In-situ Weld Repair Of Cracked Shrouds Of Turbine And Characterization Of The Weld Joint

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ABSTRACT

Cracked shrouds of the 3rd stage of a Low Pressure turbine was in-situ repaired by removing the cracked pieces of the shroud and welding new shroud pieces to the existing shroud. The shroud material was made of AISI 414 martensitic stainless steel (SS), and the repair welding was carried out using ER 410NiMo filler wire. The tenon heads of the blades, which were removed for carrying out the in-situ repair, were also built-up by weld deposition. The repair welds were subjected to in-situ two-stage post weld heat treatment (PWHT) as required for the 414 SS material and the 410NiMo weld metal. For prior to simulation of the constraints of actual in-situ repair, a mock-up piece was made using the same blade material, welding consumable, welding procedure and PWHT as were to be used for the actual repair. After successful completion of the repair, the mock-up piece as well as separate weld pads prepared using the shroud material and ER 410NiMo consumable were subjected to detailed microstructural characterization and mechanical properties testing to generate data on the properties of the repair weld now in service. The paper discusses the details of the in-situ repair and results of the characterization of the weld joints. Results confirm the repair weld has adequate strength and ductility. The turbine with repair welded shrouds has been performing satisfactorily since 2008.

Key words: Repair welding, Turbine shroud, PWHT, Supermartensitic stainless steels.

INTRODUCTION

Thanks to the in situ repair welding procedure developed to repair cracked turbine components like shroud, blades, understraps etc, many of the failed steam turbine components of Nuclear Power Corporation of India Limited (NPCIL) have been repaired and these components after repair are in service for several years now [1-2]. Recently, two cracks were observed in the shroud of third stage of the low-pressure turbine of Madras Atomic Power Station (MAPS-II). These cracks propagated from one side of the shroud to the tenon head. The shroud was made up of AISI 414 martensitic stainless steel. The cracked portion of the shroud was removed and the remaining portion was welded carefully to a new one so that the under strap made up of Ti -6Al-V was not affected during the process. The welding was carried out using ER410NiMo filler wire by GTAW process. This particular filler was chosen in spite of other available grades such as E/ER410, E/ER308, 309, 316L, to match the strength and toughness of the weld metal with the base metal by appropriate heat treatment. This steel is widely used in offshore oil pipelines because it has high resistance to pitting corrosion and stress corrosion cracking [3]. The 410NiMo welds are generally subjected to double stage PWHT after welding to improve the toughness of the weldment. The two stage heat treatment consists of first stage tempering above the Ac_1 transformation temperature followed by cooling to room temperature and the second stage tempering below the Ac_1 temperature. In one of our earlier work, the martensitic stainless steel weld metal made out of this filler wire, when subjected to a double stage heat treatment consisting of 675°C/2hr and 615°C/4hr exhibited a very low Charpy V-notch impact toughness of around 13

J [2], which is considerably lower than that of the blade material. Hence for the present repair work, we modified the two stage PWHT to 650°C/2hrs + 600°C/4hrs. The PWHT was carried out using a custom built furnace with programmable temperature controller with an accuracy of 1C which has been used in many of our repair welding processes for more than 10 years [4].

The paper describes the procedure adopted during in-situ repair welding process and details of characterization of mechanical and metallurgical properties of the weld joint. The role of post weld heat treatment (PWHT) time and temperature in determining the quality of the joint is emphasized.

REPAIR OF THE CRACKED SHROUD

Mock up trials

Before taking up the actual repair of the component, a mock up welding was carried out prior to actual repair welding. The welding parameters used are tabulated in Table1. The chemical composition of the weld metal is given in the Table 2.

Mock up welding was carried out to replicate the actual constraint that prevails in the turbine component during the repair welding. This provides the welder to decide suitable position for welding in actual job under constraint condition. Two LP-3[rd] stage blades were tack welded such that distance and orientation between the two adjacent blades in that stage of the turbine is simulated. Two pairs of tenon holes (one pair corresponding to two tenons of one blade) were machined at exact locations on the shroud piece so that it is in line with the tenons on the blades when the shroud piece is placed on the blades. The dimensions of the new shroud piece were 100 x 40 x 3 mm^3 corresponding to the actual one. In order to reproduce the crack present in original shroud to be repaired, the shroud piece brought for mock up was cut intentionally along the width after it was placed over the blades. Subsequently, the cut edges were prepared for welding. The setup for the mock-up welding with edge preparation is shown in Fig.1

