A Study on Welding of Ultrahigh Strength Steels

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I feel deeply honoured for being invited by the Indian Institute of Welding (IIW) to deliver the prestigious Prof. Placid Rodriguez Memorial Lecture. This is a great occasion to recall the fond memories of a renowned metallurgist, eminent scientist and technologist Prof. Placid Rodriguez and his contribution to advancement of science and technology in general and to welding fraternity in particular. This occasion becomes more unforgettable as it coincides with the Golden Jubilee Celebrations of the Indian Institute of Welding. I humbly accept this award and profusely thank the President, Hon. Secretary General, Chairman-Technical Committee and Council Members of IIW for bestowing the honour upon me and the Chairman and Managing Committee members of IIW Hyderabad Branch for having nominating me. The topic I have chosen for this lecture is on welding of ultrahigh strength steels, which is of great importance as these steels are being widely employed in aerospace and defence applications.

Keywords : Welding, Ultrahigh Strength Steel, Similar Welding, Dissimilar Welding, Testing.

1.0 INTRODUCTION

Ultrahigh strength steels are the structural steels with very high strength levels capable of developing minimum yield strength of nearly 1400 MPa. These steels are in a great demand in recent times, for critical structural air craft and aerospace applications. Dissimilar combinations of steels are necessary for both technical and economic reasons in aircrafts, automobiles, power plants, chemical industries etc. In such applications ultrahigh strength materials such as maraging steel and medium alloy medium carbon steel are used. The steels used in the present study are 18% Ni (250) maraging steel and medium alloy medium carbon steel or quenched and tempered steel, similar to AISI 4340 but, with enhanced toughness.

Maraging steels are a class of precipitation hardenable martensitic steels, which develop strength due to the precipitation of intermetallic compounds. They exhibit a unique combination of properties that include ultrahigh strength and excellent fracture toughness.

One of the main virtues of maraging steels is their excellent weldability. Medium alloy medium carbon steel has been developed as an inexpensive and an attractive substitute especially for more expensive and high-alloy 18Ni (250) maraging steel. Medium alloy medium carbon steels also exhibit reasonable weldability.

Widely employed fabrication process for ultrahigh strength steels is fusion welding. Gas tungsten arc welding (GTAW) and Electron beam welding (EBW) are the two fusion welding processes employed in this study.

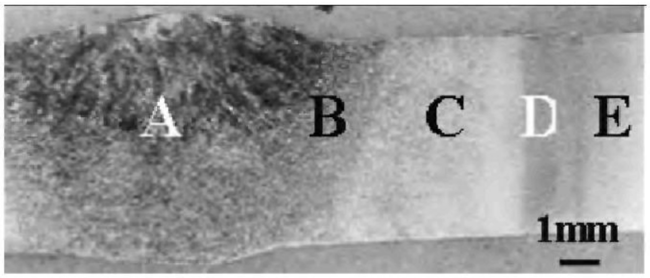
The main objective of the present study is to understand the structure-property correlation and residual stress distribution of similar and dissimilar metal weld joints of maraging steel and medium alloy medium carbon steels employing gas tungsten arc welding and electron beam welding. The aim is also to study the effect of pre-weld and post-weld heat treatments on the same welds. This study assumes special significance as the data on these steels are scarce. The scope of the present work is to study on (i) the effect of filler material variation on the structure-property correlation and residual stress distribution of the similar metal welds of gas tungsten arc maraging steel weldments. (ii) the influence of parent material strength on the microstructure, mechanical properties and the residual stress distribution of similar and dissimilar metal welds of maraging steel and medium alloy medium carbon steels. (iii) variation of the microstructure and mechanical properties when the welds are subjected to post-weld heat treatments and (iv) employing surface remelting technique to alter the weld residual stresses of medium alloy medium carbon steel gas tungsten arc weldment.

