EXPERIENCE IN IN-SITU REPAIR WELDING OF STEAM TURBINE SHROUDS AND BLADES

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Abstract

Cracking have been observed in the turbine shrouds and blades during routine maintenance shut down of power plants owned and operated by Nuclear Power Corporation of India Ltd. In-situ repair of these cracks were carried out using a welding procedure developed indigenously that employed gas tungsten arc welding process and austenitic stainless steel filler wire. Localised post weld heat treatment (PWHT) of the repair welds were also carried out. The turbine components thus repaired have been performing satisfactorily in service for more than three years. This paper presents the development of this welding procedure, its successful execution in the plant and performance of the repair weld in service.

Key words: Repair, welding; austenitic steel, turbine.

1. Introduction

Nuclear Power Corporation of India Ltd., (NPCIL), owns and operates many power plants with pressurized heavy water reactors, (PWHR), in India. These plants are of 230 MWe capacities with steam temperature less than 473K and operating frequency is 50 Hz. During annual inspection of the turbines of these plants, cracks were noticed in the shrouds, understraps and blades of the turbines of some of the plants. Cracks were mainly observed in the shrouds of the stage-III in both low-pressure (LP) and high-pressure (HP) turbines, understraps of HP stage -III and near the lacing-hole of the LP stage -IV blades. As the safety regulations do not permit operation of the turbine with cracks in the blades and shrouds, it is required to either replace or repair these components before the turbine is put back into operation. Though original manufacturers of the turbines recommend the replacement of the cracked components with new ones, there are many practical limitations for exercising this option. In general, shrouds and understraps are riveted with a number of blades, depending on the location. Hence, replacement of a single shroud piece or understrap would cause damage to all the blades riveted to it and would lead to replacement of not only the cracked component but also the blades fixed to it. If the same blades are to be used, then the turbine should be operated with one set of blades having shorter length than the rest of the blades in the same stage. This option also calls for dynamic balancing of the turbine, before putting it back into operation. This whole exercise is both time-consuming and expensive. Further, spares for many of the components that have to be replaced may not be readily available even with the original turbine manufacturer, leading to further time delays and consequent loss of revenue.

Under these circumstances, NPCIL considered the option of weld repair of cracked understraps, shrouds and blades. The understraps are made of a high strength titanium alloy, (Ti-6Al-4V), while both the shrouds and blades are made of martensitic stainless steel, (SS). The procedure for repair of understraps, shrouds and blades were developed in-house, and repairs were successfully carried out in different power plants of NPCIL. This paper describes the development of the welding procedure for repair of cracks in the blades and shrouds, its successful execution in various plants and the performance of the repaired component in service until now. Figure 1(a) shows details of cracking usually observed in the shrouds, while Fig. 1(b) shows a typical crack starting from the lacing hole of a LP stage-IV blade.

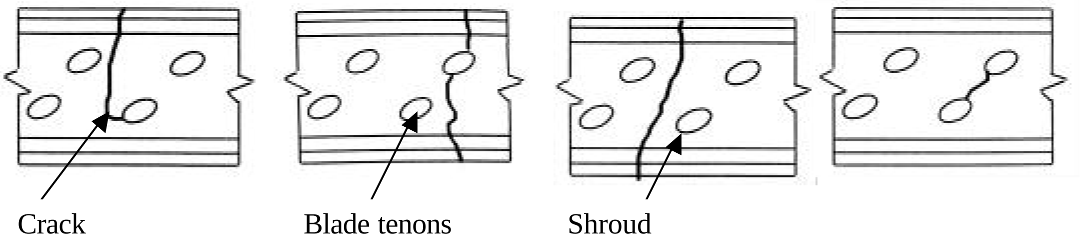


Fig. 1(a): *Schematic of the type of cracks observed in the shrouds of stage-III LP turbine*

