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In Situ Repair Welding of Steam Turbine Shroud for Replacing a Cracked Blade

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A root-cracked blade in a high-pressure steam turbine of a nuclear power plant had to be replaced with a new blade by cutting the shroud to remove the cracked blade. This necessitated in situ welding of a new shroud piece with the existing shroud after the blade replacement. The in situ welding of the shroud, a 12%Cr martensitic stainless steel with tempered martensite microstructure, was carried out using gas-tungsten arc welding and 316L austenitic stainless steel filler metal followed by localized postweld heat treatment at 873 K for 1 h using a specially designed electrical resistance-heating furnace. Mock-up trials were carried out to ensure that sound welds could be made under the constraints present during the in situ repair welding operation. In situ metallography of the repair weld after postweld heat treatment confirmed the adequate tempering of the martensitic structure in the heat-affected zone. Metallurgical investigations carried out in the laboratory on a shroud test-piece that had been welded using the same procedure as employed in the field confirmed the success of the in situ repair operation. The alternate option available was replacing the cracked blade and the shroud piece to which it is riveted with a new one, reducing the height of all the blades attached to the shroud by machining, riveting the blades with reduced height to the new shroud, and, finally, dynamic balancing of the entire turbine after completion of the repair. This option is both time-consuming and expensive. Hence, the successful completion of this repair welding resulted in enormous savings both in terms of reducing the downtime of the plant and the cost of the repair. The turbine has been put back into service and has been operating satisfactorily since December 2000.

Keywords in situ welding, 12% martensitic stainless steel, shroud repair, steam turbine

1. Introduction

Steam turbine blades are critical components in power plants. These blades convert the linear motion of the high-temperature, high-pressure (HP) steam flowing down a pressure gradient into a rotary motion of the turbine shaft at about 3000 rotations per minute (rpm). Consequently, these blades are subjected to very high centrifugal and bending stresses during operation. In a steam turbine, the root of the blades are locked to the rotor while their free ends are held together by a shroud, by a lacing wire, or by a lacing rod, depending on the size of the blades and their position in the rotor. This reduces vibratory stresses of the blade during the rotation of the turbine. As the steam enters the turbine from the boiler, it passes through different stages such as HP to low-pressure (LP) zones. Reports available in the literature[1-3] show that the blades of the LP turbine are generally more susceptible to failure than those of the HP turbine.

Routine inspection of the turbines during an annual maintenance shutdown of a nuclear power plant revealed a crack in the root region of one of the closing blades in the III-stage of the HP turbine. The closing blade is the last blade inserted into the specially machined slot that is available in the rotor for a particular stage (in this case the third stage). This blade alone is connected to the rotor using three pins, and for the removal of any blade from the rotor, the closing blade should be taken out first. The crack appeared to have initiated from the middle hole provided for inserting the pin, and it extended to the surface. It was decided to replace the cracked blade with a new one. In the HP III-stage, the free ends of the blades have two tenons, and these are used to rivet the blades to the shrouds. Ten to twelve blades could be riveted to one shroud. Any attempt to remove the blade would necessarily damage the shroud to which it is riveted. Similarly, the removal of the shroud could be performed only after damaging the tenons of the blade that are riveted to the shroud. Thus, the option of replacing the cracked blade along with shroud to which the blade is riveted calls for the replacement of an entire bundle of blades that are attached to this shroud. An alternate option is to remachine the blade tenons, with a consequent reduction in the height of all the blades that are riveted to this particular shroud. The turbine manufacturer suggested the blade remachining option, as sufficient numbers of suitable blades were not readily available.[4] However, this option would be time-consuming and could result in a substantial delay in restarting the turbine. Furthermore, the blade remachining option could also adversely affect the performance of the turbine due to one set of blades having reduced blade height compared to the other blades in the same turbine stage. Hence, the decision was made to remove only the cracked blade by cutting a portion of the shroud just above it and to replace it with a new blade. The shroud piece, which was removed by cutting, should also be replaced and welded to the existing shroud after inserting the tenons of the new blade into the tenon holes in the new shroud piece. Finally, tenons of the new blade should be riveted to the welded shroud piece. This option involves actual joining of the

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Table 1 Chemical Composition (wt.%) of the Shroud for the III-Stage of the HP Turbine and 316L Filler Wire

