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Review

Residual stress influences on structural reliability

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ABSTRACT

Structural integrity is affected by residual stresses in a number of ways, some of which are well known to be beneficial in terms of enhancing fatigue performance of engineering components and structures, e.g. surface peening. Knowledge of some of the other more detrimental consequences of residual stresses is more confined within the metallurgical and materials science community and their occurrence during manufacture or service can cause consternation. The purposes of this paper are thus twofold; firstly to introduce several examples of failures which demonstrate more interesting or unusual problems associated with residual stresses and, secondly, to briefly outline the origins of residual stresses and to consider powerful modern ways of measuring residual stress data in real components.

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1. Introduction

The magnitude and distribution of residual stresses in a component or structure are a significant source of uncertainty in engineering design and can also affect subsequent machining as well as life prediction and assessment of structural reliability [1]. Residual stresses are an unavoidable concomitant of almost all manufacturing and fabrication processes and can also arise during service; they will occur under any set of circumstances that leads to differential expansion or contraction between adjacent parts of a body in which the local yield strength is exceeded. Their influence depends on their magnitude,

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Table 1
Illustration of the dependency of the effect of residual stresses on the mechanism of failure and on their magnitude, sign, and extent.

Magnitude	Sign	Extent	Primary effect	Induced effect
Moderate to high	+ve or −ve	Component dimensions	Distortion during machining	Higher scrap rate Fretting and fatigue crack initiation
	+ve or −ve	Localised microstructure	Increase in dislocation density	Higher corrosion rates, e.g. in HAZ of welds in marine environment
	+ve or −ve	Component dimensions	Change in eccentricity of stress application along column	Change in buckling mode and load for welded columns
	−ve	Critical zone for crack initiation	Increase in resistance to fatigue cracking or fracture	Enhanced service life
	+ve	Component dimensions	Adds to tensile applied stress	Increased possibility of fast fracture in-service
	+ve	Local defects, e.g. inclusions, weld defect	Decrease in resistance to fatigue cracking	Decreased service life
	+ve	Critical zone for crack initiation	Possibility of environmentally assisted cracking	Decreased service life

Fig. 1a. 12CrNiMo steel low pressure turbine blade from a 600 MW turbine-generator set that lost a blade during service.

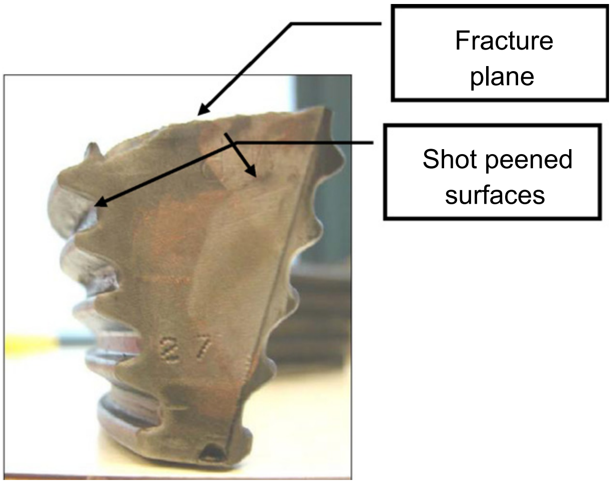

Fig. 1b. Section across the fir tree attachment of the failed steam turbine blade. The fracture has initiated at the first notch root on the left hand side in the image and the failure mechanism was stress corrosion cracking.

sign and extent relative to the controlling length, area or volume of material associated with any particular mode of failure. Several illustrative examples of this are given in Table 1.

A number of these influences of residual stresses are well known to engineers and are used in standard techniques for enhancing the fatigue performance of a wide variety of engineering components and structures through surface modification, e.g. shot peening [2], or reduction in weld toe stress concentration factor by grinding, peening or localised compression [3]. As an example of the engineering importance of residual stresses induced by shot peening to service performance and structural integrity, consider the example of the low pressure blades on a steam turbine used for electricity generation. The blades weigh some 24 kg each, rotate at 3000 rpm in a wet steam environment at 120 °C, and are retained on the disk by a fir tree attachment. Fig. 1a shows a typical blade from a 600 MW generation set which experienced failure when stress corrosion cracking from the root of the first notch in the fir tree led to loss of a blade (Fig. 1b). Repairing this damage cost €100M and led to an outage of the unit for some 6 months [4]. Shot peening is commonly applied to the fir tree region on such turbine blades to improve the resistance to stress corrosion cracking and to fatigue crack initiation. The process consists of exposing the surface of the component to a stream of compressed air containing small steel shot or short wire segments. The kinetic energy of the shot impacting on the surface of the component causes a thin layer of plastically deformed material to develop. The constraint of the elastic structure beneath the plastic layer then forces the surface into a compressive stress state. This surface effect slows down crack initiation (arising from either fretting fatigue or stress corrosion cracking) significantly and thus improves service life.