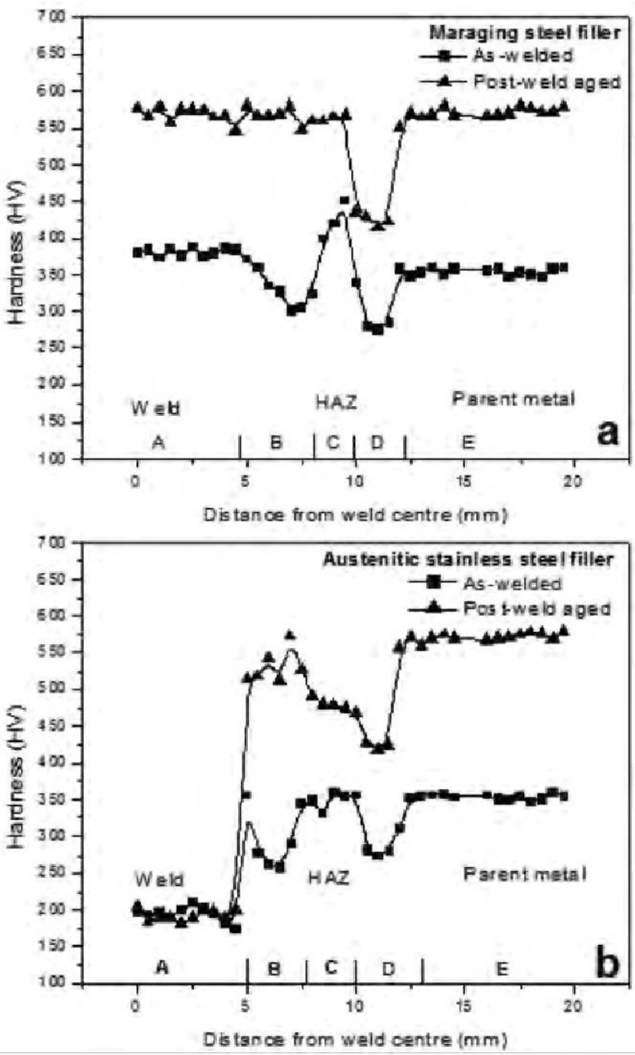
2.0 SIMILAR AND DISSIMILAR METAL GAS TUNGSTEN ARC WELDMENTS - INFLUENCE OF WELDING CONSUMABLES

The focus is on the study of influence of filler metal composition on the microstructure, residual stress distribution, and mechanical properties such as hardness, tensile strength and impact toughness of the similar metal welds of maraging steel gas tungsten arc weldments. The influence of post weld aging treatment on all the properties mentioned above also forms part of the study. Three types of filler materials were used, they include, maraging steel filler, austenitic stainless steel filler and medium alloy medium carbon steel filler.

In the as-welded condition, microscopy revealed that austenite transforms to martensite during cooling in the fusion zone in maraging steel welds. The microstructure of the austenitic stainless filler weld consists of duplex structure of austenite and ferrite. Microstructural features of medium alloy steel weld show that columnar grain growth is prevalent at the center, with intragranular martensitic microstructure. After post-weld aging, no variation is observed in microstructure compared to that in as-welded condition in respect of austenitic stainless steel and medium alloy medium carbon steel filler welds.

Micro-hardness survey across the weld beads for the three filler welds in the as-welded condition was carried out in the five different regions (A. Fusion zone, B. Coarse grained region, C. Fine grained region, D. Dark etched region and E. Unaffected parent material) as revealed in the optical microscopy (**Fig.1**). Austenitic stainless steel weld metal exhibited lowest hardness. The weld region of medium alloy medium carbon steel filler exhibited highest hardness. The hardness of maraging steel filler welds is comparable to the parent metal. Maraging steel filler weld hardness shows that when the joint is aged after welding, the hardness of all the regions except region 'D' increases almost to the hardness of the aged parent metal. Austenitic stainless steel welds did not respond to aging treatment due to absence of phase transformation whereas medium alloy medium carbon steel filler welds exhibited reduction in hardness due to tempering effect during aging.





