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Recent trends in repair and refurbishing of steam turbine components

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Abstract. The repair and refurbishing of steam generator components is discussed from the perspective of repair welding philosophy including applicable codes and regulations. Some case histories of repair welding of steam generator components are discussed with special emphasis on details of repair welding of cracked steam turbine blades and shrouds in some of the commercial nuclear power plants using procedures developed.

Keywords. Repair welding; steam turbine components; repair philosophy; codes and regulations; case histories.

1. Introduction

Reliability of an engineering component requires that quality or *fitness-for-purpose* aspects be adequately addressed at various stages of its design and fabrication. Both economic and safety considerations influence the quality, and hence the reliability of a system. Economics dictate the competitiveness of the product, while safety requires the smooth functioning of the component without hazard to personnel and property. It is possible to build a highly reliable engineering system but it may not be economically competitive. On the other hand, if reliability is poor the component may violate safety standards. Therefore, features are specified to incorporate *fitness-for-service* attributes at the design stage. This means that each component should be (a) designed to meet the service requirements for the required life, (b) fabricated with specified materials, conforming to design concepts and inspection standards, and (c) operated and maintained properly. Despite incorporation of concepts of quality or fitness-for-service, engineering components are known to fail prematurely. In order to constantly monitor the health of a system and to avoid sudden and unexpected failure, advanced concepts of in-service inspection, prediction of remnant life and preventive maintenance of components are becoming increasingly important.

The term failure, as applied to engineering systems, can be described as non-performance of components or systems due to some deficiency that limits their service life. Failures are not uncommon in industry and can occur at any of the various stages such as fabrication, testing, transportation and service. Failures can be broadly classified as *end-of-life failures* that are predictable and for which proper preventive actions could be taken in advance, and *premature failures* that are unpredictable and occur without sufficient warning. The latter may lead to plant shutdown, loss in production and productivity, fire explosion, radiation or gas leak or in extreme cases may end up in catastrophes resulting in loss of life and/or damage to property and environment. These sudden failures may also adversely affect the morale of the workforce and their confidence in the safety of the system. Two such industrial accidents that led to heavy loss of life and damage to environment are the Bhopal gas leak and Chernobyl nuclear accident.

Welding is an important and reliable joining process; all joints introduce discontinuities and gradients and affect safe operation of components. It is for this reason that welds are considered weak links. A large number of failures in industry are either directly or indirectly attributed to welds. Moreover, a vast majority of repairs of failed components is carried out using one of the welding processes. Since repair of each failure requires a different strategy, codes and standards provide only general guidelines, and it is essential to consult a competent Welding Technology Group to carry out successful repairs.

Once a component fails, it is important to take "*time-critical*" decisions to put back the system in operation without much delay. One of the options is to replace the damaged or failed component. Often, this is a very expensive and time-consuming option. Repair rather than replacement can achieve substantial reduction in downtime and cost. Repair welding is one of the most common methods employed in industry to salvage defective, damaged or failed components. However, success of repair-welding operations depends on many factors such as weldability of the material, type of damage, availability of a suitable welding technique and welding consumable, possibility of carrying out preheating and post-weld heat treatment (PWHT), post-repair inspection by non-destructive testing (NDT) techniques etc. Occasionally, the welding process and/or welding consumable for repair may be different from those used for the original fabrication. A typical example is the repair of a submerged arc weld using the shielded metal arc welding process. Care should be taken that the differences in the heat input employed and the composition of the welding consumables do not introduce defects during repair. Weld repair of components failed in service is more complex than repair carried out to remove defects noticed during fabrication. Proper analysis of the failure should be carried out before attempting a repair. Failure might have occurred because of faults in design, fabrication or manufacturing, wrong selection of material or operational mistakes. Unless the real cause of the failure is identified and removed, the repair might prove to be only a temporary solution.

Depending on the specific application any of the common welding processes like shielded metal arc welding (SMAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), submerged arc welding (SAW) etc. may be used. For very high quality welds, the GTAW process finds the widest application. SAW and GMAW may be advantageous for long weld runs or when large amount of weld metal has to be deposited, and where mechanisation is feasible. The GMAW process is chosen for remote repairs carried out with robots due to amenability to automation. This is of special importance to repair welding in nuclear rectors where high radiation levels often restrict human access to the repair site. For general-purpose repairs, the SMAW process enjoys a dominant position for out-of-position welding and short weld runs, especially when time is critical and portable equipment is available.

When one thinks about welding repairs, the first reaction is to deal with the type of repair, in other words, to concentrate on welding engineering aspects which need to be fixed and checked. This reaction is understandable, but is usually wrong. One has to differentiate between manufacturing-related and operation-related failures. With manufacturing-related failures one always has the design plan to refer back to as a benchmark, and these failures are usually due to inadmissible pores or slag inclusions, misalignment, forced ruptures, relaxation cracks, hydrogen-induced cracking, lamellar tearing etc. On the other hand, with operation-related failures, solution by change in the design is usually not possible as this type of failure is not normally linked to welding, but is caused by wear, corrosion, cavitation etc. There are varying repair strategies that can be adopted depending on the type of defect and its possible cause (Gnirss 1992).

