ROLE OF REPAIR WELDING IN THE MANAGEMENT OF POWER PLANT COMPONENTS

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Abstract : The management of power plant components is discussed from the perspective of the repair welding philosophy including applicable codes and regulations. A few case histories of repair welding of power plant components are discussed with special emphasis to steam turbine components. Details of indigenous repair welding of cracked steam turbine blades and shrouds in some of the Indian nuclear power plants are also presented.

Keywords : Repair welding, Power plant components, Repair philosophy, Codes and regulations, Case Histories, Steam turbine components.

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INTRODUCTION

Reliability of an engineering component is incorporated at the design stage that essentially requires that quality or fitness-for-purpose aspects be adequately addressed at various stages of its fabrication. Both economics and safety concerns influence quality and hence reliability of a system. Economics dictates the competitiveness of the product while safety concerns 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 and conforming to design concepts and (c) operated and maintained properly. Despite the incorporation of concepts of quality or fitness-for-service, the engineering com-ponents are known to fail prematurely. In order to constantly monitor the health of a system and to avoid sudden and unexpected failure, the advanced concepts of in-service inspection, prediction of remnant life and preventive maintenance of the components are becoming increasingly important.

The term failure, as applied to engineering systems, can be described as non-performance of components/systems due to some deficiency that limits their designed life. Failures are not uncommon in industry and can occur at any of the various stages such as during fabrication, testing, transportation and service. These can be broadly categorised as end-of-life failures, which are predictable and proper preventive actions could be taken in advance and premature failures, which are unpredictable and without sufficient advance warning. The latter may lead to plant shutdown, loss of 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 environment. The sudden failures may also adversely affect 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 accidents.

Welding is one of the most important and reliable joining processes but it also introduces several discontinuities in the joint and affects safe operation of the component. It is no coincidence that weldments are considered weak links. A large number of failures in industry are either directly or indirectly attributed to the presence of welds. Moreover a vast majority of the repairs of failed components is carried out using one of the welding processes. Since repair of each failure requires a different strategy, the codes and standards provide only general guidelines, 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 option and also time consuming. Repair rather than replacement can achieve substantial reduction in down time and cost. Repair welding is one of the most common methods employed in industry to salvage defective, damaged or failed components. However, success of a repair welding operation depends on many factors such as the weldability of the material, type of damage, availability of a suitable welding technique and consumable, possibility of carrying out pre- and post-weld heat treatments, post-repair inspection by NDT techniques etc. Often, the welding process and/or consumable for repair may be different from those used for original fabrication. A typical example is the repair of a submerged arc weld using SMAW process. Care should be taken that the differences in the heat input employed and the composition of the welding consumables do not lead to formation of additional defects during repair. Weld repair of the components failed in service is more complex than the repair carried out to remove the defects noticed during fabrication. Proper analysis of the failure should be carried out before attempting a repair. Failure might have occurred because of the design fault, fabrication or manufacturing defect, 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 specific application any of the common welding processes like, SMAW, GMAW, GTAW, SAW etc. may be used. For very high quality welds, GTAW process finds the widest application. For long runs or when a large amount of weld metal must be deposited and where mechanisation is feasible, SAW and GMAW may be advantageous. GMAW process is also chosen for remote repairs carried out with robots due to its amenability to automation. This is of special im-portance to repair welding in nuclear reactors where high radiation levels often restrict human access to the repair site. For general-purpose repairs, SMAW process enjoys dominant position for out-of-position welding and short runs, especially when time is critical and portable equipment is utilised.

When we think about welding repairs, our first reaction is to deal with the type of repair, in other words to concentrate on the welding engineering aspects which need to be fixed and checked. This reaction is understandable but is usually mistaken. One has to differentiate between manufacturing-related and operation-related failures. With manufacturing-related failures one always has the design plan to refer back as a benchmark, and 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 there is usually no possible solutions by changes of the design as this type of failure is not normally linked to welding and consists of wear, erosion, cavitation etc. According to the type of defect and its possible causes, there are varying repair strategies that can be performed [1].

REPAIR PHILOSOPHY

As some common features apply to repair of large structures, there are certain rules that can be applied in most cases. These features include [2]:

- Repair of a large structure is typically of an urgent and critical nature since the failure of the structure may have devastating effect on industrial or financial activity, jeopardise human safety, and have serious economic impact.