There are some concerns regarding the effectiveness of shot-peening in this application, i.e. around the fir-tree attachment area, relating to the uniformity of coverage as well as the magnitude of induced stresses and their level of relaxation during service. In particular, over-speed tests, up to 3300 rpm, are conducted periodically, normally after maintenance procedures that may affect the balance of the rotor. The over-speed tests can result in localised stresses in the fir tree region of yield magnitude, which would be likely to reduce the level of compressive stress. Ref. [4] reports the results of a systematic programme of work aimed at exploring residual stresses and their relaxation under load in 12CrNiMo steel steam turbine blades in both a peened and an unpeened condition. Some of the data acquired using synchrotron radiation diffraction will be presented later in this paper to demonstrate the power of modern experimental techniques for residual stress measurement.

Knowledge of some of the other consequences of residual stresses is more confined within the metallurgical and materials science community and their occurrence during manufacture or service can cause consternation. The purposes of this paper are thus twofold; firstly to briefly introduce several of the more interesting or unusual reliability problems associated with residual stresses and, secondly, to outline the origins of residual stresses and to consider several powerful ways of measuring residual stress data in real components.

2. Embrittlement problems

Included amongst residual stress-induced embrittlement phenomena are:

1. Strain-age embrittlement [5,6] which occurs in cold worked parts that have been reheated into a critical temperature range (150–400 °C for 1–5 h).
2. Environmentally assisted cracking mechanisms (hydrogen cracking, which can occur either as a consequence of surface plating processes or of welding, stress corrosion cracking and liquid metal assisted cracking, LMAC).

2.1. Strain-age embrittlement

Pinning of dislocations by a diffusion interaction with small interstitial atoms, in particular nitrogen and carbon, is the principal cause of strain ageing in steels. Strain ageing reveals itself as an additional increase in flow stress, occurring after or during straining. Strain ageing of continuously annealed low carbon steels that occurs during storage, arising from the presence of carbon and nitrogen in solid solution, is a well-known problem in the steel industry. Nitride-forming alloying additions to steel alloys are used to counter any tendency towards strain ageing, which manifests itself in a change to mechanical properties (increase in strength and reduction in ductility). These property changes make difficult the subsequent forming of steel sheet which may then suffer tearing or cracking during the deformation process. It can also result in a decrease in surface quality of finished products due to the appearance of Lüders bands. These are regions of plastic strain localisation resulting from the yield point drop phenomenon observed in some steel alloys. The hardening and ductility loss that occurs in strain ageing, if combined with high levels of residual stress, e.g. at welds that have not experienced post-weld heat treatment (PWHT), can lead to delayed cracking problems. Cold formed and welded steel chain links are a classic example of a component which can exhibit strain age embrittlement. Strain age embrittlement problems can also occur during hot dip galvanising of cold formed ferritic steels, as discussed below.

Galvanising is a highly cost-effective method of conferring good corrosion resistance to low alloy steels but provides almost perfect conditions for strain ageing to occur in susceptible components and fabrications. Guidelines to avoid cracking problems during galvanising have therefore been developed by many national bodies, e.g. [7]. Weld root runs are particularly at risk because of high contraction stresses which cause plastic deformation, and hence appropriate pre-heat and interpass temperatures should be selected to reduce cooling rates in the critical temperature regime of 800–500 °C. Heavy cold working should be avoided in susceptible steels, e.g. C–Mn steels that are insufficiently killed (not fully deoxidised by the addition of silicon or aluminium prior to casting). Recommendations for avoiding a strain ageing problem include keeping cold bend radii at least three times the section thickness and producing holes by punching only in steel sections thinner than 6 mm [7]. Stress relief heat treatment is very effective in eliminating the problem and typically involves heating components or fabrications to 600 °C for 1 h per each 25 mm of thickness prior to galvanising.

Fig. 2a shows one of a pair of cold formed straps which are bolted together around a vertical column. The strap is manufactured from S275 structural steel to BS EN 10025 and is one of a number of examples that fractured either during bolting together of a pair of straps or when the service load was applied to the straps. The parent plate has an average Vickers hardness measured under a 500 gf load of around 172 H_V equivalent to a tensile strength of 550 MPa, which is inside the specification for S275 steel of 430–580 MPa. The cold formed bends have hardness values in the range 248–287 H_V giving local tensile strengths in this critical region of around 783–905 MPa. The mechanism of fracture was brittle cleavage in all cases and the cause of the fracture was strain age embrittlement. The nitrogen content in these straps was low (<20 ppm) and the embrittlement was therefore driven carbon content and by any hydrogen exposure during pickling or galvanising. Interest-

Fig. 2a. Cold formed and galvanised strap that has fractured via strain age embrittlement during assembly by bolting.

