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Characterization of Stress in Engineering Materials by Special Non-Destructive Techniques

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1.0 INTRODUCTION

Characterization of materials through non-destructive evaluation has been a subject of study ever since shaping, forming and welding of materials became popular for production and erection of critical engineering components and structures. Amongst the Non-destructive methods that are in vogue, several developments have taken place in the field of conventional Non-destructive methods for characterization of flaws in materials.

Industrial experience has shown that besides flaws, several other characteristics and imperfections that occur during manufacturing, can also adversely affect the quality and performance of welded structures. Though characterization of flaws and elimination of them ensures the quality and soundness of the components at the manufacturing stage, the service performance is influenced by several other characteristics and imperfections. Amongst such characteristics, stress levels realized in the component during loading and presence of residual peak stress in the components are two important factors that play a vital role in the failure of components. In fact, they provide the motive force for the flaws to propagate and cause failure in service. It is well known that even if certain undetected flaws do exist in the components, if favourable stress fields are not associated with them, they remain dormant without causing failure. At the same time, if favorable stress fields accompany them, they start growing in service causing premature failures. So there exists a very vital link between flaws and stress field and unless they are evaluated and controlled prevention of premature failures and ensuring the safety of critical structures cannot be accomplished. This is more so in critical internal and externally loaded pressure vessels and welded structures. In recognition of this, ASNT refers to characterization of stress fields by strain gauging method as one of the special non-destructive methods.

In this context, characterization of stress field has been a subject of our study over the past two decades. The characterization task includes both applied and residual stress fields using special non-destructive evaluation techniques namely Strain gauging and X-ray diffraction based methods. These techniques have been extensively used both at the manufacturing stage as well as for evaluation of the components in service. These techniques have been established for different materials and conditions and have been applied in several industrial components employed in Power, Automobile, defense, and Aerospace sectors. These applications have benefited many industries and industrial establishments including BARC, NPC, RDSO, CVRDE, MDL, L&T, BHEL, HAPP, ADA, LPSC, and VSSC.

In this paper, the application of these two techniques to some of the major components and critical structures is described along with the outcome of these studies.

2.0 NON-DESTRUCTIVE EVALUATION OF STRESS IN METALLIC MATERIALS

2.1 EVALUATION OF STRESS BY STRAIN GAUGING TECHNIQUES

Stress analysis by electrical resistance strain gauge is one of the most widely used quantitative methods of evaluating stresses in materials. The method consists of installing a resistance-based strain gauge in the location of interest and orientation and connecting them to the strain meter. When a change in the resistance of the gauge is brought about as a consequence of the change in length of the strain gauge that in turn is brought about by the strain in the material, the bridge balance is affected. As the millivolts required for balancing the bridge is proportional to the strain the unbalance voltage is measured very accurately using sophisticated instrumentation amplifier. This measured unbalance voltage is converted in to strain and stress by using appropriate stress analysis equations and constants. Different types of strain gauges and bridge configurations are used for different measurement applications. The evaluation of applied stress by strain gauging is totally non destructive in nature and can be used to determine the peak stress at a given location of the structure.

In the case of residual stress measurement, the change in length and consequential change in resistance and unbalance voltage is brought about by either drilling a blind hole in the vicinity of the gauge or by sectioning or boring the part containing the strain gauge. Similar set of equations [1] is employed for computations of stress along with appropriate constants that depend on the configuration of the strain gauge. The blind hole drilling method is wither semi-destructive or destructive depending on the thickness of the section in relation to the depth of the hole that normally does not exceed 2 mm. The accuracy of this method is affected by the stress gradients present in the material.

2.2 EVALUATION OF STRESS BY X-RAY DIFFRACTION TECHNIQUES

The X-ray diffraction method of evaluating the residual stress is one of the most widely used non-destructive methods used for characterization of crystalline materials. The method works on the principle of diffraction phenomena of X-rays described by Bragg's law. In this method the interatomic lattice spacing associated with type of crystal structure becomes the gauge length and the strain is proportional to the change in the spacing. This change causes a shift in the diffraction angle from that associated with stress free crystal structure. By measuring the shift from its stress free state for a particular lattice plane and with a particular radiation the stress is computed using either bulk or X-ray elastic constants of the material [2]. Though it is very accurate in general, the accuracy suffers from the presence of texture or grain orientation and grain coarsening especially in the weld regions.

This method can be directly applied in fully machined parts and components, as it is a totally non-destructive.