Table 1 : Welding parameters used for mock up procedure

Current (A)	Voltage (V)	Heat input (kJ/mm)	Shielding gas	Preheat temperature °C	Interpass temperature °C	Post heating °C	PWHT
50-60	12	1.1	99.99% argon	250	200	250 (15 minutes)	650°C/2h +600°C/ 4h

Table 2 : Composition of ER410NiMo weld metal in wt%

Elements	C	CR	Ni	Mn	Mo	P	S	Si	V	Co	Cu	Sn	Cr_{eq}	Ni_{eq}
Wt%	0.02	12.5	5.0	0.45	0.50	0.025	0.045	0.40	--	--	0.32	--	13.6	5.8

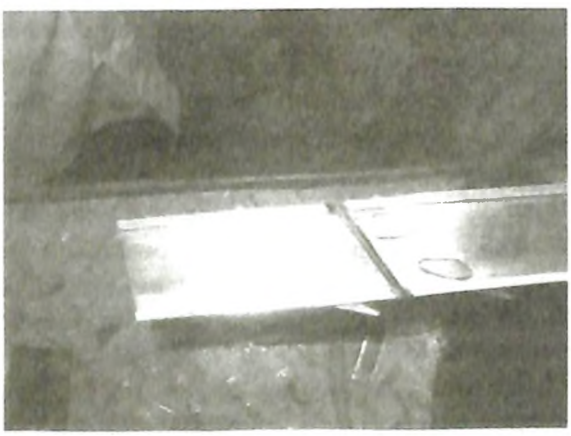


Fig.1 Setup of shrouds during the mock up welding.

Fig.2 Shroud piece after mock up welding

Welding procedure

The shroud and blades were tack welded at four locations to keep them intact in the position using gas tungsten arc welding (GTAW) process with 410NiMo filler wires of 0.8 mm diameter. This filler wire was extruded from 2mm diameter 410NiMo wire in an extruder. A thermocouple was dipped in to the weld pool by GTAW process on the ridge of the shroud and connected to temperature controller to monitor the temperature during heat treatment. The shroud piece was then preheated to 250°C and welding was carried out using the same filler wire using the welding parameters given in Table 1. Figure 2 shows the shroud piece after completion of mock up welding.

Post weld heat treatment (PWHT)

Two-stage PWHT used in the mock up welding would be incorporated in the actual repair welding. This heat treatment was carried out in situ using an indigenously fabricated furnace with built in temperature controller in which the entire heat treatment cycle can be pre programmed using constant heating rate of 100 °C/h. The heat treatment was carried out in two stages. In the first stage the weld was heated to 650°C and held at constant temperature for 2 hours and cooled to room temperature. In the second stage it was again heated to 600°C and held for 4 hours then cooled to room temperature. Figure 3 shows the PWHT carried out on the mock up shroud piece after welding was completed. The heat treatment cycle programmed during the mock up is shown in the Fig. 4.

After demonstrating the feasibility of repair and PWHT on mock up piece, it was subjected to metallurgical characterization. The details are given in the forth-coming section