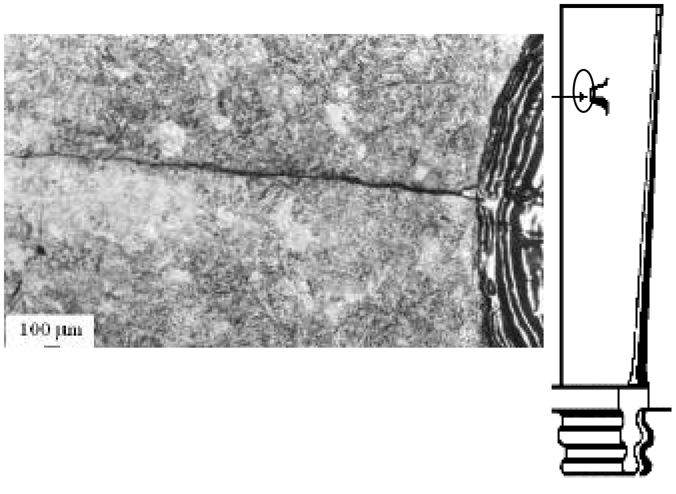


Fig. 1(b): *Details of the lacing hole crack in the blade.*

2. Development of the welding procedure

The chemical compositions of the shroud and blade materials are given in Table 1, along with the ASTM specification for AISI 410 SS. A comparison of the compositions of the blades and shrouds with the ASTM specification reveal that these materials conform to AISI 410, and hence AISI 410 pipe of OD 88.9 mm and wall thickness 3.2 mm was chosen for the welding procedure development. The chemical composition of this pipe material is also given in Table 1. During the weld cooling cycle, the heat-affected zone, (HAZ), in martensitic SS transforms to fresh martensite and, if welding were carried out using matching composition consumable, the microstructure of the weld metal would be martensitic. The toughness of the martensitic phase in the as-welded condition is poor, which necessitates PWHT to temper the martensite structure to improve the toughness of the weldment. Further, the martensitic structure is susceptible to hydrogen assisted cracking, (HAC), and preheating of martensitic SS joints is necessary to avoid HAC, especially when matching composition consumables are employed during welding. The recommended PWHT temperature for martensitic SS weldments is very high, (923-1023 K), [1], and attaining this temperature during on-site localised PWHT is very difficult as failure of heating elements at such high temperatures may occur. To overcome the difficulty of attaining high temperatures during on-site localised PWHT after repair welding with matching composition consumable, it was decided to develop an alternative repair welding procedure using austenitic welding consumable. Further, if austenitic SS consumables, and a welding process that does not use any flux, are used, preheating of the weld joint also can be avoided, provided PWHT is carried out immediately after welding.

Element	Shroud material	Blade material	Pipe material	AISI 410 SS	ER 316L filler wire
C	0.126	0.13	0.127	1.00 max	0.018
Cr	11.5	11.8	12.8	11.5–13.5	18.52
Mn	0.55	0.52	0.34	1.00 max.	1.64
Si	0.26	0.25	0.32	1.00 max.	0.33
Mo	0.37	0.36	0.12	Not specified	2.22
Ni	0.45	0.43	0.20	0.75 max.	11.52
P	0.024	0.024	0.024	0.04 max.	0.028
S	0.007	<0.006	<0.006	0.03 max.	0.013

Table 1: *Chemical Composition of the Shroud, Blade, Pipe and Filler materials, along with the composition requirement for AISI 410 SS as per ASTM A240-67*

Hence, a repair welding procedure using gas tungsten arc welding, (GTAW), process and an austenitic consumable was developed for repairing cracks in shrouds and blades of steam turbines [2,3]. During this procedure development, three different austenitic filler wires, namely ER 316L, ER 309L and ER NiCr-3, were considered and mechanical properties of the weld joint, both in the as-welded condition and after PWHT, were evaluated. For qualification, weld joints were prepared by joining the AISI 410 pipe with a groove angle of 70°. Table 2 gives the tensile properties obtained for the weld joints made with the three different consumables. In the as welded condition, the weld joint made with 309L filler metal fractured in the base metal, (except in one case), while those made with the other two filler metals failed in the weld metal showing lower ductility values. On the other hand, after PWHT, the joint made using 316L filler wire failed in the base metal. However, the weld joint made with 309L filler metal failed during the bend test, while the weld joint made with the other two filler metals passed the bend test without any cracking. The hardness profiles across the fusion boundary after 873 K/1h PWHT for all the three weld joints, (Fig. 2), show that the hardness of the 309L weld metal is higher than that of the HAZ after PWHT. This can be attributed to the dilution of the 309L weld metal by the base metal, which leads to the formation of highly alloyed martensite phase in the weld metal with the martensite remaining untempered even after PWHT. The formation of this highly alloyed martensite is also responsible for the 309L joint failing in the bend test. In the case of the ER NiCr-3 joint, the weld metal hardness is much lower than that of the base metal. For the 316L joint also, the weld metal hardness is lower than that of the base metal; but the difference is not as high as that in the ERNiCr-3 joint. Hence, after PWHT, the 316L joint has the minimum hardness mismatch between the weld metal and base metal, (about 30 VHN). The results of tension tests, (Table 2), show that the location of fracture in 316L weld joint shifts from the weld metal in the as-welded condition to the base metal after PWHT. The 873 K/1h PWHT of the 316L joint also results in significant improvement in ductility accompanied by a decrease in its yield strength due to tempering of the HAZ. Based on all these results, a welding procedure involving the use of ER 316L filler wire and a PWHT of 873 K/1 h was chosen for repair of shroud cracks [2,3].