3.0 APPLICATION OF STRAIN GAUGING TECHNIQUES TO EVALUATE APPLIED STRESSES

3.1 Proof testing of Steam Generator vessel

In this study, experimental stress analysis of the steam generator for NARORA Project was carried out using electrical resistance strain gauges as per ASME section VIII div I. The stresses were measured in all the critical locations of the primary and secondary parts of the vessel during hydro testing up to 1.5 times the design pressure (Fig 1-4). The maximum stresses realized at the design and test pressure were compared with those obtained from design calculations and with the allowable stress of the material to evaluate the safety of the vessel as per the various theories of failure [3,4]. The test was carried out as a type test for all the eight steam generators designed and manufactured with the same design.

3.2 Proof testing of Externally Loaded Pressure Vessel

The hull structure of the first indigenously built ship by one of the ship builders was tested by Electrical resistance strain gauging during deep dive testing as a part of the protocol tests that are required to establish the structural integrity of the hull structure. The study involved strain gauging over all critical locations in the hull structure and associated instrumentation to record the strains while deep diving to different depths. The maximum stresses realized were evaluated using the various failure theories to determine the safety and integrity of the hull structure.

3.3 Safety assessment of serviced ships through strain gauge testing

This study involved Non-destructive testing and strain gauge testing of the repaired zones of the 25 to 30 years old and serviced ships after refits and repairs. In these vessels three element rosette type strain gauges were installed in all critical zones and repaired regions and the maximum stresses realized were measured during deep dive test. Based on the measured results and in comparison with the allowable stresses, the safety of the vessel was evaluated and safe operating depth was recommended.

3.4 Design Validation of the Heat Exchanger vessels

In this study the maximum stresses realized in the tube sheet regions and nozzle to shell joint regions were evaluated using electrical resistance stain gauges during hydro testing of a heat exchanger for refinery plant (Fig 6). The results were compared with the designed (calculated) values for validating the design calculations [3,4].

A similar study had been carried out to evaluate the maximum stresses realized in the reinforcement pad region of the nozzle opening to shell joint of a stainless steel heat exchanger vessel using strain gauges (Fig 5) during hydro testing. Based on the measured results the design values were validated.

3.5 Design validation of high-pressure valves

In this study the design validation of a 2-1/16" size 16000-psi class full bore valve was carried out using electrical resistance strain gauges during hydro testing of the valve up to design pressure. The measured stress results (Fig7,8) were compared with those made by calculations for validation of the design for ONGC.

A similar study was conducted to study the design of a 36" gate valve body for EIL. The initial study showed that the due to lower wall thickness the body and consequential deformation water was leaking during hydro test through the seating areas. Based on the strain gauge results made in the ribbed regions of the cylindrical and flat portions of the valve, the thickness was redesigned and manufactured to meet the requirements of the customer.

3.6 Design validation of Reactor Pressure Vessel

In this study, the design of the reactor vessel was validated using electrical resistance strain gauging test during hydro testing of the vessel up to design and test pressure. In this test, strain gauges of different types had been installed both on the inside and outside surface of the vessel. The strain readings for different pressure steps were recorded through a computer during hydro test and on-line evaluation of the results were carried out to study the elastic behavior of the material and to quantify the magnitude of the stresses realized in all critical zones of the vessel (Fig 9,10,11). The measured values were compared with those obtained through finite element calculations to validate the design. The test was carried out for M/s BARC, Mumbai.

3.7 Evaluation of discontinuity stresses in a conical vessel

This study was conducted to evaluate the discontinuity stresses in the interface regions where the vessel changes its shape from cylindrical to conical section. The cone angle had gone few degrees beyond acceptable limits and warranted validation for acceptance by the third party inspection agency. This validation was carried out by measuring the discontinuity stresses using electrical resistance strain gauges and the measured results during different hydro test pressures were compared with calculated values for validation.

3.8 Design validation of Steam generator of reactor vessel

In this study, the peak stresses realized during hydro testing was evaluated in the primary and secondary regions of the heat exchanger vessel using electrical strain gauges of different types. The overall arrangement of the system and the measured results are given in Fig 12,13,14. The results were compared with FEM results to determine the high stress regions of the vessel and for validation.

3.9 Torque measurements in Gates

In the damper gates used in the power boilers, often the actuator was failing and the high torque being realized due to imperfections in the manufacture of the gate was suspected as one of the reasons. To study this, starting and cruising torque were measured using strain gauges and were compared with the design torque values in four sites to study the maximum torque acting on the shafts in operation. For the measurement, strain gauge based transducers were used in conjunction with digital strain meter [5]. Based on the results suitable modifications have been made to solve the problem.