- In most cases, the only alternative to repair is the replacement of a substantial portion of the structure or even the entire structure. This is usually associated with considerable replacement cost, prolonged schedule disruption and, there-fore, considerable sales losses.
- Typically repair is performed in the field under unfavourable conditions in a very compressed time frame which demands much subjective on-the-spot human intervention (compared to fabrication of a new structure).
- Many large structures can only be repaired once without facing risk of significant damage to the structure.

A typical scope of repair may be divided into three basic stages. They include 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 structural design and the suitability of that design for possible repair welding and development of repair approach, main requirements and detailed specification for assembling, welding and inspection. Performance includes all repair activities at a shop and/or in the field.

The main objective of repair welding is to extend the service life of a failed structure by using welding. In reality, there are two typical approaches to meeting this objective, research-oriented and pragmatic. In the former, the main emphasis is made 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 a complete and extended stress analysis. Unfortu-nately, the data obtained will rarely find their way into a repair approach or a welding procedure. However, it is often forgotten that in many cases the analysis is needed to provide support for the repair effort. Considering the high cost of such an analysis, the main objective should be to generate sufficient input data to support development of a comprehensive and realistic repair approach and welding procedure.

In contrast, the pragmatic approach is more typical in fabrication and repair shops. The main emphasis here is on the performance aspects of repair, while the analysis stage is neglected. Unfortunately, in both approaches the developmental stage and thus the welding engineering aspect of a repair is not usually given adequate attention. A Welding Technology Group is an important link between a research organisation, which lacks repair performance expertise, and a fabricator relying only on 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 the welding engi-neering developmental efforts.

The approach which proved to be the most efficient and successful in repair welding of large structures is a balanced approach [2] in which :

- Scope and nature of analysis is determined by the necessity of repair welding.
- The Welding Technology Group is in the centre of the developmental effort.
- Performance of repair is carried out under the supervision of the Welding Technology Group and strictly according to a detailed welding procedure with little room for improvisation by shop personnel

IGCAR Kalpakkam used a similar approach for repair welding of cracked steam turbine components of steam generators in four power stations of NPC; a resume of which is given in a later section of this paper. Before that is done, it is appropriate that we consider the role of repair welding in the management of power plant components in general and steam turbine components in particular.

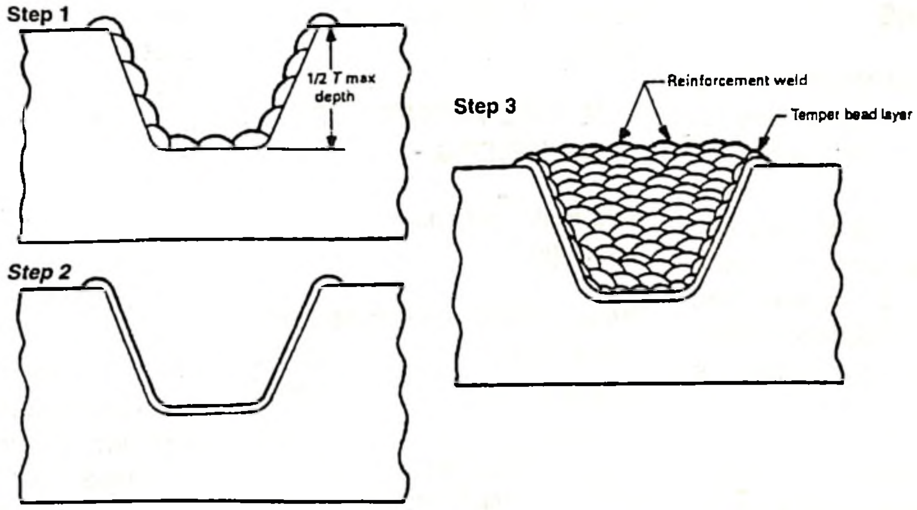

Fig. 1 : Temper bead weld repair and weld temper bead reinforcement [6] by the SMAW process. (Step 1: Butter cavity with one layer of weld metal 2.5mm diameter coated electrode. Step 2: Remove the weld bead crown of the first layer by grinding or machining. Step 3: The second layer shall be deposited with a 3.15mm diameter electrode, and subsequent layers shall be deposited with welding electrode no larger than 4mm diameter.)