2. Repair philosophy

There are certain guidelines and rules available for repair of large components and structures (Malin & Fields 1992).

(1) Repair of a large component is typically of an urgent and critical nature since the failure of the component may have a devastating effect on industrial or financial activity, jeopardise human safety, and have serious economic impact.
(2) In most cases, the only alternative to repair is the replacement of a substantial portion of the component or even the entire component. This is usually associated with considerable replacement cost, prolonged schedule disruption and, therefore, considerable financial burden.
(3) Repair is typically required to be performed in the field under unfavourable conditions in a very compressed time frame, which demands much subjective on-the-spot human intervention (in contrast to fabrication of a new component).
(4) Many large components can only be repaired once without facing the risk of significant damage to the component.

Repair welding, in actual implementation, involves three basic stages: analysis, development and performance. Analysis may include the determination of the possible cause of failure and the assessment of a stress situation in the area to be repaired. The development stage may include an evaluation of the component design and the amenability of that design for repair welding and development of repair approach, as also the main requirements and detailed specification for assembling, welding and inspection. The performance stage includes all repair activities at a shop and/or in the field.

The objective of repair welding is to extend the service life of failed components. In practice, there are two typical approaches to meeting this objective, *research-oriented* and *repair-oriented*. In the former, the main emphasis is on failure and/or stress analysis, which sometimes accounts for a disproportionately large portion of the repair budget. Study of the probable cause of failure turns into extensive failure and metallurgical analyses, and the determination of stresses in a failed area can become an elaborate stress analysis exercise. Unfortunately, the data obtained will rarely find their way into a repair approach or a welding procedure. There is, however, a danger in the process as the focus of such analysis, viz. to provide support for repairs, may be lost. Considering the high cost and time of such an analysis, the main objective should be to generate adequate input data to support the development of a comprehensive and realistic approach and welding procedure.

In contrast, the repair-oriented approach is more typical of fabrication and repair shops. The main emphasis here is on the performance stage of repair, while the analysis stage is (almost) neglected. Unfortunately, in both approaches the developmental stage and thus the welding engineering aspects of a repair are not given adequate attention. A *Welding Technology Group* is an important link between a research organisation, which lacks performance expertise, and a fabricator relying only on the collective experience of the shop personnel. In fact, industrial practice shows that the probability of successful repair depends mainly on how closely the analysis and performance stages of repair are linked together by welding engineering developmental efforts.

The approach that proved to be most efficient and successful in repair welding of large components is a *balanced approach* (Malin & Fields 1992) in which:

(a) the scope and nature of analysis is dictated by the requirements of repair welding;
(b) the Welding Technology Group is in the centre of the developmental effort; and
(c) the performance stage of repair is carried out, under the supervision of the Welding Technology Group, strictly according to a detailed welding procedure with no room for improvisation by shop personnel.

A very similar approach was used for repair welding of cracked steam turbine components in some of the commercial nuclear power plants in India using in-house developed procedures (Albert *et al* 1999, 2002; Gill *et al* 2000; Rodriguez *et al* 2000; Bhaduri *et al* 2001) – a resume of which is given in a later section of the paper. Before that, it is appropriate that we consider the role of repair welding in the repair and refurbishing of steam turbine components.

3. Codes and regulations on repair welding

Among the various codes and regulations that have been used to lay down guidelines and procedures for repair welding, those from the US Nuclear Regulatory Commission are the most comprehensive and adopt a *defence-in depth philosophy* (Hermann 1991). For steam turbines and other power plant components, in these codes, conservatism in design and material selection, stringent quality assurance, non-destructive examination during component fabrication, and hydrostatic pressure testing are required. Inspection, repair or replacement, assessment of structural integrity and pressure testing of components for power plants are required under an alternate set of rules. For example, in Section XI of the ASME Pressure Vessels and Piping Code, Article IWA-4000 is devoted to “Repair and Replacement” (ASME 1989; Hedden & McDonald 1991; Mathews 1991). For similar materials, repair of specific base materials and associated weld may be made without post-weld heat treatment (PWHT). For repair welding by the shielded metal arc welding (SMAW) or automatic gas tungsten arc welding (GTAW) process, the temper-bead weld repair procedures as given in figures 1 and 2 respectively, can be adopted. Similar weld repair procedures can be adopted for repairs of specific dissimilar material combinations as well (ASME 1989). Similarly, ANSI/AWS has specifications for modification and repair of welds and base metal defects, e.g. the “Specification for Welding of Rotating Elements of Equipment” (AWS 1981).