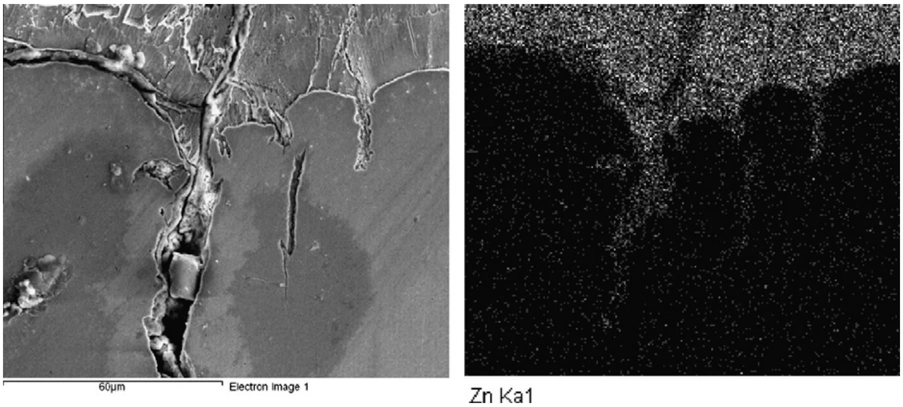

Fig. 2b. SEM image showing intergranular branched secondary cracks just behind the fracture surface. Energy dispersive spectroscopy in the SEM reveals zinc to have penetrated down these cracks, demonstrating that they were formed by LMAC.

ingly, the high local hardness values at the bend also led to some straps experiencing LMAC during galvanising, which was demonstrated by the presence of branched intergranular secondary cracks which had been infiltrated by zinc (see Fig. 2b).

The mechanism of intergranular reheat (or stress relief) cracking is very similar to strain ageing, although it is driven by the presence of other alloying elements that are responsible for secondary precipitation hardening. It can occur in the heat-affected zone or weld metal of low-alloy constructional steels, ferritic creep-resisting steels, nickel-base alloys and austenitic stainless steels [8]. The risk of reheat cracking increases with both the triaxiality of residual stress (which increases the hydrostatic stress component and reduces ductility) and with pre-strain [9]. It is therefore more often a problem in thick-walled pressure vessels with multipass welding which increases both weld constraint and pre-strain.

2.2. Hydrogen cracking

Hydrogen cracking [6] is an embrittlement mechanism that occurs readily when the hardness of ferritic steels is greater than perhaps 350 Vickers and a mechanism for fast hydrogen diffusion and entrapment is available. Hydrogen is highly mobile and soluble in molten steel and can therefore become trapped inside the metal if cooling rates are high, which also leads to high hardness values. Thus fusion welding processes can cause hydrogen cracking in the weld metal and coarse-grained heat-affected zone (HAZ), unless low hydrogen electrodes are used and pre-heat, interpass and post-weld heat treatment temperatures follow stipulated guidelines for the alloy being welded [10,11]. A further difficulty can arise in that various types of steel fabrications, particularly in refinery operations, absorb hydrogen during service. Welds intended to effect modifications or repair in these steels require careful attention to welding procedures and choice of consumables, if hydrogen cracking problems are to be avoided [12]. In practice this is likely to involve a pre-weld hydrogen-release heat treatment and conservative welding procedures, i.e. high preheat and low hydrogen consumables [12].

In principle, avoiding hydrogen cracking problems is relatively straightforward through control of hydrogen levels, the magnitude of residual stress, or the hardness of the local microstructure at potential crack initiation sites. The importance of proper temperature control before, during and after the welding process is clear, as it influences all three of these factors.

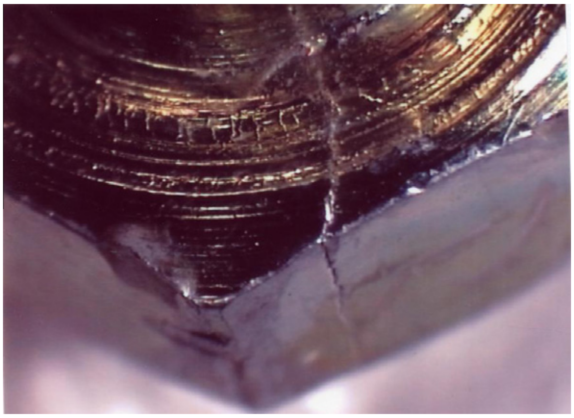

Fig. 3. Pre-existing forging lap in the head of the carburettor bolt.

