine dimpled fracture surface is evident for the welds in AW and PWQT conditions. This may be due presence of more low carbon martensite in the maraging steel weld as one of the adjacent parent materials is maraging steel. The weld in PWSTA exhibited fracture surface with cracks. This may be due to the precipitation hardening of low carbon martensite in maraging steel weld and over tempering of the high carbon martensite in the maraging steel weld diluted from medium alloy medium carbon steel.

3.4.2 Dissimilar metal welds of maraging steel and medium alloy medium carbon steel with medium alloy medium carbon steel filler

From **Table 7** it is evident that the toughness value of the welds in AW and PWQT conditions is almost same. The weld in PWSTA condition exhibit very low toughness compared all other welds mentioned in the Table.

Both the welds in AW and PWQT conditions contain a mixture of hard high carbon martensite of medium alloy medium carbon steel and soft low carbon martensite. The marginal difference in the toughness value of the weld in AW condition can be attributed to the presence of untempered high carbon martensite. This untempered martensite when tempered during PQWT process results in marginal increase in the toughness value. The very low toughness in the PWSTA

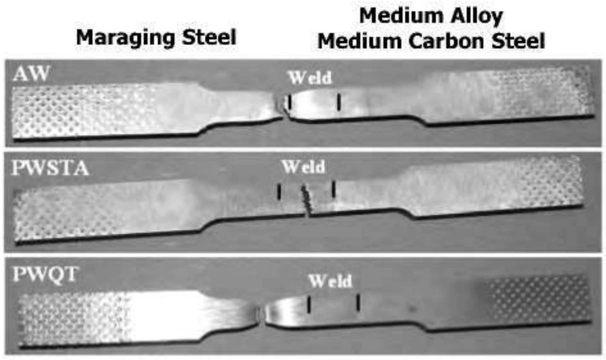

Fig.7 : Fracture location of tensile samples of dissimilar metal gas tungsten arc weldment of maraging steel and medium alloy medium carbon steel with medium alloy medium carbon steel filler in various heat treated conditions

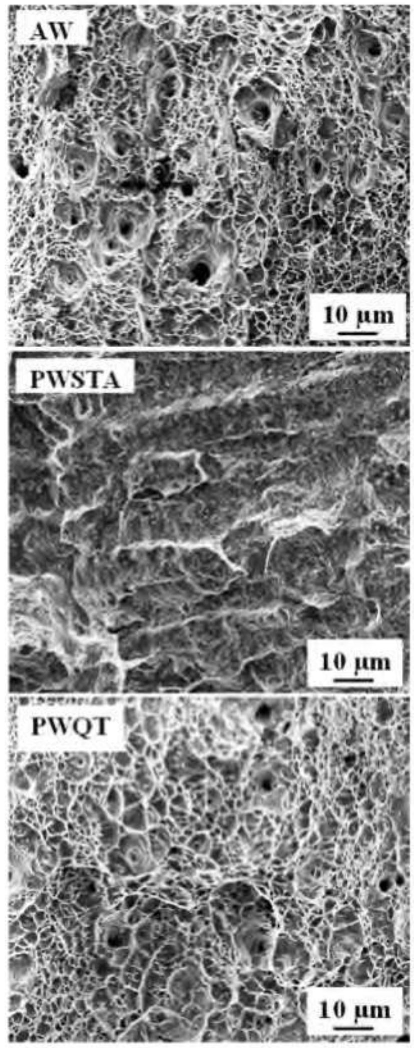

Fig.8 : Fractographs of tensile samples of dissimilar metal gas tungsten arc weldment of maraging steel and medium alloy medium carbon steel with medium alloy medium carbon steel filler in various heat treated conditions

Table 5 : Impact toughness of gas tungsten arc weldments in various post-weld heat treated conditions

Weldment	Post-weld condition	Impact Toughness (J)	
		Maraging steel filler	Medium alloy medium carbon steel filler
Maraging steel filler Medium alloy medium carbon steel filler	As-welded	32	34
	Solutionised and aged	4	2
	Quenched and tempered	40	35

condition can be attributed to the temper embrittlement of the medium alloy medium carbon steel weld.