The chemical composition of the ER 316L filler wire is also included in Table 1, while the optimised welding conditions are given in Table 3.

Filler Wire Used	PWHT Condition	Ultimate Tensile Strength (N.mm^{-2})	Yield Strength (N.mm^{-2})	Elongation (%)	Location of Fracture
ER 309L	As-welded	819	685	12	Base metal
		795	629	11	Base metal
		812	695	14.2	Base metal
		779	449	5	Weld metal
ER NiCr-3	As-welded	699	426	6	Weld metal
		726	450	7.6	Weld metal
ER 316L	As-welded	808	612	7.6	Weld metal
		819	574	7.6	Weld metal
	873 K/ 1 h	745	346	13.6	Base metal
		748	368	17	Base metal

Table 2: *Transverse-weld tensile properties of 410 SS weldments made using austenitic consumables*

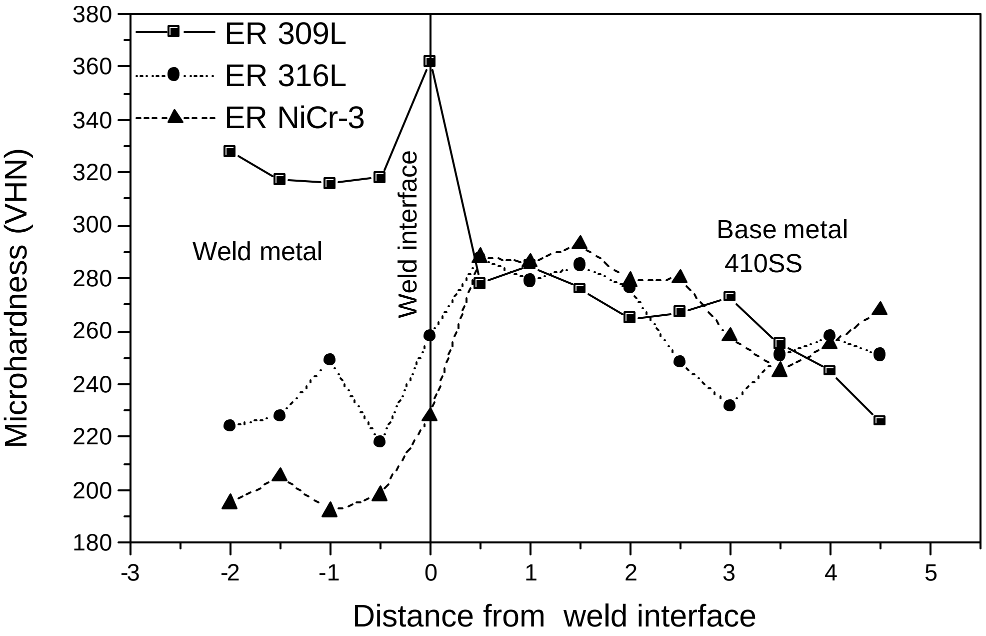


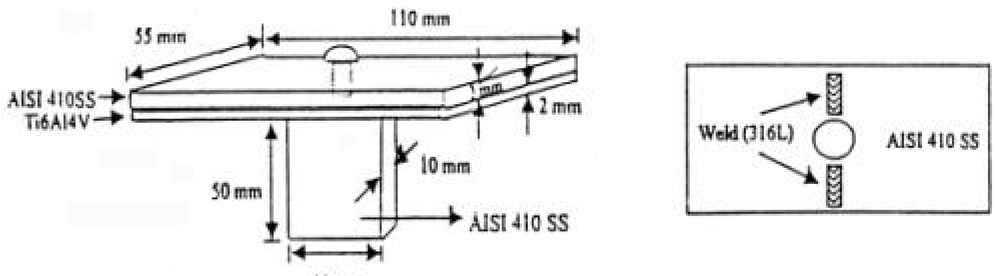
Fig. 2: *Hardness profile after 873K/1h PWHT across the fusion line for welds prepared using three different welding consumables during procedure development.*

Parameters	Root Pass	Filler Passes
Welding process Polarity	GTAW DCSP (direct current straight polarity)	
Welding current	80 A	115 A
Welding voltage	10 V	13 V
Welding speed	95 mm.min^{-1}	135 mm.min^{-1}
Preheat temperature	–	
Interpass temperature	–	
Argon gas purity	99.999%	
Shielding gas flow rate	25 l.min^{-1}	
Backing gas flow rate	35 l.min^{-1}	

Table 3: *Optimised welding conditions evolved during procedure development*

3. Mock-up trials

It was not just sufficient to develop a welding procedure to take up the repair work directly. There are many constraints during welding of the cracked shroud piece to which blade and understraps are riveted. Many of the cracks originated from the tenon holes through which blade tenons were inserted and subsequently riveted, as shown in Fig. 1(a). In certain other cases, it was found that just below the cracks were located the understraps, made of a titanium alloy which was not metallurgically compatible with steel. Hence, it was required to demonstrate that that during repair welding, no inadvertent welding of the shroud piece with either the blade or the understrap takes place. For this purpose, a mock up assembly that simulates the presence of understrap, blade and tenon hole in the shroud, as shown in Fig. 3(a), was prepared. Welding was carried out using the optimised parameters on top of this assembly as shown in Fig. 3(b) and it was possible to successfully demonstrate that repair welding can be carried out by a skilled welder without causing any damage to both the understrap and blade by carefully controlling the welding parameters.