In practice, small hydrogen cracks are quite common at highly constrained welds (thick sections, multipass welding and overlapping welds) and can then trigger other subsequent cracking problems during galvanising (either from LMAC or by additional hydrogen cracking which can occur during pickling or plating) or from fatigue crack growth during service.

As noted above, welding is not the only way that hydrogen can be introduced into a metal, and plating processes, e.g. cadmium, chromium and zinc, are all known to be capable of causing delayed cracking problems from hydrogen charging that occurs during the process. Plating conditions, in particular those relevant to acid pickling, offer one way of controlling the problems. However, post-plating 'baking' treatments are widely used to counter hydrogen cracking problems. For the case of cadmium plated mechanical fasteners effective baking typically requires 12–20 h at temperatures around 200 °C [13]. Fig. 3 shows the head of a yellow passivated zinc plated hollow banjo bolt from a carburettor which has split lengthways during tightening and led to fuel leaking out onto the engine. This failure started with what appeared to be a pre-existing forging lap in the head of the 4.5 mm diameter bolt, which had been machined from 10 mm hexagon steel bar. This forging lap is shown in Fig. 4, evidenced by the yellow passivated zinc plating on the outer edge of the fracture surfaces of the bolt head. The initial defect extended further by either hydrogen charging or intergranular LMAC during the zinc plating process. The defect by this time was large enough that the bolt experienced fast fracture under the tightening stresses.

2.3. Liquid–metal assisted cracking

The existence of localised regions of plastic deformation or small hydrogen-induced defects associated with the weld zone in structural components have also been implicated in severe cracking problems encountered during hot dip galvanising [14], where they can act as a trigger for liquid–metal assisted cracking (LMAC) during the galvanising process. The issue of LMAC has attracted considerable attention in recent years following changes in steel supply sources and in composition of the galvanising bath (to reduce lead content). The combination of these factors has led to a limited number of high profile cracking problems in galvanised steel structures which were detected only after a period in-service. Several excellent reports were compiled outlining the work done to understand the problem and to issue clear guidelines on design and galvanising

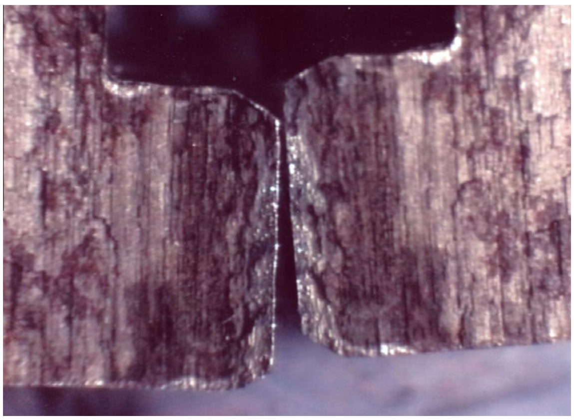

Fig. 4. Fracture surfaces of the failed bolt at about 7× magnification, showing yellow zinc deposits on the outer edges of the bolt head.

Fig. 5. LMAC crack some 1.1 m long in a hot rolled and galvanised low carbon steel I-beam.

practice, e.g. [14–16]. The type of problem observed in galvanising of steel fabrications and rolled sections is shown in Fig. 5 which illustrates a severe LMAC crack some 1.1 m long in a hot rolled I-beam with a depth of 208 mm.

The crack has initiated at a sharp rectangular cut-out approximately 65 mm long and 25 mm deep, near the end of the beam. Such a rectangular cut-out in the beam would have significant local plastic deformation and a high local stress concentration at the corner. The crack has started growing at perhaps 30° to the longitudinal axis of the beam. As it grew towards the centre-line of the beam it has progressively turned, eventually growing parallel to the longitudinal axis and finally arresting at a length of some 1100 mm. Published work has demonstrated that in a rolled I-beam the longitudinal residual stress demonstrates an "end effect" leading to the existence of a "tension bow" towards the end of the beam [17,14]. If a crack initiates from the corner of the cut-out this stress field can drive further crack growth. A finite element stress analysis by Feldmann [17] of the residual fabrication stresses in a rolled steel 'I' beam demonstrates that although the longitudinal stresses in the web are compressive, symmetry in the beam implies that they must form a "tension bow" along the centre-line near the free end (Fig. 6). Overlaying the shape of this tension bow onto the crack initiated at the cut-out corner in the cracked I-beam clearly shows how the residual stresses could drive growth. Crack growth would cause the tension bow to move along the beam, keeping pace with the crack extension, but with a steady decay in magnitude. This allows the crack to reach a significant length during galvanising before arresting.