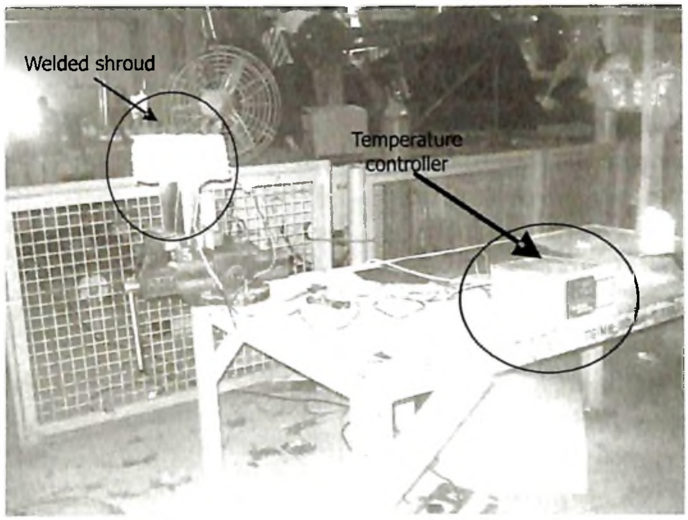


Fig.3 : Heat treatment of the welded shroud after mock up

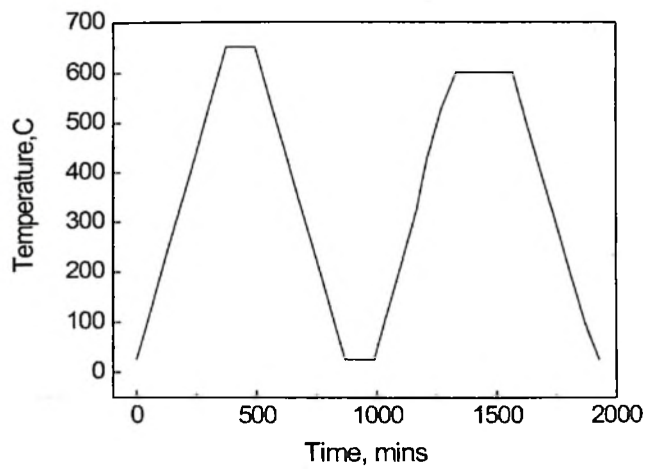


Fig 4 : Schematic diagram of heat treatment cycle

Execution of the Actual Repair welding

Preparation of shroud

The new shroud piece, which has been received from BHEL for replacement, was machined exactly to the dimension of the actual shroud and rolled to produce the curvature as that of the original shroud. Subsequently, tenon holes were machined on it and single V groove was made on the cut faces of existing shroud and new shroud by grinding.

Welding

The new shroud piece was placed in position and tack welded to the existing shroud as shown in Fig.5. A thermo couple was also tack welded to the shroud to measure and monitor the temperature progress during PWHT. Root gap was maintained 1.00 mm. The joint area was preheated to a temperature of 270-250°C using oxy acetylene flame. Welding was carried out using the same parameters used for the mock up procedure. The average heat input for the weld was estimated to be ~ 1 kJ/mm. The ridges present in the shroud were also built up by welding. Figure 6 shows the shroud piece after completion of welding. Post weld heating was carried out with at 250°C for 15 minutes by flame heating. After post heating, the shroud was cooled down to room temperature and checked for any discontinuities using dye-penetrant (DP) test. The surface was ground and it was found that it was free of defects.

The next step was to build up the tenon using ER NiCr-3 (Inconel-82) filler wire from the pre existing tenon root. Schematic diagram of turbine blade with tenon cap is shown in Fig.7. The pre existent tenons were machined and subjected to DP check to identify defects if any present in it. No preheating was done but interpass temperature ~250°C was maintained. Welding current employed was in the range of 20-30 A. The tenon cap was machined from alloy 800 pieces of 2.00 mm thickness so that it is fitted and welded to the rebuilt tenon. After welding of the cap to the tenon head and careful grinding of this welded assembly, the repaired tenon head matches with that of the actual teonon head in almost all respect. After the repair, the tenon head was subjected to DPT and cleared for post weld heat treatment. The two-stage PWHT consisting of 650°C/2h then air-cooling and 600°C/4h then air-cooling was carried out on the welded shrouds using the indigenously built furnace. The welds subjected to PWHT were checked again using DPT and found to be perfectly sound.

METALLURGICAL CHARACTERIZATION OF WELDMENTS

Three separate weld pads were used for characterization of the weldment. One is the mock up piece which was brought to laboratory for metallography and micro hardness studies. This was used only for microstructural examination and hardness measurement. Another is the