Material	C	Cr	Ni	Mo	Mn	Si	P	S	Cu	V	Sn
Shroud	0.15	11.5	0.40	0.60	0.6	0.30	0.025	0.006	0.06	0.02	<0.004
ER316L	0.018	18.52	11.52	2.22	1.64	0.33	0.028	0.013	*	*	*

* Not analyzed

new shroud piece to the existing shroud by a welding process, and this has not been carried out earlier in any of the Nuclear Power Corporation of India Limited (NPCIL) units. Furthermore, the turbine manufacturer did not support the welding of the shroud pieces. Despite these conditions, the decision was made in view of the successful performance of shrouds, which had had cracks repaired by welding two years earlier during the previous shutdown of this plant.[5,6] It may be noted that many of the criteria, for example, urgency, cost of the alternative, the constraints present, and the need for a mock-up, which were discussed by Milin and Fields[7] with respect to the repair of large structures by welding, were found to be applicable in this case. This article discusses the details of the successful replacement of the root-cracked III-stage HP turbine blade by in situ repair welding of the shroud.

2. Choice of Welding Procedure

The chemical composition of the new shroud piece, a martensitic stainless steel conforming to AISI 410, is given in Table 1. From the plant records, it was confirmed that the composition of the old shroud material also conformed to AISI 410, although the exact composition was not available. During the welding of these steels, the heat-affected zone (HAZ) transforms to martensite, and if welding were carried out using consumables with matching composition, the microstructure of the weld metal would also be martensitic. As the toughness of the martensitic structure in the as-welded condition is poor, a postweld heat treatment (PWHT) is necessary to temper the martensitic structure and thus to improve the toughness of the weldment. Furthermore, as the martensitic structure of the weldment is susceptible to hydrogen-assisted cracking (HAC), preheating of martensitic stainless steel joints is the most widely accepted method to prevent HAC, especially when matching composition consumables are used during welding. The recommended PWHT temperature while using a matching composition consumable (ER410) for the welding of martensitic stainless steels is high (923 to 1023 K),[8] which may be difficult to attain during on-site localized heat treatment. In fact, PWHT carried out at 1008 K by localized heat treatment during on-site repair welding of a cracked turbine shroud using a matching composition consumable did not succeed initially due to the failure of heating elements.[9] To safely overcome the difficulty of attaining high temperatures during on-site localized PWHT after repair welding with a matching composition consumable, it was decided that an alternate procedure would be developed using an austenitic welding consumable. Furthermore, if austenitic stainless steel consumables and a welding process that does not use any flux are used, the preheating of the weldment can be safely avoided, provided that PWHT is carried out immediately after welding.

Hence, a repair welding procedure using a gas-tungsten arc welding (GTAW) process and an austenitic consumable was developed for repairing cracks in the shrouds and blades of steam turbines.[6,10] During the development of this procedure, three different austenitic filler wires, namely, ER316L, ER309L, and ERNiCr-3, were considered, and the mechanical properties of the weld joint, both in the as-welded condition and after PWHT, were evaluated. For qualification, the weld joints were prepared by joining AISI 410 pipe with an outer diameter 88.9 mm, a wall thickness of 3.2 mm, and a groove angle of 70°. Table 2 gives the tensile properties of the weldments made with the three different consumables. The weldment made with the E309L filler metal fractured in the base metal (except in one case), while the other two failed in the weld metal, showing lower ductility values. However, the weldment made with E309L filler metal failed during the bend test, while the weldments made with the other two filler metals passed the bend test without any cracking. The hardness profiles across the fusion boundary after 873 K/1 h PWHT for all the three weldments (Fig. 1) show that the hardness of the 309L weld metal is higher than that of the tempered 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 a highly alloyed martensite phase in the weld metal that remains untempered even during PWHT. The formation of this highly alloyed martensite is also responsible for the failure of the 309L joint in the bend test. In the case of the ERNiCr-3 joint, the weld metal hardness is much lower than that of the base metal. For the 316L joint, the weld metal hardness is also 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 the base metal. The results of tension tests (Table 2) show that the location of the fracture in 316L weldments shifted from the weld metal in the as-welded condition to the base metal after PWHT. The 873 K/1 h PWHT of the 316L joint also resulted in a significant improvement in ductility, which was accompanied by a decrease in its yield strength due to the tempering of the HAZ. Based on all these results, a welding procedure involving the use of ER316L filler wire and a PWHT of 873 K/1 h was chosen for the repair of shroud cracks,[6,10] the chemical compositions of which are given in Table 1. The shroud with cracks that were repair-welded using this procedure has been performing successfully in service for almost three years now, with in situ metallographs of the repair welds that were performed after two years of service (Fig. 2) confirming their good health. In view of the proven success of this welding procedure for repairing cracked shrouds, it was again chosen for the in situ welding of the shroud piece to the existing shroud that was necessary for replacing the cracked blade.