The possibility of LMAC is greatly reduced by attention to galvanising bath composition, dipping rate as a function of component/fabrication size, and by attention to design detailing that maximises resistance to several cracking mechanisms [14]. Poor design details that increase susceptibility to cracking during galvanising include:

- Misalignment and poor fit-up, which can lead to undercut, lack-of-fusion, high local stress and strain concentrations, and high levels of residual stress.
- Welds coincident with other stress/strain concentrating features, e.g., punched holes, flame cut cope holes and edges, etc. Fig. 7 illustrates an example of LMAC from a drain hole in a large structural beam and guidance from galvanisers indicates that any drain holes in fabricated structures should be a minimum distance from welds of perhaps 4–5× the hole diameter.

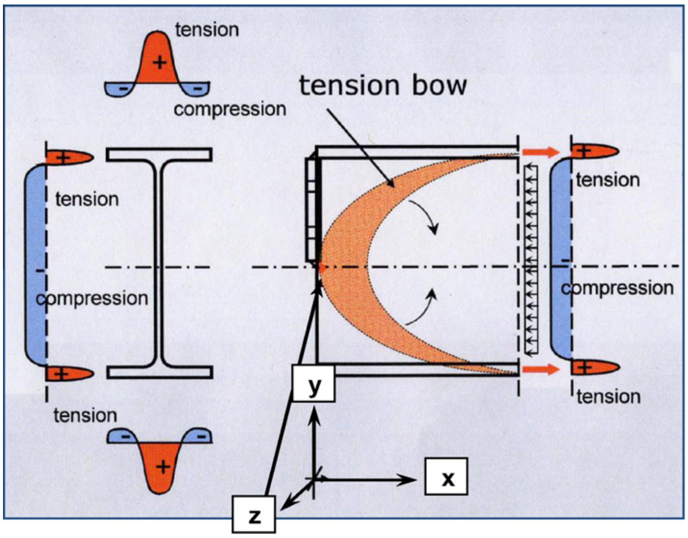

Fig. 6. Residual stresses associated with a rolled steel 'I' beam with a welded end-plate [17]. If the end-plate termination is at the half-depth position, it coincides with a very high level of tensile residual stresses and is a site of potential cracking. This stress distribution can also drive extensive cracking of the type seen in the previous figure.

Fig. 7. Cracking from a drain hole that was situated too close to a weld junction in a fabricated steel beam. Drain holes are added to allow molten zinc to drain off the galvanised item when it is removed from the bath, but they may be unnecessary and advice should be sought from galvanisers.

Fig. 8. LMAC that has occurred from the end of the intermittent weld joining a stiffener plate to a channel section250 mm deep.

- Joining of dissimilar thickness sections, e.g. thick connecting or reinforcing plates welded to the web or flange of I-beam, channel and other sections. This leads to high local strain concentration coupled with high local hardness differences and with weld defects (Fig. 8).
- Plate terminations coincident with regions of high fabrication stress in rolled or fabricated steel sections. This ensures an optimum combination, in terms of assisting crack initiation under either static or dynamic loading, of high local strain and stress concentration, weld defects and high tensile residual stresses, as evidenced in Figs. 5 and 6.

3. Effect of residual stresses on the buckling of columns

In the structural engineering community, it is well known that residual stresses affect the buckling resistance of steel profiles, e.g. hot rolled and welded columns, plates and cylindrical shell structures [18–20]. These stresses arise either from hot-rolling during the manufacturing process, which leads to unequal cooling of distinct parts of the profile after the rolling process, or from weld-induced residual stresses. In the case of beams these arise from fillet welding along the web-flange junction, whilst for stiffened plates they are due to the weld along the panel-web joint.

In shell structures, residual stresses can significantly lower the elastic buckling load, or even result in buckling occurring without any external loading. For more thick-walled shell structures, or for columns where buckling occurs in the plastic

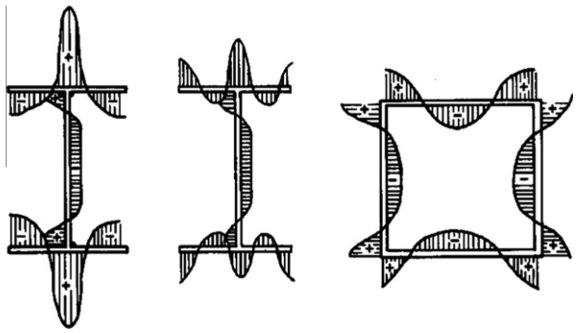

Fig. 9. Stresses from multiple fabrication operations are often termed 'reaction' stresses, which are superimposed on the welding residual stresses. They are balanced by reaction of other members and are not in equilibrium within one member. Their resultant force may then not act through the centroid of the member and this eccentricity lowers the critical Euler buckling load.