4. Some case histories of repair welding

4.1 *Weld build-up repair of turbine rotors*

Through careful development and testing, it is possible to use the process of weld overlays for weld build-up repair of turbine rotors (Morin *et al* 1991). Thus many rotors that would have been condemned or derated just a few years ago, can today be restored to full operating potential. Though any of the popular welding processes is in principle suited for build-up

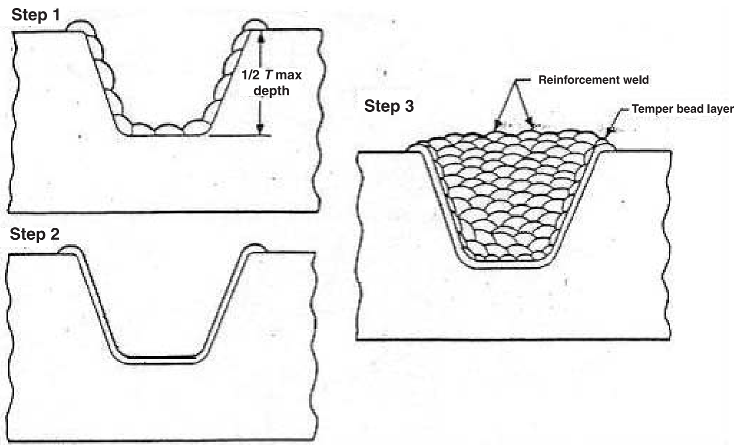

Figure 1. Temper-bead weld repair and weld temper-bead reinforcement by the SMAW process. (Step 1: Butter cavity with one layer of weld metal with a 2·5 mm diameter coated electrode. Step 2: Remove the weld crown of the first layer by grinding or machining. Step 3: The second layer is deposited with a 3·15 mm diameter electrode, and the subsequent layers with welding electrodes no larger than 4 mm diameter.)

welding, the submerged arc welding (SAW) process is the most recommended because of its high deposition rates and trouble-free execution. When a proper combination of SAW wire and flux is selected and used in conjunction with appropriate welding parameters and PWHT, the resulting weld metal properties, including creep notch sensitivity, can be nearly identical to their wrought steel counterparts.

In a case where a low-pressure (LP) rotor of a CrMoV steel was successfully repaired using the SAW process (Morin *et al* 1991), an intermediate layer of 5%CrMoV weld metal was initially deposited to inhibit carbon diffusion and to give a gradual variation in coefficient of thermal expansion. The balance of the weld metal was of 12%CrMoV weld material. With the

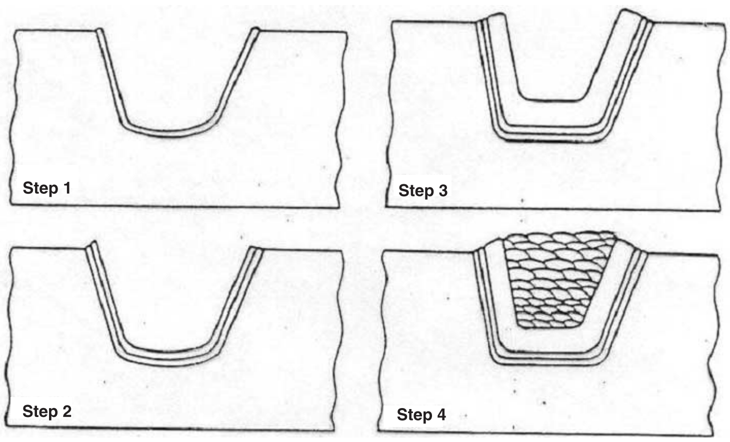

Figure 2. Automatic or machine (GTAW) temper-bead weld repair. (Step 1: Deposit layer one with first layer weld parameters used in qualifications. Step 2: Deposit layer two with second layer weld parameters used in qualifications. Step 3: Deposit next four layers with layer three through six weld parameters used in qualifications. Step 4: Subsequent layers to be deposited as qualified.)

resulting deposit the same creep rupture strength in the weld build-up deposit was achieved as in the original CrMoV material, in addition to substantial corrosion resistance and reduced susceptibility to stress corrosion cracking. The tensile strength could also be adjusted over a wide range by varying the heat treatment.

In another case, weld repair on the blade attachment of a high-pressure (HP) impulse wheel was accomplished (Morin *et al* 1991) using a similar procedure as in the preceding case. Here 12%CrMoV was selected to achieve adequate high-temperature creep resistance as well as high high-temperature strength. As before, an intermediate layer of 5%CrMoV was applied to the base metal in the area to be repair-welded, and then the 12%CrMoV was applied to cover the 5%CrMoV. Gas turbine rotors that had a damage resulting from corrosion or mechanical impact were also repaired in this way (Morin *et al* 1991).

4.2 *Repair welding of cast steel casings*

Cracks in the steam inlets of turbine casings made of CrMoV cast steel were successfully repair-welded using austenitic filler metals (Geissler 1992). Preheating at 423 K was required when nickel-base ENiCr19Nb austenitic filler metal was used, while preheating was dispensed with when iron-base 0.10%C–16Cr–25Ni–6Mo filler metal was used. The turbine operated satisfactorily after the repair.