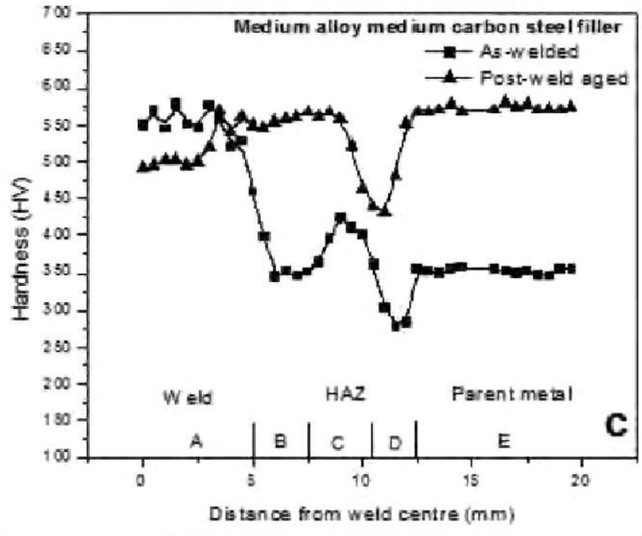


Fig. 1 : Hardness traverse across gas tungsten arc weldments (as-welded and post-weld aged conditions) (a) maraging steel filler (b) austenitic stainless filler (c) medium alloy medium carbon steel filler

In the case of maraging steel and medium alloy medium carbon steel weld metals the residual stress at the center of the weld metal zone is compressive. In the case of austenitic weld metal the residual stress at the center of the weld metal zone is tensile. Post weld aging relieved stresses to some extent, in case of austenitic stainless steel weldments and medium alloy steel weldments. Maraging steel weldments had acquired compressive stresses.

The tensile strength of the maraging steel weld in the post-weld aged condition is observed to be higher compared to that of all other welds tested. The austenitic stainless welds exhibited better ductility.

In the as welded condition, toughness of fusion zone is in the order: austenitic stainless steel filler weld > maraging steel filler weld > medium carbon medium alloy steel filler weld. After post weld aging treatments the toughness is in the order: austenitic stainless steel filler weld > medium carbon medium alloy steel filler weld > maraging steel filler weld. Toughness improvement after aging treatment in case of medium alloy medium carbon filler welds is attributed to the tempering of high carbon martensite during aging treatment that would blunt an advancing crack necessitating higher energy for further crack extension [1-2].

3.0 SIMILAR AND DISSIMILAR METAL GAS TUNGSTEN ARC WELDMENTS - EFFECT OF PRE-WELD HEAT TREATMENT

As the steels used in this study exhibit their best properties in heat treated condition, the steels are subjected to their respective heat treatments and are then welded in similar and dissimilar combinations. Out of all the combinations, one dissimilar weld is made with maraging steel in solutionised condition and medium alloy medium carbon steel in heat treated condition. The influence of starting parent material strength on the microstructure, residual stress distribution, and mechanical properties is studied. Two filler materials viz., maraging steel and medium alloy medium carbon steel are employed.

The optical microscopy revealed that the similar metal welds exhibited symmetrical fusion zone and heat affected zones, whereas the dissimilar metal welds exhibited un-symmetrical fusion zone and heat affected zones. This un-symmetrical nature is due to the difference in the thermal conductivity of the materials. The width of heat affected zone of medium alloy medium carbon steel is observed to be more than that of the maraging steel, shown in **Fig. 2**, because the thermal conductivity of medium alloy medium carbon steel is higher than the thermal conductivity of maraging steel. In dissimilar metal welds the microstructure at the fusion boundaries is found to be dependant on the magnitude of thermal conductivity.

In the fusion zone, residual stresses are compressive in similar metal welds of maraging steel and tensile in similar metal welds of medium alloy medium carbon steel. In the dissimilar metal welds the nature of residual stresses in the weld varied from compressive in maraging steel to tensile in medium alloy medium carbon steel. Compared to the dissimilar metal welds of age hardened maraging steel and quenched and tempered