4.0 APPLICATION OF STRAIN GAUGING TECHNIQUES TO EVALUATE RESIDUAL STRESSES

Residual stress evaluation by strain gauge techniques has been extensively employed for validating prediction of residual stress using analytical models as well as to study the effect of fabrication related processes [6,7,8]. Some of the specific applications of blind hole drilling method are described below.

4.1 Reduction of residual stress through sequence technique

In this study, the weld sequence method had been applied to reduce the residual stress generated during welding of welded loc bogie frames used in high-speed trains. The method had been successfully applied for the fabrication of 3500 HP (WCAM 3 and 5) bogies for Indian Railways. To demonstrate the effectiveness of the method residual stresses were evaluated using blind hole drilling method (Fig 15-18) using strain gauges [9,10,11]. Based on the results, the thermal stress relief heat treatment could be eliminated for the bogie frames manufacture resulting in a substantial saving of expenditure, which would have been otherwise incurred.

4.2 Reduction of residual stress by overstressing method

In this consultancy study for one of the fusion welded pipe manufacturer, overstressing technique was applied to minimize residual stress in long seam welded line pipes made of API grade X-65 steels welded by Submerged welding process. After control of certain forming parameters like gap between the edges of the rolled pates and welding, the stress levels of the order of 90% of yield strength of the pipe material was applied during hydro testing two to three times. The stress levels in the pipe were monitored by strain gauge method during hydro testing (Fig 19,20). The residual stress measured before and after the overstressing showed that residual stress in the weld and HAZ regions could be reduced to levels less than 10% of yield strength of the steel [12].

4.3 Residual stress analysis in large petro-chemical vessel.

In this study the residual stress levels at all critical locations were evaluated after application of thermal heat treatment of the vessel by using overlapping technique. As the size (45 meters long and 11 meters dia) of the Co_2 absorber for petro-chemical vessel (Fig 21) did not permit heat treatment in a single cycle, overlapping technique was applied in two cycles. The residual stress was evaluated by blind hole drilling method at 11 locations at site to check if the magnitude of the stress were within 100 MPa as per the specifications. The study revealed that the stresses were well within 100 MPa [13,14] and the vessel was cleared for service based on the results.

4.4 Evaluation of residual stress in large dia shell structure

In this study project for one of the customer, the residual stress distribution had been evaluated in a large (8000 mm dia) shell type structure at site. The aim of this study was to compare the residual stress in the weld seams of shell-to-shell section and in shell cylinder section after assembly welding. The residual stress measurement was carried out in weld and HAZ regions of all critical welds in the shell structure in al positions to determine the high stress regions by blind hole and X-ray diffraction methods.

4.5 Residual stress analysis in Narrow Gap SAW welded plates

In this study, the residual stress level in thick wonderments made by in-house developed Narrow gap technology has been analyzed by the blind hole drilling method [15]. In this study, the residual stress levels was analyzed at various stages such as after fit up, after completion of 30% of welding, after completion of 60% of welding, after completion of the joint and after removal of the strong backs. The study was carried out in 125 mm thick plate with narrow groove (Fig 22) and with conventional grooves. The study revealed that the residual stress magnitude and distribution was less in the case of narrow gap welded plate and was sensitive to the strong back used for constraining the plates from deforming during welding.

Some of the recent developments of blind hole drilling techniques are described in ref [16].

5.0 APPLICATION OF X-RAY DIFFRACTION TECHNIQUE TO EVALUATE RESIDUAL STRESSES

The X-ray diffraction technique has been widely used for quality control of critical components where the presence of tensile stress plays a key role on the performance of the component [17]. Besides this technique has also been used for many critical applications as described below.

5.1 Residual stress analysis in Electro-gas welded plates

In this study, the residual stress analysis has been carried out in thick plates welded by vertical electro gas welding process. The welding machine has been indigenously developed at WRI and the study was carried out to evaluate the stress levels in the as welded and stress relieved conditions. The X-ray diffraction and blind hole drilling method has been used for the evaluation purpose.

5.2 Evaluation of residual stress in Al alloy tanks

In this study, the residual stress analysis was carried out in high strength Al alloy (Al 7020 alloy) torroidal shaped tanks used in an aerospace application. The study was conducted to determine the welding sequence and heat treatment process to minimize the residual stress to levels below that stress corrosion cracking in this alloy. The study included residual stresses in fabricated sections and ring forgings (Fig 23,24) that join them together [19,20]. The residual stress was measured by the non-destructive X-ray diffraction method and the results revealed that optimizing the weld sequence and triple heat treatment process could minimize the stress levels.

