Residual Stresses: Their Causes, and the Effective Means of Treatment to Reduce the Residual Stresses and to Improve the Fatigue Life in Engineering Components

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Residual Stresses

Residual stresses are stresses that remain in a component after any external loading or forces are removed.
Residual stresses can be viewed as a form of potential energy, and the stress relieving, whether by thermal, peening, vibratory, long term storage (aging), or even by unintentional "bumpy" transport, act as a means of release of this potential energy. It has been observed for many years that a workpiece that has been final machined can often change shape during transport, outside of the final workpiece tolerances.
Residual stresses in metal structures occur for many reasons during the manufacturing processes such as hot and cold working, rolling, bending, forging, casting machining operations and the various welding processes.
In welding, residual stresses result from thermal strains during heating and cooling cycles of the weld metal and the adjacent heat affected zones (HAZ).
They occur in all weldment zones and at microscopic levels they develop due to the restraint of thermal expansion and contraction and with volumetric changes associated with phase transformation. Since residual stresses can affect structural behavior, it is important to be able to predict and model the residual stresses under different scenarios. The modeling of residual stresses is not an easy task as there are many different and often complex variables involved:

- Material types.
- Material thicknesses and mass.
- Component configuration.
- Design and manufacturing process.

Residual stresses can be classified into two different groups in accordance with the mechanism that produces them:

- Residual stresses produced by poor joint alignment and structural mismatch.
- Residual stresses produced by an uneven distribution of non-elastic strains of both mechanical and thermal strains.

The above are all possible with all welding processes. Residual stresses can also be produced when materials of varying lengths are forcibly connected (structural mismatch). Figure 1 shows a schematic diagram (*courtesy ASM Handbook Vol. 6, 1983*) of a three bar frame which can be used to explain the residual stresses that are caused by a structural mismatch.

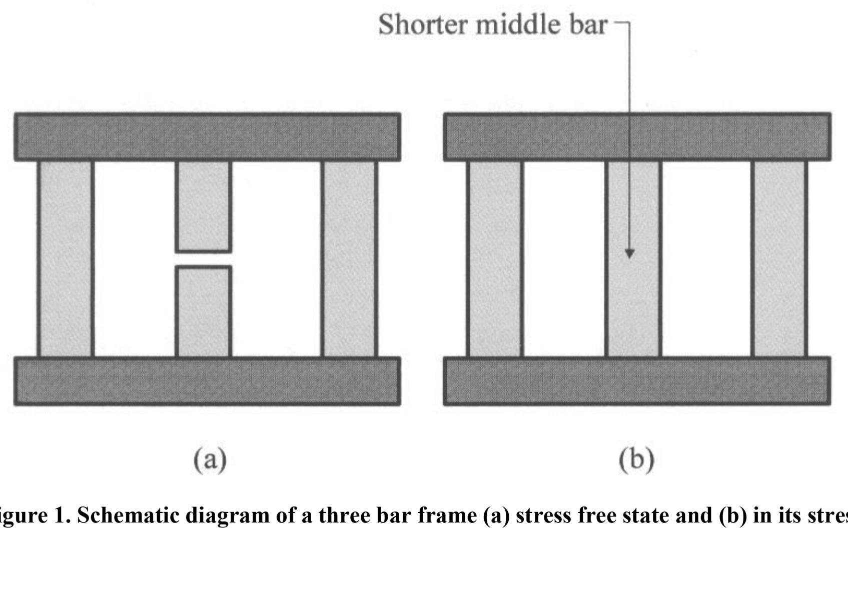


Figure 1. Schematic diagram of a three bar frame (a) stress free state and (b) in its stressed state