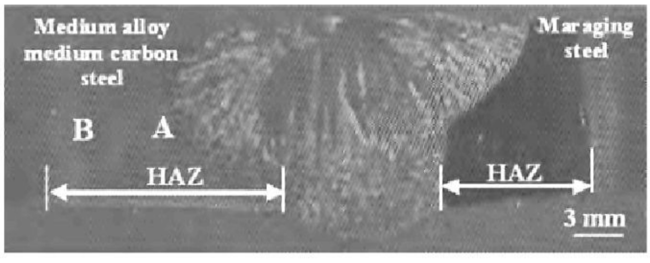


Fig. 2 : Width of heat affected zones of dissimilar metal gas tungsten arc weldment of age hardened maraging steel and quenched and tempered medium alloy medium carbon steel

steel, in as-welded condition, lowering of the magnitude of residual stresses in dissimilar metal welds is observed when maraging steel is taken in soft solutionised condition and post-weld aged. In medium alloy medium carbon steel, post-weld aging resulted in lowering of residual stresses (**Fig.3**).

Maraging steel welds exhibited low hardness compared to that of medium alloy medium carbon steel, in the as-welded condition. The fusion zone hardness in the dissimilar welds is influenced by the dilution of filler material and diffusion of manganese. Post-weld aging resulted in lowering of hardness in medium alloy medium carbon steel.

In the tensile test specimens (**Fig.4**), the fracture occurred in the heat affected zone of maraging steel in the similar metal weld of age hardened maraging steel, and dissimilar metal weld of age hardened maraging steel and quenched and tempered steel. This is due to the low hardness in the heat affected zone resulted due to dissolution of strengthening precipitates.

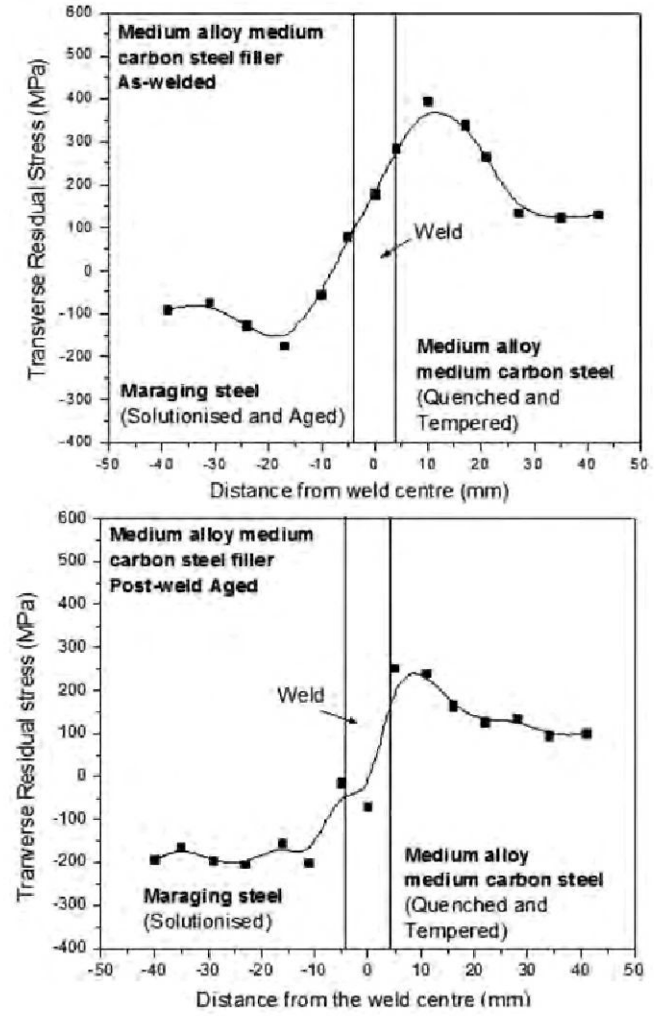
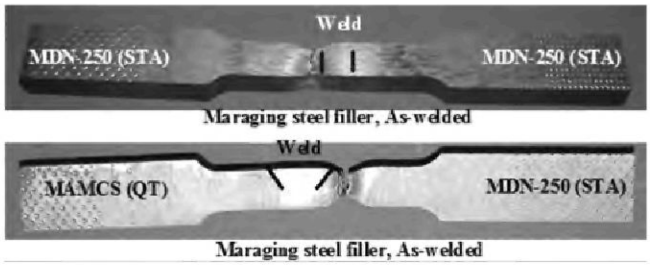