5.3 Evaluation of Residual stress in Aluminum alloy forged rings

In this study the residual stress state was evaluated in various stages of manufacture of rings (Fig 25) through ring rolling from billets. The study was conducted to optimize the manufacturing process that included, pancake preparation, piercing, ring rolling and heat treatment. The rings were made of Al 7020 alloy. The residual stress was measured non-destructively by X-ray diffraction method using a Chromium target to a high degree of accuracy. The study revealed that residual stress values were sensitive to the fabrication process and quenching induced high level of stresses and tempering partially relieved the stresses. This project was carried out for an aerospace application.

5.4 Reduction of residual stress by Needle Pin Peening

In this research study a new peening method has been developed and the optimum parameters of peening have been established to introduce compressive stresses in localized areas of a material. The optimization of peening parameters has been established by characterizing the surface finish, residual stress hardness and microstructure obtained for different sizes of needles. The process can be easily applied in selected regions of the weld joint like toe regions of the fillet weld and can be applied without removing or dis-assembling the part from the assembly locally [18]. The application of this method in the Mock up fan shafts (Fig 26) showed that high levels of compressive residual stress could be introduced in the toe regions of the fillet weld regions thereby reducing the tensile stresses in toe regions. This method has been applied during the repair of moving beam of 8000 Ton press to minimize residual stress.

5.5 Residual stress analysis in Ti-6Al-4V alloy components

In this R& D project the residual stress levels in Titanium alloy components have been analyzed by the non-destructive X-ray diffraction method. The aim of the study was to establish the diffraction parameters to obtain high reliability while measuring residual stress in these exotic materials. These materials are associated with fluorescent radiation effects that reduce the reliability of the measured values. The study revealed that titanium target tubes might have to be used for obtaining high reliability instead of conventional tubes. The method has been successfully employed to characterize residual stresses after Electron beam welding (Figs 27,28)

The general applications and use of these methods have been described in references [21,22,23,24,25,26,27].

6.0 SUMMARY

The Electrical resistance strain gauge method and X-ray diffraction methods have been successfully employed in characterization of applied and residual stresses in critical components and welded structures in different materials. The applications have resulted in

- ❖ Evaluation of the overall safety of critical high-pressure internally loaded vessels,
- ❖ Validation of the design of critical reactor vessels,
- ❖ Indigenisation of components,
- ❖ Optimization of manufacturing processes like welding, heat treatments, prevention of possible failures in service,
- ❖ Evaluation of the structural integrity of critical externally loaded pressure vessels after refits & repairs.
- ❖ Evaluation of stress state in

  Large Petro-chemical vessels,

  Heat exchangers,

  Nuclear Steam generators,

  High-speed railway bogie frames,

  Aerospace (PTO Shaft) components

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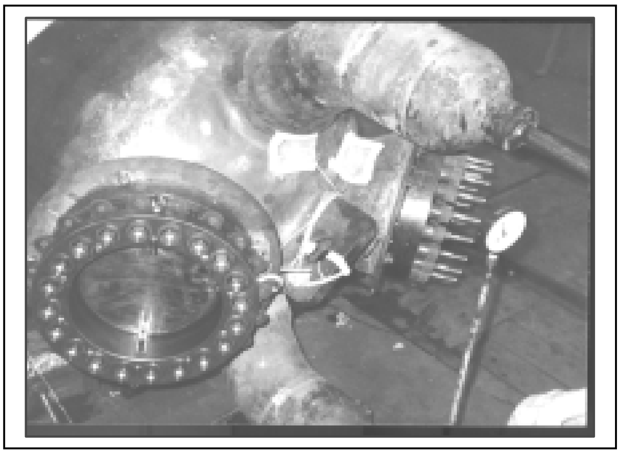


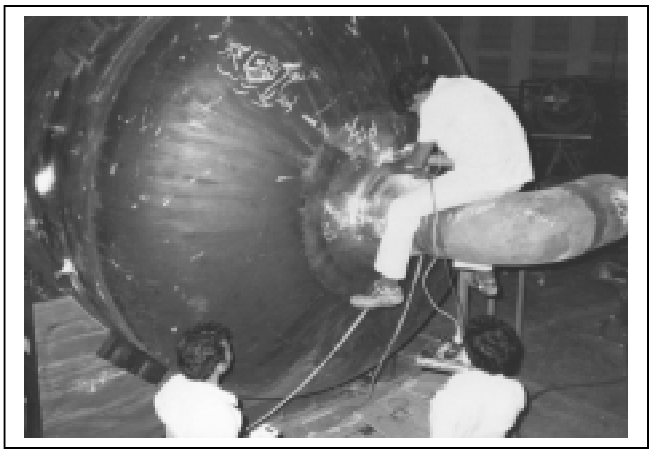
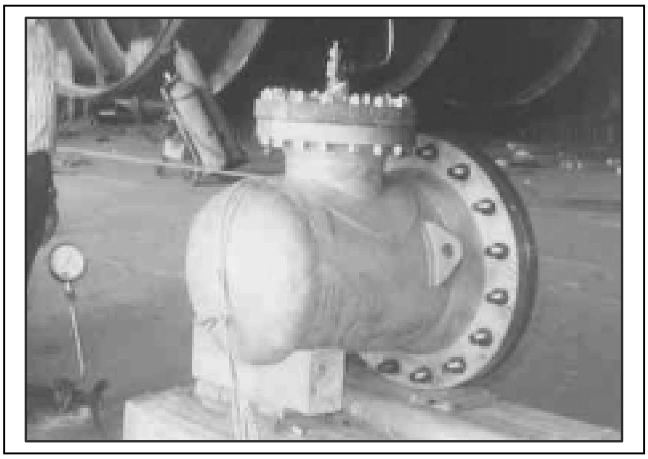