The crack paths are similar for the welds in AW and PWQT conditions as shown in **Fig.11.** The weld in PWSTA exhibit straight crack path showing low toughness. From **Fig.12** it is clear that the welds in AW and PWQT exhibit high toughness with fine dimpled fracture surface. The fracture surface of weld in PWSTA exhibit fibrous structure with macro cleavages. The fibrous structure can be attributed to the presence of low carbon martensite diluted from the maraging steel to medium alloy medium carbon steel weld.

In summary, it is observed that the dissimilar metal weld of maraging steel and medium alloy medium carbon steel with maraging steel exhibited high toughness compared to the other weldments whereas the dissimilar metal weld with medium alloy medium carbon steel filler exhibited the lowest impact toughness.

4. CONCLUSIONS

Influence of post-weld heat treatments on the microstructure and mechanical properties of dissimilar metal welds of maraging steel and medium alloy medium carbon steels has been investigated. Following observations are made:

1. Maraging steel responded to solutionising and aging whereas medium alloy medium carbon steel responded to quenching and tempering treatment.
2. In the as-welded condition, medium alloy medium carbon steel displayed high hardness compared to that of maraging steel in the same condition.
3. Maraging steel showed slight decrease in the hardness due to the quenching but did not respond to the tempering temperature.
4. Medium alloy medium carbon steel showed lower hardness, when subjected to solutionising and aging due to over tempering.
5. If the strength is the criterion dissimilar metal weld of maraging steel and medium alloy medium carbon steel with maraging steel filler in PWSTA condition may be used.
6. If the ductility is the criterion dissimilar metal weld of maraging steel and medium alloy medium carbon steel either with maraging steel filler or medium alloy medium carbon steel filler may be used.
7. If both strength and ductility are the criterion dissimilar metal weld of maraging steel and medium alloy medium carbon steel with medium

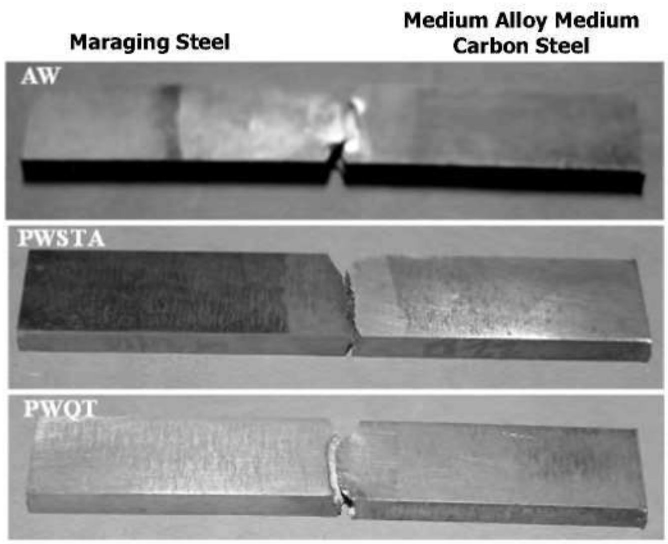

Fig.9: Impact test samples of dissimilar metal gas tungsten arc weldment of maraging steel and medium alloy medium carbon steel with maraging steel filler in various heat treated conditions