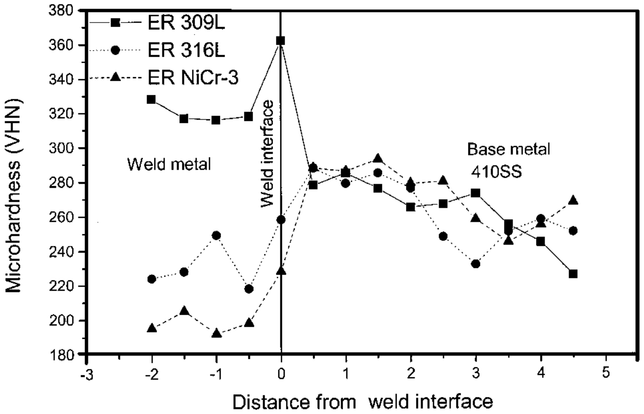

Fig. 1 Variation of hardness across the weld interface for the weldment made with three different austenitic filler wires after 873 K/1 h PWHT

Table 2 Transverse-Weld Tensile Properties of 410 SS Weldments Made Using Austenitic Consumables

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

3. Mock-Up Trials Before Repair

As the in situ welding of a new shroud piece to the existing shroud was being attempted for the first time (earlier, only cracks had been repair welded), a mock-up welding trial was carried out simulating the constraints that would be present during the in situ repair welding operation. From Fig. 3, which shows the portion of III-stage of the HP turbine after the removal of the cracked blade, it is evident that the blades on either side of the new, replaced blade could limit the access to the underside of the weld joint. Hence, a mock-up assembly was fabricated using 1 mm thick austenitic stainless steel sheets that had the contours of the inner and outer surfaces of the blades of III-stage of the HP turbine. These austenitic stainless steel sheets were then welded to two separate 3 mm thick austenitic stainless steel plates having the same width as that of the actual shroud. This assembly was prepared so that it closely simulated the actual arrangement of the III-stage HP turbine blades. Figure 4 shows a simple schematic representation of the mock-up assembly.

Using the mock-up assembly, it was demonstrated that it would be possible to access the underside of the weld joint for any necessary welding and also for the final grinding operation after welding. This access to the underside of the weld joint is essential to ensure that no defect is left unattended in the root of the weldment, which could subsequently act as a stress raiser and lead to its premature failure during operation. As the blades of the III-stage HP turbine are riveted to the shroud at an angle, it was necessary to carry out the welding operation at an angle parallel to the direction of the blade orientation to ensure that the blades were not directly exposed to the welding arc. The mock-up assembly was prepared taking even this condition into consideration. After suitable edge preparation, the mock-up welding of the 3 mm plates was carried out in the vertical down (1G) position. Next, the mock-up assembly was rotated by 90° (as this was the maximum rotation of the turbine possible during repair), the underside of the weld was fused to make it smooth, and the final grinding operation of the root region was executed. Inspection by liquid penetrant testing (LPT) of the mock-up welding assembly confirmed the successful welding by the welding technique adopted.