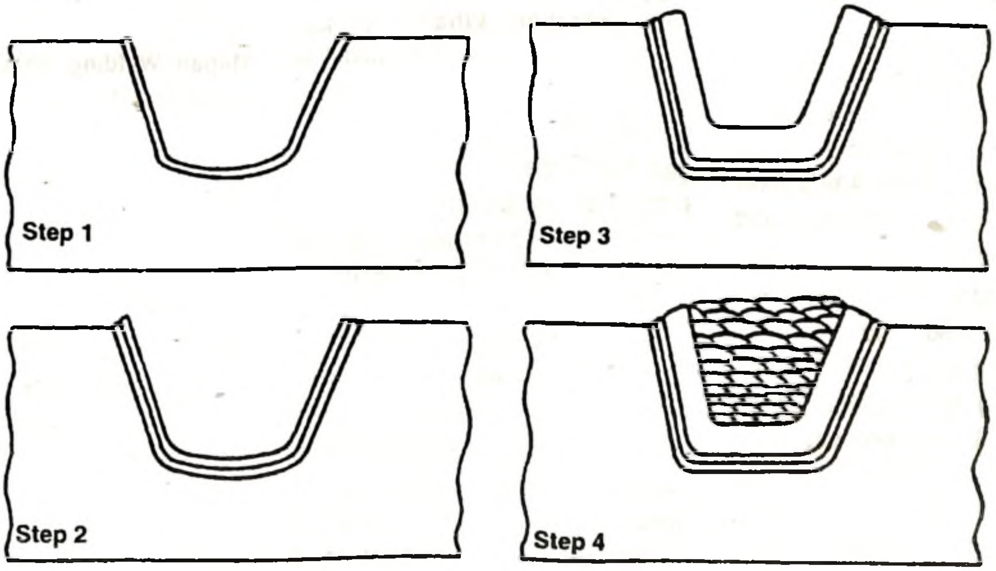

Fig. 2 : Automatic or Machine (GTAW) temper bead weld repair [6]. (Step 1: Deposit layer one with first layer weld parameters used in qualifications. Step 2: Deposit layer two with second layer weld parameters used in qualifications. Step 3: Deposit next four layers with layer three through six weld parameters used in qualifications. Step 4: Subsequent layers to be deposited as qualified.)

CODES AND REGULATIONS ON REPAIR WELDING

Various codes and regulations have laid down rules and procedures for repair welding. The mission of these codes and regulations is to protect the health and safety of the public by regulating the commercial power industry. These codes and regulations adopt a defence-in-depth philosophy that is utilised since the initial licensing stage for commercial power plants [3]. With regards to design and fabrication of power plant components, conservatism in design and materials selection, stringent quality assurance, and non-destructive examination of component fabrication and hydrostatic pressure testing have been required. Inspection, repair/replacement, assessment of structural integrity and pressure testing of components are required for operating plants under an alternate set of rules. For ex-ample in Section-XI of the ASME Pressure Vessels & Piping Code, Article IWA-4000 is devoted to "Repair and Replacement" [4-6]. For similar materials, repair to specific base materials and associated welds may be made without PWHT. For the repair welding by the SMAW or the automatic GTAW process, the temper-bead weld repair procedures as given in Figs. 1 and 2, respectively, can be adopted. Similar weld repair procedures can be adopted for repairs to specific dissimilar material combinations as well [6]. 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" [7].

SOME CASE HISTORIES OF REPAIR WELDING

Weld Build-up Repairs of Turbine Rotors [8]

Through careful development and testing it is possible to use the process of weld overlays for weld build-up repair of turbine rotors. Thus, many turbine rotors that would have been condemned or derated just a few years ago can today be re-stored to full operating potential. Though any of the current popular welding processes are fundamentally suited to build-up welding, the 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 are 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 LP rotor made of CrMoV steel was successfully repaired using the SAW process, an intermediate layer of 5%CrMoV weld metal was initially deposited to inhibit carbon diffusion and to accommodate the various coefficients of thermal expansion. The balance of the weld was of 12%CrMoV weld material. With the resulting deposit, the same creep rupture strength in the weld build-up deposit was achieved as in the original CrMoV material, besides adding substantial corrosion resistance and reducing 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 HP impulse wheel was accomplished using a similar procedure as in the preceding case. Here 12%CrMoV was selected to achieve high temperature creep resistance as well as high temperature strength. As before an intermediate layer of 5%CrMoV was applied to the base metal in the area to be welded, and then the 12%CrMoV is applied to cover the 5%CrMoV. Gas turbine rotors that had damage resulting from corrosion or mechanical impact were also repaired in this way.