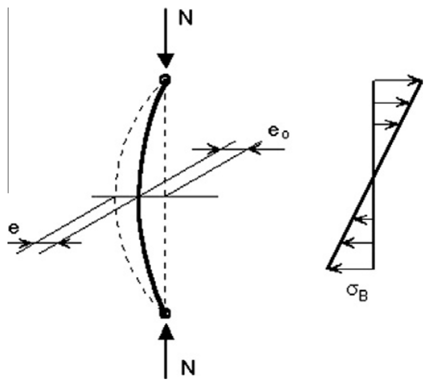

Fig. 10a. Bending stress induced in a column of medium slenderness ratio by an initial out-of-straightness.

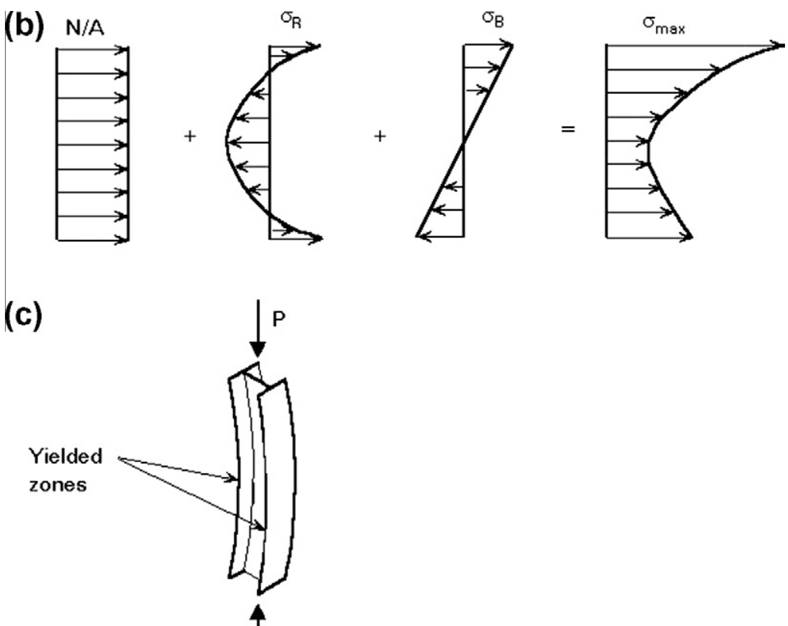

Fig. 10b and c. Adding the applied stress, $\sigma_A = N/A$ to the bending and residual stress components gives the value of σ_{max} and the consequent distorted column shape shown in the diagram [21].

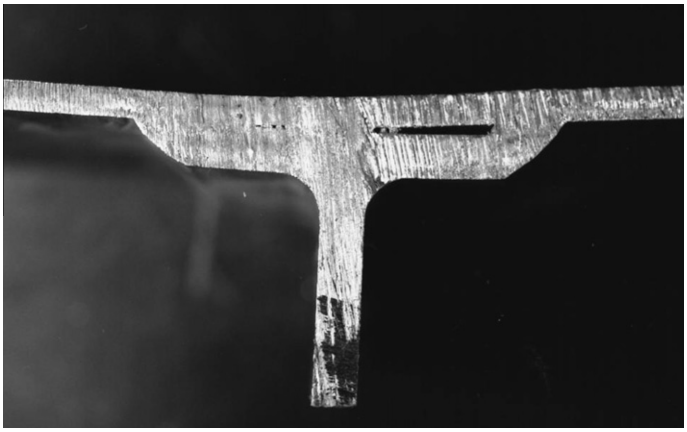

Fig. 11. Distortion caused by welding associated with the internal reinforcing at a typical panel joint in the aluminium fuel tanker.

range, the influence of residual stresses is mostly related to the earlier onset of plastic yielding with the corresponding loss of stiffness in some parts of the material. An additional effect arises if the column or section has a built-up shape where 'reaction' stresses resulting from multiple fabrication operations (Fig. 9) add to the weld-induced residual stresses such that the resultant force from these stress distributions either causes initial crookedness in the column, or acts at a position not coincident with the centroid of the cross-sectional area. The effect of residual stresses is most marked in the range of intermediate slenderness; in this case premature yielding reduces the bending stiffness and the struts buckle inelastically at a load below both the elastic critical buckling load and the plastic squash load.

The influence of an initial out-of-straightness e_o is demonstrated in Fig. 10a. It produces a bending moment giving a maximum bending stress σ_B (see Fig. 10a), which when added to the residual stress, σ_R, gives the stress distribution shown in Fig. 10b. If σ_{max} is greater than the yield stress the final stress distribution will be partly plastic and part of the member will have yielded in compression [21].