Fig. 5 : Photograph taken during welding of shroud piece

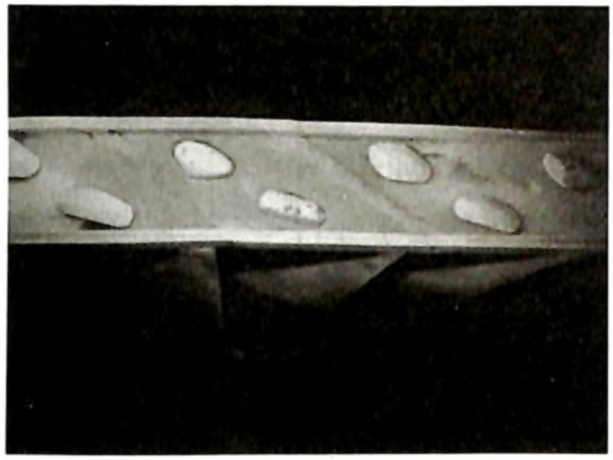


Fig. 6 : Turbine shroud with tenons after completion of welding

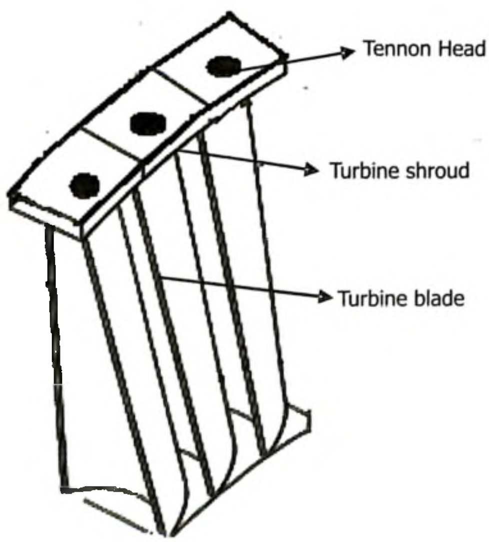
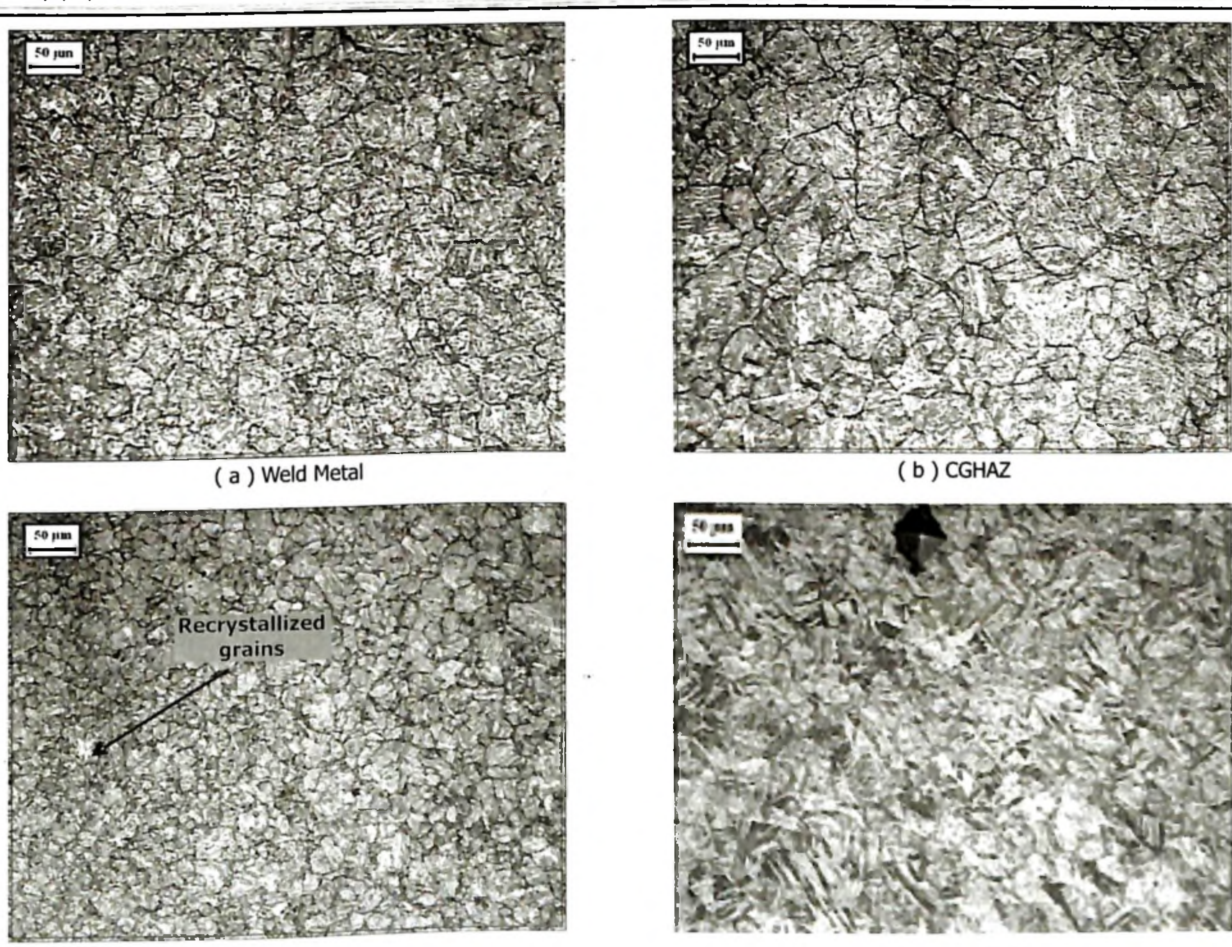