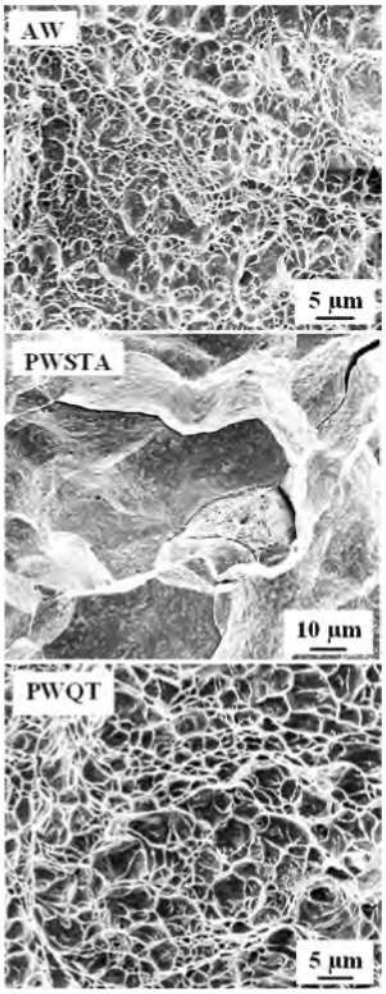

Fig.10: Fractographs of impact samples of dissimilar metal gas tungsten arc weldment of maraging steel and medium alloy medium carbon steel with maraging steel filler in various heat treated conditions

Maraging Steel

Medium Alloy Medium Carbon Steel

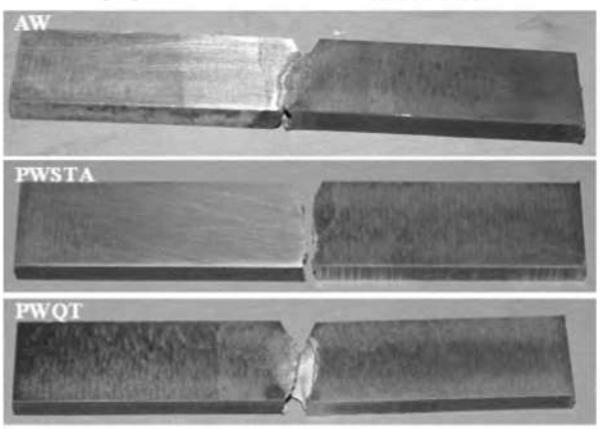

Fig.11 : Impact test samples of dissimilar metal gas tungsten arc weldment of maraging steel and medium alloy medium carbon steel with medium alloy medium carbon steel filler in various heat treated conditions

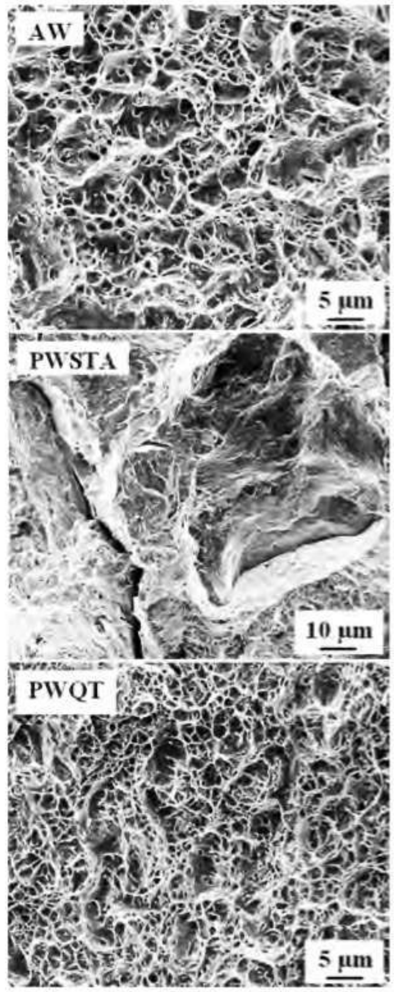

Fig.12 : Fractographs of impact samples of dissimilar metal gas tungsten arc weldment of maraging steel and medium alloy medium carbon steel with medium alloy medium carbon steel filler in various heat treated conditions

alloy medium carbon steel filler in PWQT condition may be preferred.

8. Dissimilar metal weld with maraging steel filler, in quenched and tempered condition, exhibited high toughness compared to the other weldments whereas the weld with medium alloy medium carbon steel filler, solutionised and aged condition exhibited low toughness.

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