In thin shell structures residual-stress induced distortion near weld seams can have a significant effect on resonant frequencies of the structure. If one of the resonant frequency modes of the structure then coincides with an operational frequency, fatigue cracks can very quickly initiate at the welds. An example of the type of distortion which led to a severe cracking problem in an aluminium body fuel tanker, within 1600 km of road travel, is shown in Fig. 11. A very complex arrangement of internal bracing was used to stiffen the flat panel aluminium shell, and the welding was of very poor quality. Finite element analysis demonstrated that the distortion observed in the panels had altered the natural frequencies so that one of them now coincided with road-induced vibration at the cruising speed of the fuel tanker.

4. Origins and measurement of residual stress

Several excellent recent reviews have been produced which detail the types, origins and measurement of residual stresses, e.g. [22–24]. Residual stresses can be defined as either macro- or micro-stresses and both may be present together in a component. Macro-residual stresses, which are often referred to as Type I residual stresses, vary within the body of the component over a range much larger than the grain size. Micro-residual stresses, which result from differences within the microstructure of a material, can be classified as Type II or III. Type II residual stresses are micro-residual stresses that operate at the grain-size level while Type III are micro-residual stresses that exist within a grain, essentially as a result of the presence of dislocations and other crystalline defects. Micro-residual stresses often result from the presence of different phases or

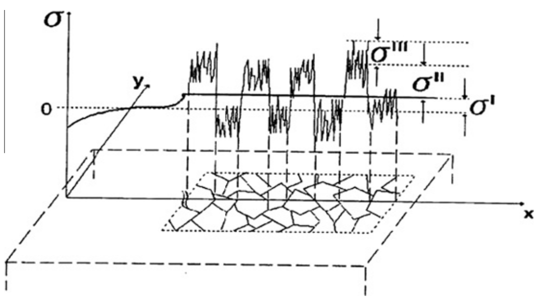

Fig. 12. Categorisation of residual stresses according to distance over which they self-equilibrate.

constituents in a material and they can change sign and/or magnitude over distances comparable to the grain size of the material under analysis. The different types of residual stress are shown schematically in Fig. 12 [22].

Residual stresses develop during most manufacturing processes intended to either transform the shape or change the properties of a material. They arise from mechanical, thermal or chemical influences and hence can be present in the billets or ingots of the unprocessed alloy, introduced during manufacturing or can arise from in-service loading. Mechanically generated residual stresses arise as a result of manufacturing processes that produce non-uniform plastic deformation. Examples of such operations are rod or wire drawing (deep deformation), welding, machining (turning, milling) and grinding (normal or harsh conditions). On a macroscopic level, thermally generated residual stresses are often the consequence of localised non-uniform heating or cooling operations. This can lead to severe thermal gradients and the development of internal stresses of the order of the yield strength. An example is the quenching of steel or aluminium alloys, which leads to surface compressive stresses, balanced by tensile stresses in the bulk of the component; severe quenching can cause intergranular cracking problems in the hard exterior case of a component. Chemically generated stresses can develop due to volume changes associated with chemical reactions, precipitation, or phase transformation. Chemical surface treatments and coatings can lead to the generation of substantial residual stress gradients in the surface layers of the component; for instance, nitriding produces compressive stress in the diffusion region because of expansion of the lattice and precipitation of nitrides, and carburising causes a similar effect.

Clearly, assessment of residual stress distribution is important in a number of areas of mechanical engineering but measurements of residual stress and strain fields have, until recently, been limited in terms of one or more of the following issues; ease of measurement and analysis, number of data points, penetration, reliability and repeatability. Latterly, however, very comprehensive non-destructive measurements of residual stress in small and large samples can be carried out following three linked developments:

- The commissioning of dedicated instruments at new generation high intensity synchrotron X-ray and neutron radiation sources, e.g. the European Synchrotron Radiation Facility (ESRF) and the Institute Laue-Langevin (ILL) in Grenoble, France; ISIS and Diamond at the Rutherford Appleton Laboratories, Didcot, England;
- The installation of associated automated 3D sample manipulation stages and loading rigs capable of precisely handling large structural components (with precision of spatial location ~10 μm);
- The development of user-friendly software to analyse diffraction data.

Alongside these achievements, new destructive techniques of assessing residual stress and strain have been developed [25,26] and more complex finite element modelling can be handled by high speed computers. It is therefore possible to obtain detailed experimental results from engineering components up to 500 kg in mass at depths of up to 50 mm (using neutron radiation) and perhaps 10–20 mm deep using third generation synchrotron radiation sources. There is thus for the first time an opportunity to understand the causes of residual stresses and interpret their effects on mechanical engineering performance in a much more comprehensive way, as well as to verify sophisticated numerical models for residual stresses development and distribution.