Fig.3 : Transverse residual stress distribution across the dissimilar metal weld of maraging steel in solutionised condition and quenched and tempered medium alloy medium carbon steel, with medium alloy medium carbon steel filler



MDN-250 : Maraging Steel; MAMCS : Medium Alloy Medium Carbon Steel; STA : Solutionsed and aged; QT : Quenched and tempered

Fig.4 : Fracture locations in the transverse tensile specimens of the gas tungsten weldments with maraging steel

Post-weld aged dissimilar metal welds of solutionised maraging steel and quenched and tempered steel exhibited high strength and low ductility whereas the dissimilar metal welds of age hardened maraging steel and quenched and tempered steel, in as-welded condition, exhibited moderate strength and ductility.

Similar metal weld of maraging steel with maraging steel filler exhibited highest impact toughness compared to all the welds investigated whereas the post-weld aged dissimilar weld of solutionised maraging steel and quenched and tempered steel exhibited the lowest [3].

4.0 SIMILAR AND DISSIMILAR METAL GAS TUNGSTEN ARC WELDMENTS - INFLUENCE OF POST-WELD HEAT TREATMENT

Maraging steel and medium alloy medium carbon steels are welded in soft as-received condition and are subjected to various post-weld heat treatments and the effect of post weld heat treatment on the microstructure and mechanical properties is investigated. The influence of filler materials is also investigated.

In the as-welded condition (AW), the similar welds with maraging steel filler exhibited coarse grain size with intra-granular BCC martensite where as the welds with medium alloy medium carbon steel filler exhibited comparatively smaller grain structure with fine BCT martensite. With complete disappearance of dendritic structure both the welds responded to their corresponding post-weld heat treatments (**Fig.5**). In dissimilar metal welds, the maraging steel weld responded to the post-weld solutionising and aging (PWSTA) but did not respond to post-weld quenching and tempering (PWQT), whereas medium alloy medium carbon steel weld responded to both PWSTA and PWQT.

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 steels responded to their respective heat treatments with high hardness. 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.

Among all the welds investigated, similar metal weld of maraging steel with maraging steel filler exhibited high ductility, whereas the same weld when subjected to PWSTA

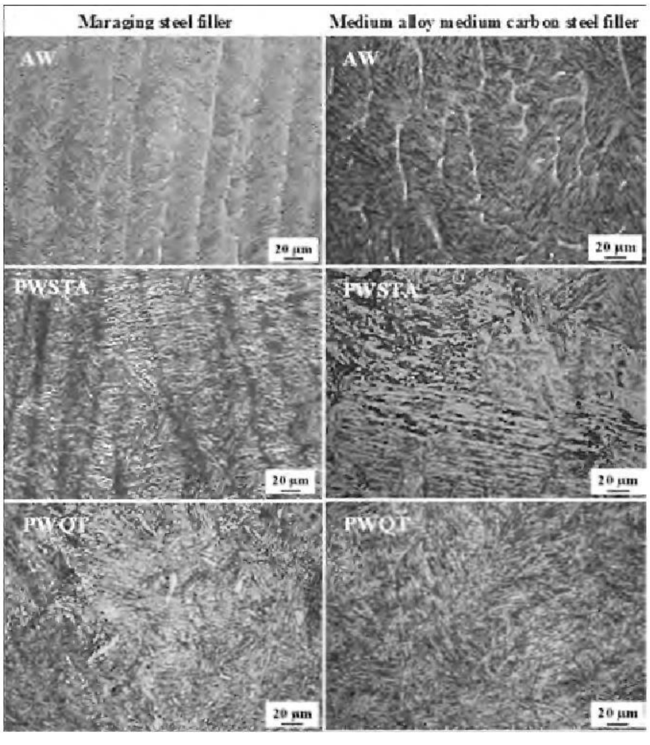


Fig. 5 : Optical microstructure of weld centre of similar metal gas tungsten arc weldment of medium alloy medium carbon steel, in various heat treated conditions

exhibited highest strength but with reduction in the ductility. The similar metal weld of medium alloy medium carbon steel with medium alloy medium carbon steel filler exhibited moderate strength and ductility. Dissimilar metal weld of maraging steel and medium alloy medium carbon steel with medium alloy medium carbon steel filler subjected to PWQT exhibited moderate strength and ductility compared to other dissimilar metal welds.