Fig 1.Close up view of the strain gauge location in the steam generator

Fig 2. Installation of strain gauge at nozzle to dished end location

Fig 3. Calibration of the procedure with tensile testing machine

Fig 4. The digital strain meter used for measurement of strains



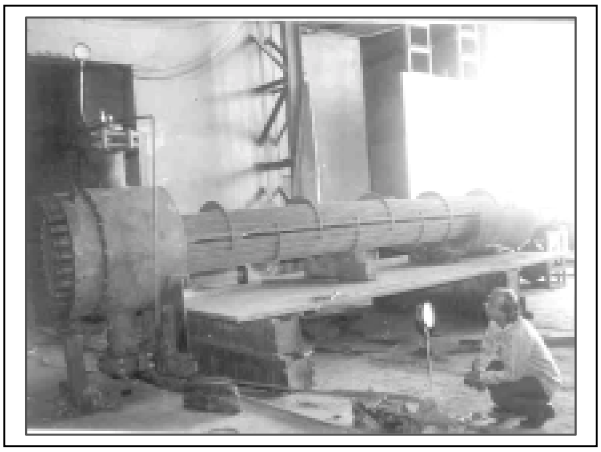


Fig 7. The strain gauge test for validation of the design of oil field equipment valve

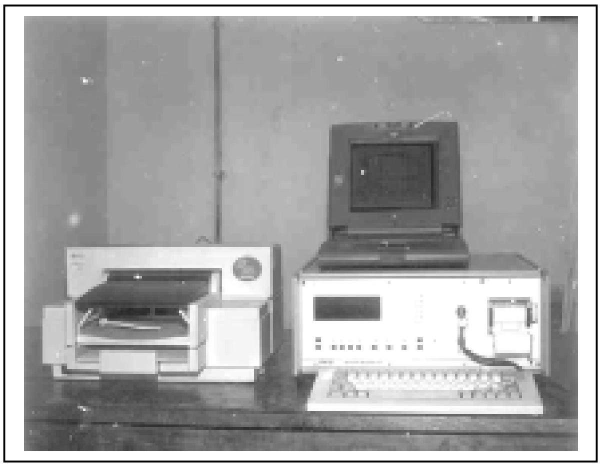


Fig 8. The digital strain meter used for strain measurements

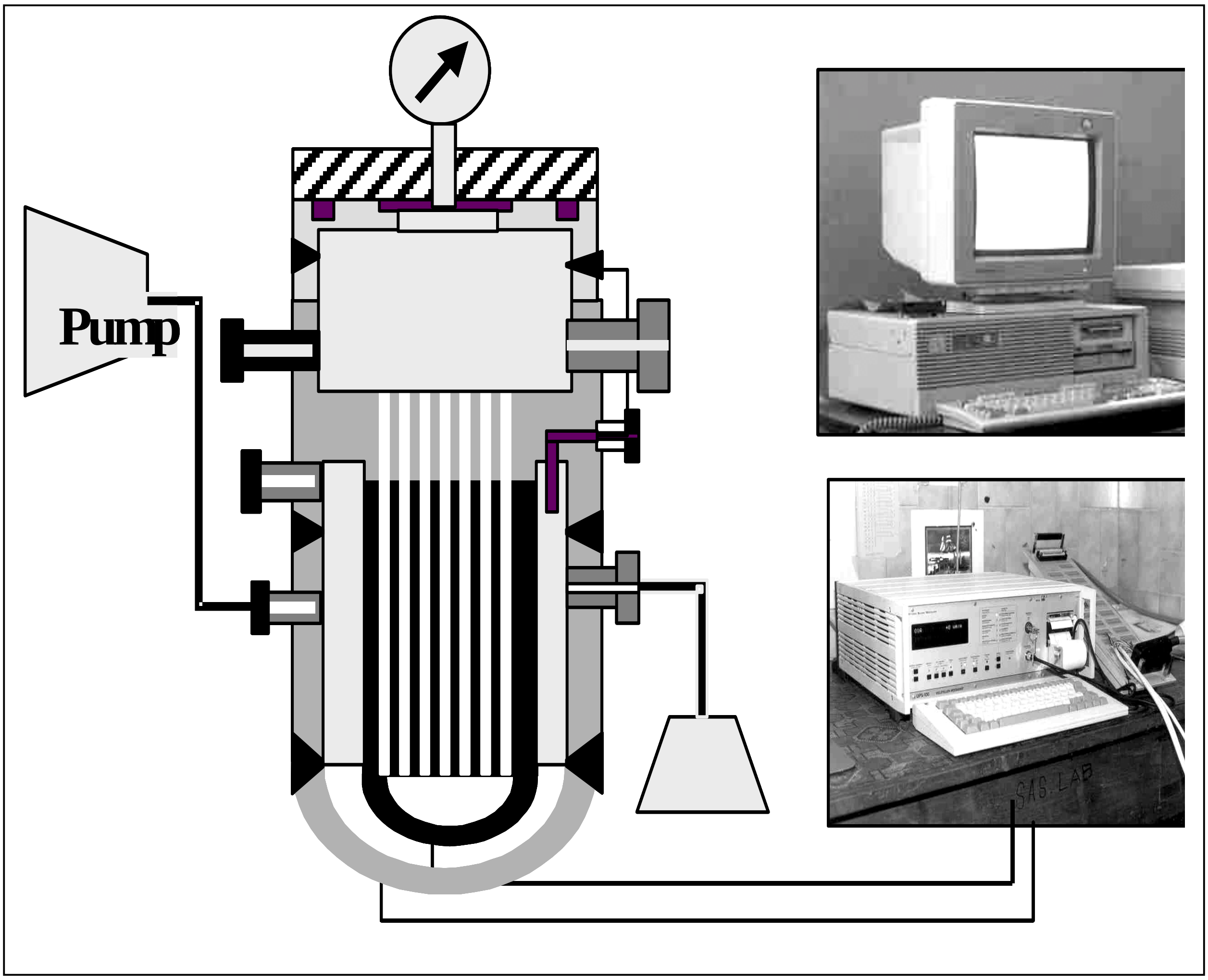