(a)

(b)

Fig. 3: *Mock-up for welding of the shroud at a location where blade and understrap are riveted: (a) mock-up assembly; and (b) top view of the assembly after welding.*

Another important aspect that had to be demonstrated was the viability of the localised PWHT. For this purpose, a small electric resistant furnace, which can be kept on one side of the shroud piece or blade, was specifically designed and fabricated. In the case of shroud repair, PWHT has to be carried out in-situ and excessive heating of the blades fixed to the shroud had to be avoided. Even in the case of the blade repair, it was required to confine the PWHT to the area of repair, though heat loss due to conduction through the blades cannot be avoided. Initially, direct heating of the repaired area with flame heating was considered and it was subsequently abandoned, as proper control of the temperature and heating rate was very difficult. In the case of the resistance-heating furnace, the heating is indirect, but accurate control of the heating rate and temperature was possible with the use of thermocouple and temperature controller. It was decided to use copper blocks with contours closely matching with that of the shroud/blade, to facilitate the heat transfer from the furnace to the weldment through copper block, and to use good insulation to prevent heat loss to outside environment. More constraint is present during the localised PWHT of the shroud than of the blade, which necessitated mock-up of PWHT on a simulated structure to ensure that PWHT can be carried out successfully. The heating rate to achieve the PWHT temperature of 873 K was carefully monitored and controlled so that the same can be employed in the actual repair weld.

4. Repair welding

The first task for executing the actual repair is the removal of the existing crack by careful grinding. In the case of the shrouds, many cracks were observed to have initiated from the tenon holes. Hence, the blade tenons were partly ground off to expose the crack completely. The blade tenons were then subsequently built-up to their original shape by re-welding and machining. After removal of the crack, Dye Penentrant Testing, (DPT), was carried out to ensure complete removal of the crack. Subsequently, using fine grinding tools, a weld groove with a groove angle of about 70° was prepared for weld deposition.