Repair Welding on Cast Steel Casings [9]

Cracks in the steam inlets of turbine casings made of CrMoV cast steel were successfully repair welded using austenitic filler metals. Preheating at 150°C was required when Ni-base E-NiCr19Nb austenitic filler metals were used, while preheating was dispensed with when Fe-base 0.10%C-16Cr-25Ni-6Mo austenitic 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 no. 1.0553 was also successfully repaired using build-up welding under inductive preheating at 150°C 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-off. The pump turbine is in operation for more than 15 years after the repair welding was performed.

Repair Welding of Steam Turbine Components in Indian Nuclear Power Plants

A steam turbine is the most critical component in a power plant. As the steam expands through the turbine its condition changes, requiring a spectrum of different blades between the turbine inlet and exhaust. In this regard, the low-pressure (LP) steam turbines are the most interesting with the materials used belonging to the following alloy classes: martensitic stainless steels (SS), precipitation hardened (PH) SS, duplex SS and titanium alloys (e.g. Ti-6Al-4V). The most popular alloy used for the blades remains 12Cr-1Mo-V martensitic SS [10]. The failure statistics of blade related outages based on an EPRI survey of US utilities between 1971 and 1981 is shown in Fig. 3 [10-13]. The estimated cost of 207 of these outages in terms of the lost power production is shown in Fig. 4, and has averaged 140 M$ annually since 1976 or approximately 3.6 M$ annually for an "averaged" utility experiencing problems [10]. The location of blades causing problems is given in Fig. 5 which shows that there are problems associated with the first stages of high pressure (HP) and intermediate pressure (IP) turbines and the last stages of LP turbines. The LP blade failure locations (Fig. 6) can be summarised as occurring 46% 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 blade failures are shown in Fig. 7.This shows that over 50% of the incidents are related to corrosion/fatigue when the categories of stress corrosion cracking, high cycle fatigue, corrosion fatigue cracking, low cycle fatigue and corrosion are combined. The conventional remedial approach, requiring replacement of the cracked blades, considerably increases the duration of turbine outage, and hence reduces the performance and availability factor of the turbine. Weld repair of shrouds and blades, on the other hand, can save considerable down-time required for blade replacement, and hence would be highly economical for the competitive power utility industry. Such repairs were therefore carried out in 236 MWe steam turbines of nuclear power plants in India [14,15].

The procedures for repair welding of cracked steam turbine shrouds and blades made of AISI 410 martensitic SS have been developed using the gas tungsten arc welding (GTAW) process. Weld repair procedures were developed using ER316L austenitic SS filler wire for both shrouds and blades, and ER410 martensitic SS filler wire for the blades. The repair welding procedure with austenitic SS filler wire was developed to avoid preheating of the shroud/blade as also hydrogen induced cold cracking, and involved evaluation of three different austenitic filler wires, viz. ER309L, ER316L and ERNiCr3. The overall development of the repair welding procedure included selection of welding consumables (for austenitic SS filler metal), optimisation of post weld heat treatment (PWHT) parameters, selection of suitable method for local pre-heating and post-weld heat treatment of the blades, determination of mechanical properties of weldments in as welded and PWHT conditions, and microsturctural examination. After various trials using different procedures, the procedure of local PWHT using electrical resistance heating on the top surface of the weldment and monitoring the temperature by placing a thermocouple at the bottom of the weld, was found to give the most satisfactory results. A similar procedure was used for preheating while using ER410 filler metal. Mechanical testing of weldments before and after PWHT involved tensile tests at room temperature, face and root bend tests and microhardness measurements across the fusion line and heat affected zone (HAZ). During procedure qualification, mock-ups and actual repair welding, dye penetrant testing (DPT) was used at

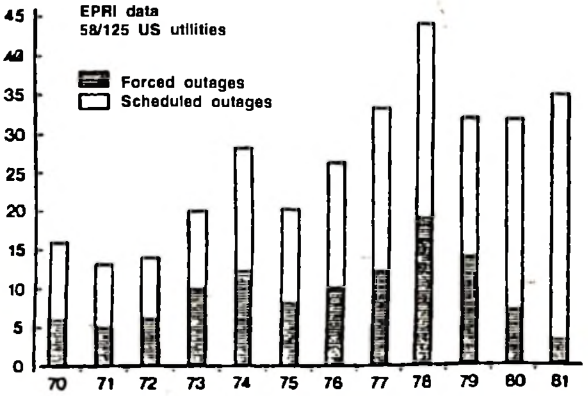

Fig. 3 : The annual number of both forced and scheduled outages related to failures reported by 58 US utilities [10].