Cracks in the casing of a pump turbine made of DIN 14315 standard cast material number 1·0553 was also successfully repaired (Geissler 1992) using build-up welding under inductive preheating at 423 K using E515 B11020 (H) electrodes. This filler metal was selected on the basis of its good toughness values. As a substitute for PWHT, which was not possible at site, three additional annealing passes were applied to the completely build-up weld which were later ground away. The pump turbine was in operation for more than 15 years after it was repaired.

5. Repair welding of steam turbine components in nuclear power plants

A steam turbine is the one of the most critical components in a power plant. As steam expands through the turbine, its condition changes, requiring a spectrum of different blades between the turbine inlet and exhaust. In this regard, the LP steam turbines are the most interesting with the materials used belonging to the following alloy classes: Martensitic stainless steel (SS), precipitation-hardened (PH) SS, duplex SS and titanium alloys (e.g. Ti–6Al–4V). The most popular alloy used for the blades is the 12Cr–1Mo–V martensitic SS (Artens *et al* 1984). The failure statistics of blade-related turbine outages based on an Electrical Power Research Institute (EPRI) of USA survey of power utilities between the years 1971 and 1981 (Dewey & McCloskey 1983; Artens *et al* 1984; Dewey & Rieger 1982, 1983) is shown in figure 3. The estimated cost of 207 of these turbine outages in terms of the lost power production is shown in figure 4, and it averaged $140 million annually during 1970 to 1981, or approximately $3·6 million for an “averaged” utility experiencing turbine problems (Artens *et al* 1984). The location of the turbine blades causing problems is given in figure 5, which shows that there are problems associated with the first stages of the HP and the intermediate-pressure (IP) turbines and the last stages of the LP turbines. The LP turbine blade failure locations (figure 6) can be summarised as 46% occurring in the shroud and damping element, 40% in the airfoil region and 14% in the blade attachment area. The mechanisms reported to have caused the turbine blade failures are shown in figure 7. This shows that over 50% of the incidents are

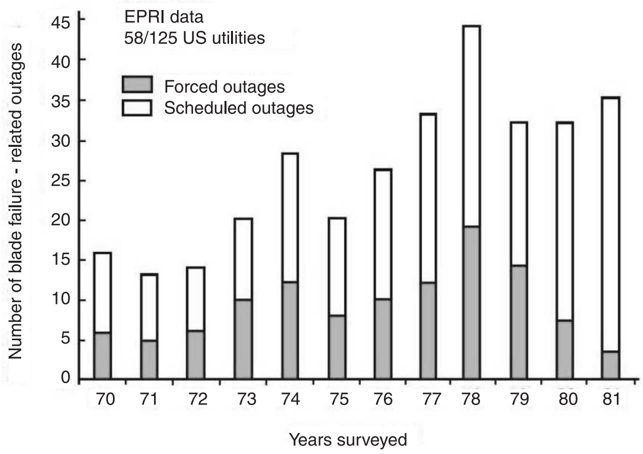

Figure 3. The annual number of forced and scheduled outages related to turbine blade failures reported by 58 power utilities (Artens *et al* 1984).

related to corrosion or fatigue, which include stress-corrosion cracking, high-cycle fatigue, corrosion-fatigue cracking, low-cycle fatigue and corrosion.

Weld repairs were carried out on some of the steam turbines of a few commercial nuclear power plants in India using in-house developed repair-welding procedures (Albert *et al* 1999, 2002; Gill *et al* 2000; Rodriguez *et al* 2000; Bhaduri *et al* 2001). The important steps and considerations for successful repair strategies include: (a) selection of filler metal and welding parameters; (b) type of weld preparation; (c) preheating conditions; (d) PWHT temperatures; (e) non-destructive testing; and (f) residual stresses.

Procedures for repair welding of cracked turbine shrouds and blades made of material similar to AISI 410 martensitic SS have been developed using the GTAW process. Weld-repair procedures were developed using ER316L (austenitic SS) and ER410 (martensitic SS) filler metals for both shrouds and blades. The repair welding procedure with the austenitic SS filler metal was developed to avoid preheating of the shroud or blade as also hydrogen-induced cold

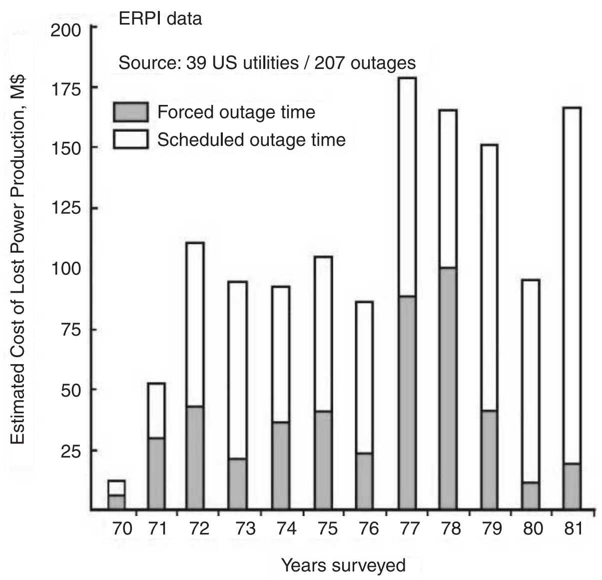

Figure 4. Estimated cost of lost power production in 39 power utilities covering 207 turbine outages (Artens *et al* 1984; Dewey & Rieger 1982; Dewey & McCloskey 1983).