Fig. 7 : Schematic diagram of a turbine blade with tenon cap and shroud

weld pad prepared in the laboratory using the same shroud material, consumable and welding parameters that are employed in the actual repair and subjected to same two stage heat treatment of the actual repair. This was used to carry out the tensile and bend test. Third one is the weld pad prepared using 12 mm thick AISI 410 stainless steel plate and 410NiMo consumable used for repair. This weld pad was used only to evaluate the toughness of weld metal. Both the second and third weld pads were given a two stage heat treatment of 650 °C/4h + 600 °C/2h. The weldments were prepared for metallography by using standard grids of emery papers and diamond slurry of 0.25 µm for final polishing. The specimens were etched using Villela's reagent and observed using optical microscope and scanning electron microscope (SEM). Microhardness profile was taken across the weldments using Schimadzu microhardness tester at 500 g load. Tensile test and Bend test was performed as per ASTM practice E 8-04 and ASTM practice E 190-92 respectively on the transverse specimens extracted from the shroud welds prepared using the same shroud material and filler wire under the same conditions of mock up welding in the laboratory. The impact tests were conducted on standard full size Charpy "V" notch specimens obtained from separate weld pads of dimension 150x70x12 mm^3. The fracture surface of the impact-tested sample was observed under scanning electron microscope.

Microstructure

The microstructures of the weldments prepared from the mock up shroud piece after the two stage heat treatment are shown in Fig.8. The weld metal microstructure is recrystallised and grain size (30-50 µm) are larger than the intercritical heat affected zone (5-10 µm) and the base metal (20-25 µm) but smaller than the coarse grain heat affected zone (80-100 µm). The microstructure of ICHAZ shows fine grains along the prior austenite grain



(a) Weld Metal (b) CGHAZ (c) ICHAZ (d) Base Metal

Fig. 8 Microstructures of various zones of weldment (a) Weld Metal (b) Coarse Grain Heat Affected Zone (CCHAZ) (c) Intercritical Heat Affected Zone (ICHAZ) (d) Base Metal boundaries because of partial transformation taken place in this region. From the microstructure it is evident that tempered lath martensite is present in the weld metal and HAZ. The SEM image in Fig. 9 shows the martensite laths of size ~ 125 nm present in the weld metal.

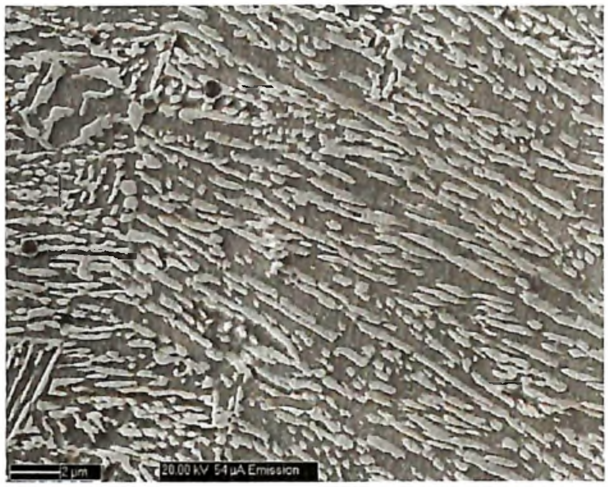


Fig. 9 : SEM image of 410 NiMo weld metal from the mock up weld shroud at 8000x magnification

Figure 10 shows the as welded microstructure of the 410NiMo weldmetal obtained from the specimen obtained from the shroud welded in the laboratory. Microstructure shows a mixture of fresh martensite and tempered martensite in the root of the weld. This is because multipass welding has lead to the tempering of previously deposited weldmetal. Presence of untempered martensite in this region may be because the Ac1 transformation temperature of the weldmetal is low, the second layer of weld deposit would have raised the temperature of previously deposited weld metal above Ac1 and reversion of austenite might have taken place which on subsequent cooling converted into untempered martensite.