In the case of stage-IV LP blades, the cracks were very tight (Fig. 1b) and could be revealed only by the Wet Florescent Magnetic Particle Test, (WFMPT). Often these cracks initiated from the inner surface of the lacing hole and hence, to remove them, it was necessary to start grinding from the blade surface, where no crack was visible, and proceed in the thickness direction of the blade till the crack was reached. WFMPT was carried out at different stages of the grinding to ensure complete removal of the crack. Subsequently a smooth welding groove with groove angle of about 70° was prepared for weld deposition.

After ensuring that the edge preparation is complete in all respect, repair welding was taken up. The welding parameters employed were same as that used during the procedure qualification. In the case of shroud repair, it was often required to rotate the turbine so that welding could be carried out in the down-hand, (1G), position, as per the qualified procedure. After repair welding, DPT was carried out to ensure that no crack is present. Figure 4 shows the photographs of one of the cracked shrouds, before and after repair welding.

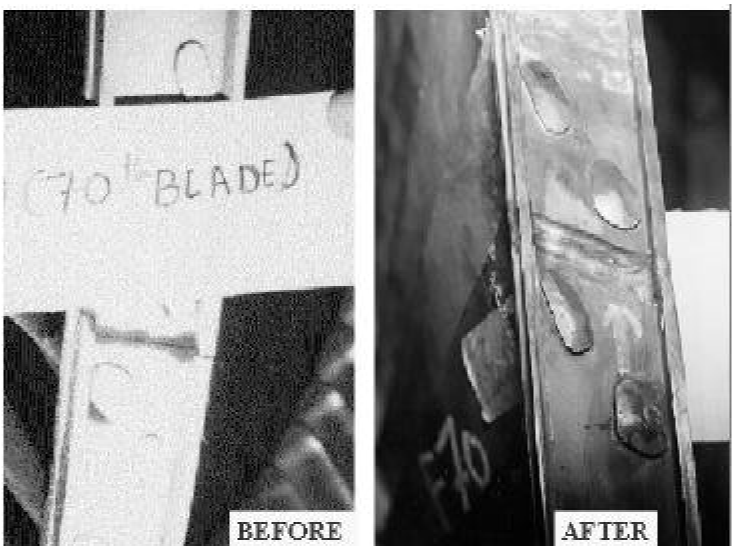


Fig. 4: *A cracked stage-III LP turbine shroud, before and after repair welding*

5. Post weld heat treatment

As already mentioned, in-situ PWHT of a repair-weldment requires a small electric resistance furnace, which transfers heat from one side with maximum heat transfer from the heating elements to the location of the weldment through copper block on the shroud and minimum heat loss to the environment. In the case of shrouds, a copper block with its bottom surface contour closely matching the top of the shrouds and the tenons projecting out of the tenon holes, and its top surface contour matching that of the furnace was used to facilitate the heat transfer to the weldment. Good insulation all around the heater and the location of the heat treatment were employed to minimise heat loss to the atmosphere. A schematic of the heat treatment set-up employed for localised in-situ PWHT is shown in Fig. 5(a), and a typical on-site heat treatment cycle used is shown in Fig. 5(b). A similar set-up was used for PWHT of the repair welds of the blades. As the repair weld was in a relatively flat portion of the blade, it was possible to remove the blade from the turbine for repair, and thus both repair welding and PWHT was much easily executed for the blades than for the shrouds.

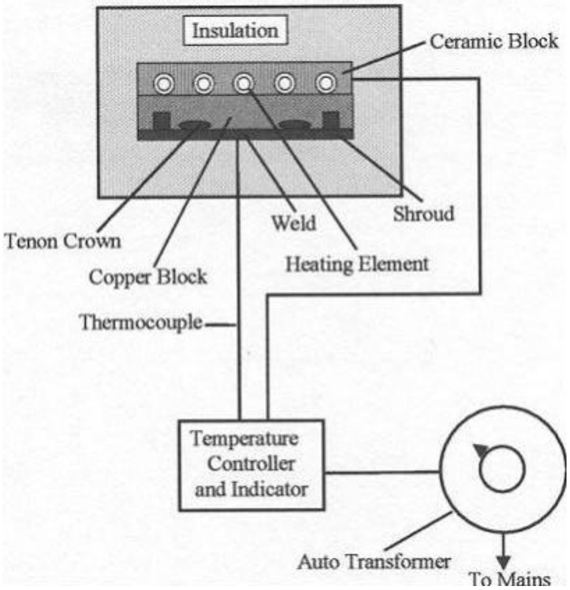


Fig. 5(a): *Schematic of the heat treatment set up used for localised in-situ PWHT of a shroud repair weld*