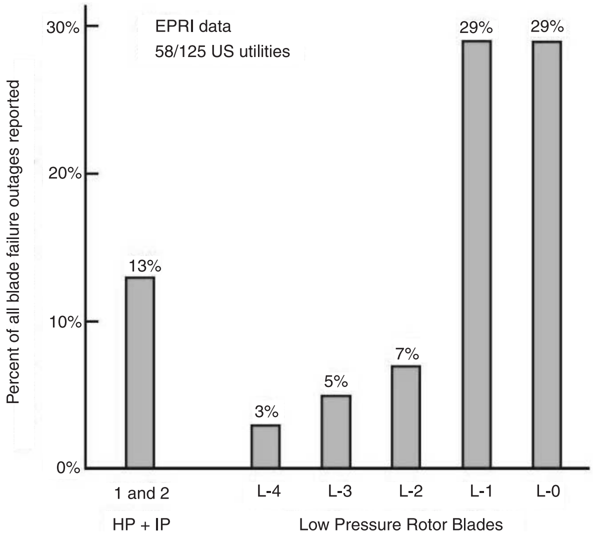

Figure 5. Location with respect to blade row of the turbine blade related outages in 58 power utilities (Artens *et al* 1984).

cracking, and involved evaluation of three different austenitic filler metals, namely ER309L, E316L and ERNiCr-3 (Inconel 82). The overall development of the repair welding procedures included selection of welding consumable (for austenitic filler metal), optimisation of PWHT parameters, selection of suitable method for localised preheating and PWHT, determination of mechanical properties of the weldments in the as-welded and PWHT conditions, and microstructural examination. After various trials using different procedures, the procedure for localised PWHT (and preheating, when using ER410 filler metal) by electrical resistance heating on the top surface of the weldment and monitoring the temperature by placing a thermocouple at the bottom of the weld (figure 8), was found to give the most satisfactory results as exemplified by the on-site record of time-temperature measurements given in figure 9. Mechanical testing of the laboratory weldments before and after PWHT involved tensile tests at ambient temperature, face and root-bend tests and microhardness measurements across the fusion line and heat-affected zone (HAZ). During procedure qualifications, mock-up trials

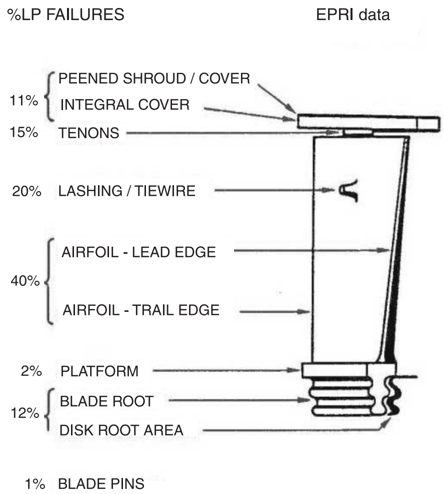

Figure 6. Location of LP turbine blade failures (Dewey & Rieger 1982; Dewey & McCloskey 1983; Dewey & Rieger 1983; Artens *et al* 1984).

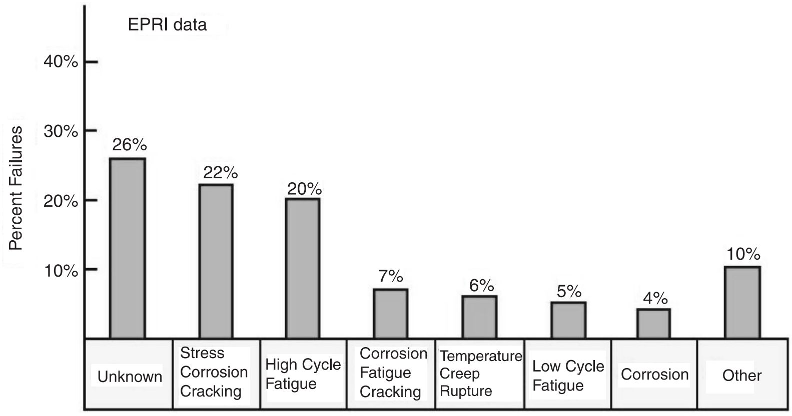

Figure 7. Mechanisms reported to have caused the turbine blade failures (Dewey & Rieger 1982; Dewey & McCloskey 1983; Dewey & Rieger 1983; Artens *et al* 1984).

and actual repair-welding, liquid-penetrant testing (LPT) was used at different stages, and radiography was carried out wherever possible.