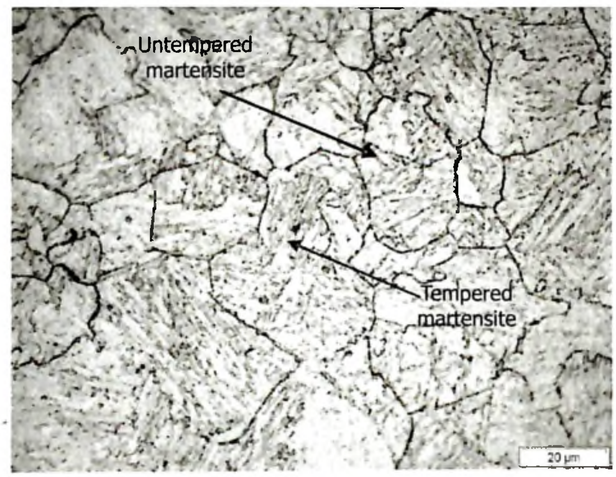


Fig. 10 : Optical micrograph of root portion of the weld metal in as welded condition

Mechnical properties

Figure 11 shows the hardness profiles across the weldment obtained from the mock up shroud piece in the post weld

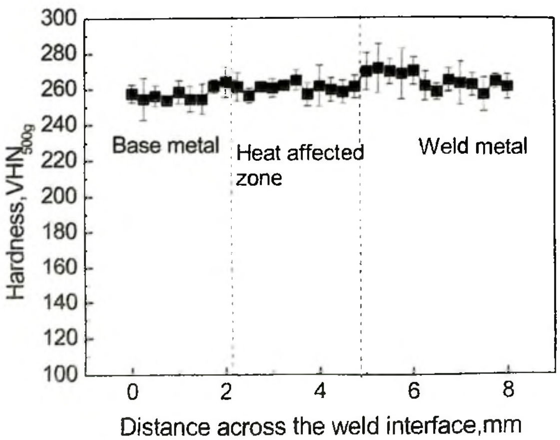


Fig. 11 : Micro hrdness survey across the weldment

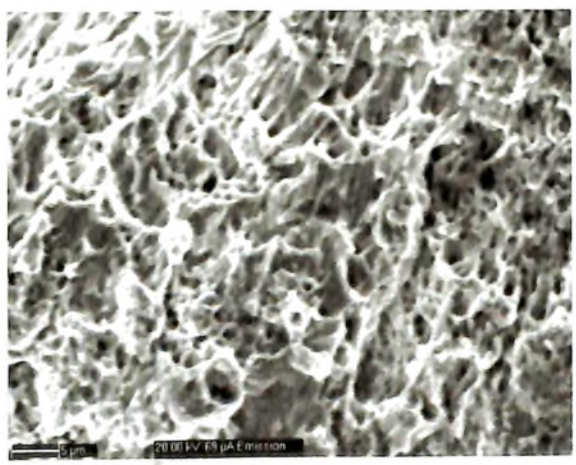


Fig. 12 : Fractograph of the impact tested sample

heat-treated condition. The hardness of the weld metal in the as welded condition was ~ 400 VHN_{500g} whereas after PWHT the overall hardness has reduced to 260VHN. This is an indication of adequate tempering of the weldment after PWHT. It is also important to note that there is no significant variation in the hardness across the weldment. The yield strength (YS) and ultimate tensile strength (UTS) of the weldment obtained from the tensile test conducted on the specimens obtained from the shroud piece welded in the laboratory are 655 MPa and 780 MPa respectively. The failure location was the base metal. The base metal YS and UTS are about 724 and 827 respectively. The difference in the UTS of weldment and base metal is only about 5% therefore; the strength of the weldment is comparable to that of the base metal. The weldment exhibits ductility 17.5 % elongation whereas the base metal ductility is 15%. This weldment also passed the 180 degree root bend test, one of the requirements for welding procedure qualification. Impact test was done on the samples extracted from the weld pads exclusively made using 12mm thick 410 martensitic stainless steel base plates and the 410NiMo filler wire. The toughness of the weld metal after this two stage heat treatment is 170 J, which is considerably higher than 13 J obtained for two-stage PWHT carried out at slightly higher temperature of 675 and 615°C. The fractographs taken from the fracture surface of the impact tested samples reveals dimple morphology indicating that the fracture mode is purely ductile (Fig.12).