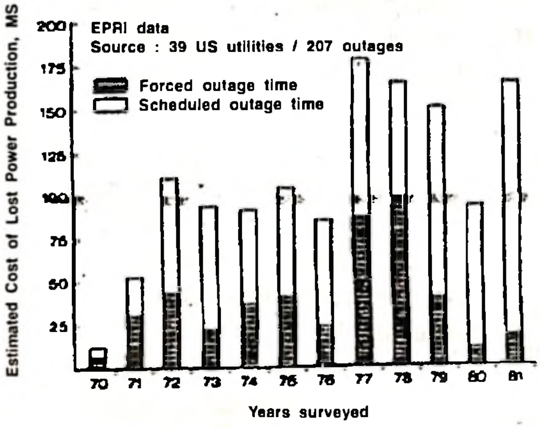

Fig. 4 : Estimated cost of lost power production [10-12].

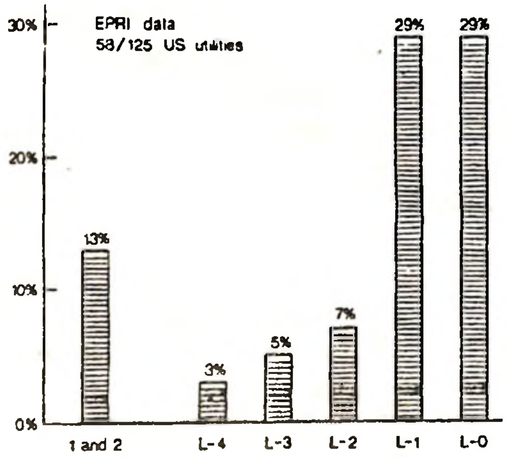

Fig. 5 : Location with respect to blade row of the blade related outages [10].

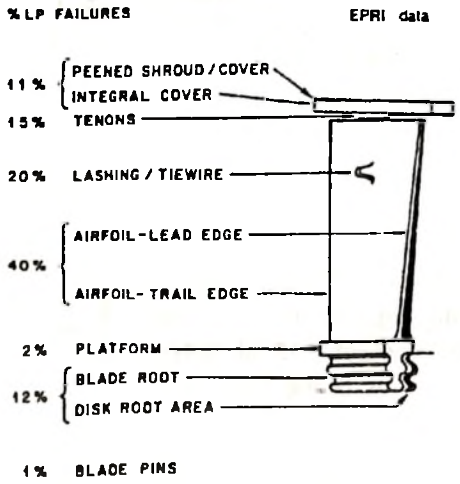

Fig. 6 : Location of LP turbine blade failures [10-13].

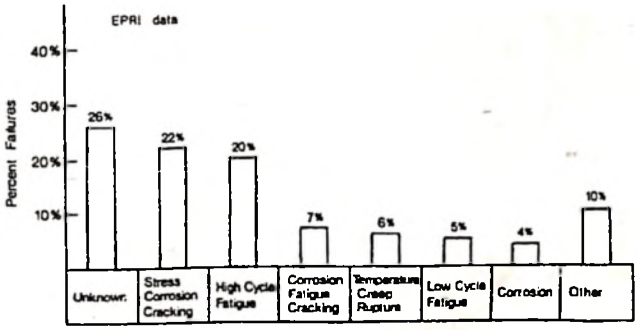

Fig. 7 : Mechanisms reported to have caused the blade failures [10-13].