These procedures have so far been successfully used in some of the commercial nuclear power plants for repair welding of 6 cracked shrouds in the III-stage of LP turbines, 3 cracked shrouds in the III-stage of HP turbines, 6 cracked blades in the IV-stage of LP turbines, and for re-welding of the shroud after replacement of a root-cracked blade in the III-stage of a HP turbine. All these repairs were carried out using ER316L austenitic SS filler metal, except for one of the cracks in the III-stage of a HP turbine that was carried out using ER410 martensitic SS filler metal. Photographs during LPT of the shroud crack in the III-stage of an LP turbine before repair and after successful repair welding using ER316L filler metal are shown in figures 10a and b respectively. Figures 11a and b respectively, show the photographs of the shroud in the III-stage of a HP turbine after cutting and removal of the root-cracked

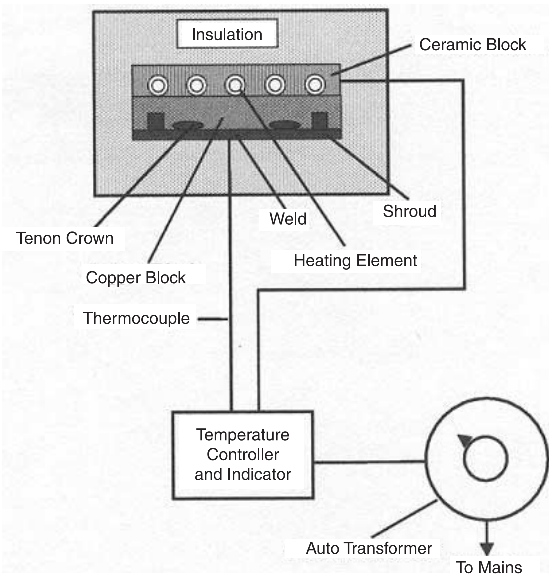

Figure 8. Schematic of set-up for localised preheating and PWHT by electrical resistance heating used during repair welding of cracked turbine shrouds.

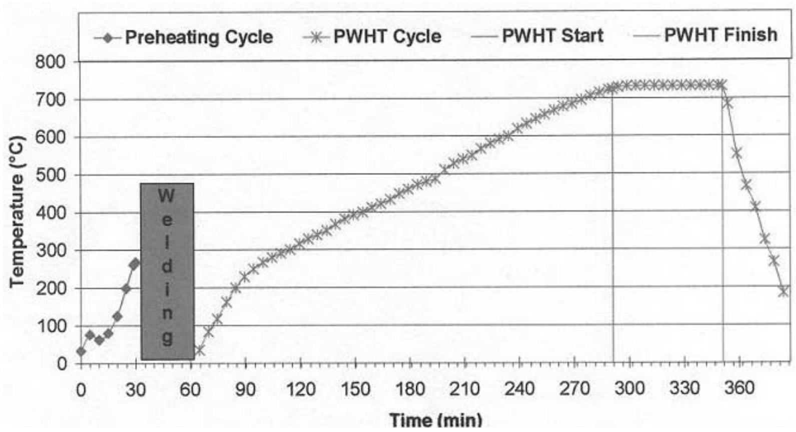

Figure 9. Record of time-temperature measurements during preheating at 523 K (250°C) and PWHT at 1008 K (735°C) for 1 h that was used during on-site repair welding of a cracked HP-III shroud using ER410 filler metal.

blade and after successful *in-situ* re-welding, using ER316L filler metal, subsequent to blade replacement.

To check and document the microstructural features of repair welds, *in-situ* metallography was performed on the mock-up weldments as well as on the repair welds of the shroud and blade cracks. The photomicrographs of the HAZ and weld metal after 873 K/1 h PWHT in the mock-up weldment, made using ER316L filler metal, are shown in figures 12a and b respectively. Figures 13a–b and 14a–b respectively show the typical microstructural features in the HAZ and weld metal after 873 K/1 h PWHT in the repair weldments, made using ER316L filler metal, of a shroud crack in the III-stage and of a blade crack in the IV-stage of LP turbines. Comparison of figure 12 with figures 13 and 14 show that the typical microstructural features after 873 K/1 h PWHT observed in the mock-up weldment are similar to those