Fig 9. The overall arrangement used for strain gauge testing of critical pressure vessel for design validation

Location	Measured Strains (Average) in Micro Strains			Principal Stress in MPa	
	ε1	ε2	ε3	σ max	σ Min
21	-305	-371	-335	-83.18	-93.98
22	-55	-212	-204	-26.82	-55.72
24	-559	1157	266.4	266.36	-33.5
25	-16	150	182	46.6	10.7
26	-409	753	568	188.3	-22.9
27	78	403	387	109.7	47.7

Fig 10. Typical strain readings and calculated stress values at six locations

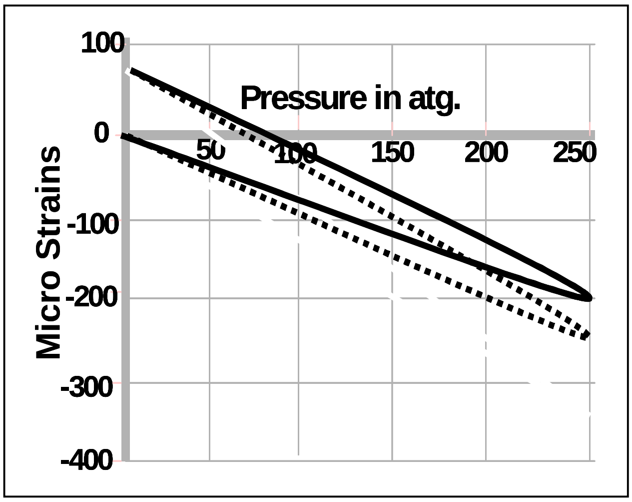


Fig 11. The variation of measured strain versus pressure at a particular location