DISCUSSION

The results of evaluation of the mechanical properties of the weldment reveal that there is a significant improvement in the toughness of the weld metal after the two stage heat treatment adopted during repair. This is in contrast to very poor toughness obtained for the same weld metal subjected to slightly different two stage PWHT (675°C/2hr and 615°C/4hr) [2]. The final microstructure of the as quenched steel depends on its chemical composition which is given in Table 2. The solidification mode of this group of steels is ferritic as shown in the Fig 13. Though the carbon content of the weldmetal is as low as 0.02 wt% the weldmetal solidifies through the austenite range because of increased Ni content. The advantage of low carbon content is that it enhances the toughness and weldability of this type of martensitic stainless steel. Also, the martensite formed in these steels is lower in hardness as compared to the martensite formed in the steels with higher carbon

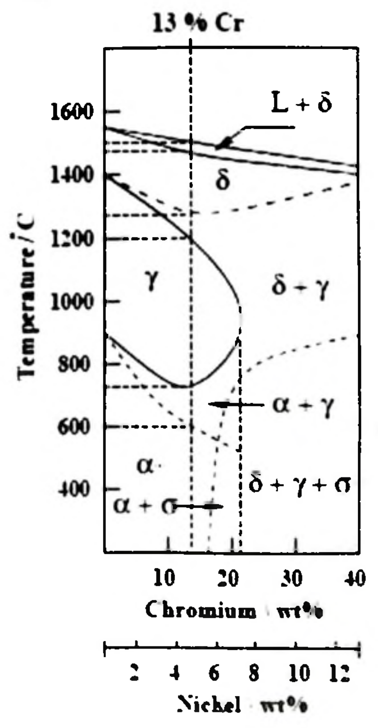


Fig. 13 : Vertical Section of Fe-Cr-Ni phase diagram for a constant Fe content of 60 wt%[5]

The drawback of higher Ni content in this steel is that it depresses the Ac1 transformation temperature and subsequently the martensitic start (Ms) temperature. This eliminates the phenomenon of auto tempering in this steels which would have taken place otherwise. The Ms temperature for this weldmetal was estimated to be ~194°C using the empirical equation (1) [6]. The martensitic transformation is expected to be complete at a temperature approximately 200°C below the Ms temperature. Therefore, the weld metal does not undergo complete martensitic transformation when it is cooled down to room temperature and some amount of austenite is retained in the weld metal.

$$Ms(°C)= 492-125(wt\%C)-65.5(wt\% Mn)-10(wt\%Cr)-29(wt\%Ni) \quad (1)$$

It is possible that in the weld metal some amount delta ferrite, formed during solidification could be retained due to fast heating and cooling experienced. However, no delta ferrite is observed in the weld metal. This is in agreement with the prediction made using Kaltenhauser ferrite factor given in the equation (2) which is widely used to predict the amount delta ferrite retained in the ferritic/ martensitic weldmetal [7].

$$FF=Cr+6Si+4Mo+8Ti+2Al+4Nb-2Mn-4Ni-40(C+N) \quad (2)$$

The FF obtained for this weldmetal is 6.08 and hence no delta ferrite is expected to be present in the weld metal (delta ferrite is predicted only FF above 8), which is in agreement with microstructural evidence. Thus, from the composition of the weld metal, it is expected that the weld metal is to have some retained austenite and no delta ferrite in the as-welded condition. Subsequent discussion shall be on presence of retained austenite in the weld metal and transformation behaviour of weld metal containing retained austenite during two stage heat treatment.

Retained austenite is normally present as thin films between the martensitic lath boundaries and it is difficult to resolve this phase in an optical microscope. Even at high magnification that is possible in SEM, differentiating martensitic lath and retained austenite is not easy. However, as retained austenite will be rich in austenite stabilizers like Ni, a compositional map using EDS can be used as an indirect evidence of retained austenite. Accordingly, Fig. 14 shows SEM image of the weld metal after the PWHT and Fig. 15, the distribution of Ni at the location of this image obtained by compositional mapping using EDS. Enrichment of Ni along the lath boundaries can be observed, indicating presence of retained austenite in the weld metal.

Having confirmed the presence of retained austenite, let us discuss the transformations that can occur in the weld metal during two stage heat treatment. The first stage heat treatment temperature, 650°C is above Ac_1 temperature [8] which means some of the martensite present in the weld metal would retransform to austenite while the rest would undergo tempering. Hence, at the end of hold time at this temperature, the weld metal will have more volume fraction of austenite than that was present at the start of the heat treatment. During cooling most of it would transform back to martensite; but as the M_f temperature is expected to be below room temperature, complete transformation of austenite would not take place. Further it is reported that fresh martensite is formed on cooling only when the temperature interval between the heat treatment temperature and Ac1 transformation temperature is high enough to produce at least 20% transformed austenite during this heat treatment [9]. Hence, at the end of the first stage of PWHT, the weld metal microstructure consists of tempered martensite, fresh martensite formed during cooling from the heat treatment temperature and retained austenite. Figure 16 shows hardness profile of the weld metal from root to face on the weldment produced from shroud piece after the first stage heat treatment. Hardness, typically of the order of 320-340 VHN, which is higher than a fully tempered structure, but lower that that of fully martensitic structure, and variation observed in the hardness of the weld metal (Fig. 16) clearly indicate presence all the three phases mentioned above.