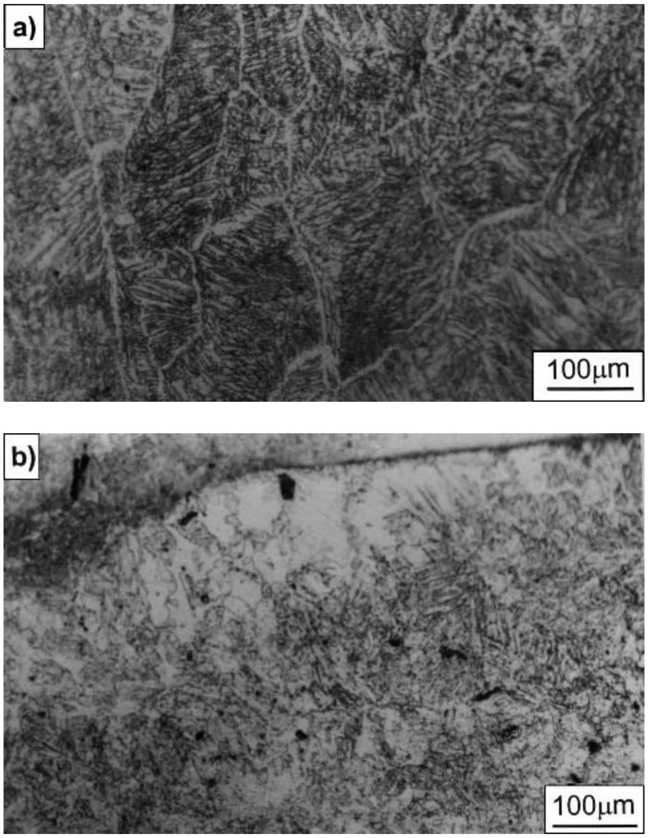

Fig. 2 In situ metallographs of the microstructures of the repair weldments after 2 years of service (repair executed in 1998): (**a**) fusion zone in a IV-stage LP-turbine blade; and (**b**) HAZ near the fusion line in a III-stage HP-turbine shroud

4. In Situ Repair Welding of the Turbine Shroud

4.1 Edge Preparation of the Old and New Shroud Pieces and Fit-Up

The in situ repair welding of the III-stage HP turbine shroud was taken up after the successful demonstration of the welding

Fig. 3 The III-stage HP turbine shroud after the cutting and removal of the cracked blade

procedure on the mock-up assembly. While cutting the shroud piece above the cracked blade, it was ensured that the cutting operation was carried out at an angle of about 45° to the plane of the shroud so that the adjacent blades were not damaged during the cutting and subsequent repair welding operations. Both of the cut edges of the original shroud were then prepared for welding by grinding them at an angle of about 35°. After edge preparation, LPT was carried out on the edges, and no defects were observed.

The new shroud piece in the as-received condition was a strip having a width and thickness the same as that of the original shroud. The ridges present on the topside of this shroud piece had a slightly different dimension from that of the original shroud shown in Fig. 3. Furthermore, it was also necessary that the shroud piece be bent so that it had the same curvature as that of the existing shroud. Hence, some machining and bending were required to match precisely the profiles of the new shroud piece with that of the existing one. The edges of the new shroud piece were then prepared by grinding them to an angle of about 35°, maintaining a root gap of about 2 mm between the old and the new shroud pieces. After the new blade was inserted into its slot in the turbine rotor, the positions and dimensions of the two tenon holes on the new shroud piece were precisely marked. The tenon holes on this new shroud piece were then made by drilling and machining, and they were inserted onto the tenons of the new blade to complete the fit-up for the repair welding.

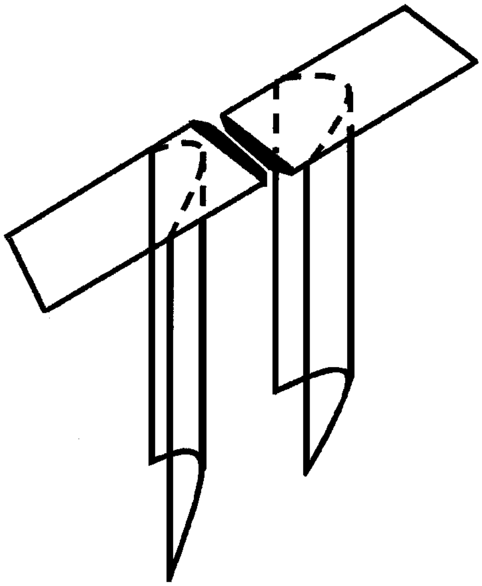

Fig. 4 Schematic representation of the mock-up assembly of the III-stage HP turbine blades and shroud piece