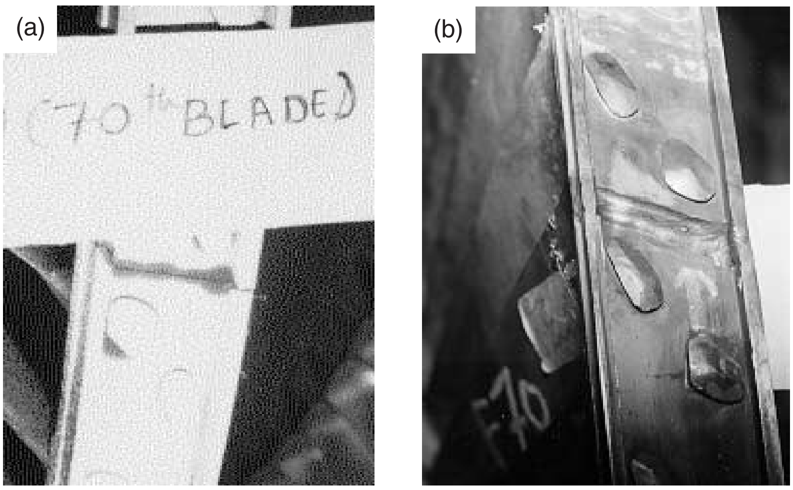

Figure 10. Photographs during liquid-penetrant testing of the III-stage of a LP turbine showing the shroud: **(a)** in the cracked condition, and **(b)** after repair welding using E316L filler metal.

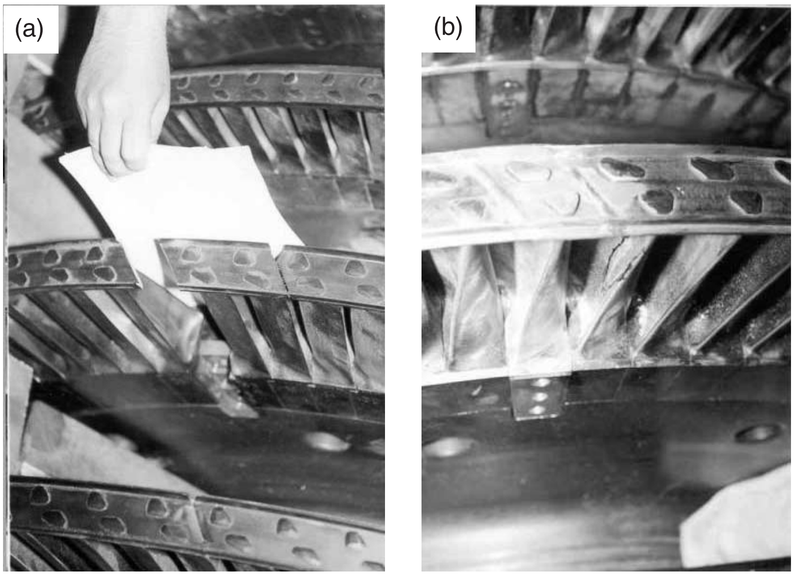

Figure 11. Photographs of the III-stage of a HP turbine showing the shroud: **(a)** after cutting and removal of the root-cracked blade, and **(b)** after *in-situ* re-welding using E316L filler metal subsequent to blade replacement.

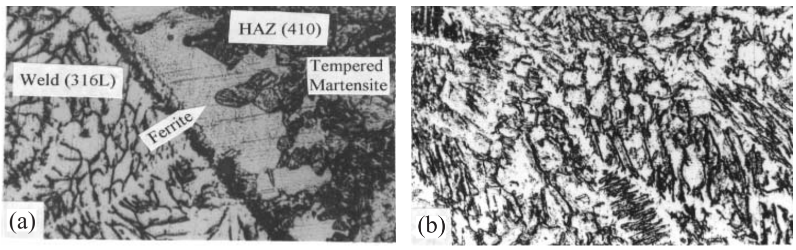

Figure 12. In-situ metallography microstructures of a mock-up weldment (made using ER316L filler metal) after 873 K/1 h PWHT: **(a)** 410 SS/316L weld interface, and **(b)** 316L weld metal.

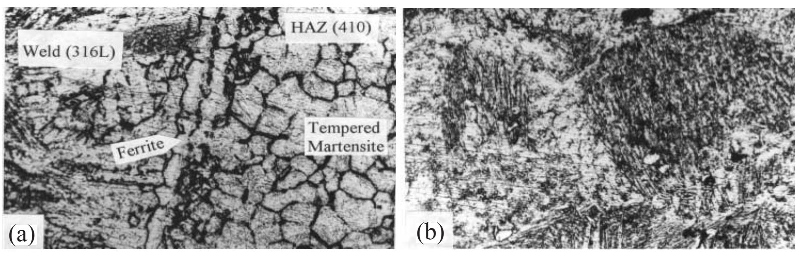

Figure 13. In-situ metallography microstructures of a repair weldment (made using ER316L filler metal) in the III-stage of a LP turbine shroud after 873 K/1 h PWHT: **(a)** shroud/316L weld interface; and **(b)** 316L weld metal.