The objective of the second stage heat treatment is to temper the fresh martensite formed during the first stage. As the temperature chosen is below Ac_1, austenite is not formed during this heat treatment. As the martensite temper, strain in the lattice come down and some of the retained austenite can transform to martensite. However, as the M_f temperature is below room temperature, this transformation would not be completed and some of the austenite would be retained. Even if the weld metal is cooled below M_f temperature, it is reported that some austenite would still be present [10]. Stability of the retained austenite depends on enrichment of austenite stabilizers such as Ni and C. In this weld metal, this

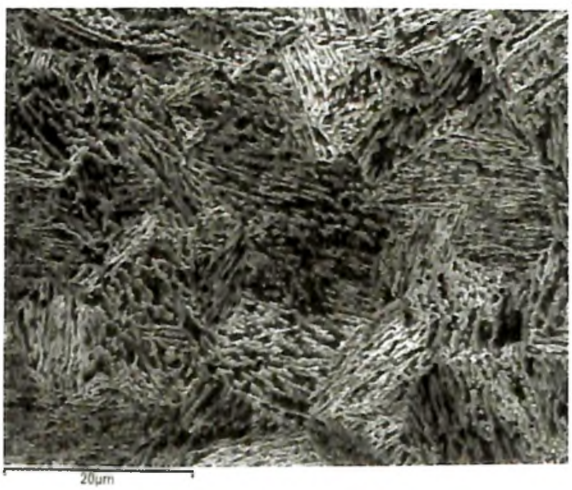


Fig. 14 : SEM image of the weldmetal from the mock up welded shroud

Fig. 15 : Ni element map shows enrichment of Ni along the lath boundaries

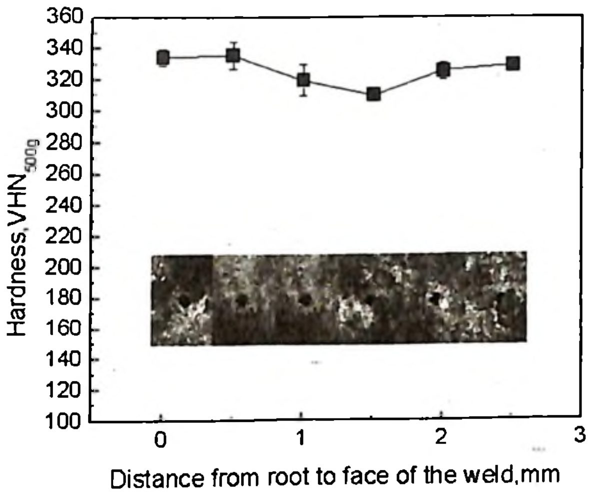


Fig. 16 : Micro hardness profile taken from the root to face of the weld after the first stage PWHT (650°C/2h) was completed

depends completely on the enrichment of Ni in the retained austenite since the carbon content in the weldmetal is very low. At higher tempering temperatures the Ni, diffuses rapidly and gets homogenized in the austenite matrix there by making it unstable [11] and hence volume fraction of retained austenite can come down if the tempering temperatures are high.

The above discussion explains how it is possible to have retained austenite present in the weld metal after two stage heat treatment. It is known that significant improvement in toughness of 13% Cr steels subjected to two stage heat treatment is possible with the presence of finely distributed retained austenite in the weld metal [11]. Appropriate PWHT temperatures for good toughness of weld metal are slightly above the Ac1 temperature for the first cycle and temperature below Ac1 for the second cycle so that volume fraction of untempered martensite is kept minimum in the weld metal and retained austenite is dispersed in the weld metal after the tempering process.

CONCLUSION

- Repair welding of cracked shrouds of low pressure turbine (third stage) of MAPS unit 2 was successfully carried out in situ using 410NiMo consumables and subjecting the repair weld to a two stage heat treatment.
- Metallurgical and mechanical property evaluation of the mock up piece weld and separate weld pads prepared using same welding parameters employed confirmed that the weld joint has sufficient strength, ductility and toughness. No variation in properties across the weldment also observed.
- Good toughness of the weld metal is attributed to presence of finely redistributed retained austenite in the weld metal.

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