4.2 Repair Welding of the Turbine Shroud

During the welding operation, the new blade and the shroud piece were held in position but without riveting the tenons to the shroud piece. The welding was carried out in the vertical down (1G) position by the GTAW process, using ultra-high-purity argon as the shielding gas and ER 316L filler wires, and adopting the procedure developed and approved earlier,[5] and the technique was finalized using the mock-up assembly. As the new shroud piece had to be welded on either side to the existing shroud, and as these two weld joint locations were very close to each other, each layer of weld metal was deposited successively at both locations to minimize distortion during welding. The root (first) weld pass was deposited using a welding speed of ~1.5 mm/s. After depositing the first pass on both the joints, the misalignment between the existing shroud and the new shroud piece, due to the minor dimensional differences between them, were machined. Subsequently, three more weld passes were deposited in each weld joint using welding speeds of 2.0 and 1.0 mm/s, respectively, for the second and the remaining passes. A welding voltage and current of 10-12 V and 80-85 A, respectively, were employed for all the passes.

After the completion of welding from the topside, the turbine was rotated by 90° to access the underside of the joints in the horizontal position for grinding the weld root and a final dressing pass was made at the weld root. Subsequently, the root of the weld was made flush with the shroud by grinding. Finally, ridges were built up on the new shroud piece by weld depositions, which were then made flush with the

Fig. 5 The III-stage HP turbine shroud after in situ repair welding

existing shroud by grinding. After completion of the welding, the joints were subjected to inspection by LPT and were found to be free of defects. Figure 5 shows the shroud after the repair.

4.3 Localized PWHT of the Repair-Welded Turbine Shroud

The repair-welded joints of the turbine shroud were subjected to local PWHT at 873 K for 1 h soon after the completion of welding. The localized PWHT was carried out using a specially designed electrical resistance-heating furnace by which both of the weldments could be heat-treated simultaneously. This furnace was provided with an on-off controller and a solid-state relay capable of controlling the temperature with an accuracy of ±2 K, while the power supply was provided from an autotransformer for controlling the heating and cooling rates. The heat from the furnace was transferred to the weldments on the shroud through a copper block, which has a flat top surface (on which the heater is placed) and a curved bottom surface, with the dimensions and shape matching those of the shroud piece (on which it was seated during PWHT). The use of the copper block ensured good thermal contact with the shroud for efficient heat transfer during heat treatment. A K-type thermocouple was welded to the underside of the shroud, and its output was fed to the controller for both monitoring and controlling the PWHT temperature. A schematic diagram of the localized PWHT set-up is given in Fig. 6.

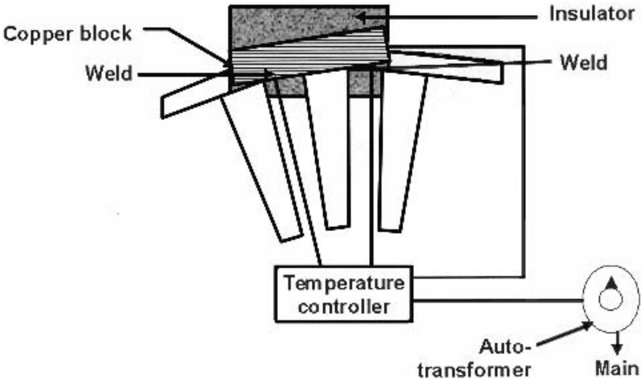

Fig. 6 Schematic diagram showing the set-up used for localized PWHT by electrical resistance heating

During the PWHT, the weldments were slowly heated to 873 K over 5 h, and after holding at this temperature for 1 h, the furnace was switched off and the weldments were allowed to slowly cool down to 573 K. Subsequently, the furnace was removed and the joint was allowed to cool in air. Heating was done slowly to minimize the chances for the failure of the heating elements by overheating and to improve the heat transfer from the elements to the weldments. Figure 7 shows the actual heating and cooling cycle achieved during the in situ PWHT of the repair-welded shroud, along with the heating and cooling cycle achieved during PWHT of the welded shroud material used in subsequent laboratory investigations.