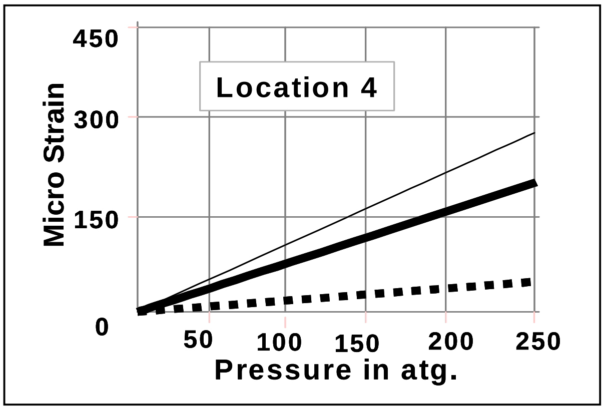


Fig 13. Measured strain versus pressure trend at location 4

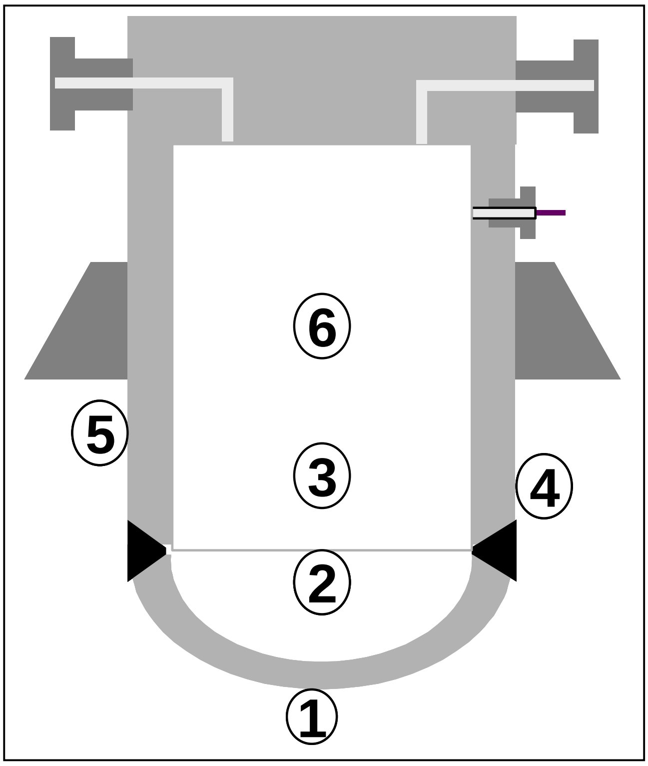


Fig 12. Strain gauge locations in a stainless steel heat exchanger vessel

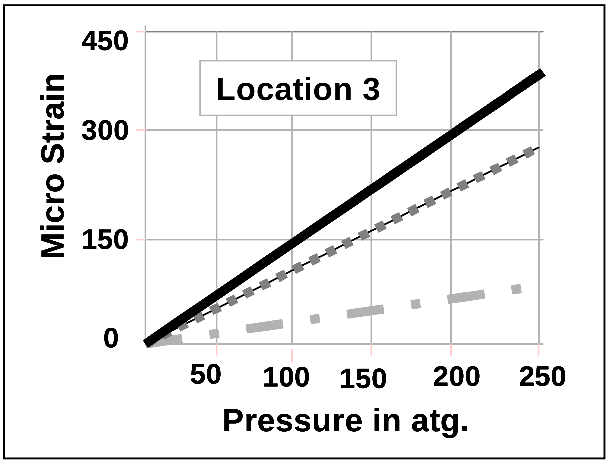


Fig 14. Measured strain versus pressure trend in location 3

Fig 15 Residual stress measurement in the horn regions of the bogie frame

Fig 16 Strain gauge installation in the bogie

Fig 17 Alignment of the RS-200 drilling jig with respect to gauge center

Fig 18 Blind hole drilling using high speed drilling mandrel

Fig 19. Application of Overstressing in long seam fusion welded pipe

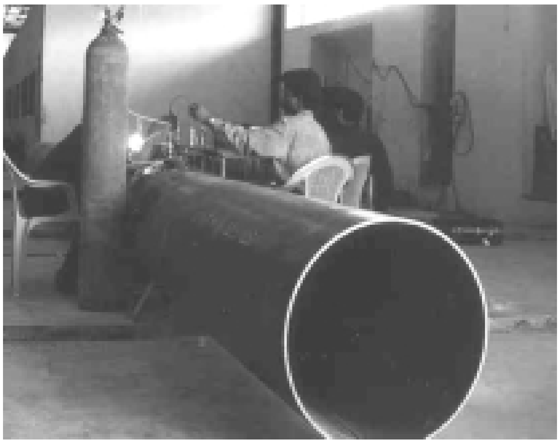


Fig 20 Measurement of residual stress by blind hole drilling method in pipe