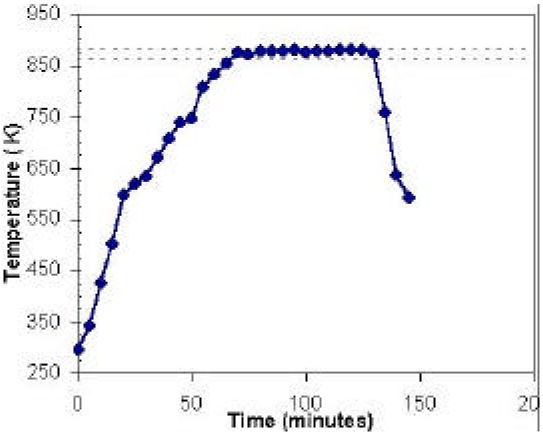


Fig. 5(b): *A typical heat treatment cycle employed during onsite localised PWHT of a repair weld*

6. In-situ metallography

In order to ensure that adequate tempering has taken place in the HAZ of the shroud and blade material, it was necessary to examine the microstructure of the repair weld after PWHT by in situ metallography. The microstructure of the weld metal, (etched using Vilella's reagent), and of weld/base metal interface, (electrolytically etched using 10% ammonium persulphate solution), for the repair weld in a cracked shroud and a cracked blade material are shown in Figs. 6 and 7, respectively. In both cases, the microstructure of the HAZ clearly shows a tempered martensitic structure, while the weld metal structure, as expected, reveals a solidified microstructure. No defects, like micro-fissures, were observed in the weld metal.

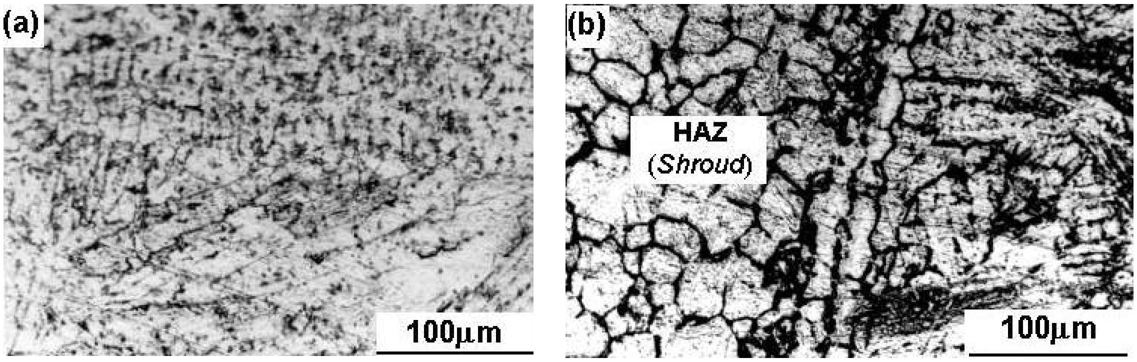


Fig. 6: *In-situ metallography microstructure of: (a) 316L weld metal and (b) weld/base metal interface after PWHT of a repair weld in a cracked turbine shroud*