4.4 Inspection of the Repair-Welded Joints

After successful PWHT, the LPT and wet florescent magnetic particle technique (WFMPT) were performed on the weldments, and no defect was found. WFMPT was also carried out after subsequent riveting of the tenons of the new blade to the new shroud piece (now welded to the original shroud). Finally, in situ metallography was carried out after PWHT, using a portable polishing unit, an etching unit, and a microscope, for which the martensitic stainless steel shroud material was etched with Vilella's reagent and the 316L austenitic stainless steel weld metal was electrolytically etched with 10% ammonium persulphate solution. The in situ metallography microstructure of the HAZ, shown in Fig. 8, indicated successful and adequate tempering of the martensite structure of HAZ during PWHT.

5. Laboratory Investigations on the Shroud Material

The repair-welding procedure was qualified using AISI 410 SS pipe material[6] and not actual shroud material, as the latter was not readily available during the development of the pro-

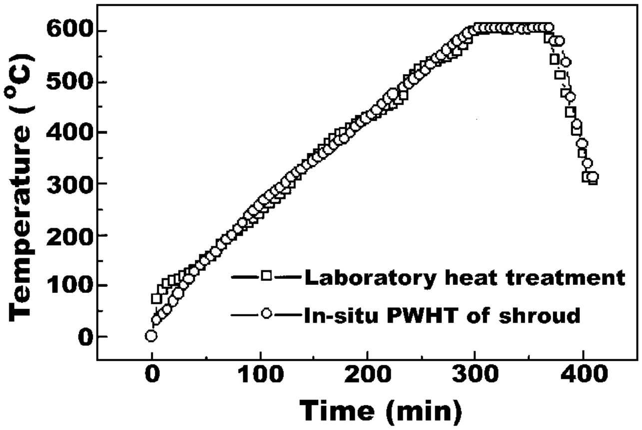

Fig. 7 Actual heating and cooling cycle achieved during localized PWHT of the repair-welded shroud at the site and in the laboratory

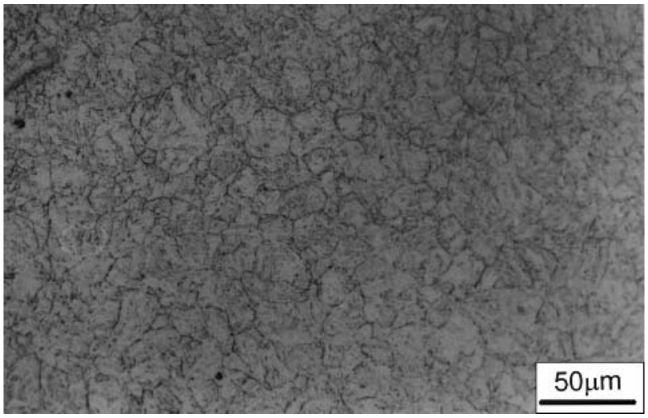

Fig. 8 In situ metallograph of the microstructure of the HAZ in the repair-welded shroud after localized PWHT at 873 K for 1 h

cedure. However, both the pipe and shroud materials conformed to the same specifications, and the procedure that was developed was successfully used for the repair welding of the cracked shrouds.[6] To enable a better comparison between the in situ metallographs of the actual repair welds and the metallographs of the laboratory welds, the same procedure employed for the actual repair welding was used to prepare a reference test-piece by welding two pieces of the actual shroud material. The welded test-piece was also subjected to inspection by LPT, as was the case with the actual shroud weldments. One part of the welded test-piece was retained in the as-welded condition, while the other part was subjected to PWHT that was similar to that employed during the actual repair welding, the heat treatment cycles of which are compared in Fig. 7. Microstructural examination and hardness measurement were carried out on the two test-pieces, comparing the as-welded and PWHT conditions. Figure 9 shows the microstructures of the HAZ in the as-welded condition and after PWHT. The microstructure of the HAZ in the as-welded condition (Fig. 9a) consists fully of untempered martensite, while the microstructure after PWHT (Fig. 9b) shows that substantial tempering of the martensite had taken place and that the microstructure was similar to that observed in the in situ metallographs of the actual repair-welded shroud (Fig. 8). The microhardness profile across the weldment before and after PWHT (Fig. 10) shows that the hardness of the HAZ decreased from >450 (VHN) Vickers Hardness Number in the as-welded condition to about 300 VHN after 873 K/1 h PWHT, thereby confirming the adequacy of the PWHT carried out on the repair-welded shroud.