It is observed that the similar metal weld of maraging steel with maraging steel filler exhibited highest impact toughness whereas the dissimilar metal weld of maraging steel and medium alloy medium carbon steel with medium alloy medium carbon steel filler exhibited the lowest impact toughness, as shown **Fig. 6** [4].

5.0 SIMILAR AND DISSIMILAR METAL ELECTRON BEAM WELDMENTS

A detailed study is carried out by employing the electron beam welding process, similar to that carried out by employing gas tungsten arc welding. The effect of the pre-weld and post-weld treatments on the microstructure, residual stress distribution, and mechanical properties of similar and dissimilar metal welds is studied. The study revealed that except for the advantages of the electron beam welding process, most of the observations are similar to that observed in case of welds carried out by employing gas tungsten arc welding [5-7].

In all the dissimilar metal welds of maraging steel and medium alloy medium carbon steel, it is observed that there is a decrease in the value of hardness at the interaction of these steels. The hardness remained low even after the welds were heat treated (**Fig. 7**). This is observed due to the diffusion of manganese (Mn) from medium alloy medium carbon steel to maraging steel. This is evident from the EPMA studies. This low value of hardness resulted in failure of the welds at fusion boundary.

6.0 DISSIMILAR METAL FRICTION WELDING OF MARAGING STEEL AND LOW ALLOY STEEL WITH AN INTERLAYER

In the dissimilar metal fusion welds of maraging steel and medium alloy medium carbon steel, diffusion of elements resulted in low hardness. The problem of diffusion of elements can be addressed by employing solid state welding process with an interlayer between the metals to be welded.