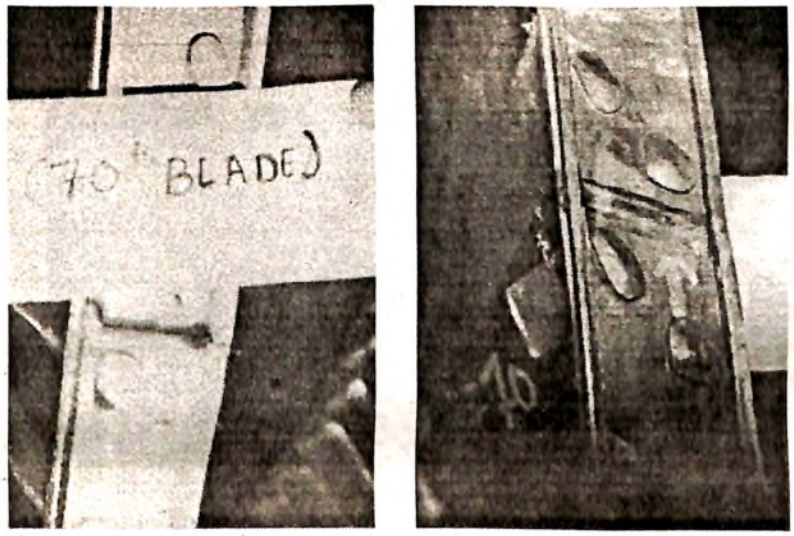

Fig. 8 : Photographs during dye-penetrant testing of a shroud crack: (a) before repair, and (b) after weld repair.

different stages and whereever possible radiography was carried out.

These procedures have so far been successfully used for repair welding of cracks in 6 shrouds and 2 blades in the LP-III stage, and 2 shrouds in the HP-III stage of steam turbines in 4 nuclear power plants in India. The photographs during DPT of one of the shroud cracks before and after repair welding are shown in Figs. 8(a) and 8(b), respectively. To check and document the microstructural features of the repair welds, in-situ metallography was performed on the mock-up weldment as well as on the repair welds of some of the shroud and blade cracks. The photomicrographs of the HAZ and weld metal after PWHT in the mock-up weldment are shown in Figs. 9(a) and 9(b), respectively. Figures 10(a-b) and 11(a-b) show the typical microstructural features in the HAZ and weld metal after PWHT in the repair weld of a shroud and a blade in a LP-III-stage of a turbine. Comparison of Fig. 9 with Figs. 10 and 11 show that the typical microstructural features after PWHT observed in the mock up weldment are similar to those observed in the repair-welds. The in-situ microscopic observations indicated that the HAZ has been effectively tempered by the PWHT. Based on the above results, the quality of the repair welds was considered to be satisfactory for the intended service.

From our experience, the following are the important steps and considerations for a successful repair strategy :

- Selection of filler metals and welding parameters
- Type of weld preparation
- Pre-heating conditions
- Annealing temperature
- NDT
- Residual-stress measurements

CONCLUDING REMARKS

Repair welding plays a very important role in the management of power plant components especially of aged components. The underlying philosophy of repair welding is not to repair components that have reached the end of their design lifetime but to put back in service those components that have prematurely failed due to designor manufacturing-related defects or had defects that went through undetected during inspection. Further, these welding repairs should be, as far as practi-cable, within the scope of the

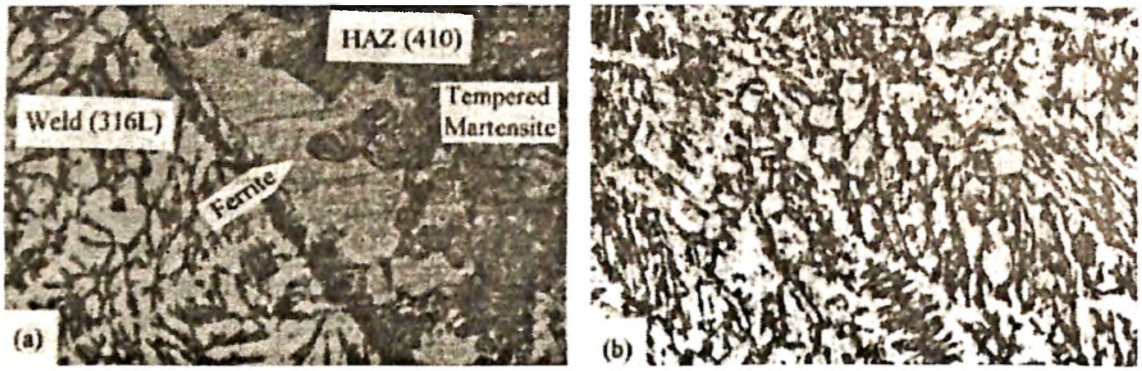

Fig. 9 : In-situ metallography microstructures of a mock-up weldment after 600°C/1h PWHT: (a) 410 SS/ER316L weld interface, (b) ER316L weld.