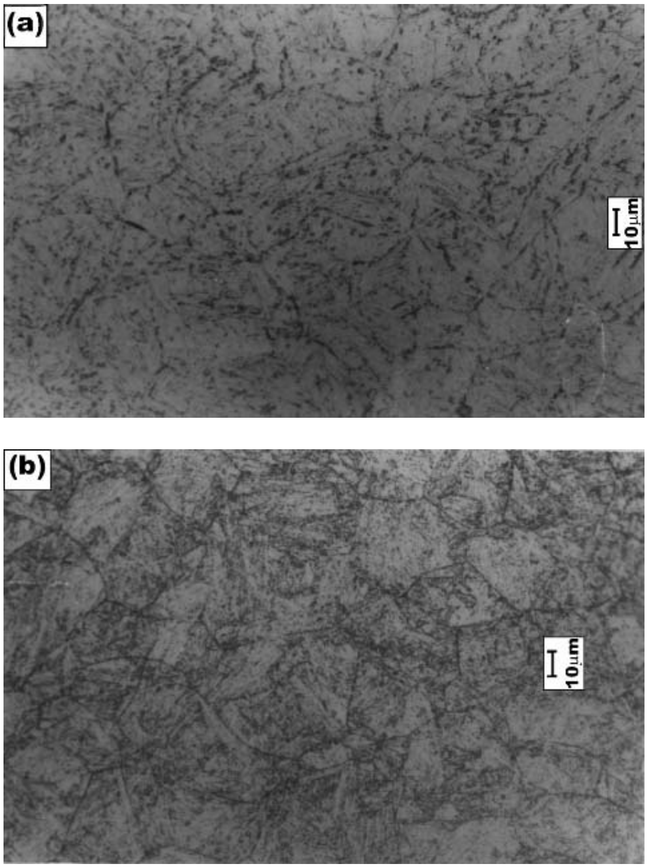

Fig. 9 Microstructures of HAZ of the welded III-stage HP turbine shroud material investigated in the laboratory **(a)** in the as-welded condition, and **(b)** after 873 K/1 h PWHT

6. Conclusions

1) In situ repair welding is a technically and economically viable solution for the replacement of cracked steam turbine blades, as the repair welding significantly reduces the down-time of the turbine and is accompanied by enormous savings because it avoids the replacement of the entire set of blades attached to a shroud segment. The repair-welded turbine has been operating satisfactorily since its repair in November 2000.
2) Inspection by LPT and WFMPT after PWHT confirmed the soundness of the repair-welded shroud weldments.
3) In situ metallography on the repair-welded shroud and the metallographs on the reference test-piece welded in the laboratory showed that the procedure for localized PWHT at 873 K for 1 hour that was adopted has been appropriate,

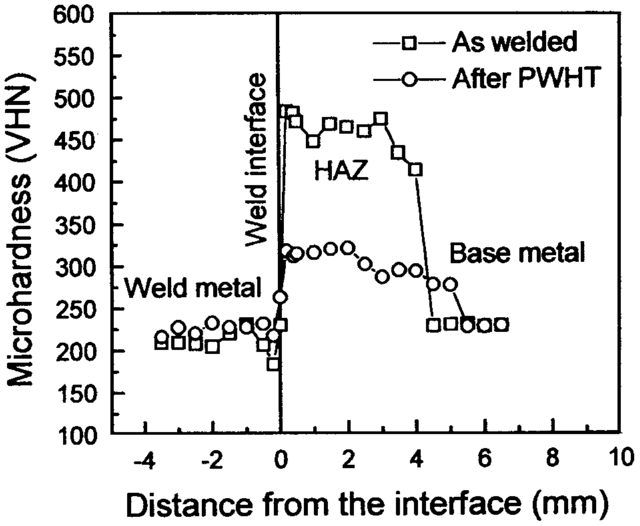

Fig. 10 Microhardness profiles across welded III-stage HP turbine shroud material before and after PWHT at 873 K for 1 h

as the microstructures of the HAZ after PWHT and the hardness distribution across the HAZ on PWHT confirmed the adequate tempering of the martensite in the martensitic HAZ.

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