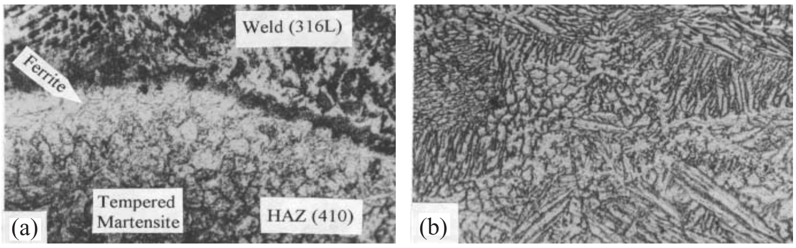

Figure 14. *In-situ* metallography microstructures of a repair weldment (made using ER316L filler metal) in the IV-stage of a LP turbine blade after 873 K/1 h PWHT: **(a)** blade/316L weld interface, and **(b)** 316L weld metal.

observed in the repair welds, all made using the ER316L filler metal. Similarly, figures 15a and b respectively show that the microstructural features in the weld interface region of weldments, made using ER410 filler metal, after 1008 K/1 h PWHT are similar in the repair-welded shroud of the III-stage of a HP turbine and in the procedure qualification weld. These microstructural observations indicate that the HAZs have effectively tempered by the PWHTs employed. Based on these observations, the quality of the repair welds was considered to be satisfactory for the intended service. This was further confirmed when *in-situ* metallography was carried out on some of the repair weldments after satisfactory service for two years. Figures 16a and b show that the microstructural features of the HAZ in repair weldments, made using ER316L filler metal, in a IV-stage blade of an LP turbine and a III-stage shroud of a HP turbine respectively, both after service for two years, continue to remain healthy as they are still similar to that observed in their as-repaired conditions two years earlier.

6. Conclusion

Repair welding plays a very important role in the economic management of steam generator components. The underlying philosophy of repair welding is not to repair components that have reached the end of their design lifetime; it is to put back in service those components that have prematurely failed due to design or manufacture-related defects. Further, these welding repairs should, as far as practicable, be within the scope of the prevailing codes and regulations. As most of the repair-welding strategies are closely guarded information with component manufacturers, there is a growing necessity for in-house development of repair-welding procedures by power utilities in close liaison with their Welding Technology Group.

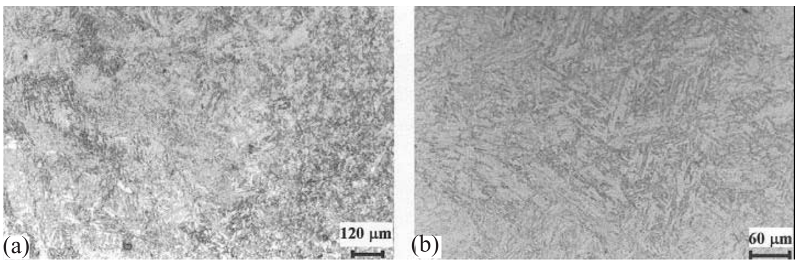

Figure 15. Optical photomicrographs of the weld interface region of weldments (made using ER410 filler metal) after 1008 K/1 h PWHT: **(a)** repair-welded shroud in the III-stage of a HP turbine (by *in-situ* metallography), and **(b)** procedure qualification weld.

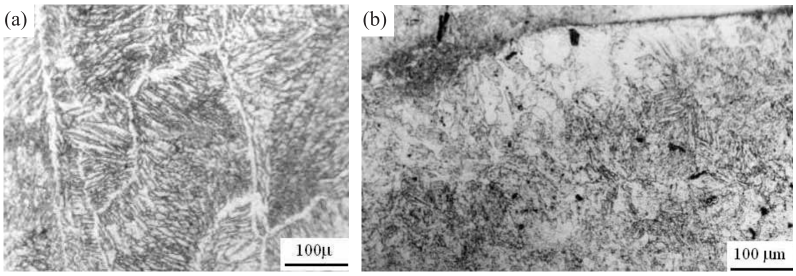

Figure 16. In-situ metallography microstructures of repair weldments, made using ER316L filler metal, after service for two years: **(a)** fusion zone in the IV-stage blade of a LP turbine, and **(b)** HAZ near fusion line in he III-stage shroud of a HP turbine.

A typical example in this regard is the synergistic approach adopted in the successful in-house procedure development and execution of repair-welding of cracked shrouds and blades in steam turbines of the commercial nuclear power plants. Further, in these as well as the other case studies of repair welding undertaken for reducing plant outage and financial loss, a very *pragmatic* approach was adopted to bring the plants back into operation by expeditiously executing weld repairs. However, there still remains a need for welding technology groups to look carefully into the causes for the failures in the steam turbine components and to study the available case histories of failure analysis. This would enable them to discern the root cause for a generic class of failures at different locations of the steam turbines, and to evolve appropriate remedies related to the structure of the material, design of the component, fabrication practice, quality assurance procedures, periodicity of in-service inspection, on-line monitoring, preventive maintenance strategy etc. so that repair and refurbishment itself can be avoided. In this regard, there is also a growing necessity for developing and using knowledge-based expert systems for failure analysis and for suggesting, wherever feasible, repair and refurbishing strategies.

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