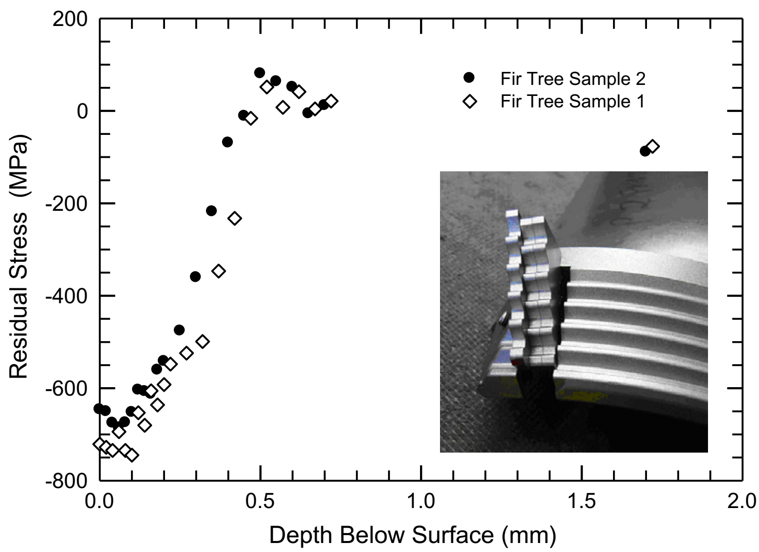

Fig. 13. Stresses measured over a distance of 2 mm below the first notch root in two adjacent LP steam turbine blade fir tree samples (shown in the inset). Stress values are consistent and have high magnitudes.

An example of the quality of data that can be obtained from synchrotron diffraction radiation experiments is shown in Fig. 13. The diagram shows the stresses measured below the root of the first notch in the fir tree attachment for two adjacent slices cut from a low pressure (LP) steam turbine blade similar to that shown in Fig. 1a. This work was part of a large programme of research aimed at exploring uniformity of coverage around the fir tree root and assessing the influence of shot peening coverage on fatigue performance of these blades [4]. Stresses have been estimated via a biaxial isotropic stress approximation and were measured using synchrotron diffraction on the very high energy beam line ID31 at the European Synchrotron Radiation Facility in Grenoble. In addition to this, measurements were made on beamline ID15B in similar positions on three complete blades, comprising one unused peened blade and two ex-service blades, one of which that had originally been peened whilst the other was unpeened. On this very high energy beam line it was possible to measure strains right across the 35 mm thick root section using synchrotron diffraction. Surface stress measured in the blades had maximum values between −300 MPa and about −500 MPa. These values can be compared with the peak surface values in Fig. 13 obtained under controlled and optimised shot peening conditions of between −625 MPa and −660 MPa.

5. Conclusions

Residual stresses are ever-present in engineering components and structures whilst their effects can be either highly beneficial (if compressive) or very detrimental (if tensile). Their influences span the complete range of size scales, from sub-micron for Type III microstresses to full structural dimensions for Type I macrostresses. Their effects depend strongly on interactions with environment, metallurgy and microstructure. Understanding their magnitude, influences and modification by stress engineering techniques, or during service, is critical to ensuring structural reliability and performance in many branches of engineering.

This paper has considered several areas where these residual stress interactions can lead to embrittlement or reduction in load-carrying capacity of structures. It has also put these difficulties into the context of the recent developments in advanced characterisation and modelling techniques which have unlocked very detailed understanding of stress-microstructure-crack-environment interactions, and have hence facilitated enhanced predictive modelling of complex aspects of structural integrity.

The remaining problematic area lies in providing an ‘intelligent’ interface between the structural integrity requirements, beamline physics and materials science. Knowledge of the way in which microstructure can influence the shape and definition of diffraction peaks, together with determining optimum crystal lattice directions on which to measure the residual stresses of interest [27] are crucial to interpreting the results obtained from expensive diffraction experiments. Consequently, the take-up by industry of the opportunities for adding value to their products offered by sophisticated European or national facilities has not been as widespread as would be desired. Nonetheless, current capability in understanding the origins and effects of residual stresses, from nano- to macro-levels, offers enormous potential benefits to academic and industrial researchers.

Acknowledgments

The European Synchrotron Radiation Facility is gratefully acknowledged for the award of beam time on beamline ID31 through experiment MA-326 (with Dr Alex Evans assisting as the beamline scientist), as is the award of FAME38 developmental beam time on beamline ID15A (Dr Thomas Buslaps assisting as the beamline scientist). The invaluable assistance of Dr Axel Steuwer and Mark Newby with the synchrotron radiation diffraction measurements is also acknowledged.

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