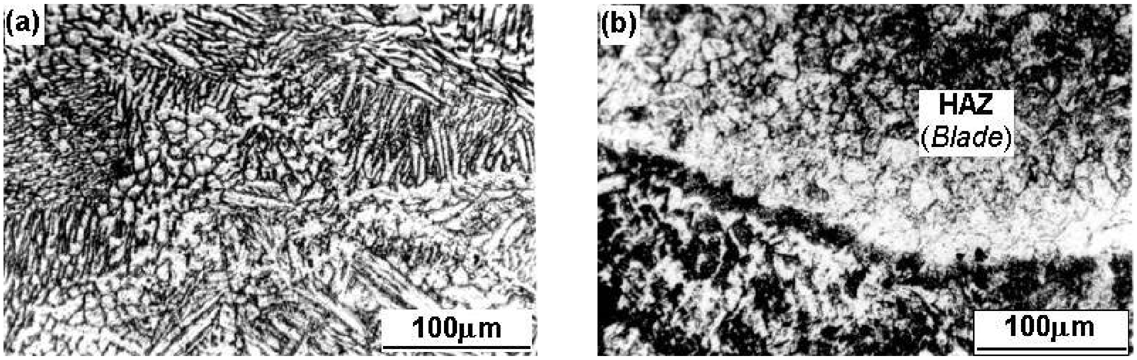


Fig. 7: *In-situ metallography microstructure of: (a) 316L weld metal and (b) weld/base metal interface after PWHT of a repair weld in a cracked turbine blade*

7. Laboratory investigation of the shroud weld

As mentioned earlier, the repair welding procedure was qualified using AISI 410 SS pipe material and not on actual shroud or blade material. Hence, microstructural examinations and hardness measurements on the actual shroud welds in the as-welded and PWHT conditions could not be carried out during the procedure development stage. Further, during actual repair welding, it was not possible to measure the hardness of the HAZ of the repair welds. However, confidence with respect to success of the repair welding procedure would be significantly better with the availability of HAZ hardness data in the as-welded and PWHT conditions on the actual shroud/blade material. During one of the repair welding operations, an actual shroud piece was made available for carrying out welding and subsequent laboratory investigations. A weld pad was prepared using this shroud piece employing the same welding parameters that were employed for the actual repair. One part of this welded test-piece was retained in the as-welded condition, while the other part was subjected to PWHT similar to that employed during the actual repair welding, and microstructural examination and hardness measurement were carried out on these two test-pieces. Figure 8 shows the microstructures of the HAZ in the as-welded and PWHT conditions. The microstructure of the HAZ in the as-welded condition (Fig. 8a) consists of fully untempered martensite, while that after PWHT (Fig. 8b) shows substantial tempering of the martensite with its microstructure being similar to that observed in the in-situ metallographs of the actual repair-welded shroud (Fig. 6). The microhardness profile across the weld/base metal interface before and after PWHT (Fig. 9) shows that the hardness of the HAZ decreases from above 450 VHN in the as-welded condition to about 300 VHN after the 873 K/1 h PWHT, thereby confirming the adequacy of the PWHT carried out on the repair-welded shroud.

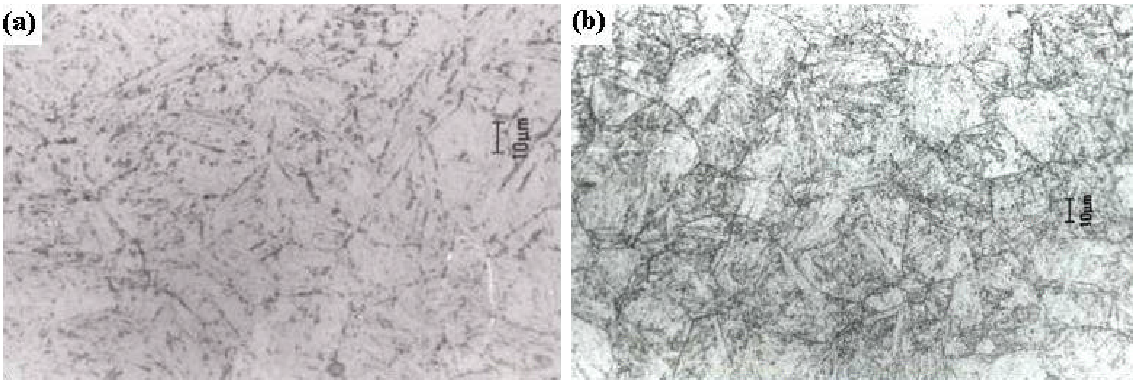


Fig. 8: *Microstructures of the HAZ in the actual shroud material examined in the laboratory: (a) in as-welded condition and (b) after 873 K/ 1 h PWHT*