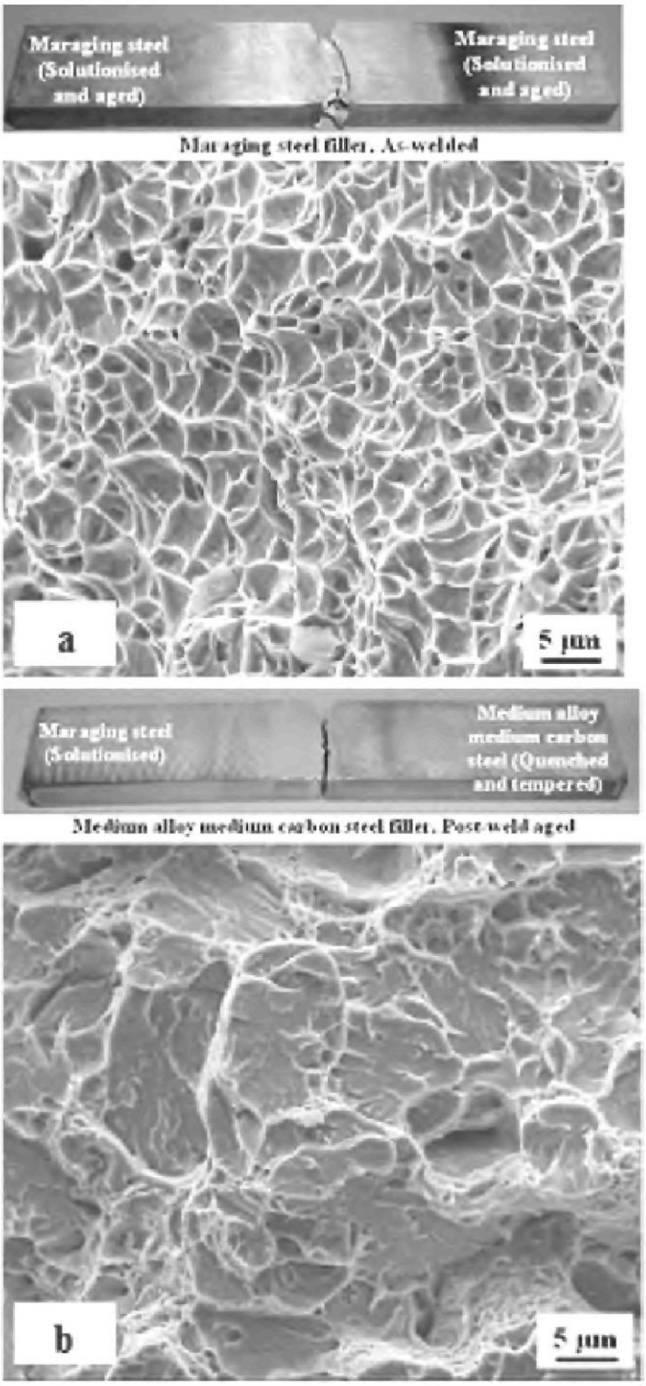


Fig. 6 : Impact specimen and fracture features of gas tungsten arc weldments (a) Similar metal weld (b) post-weld aged dissimilar metal weld

Continuous drive friction welding of dissimilar metals, maraging steel and low alloy steel was carried out. It was observed that the hardness, ductility and impact toughness of maraging steel are low due to the diffusion of elements such as

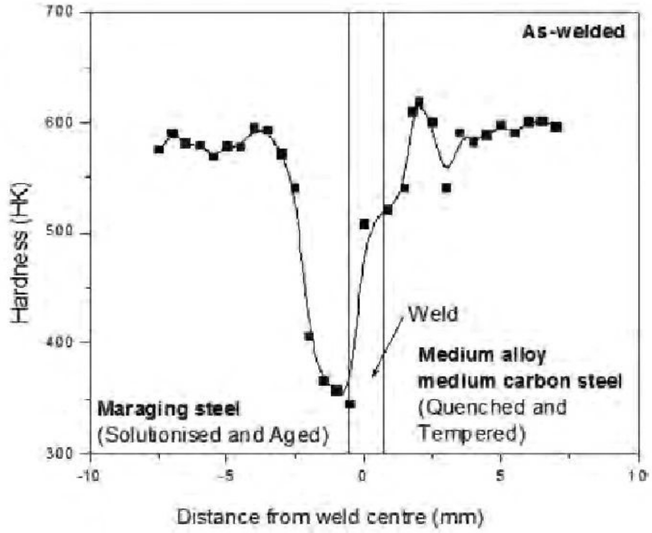


Fig.7 : Hardness distribution across the dissimilar metal electron beam weldment of age hardened maraging steel and quenched and tempered medium alloy medium carbon steel

carbon, manganese, silicon and phosphorus from low alloy steel to maraging steel. An attempt was made in this study to improve the properties by friction welding of maraging steel and low alloy steel with nickel as an interlayer (**Fig. 8**). The effect of post-weld heat treatments on microstructure and mechanical properties of dissimilar metal friction welds with and without interlayer was also studied. Dissimilar metal welds without an interlayer exhibited low strength, low notch tensile strength and low impact toughness compared to respective parent materials. The notch tensile strength and impact toughness in case of dissimilar metal weld with interlayer are observed to be more than that of the dissimilar metal weld without interlayer. Post-weld heat treatment resulted in further reduction in toughness compared to that in the as-welded condition. Such trends have not been observed in the welds with nickel interlayer, indicating that nickel acted as an effective diffusion barrier even during post-weld heat treatment. The study revealed that nickel can be employed as an effective barrier for diffusion of elements such as carbon and manganese to overcome the problem of carbon migration and retained austenite formation and consequent premature failure [8].

7.0 SURFACE REMELTING PROCESS FOR ALTERING NATURE OF RESIDUAL STRESSES

Generally compressive residual stresses are considered to be more beneficial than the tensile residual stresses. The