Fig 21 Residual stress measurement in Co_2 absorber vessel after heat treatment

Fig 22 Residual stress measurement in Narrow Gap welded joint

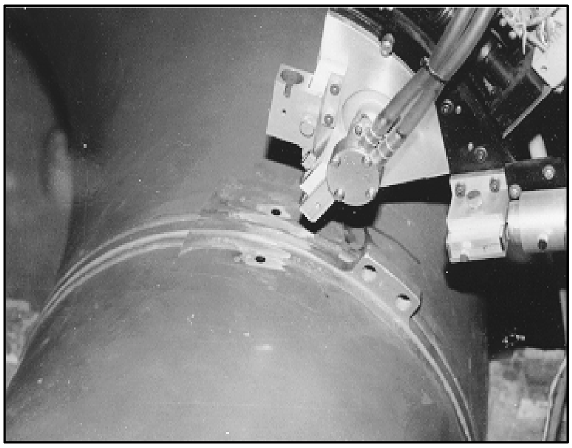
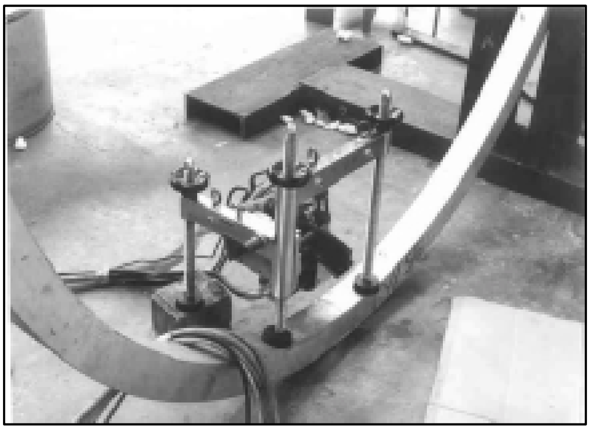


Fig 23 Residual stress measurements in High strength al alloy torroid shaped tank

Fig 24 Close up view of the X-ray source and the detector of X-ray strain meter



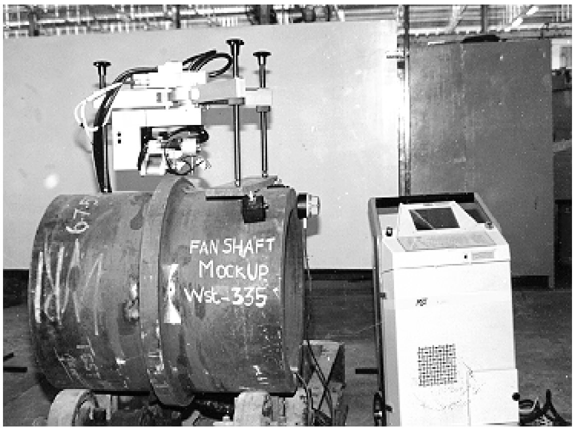
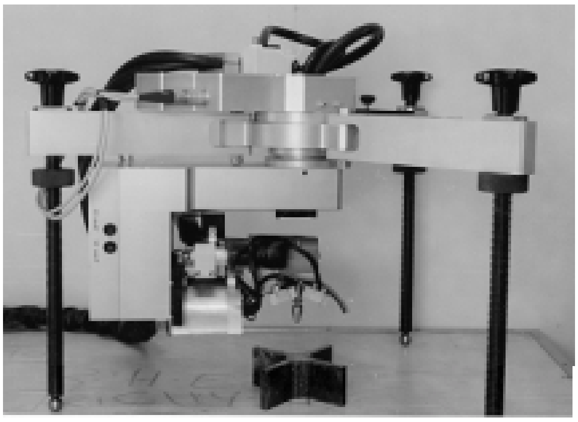


Fig 25 Residual stress measurements in ring rolled Al forgings

Fig 26 Measurement of residual stress in Fan shaft Mock up before and after peening treatment



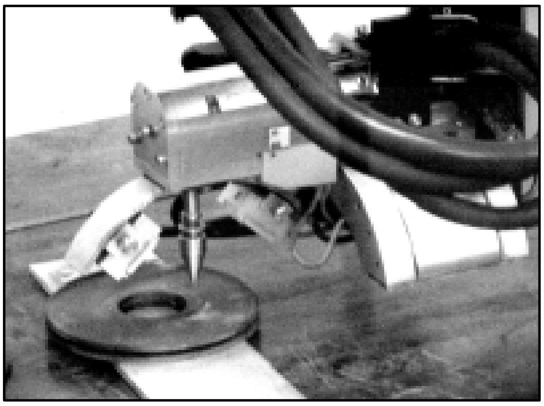


Fig 27. Close up view of the portable Goniometer

Fig 28. Residual stress measurement by XRD method in root welded diaphragm