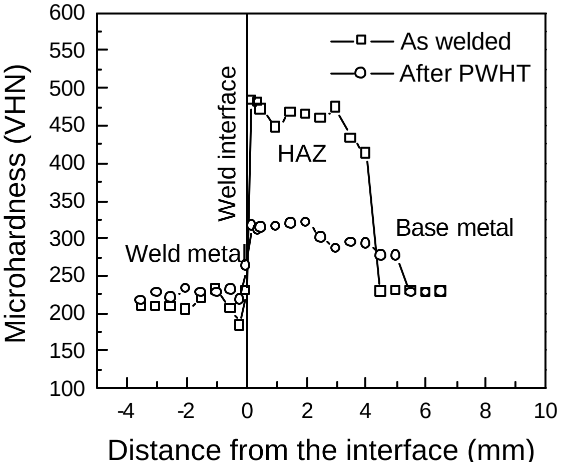


Fig. 9: *Microhardness profile across the weld/base metal interface in the actual shroud material: (a) in as-welded condition and (b) after 873 K/ 1 h PWHT*

8. Performance of repair welds in service

Repair welding, as described above, was carried out in five different turbines at three different NPCIL power plants during the period of 1998-2000. These turbines with repaired components were put back in to service after the repairs and have been performing satisfactorily since then. During routine maintenance shut down of the one of these turbines after two year, it was found that all the blades, which were repaired during the previous shut down, were still intact. In-situ metallography of all the repair-welded blades after two years of successful operation confirmed the good health of these blades. Comparison of the microstructure of one such repair-welded region of a blade after two years in service, (Fig. 10), with that before service, (Fig. 7), indicates no microstructural degradation during service.

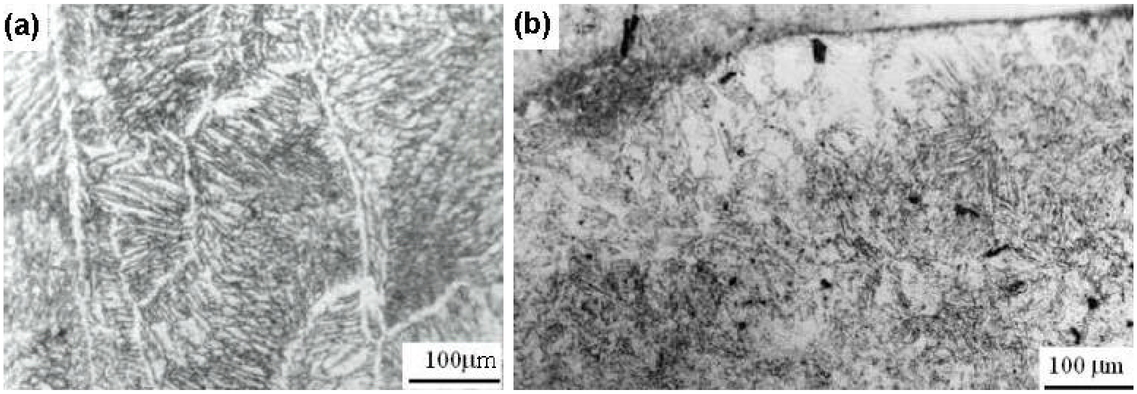


Fig. 10: *In-situ metallography microstructures of the repair-welded region of a turbine blade after two years in service: (a) 316L weld metal and (b) weld/base metal interface*

9. Summary and scope for future work

Satisfactory in-service performance of the repair-welded components for periods exceeding two years has proven that repair of the cracks in turbine components can be successfully carried out using welding and subsequent localised PWHT. However, innovative techniques have to be employed to carry out in-situ repair welding and PWHT and the whole operation should be executed with utmost care and control. The power utilities can make substantial saving by reducing both the down time of the plant and minimizing the replacement cost of the components.

Although the causes for the frequent cracking of the steam turbine shrouds and blades have not been analysed systematically, it has been observed that the cracks often originated from the tenon holes in the shrouds or lacing holes in the blades, (Fig. 1), without any indication of gross plastic deformation near the crack. In addition, minor variations in the grid frequency from 50 Hz can significantly increase the vibration levels during operation of the turbine. These suggest that the cracking could have been caused due to high cycle fatigue. Hence, it is important to study the performance of the repair-welded joints as also of the shroud/blade material under high-cycle fatigue conditions in order to increase the level of confidence of the repair-welding procedure adopted.

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