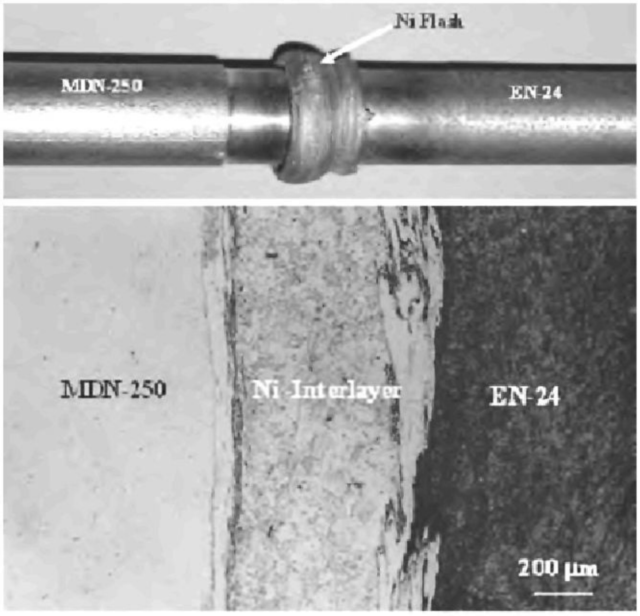


Fig. 8 : Friction welded dissimilar maraging steel (MDN 250) and low alloy steel (EN 24) joint with interlayer and corresponding microstructure

reduction of high tensile residual stresses in principle is possible by two ways i.e. post-weld heat treatments and preventive steps such as vibratory stress relief.

Metal-surface remelting is a metallurgical process widely used to improve material properties like wear resistance, surface hardening, corrosion resistance, fatigue strength etc. It is also used for repairing surface and weld defects. Surface remelting is done by lasers, electron beams, air-plasma and gas tungsten arc welding. In the present investigation an attempt is made to alter the nature of the residual stresses in the fusion zone of the medium alloy medium carbon steel weldment by surface remelting, using autogenous gas tungsten arc welding.

It has been observed that the sense of residual stresses altered from tensile in the as-welded condition to compressive stresses after surface remelting as the volume expansion due to martensitic transformation is not permitted by the core region underneath the surface remelted zone (**Fig. 9**). This interpretation is found to be in agreement with the increase in the half width of (211) diffraction line. The observed residual stress distribution was found to be in agreement with results of hardness data [9].

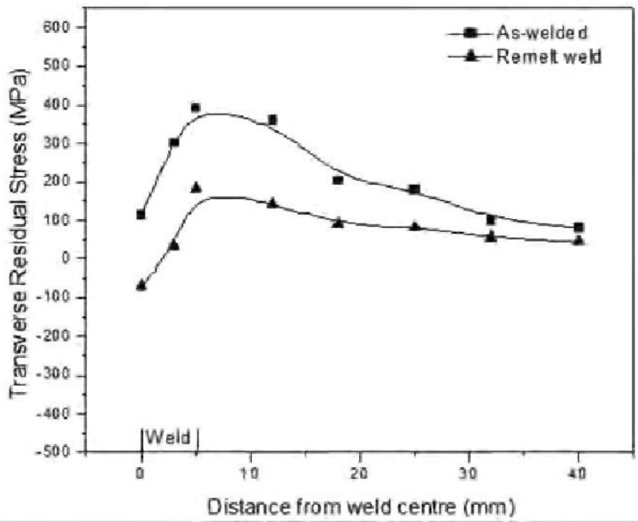


Fig. 9 : Residual stress distribution across the gas tungsten arc medium alloy medium carbon steel weldment in transverse direction

8.0 CONCLUSIONS

It may be concluded that in the as-welded condition of similar metal gas tungsten arc maraging steel weldments, medium alloy medium carbon filler welds seems to exhibit better properties where as in the post-weld aging condition except for toughness, maraging steel filler is a better choice.

If the component size is small and if it can be heat treated after fabrication, dissimilar metal gas tungsten arc weldment of solutionised maraging steel and quenched and tempered steel with maraging steel as filler, subjected to post-weld aging treatment is the best choice with respect to good hardness, high tensile strength and impact toughness. If the component size is too big to be heat treated after welding, the dissimilar combination solutionised and aged maraging steel and quenched and tempered medium alloy medium carbon steel with medium alloy medium carbon steel filler is recommended.

The diffusion of the elements at the interaction of maraging steel and low alloy steel can be avoided by employing friction welding using an interlayer.

If the nature of stresses of the welds is to be altered from tensile to compressive, the cost effective method is surface remelting employing autogenous gas tungsten arc welding.

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