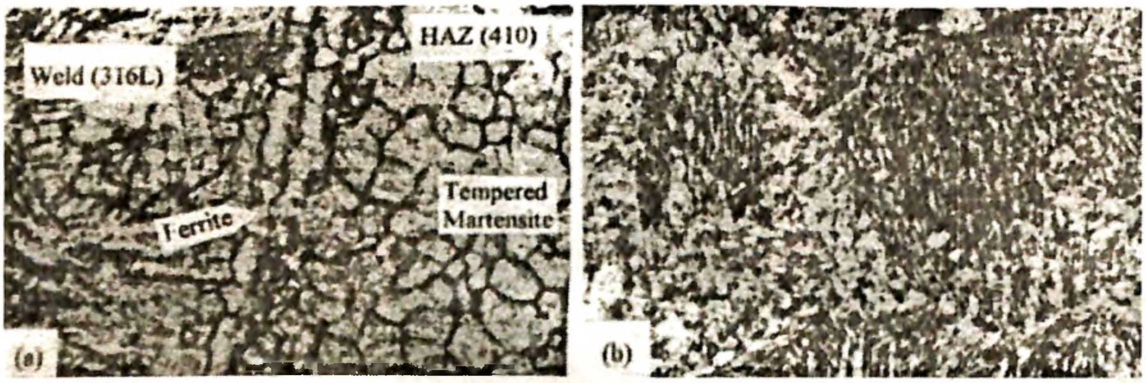

Fig. 10 : In-situ metallography microstructures of a repair weld of a shroud after 600°C/1h PWHT: (a) shroud/ER316L weld interface, (b) ER316L weld.

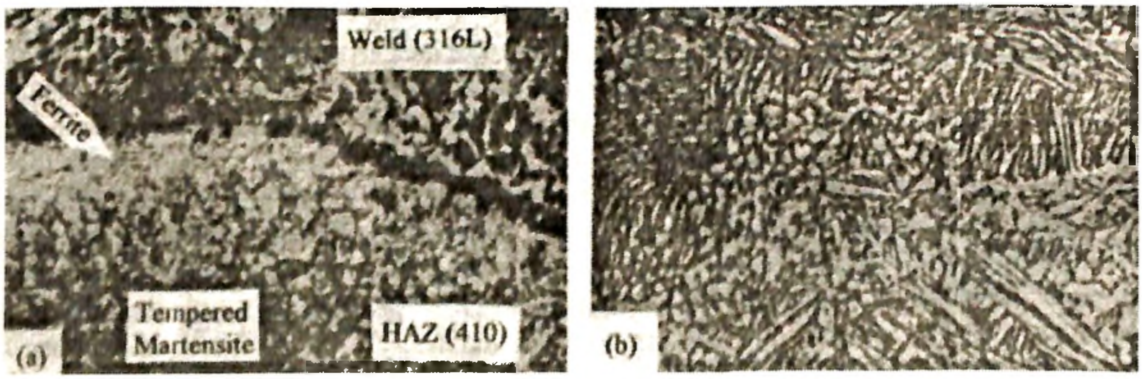

Fig. 11 : In-situ metallography microstructures of a repair weld of a blade after 600°C/1h PWHT: (a) blade/ER316L weld interface, (b) ER316L weld.

prevailing codes and regulations. As most of the repair welding strategies are closely guarded information with the component manufacturers, there is a growing necessity for in-house development of the repair welding procedures by the utilities in close liaison with their Welding Technology Group. A typical example in this regard is the synergistic approach adopted in the DAE family between NPC and IGCAR. In the specific case studies of repair welding undertaken for reducing plant outage and financial loss, a very pragmatic ap-proach was adopted to bring back the plants into operation by expeditiously executing repair welding. However, as a welding technologist, I strongly feel that the Welding Technology Group should also look carefully into the cause for the failure and study available case histories of failure analysis. This would enable them to discern the root cause for a generic class of failures at different locations. This should enable them to evolve appropriate remedies related to the structure of the material, design of the component, fabrication practise, quality assurance procedure, periodicity of in-service inspection, online monitoring, preventive maintenance strategy, etc. so that repair welding 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 suggesting repair-welding strategy wherever feasi-ble.

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Attention !!!

Young Practising Welders, Technologists & Engineers
are invited to present their work
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