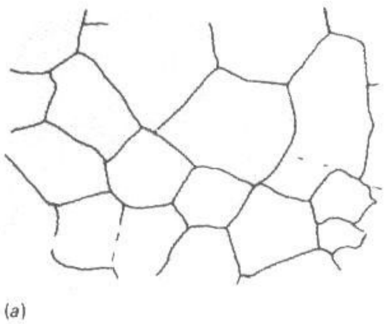
Tensile residual stresses are produced in the shorter middle bar and compressive residual stresses are produced in the longer outer bars. Following heating of the middle bar, the residual stresses in this bar decrease and may eventually become compressive due to thermal expansion and / or phase changes. A reverse scenario would occur upon cooling of the component.
Residual stresses can also be produced by an uneven distribution of non-elastic strains.
The majority of residual stresses produced by welding tend to occur by means of this mechanism. If a material is heated uniformly by means of a welding or an alternative heating process then the thermal expansion would occur uniformly and the thermal stresses would be greatly minimised.
In normal welding practice welding directs heat at the joint area only and the material or component is not uniformly heated and as a result thermal stresses are produced. The magnitude of these stresses is even greater when the welded joint is restrained or poorly fitted.

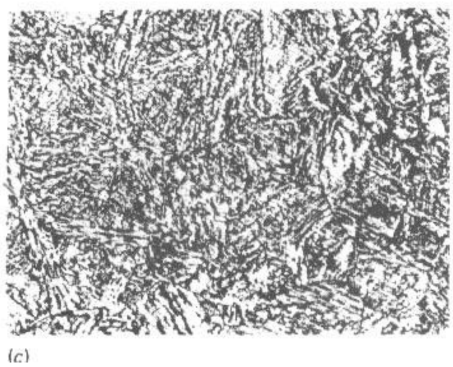
A common method of classifying residual stresses is by the region in which they are located. In this classification there are **macroscopic** and **microscopic** residual stresses (*ASM Volume 6, 1983*).
Macroscopic residual stresses occur over a long range, extending over the macroscopic dimensions of a component. In all welded structures, residual stresses are produced in regions around the weldment.
Microscopic residual stresses are of a short range, and on the smallest of scales, they result from the misfitting of solute atoms and individual dislocations. On a slightly larger scale, residual stresses can be produced by dislocation pileups, kink boundaries and diffusionless shear transformations. These developing localised strains are associated with localised accommodation stresses. It is these types of microscopic residual stresses that play fundamental roles in plastic deformation, and the growth of fatigue cracking.

Another example of the production of residual stresses on a microscopic scale is the formation of martensite. The low temperature and fast cooling rate typical of the martensite reaction in steels is associated with a volumetric expansion and subsequent localised residual stresses are produced (*A.C Davies Metallurgy 1999*). Residual stresses may also be present in inhomogeneous solids when a new phase precipitates out of a solid solution.
There are many reasons or mechanisms by which residual stresses occur. Apart from the martensitic transformation and formation of precipitates out of a solid phase, other examples include:

- Decarburisation at the surface in the presence of an oxidizing atmosphere resulting in a decrease in volume and an introduction of tensile residual stresses in a thin layer where decarburisation has occurred.
- Nitriding – heating in an ammonia atmosphere allows nitride formation thus hardening and slightly expanding the steel.

Fig.2
(a) Austenite in an 18% chromium 8% nickel steel etched to show the grain boundaries x 500
(b) Martensite x 250
(c) Bainite in a low chromium nickel and molybdenum steel transformed over the temperature range 430˚c - 570˚c x 500





The examples given may all be possible during welding of steel due to the extreme process temperatures and other variables (gas flow rates, purging etc.). Certain welding procedures can produce greater residual stresses than other welding procedures and therefore expertise is required to develop procedures that can minimise the induction of residual stresses.

Residual Stresses Related to Welding

Welding is one of the most common causes of significant residual stresses. The cooler parent metal restrains contraction of the weld metal upon cooling leading to inevitably large residual stresses.

Moreover, phase and volumetric changes at the microscopic level also contribute to the residual stress phenomenon during welding. Being able to predict and model residual stresses in different weldment configurations is important is assessing the possibility of failure. Modeling of residual stresses is not a simple task; there are many variables involved:

- Temperature.
- Time.
- Weld geometry.
- Thickness of material.
- Joint restraint.
- Weld sequences
- Heat input and cooling rates.

Residual stresses in welding occur owing to localised heating and there is an abundance of non-uniform temperature profiles (*ASM Volume 6 1983*).

Figure 3 shows a schematic representation of the changes in temperatures and stresses during the welding process. Plane stresses are also shown implying the stresses are uniform in the thickness direction.

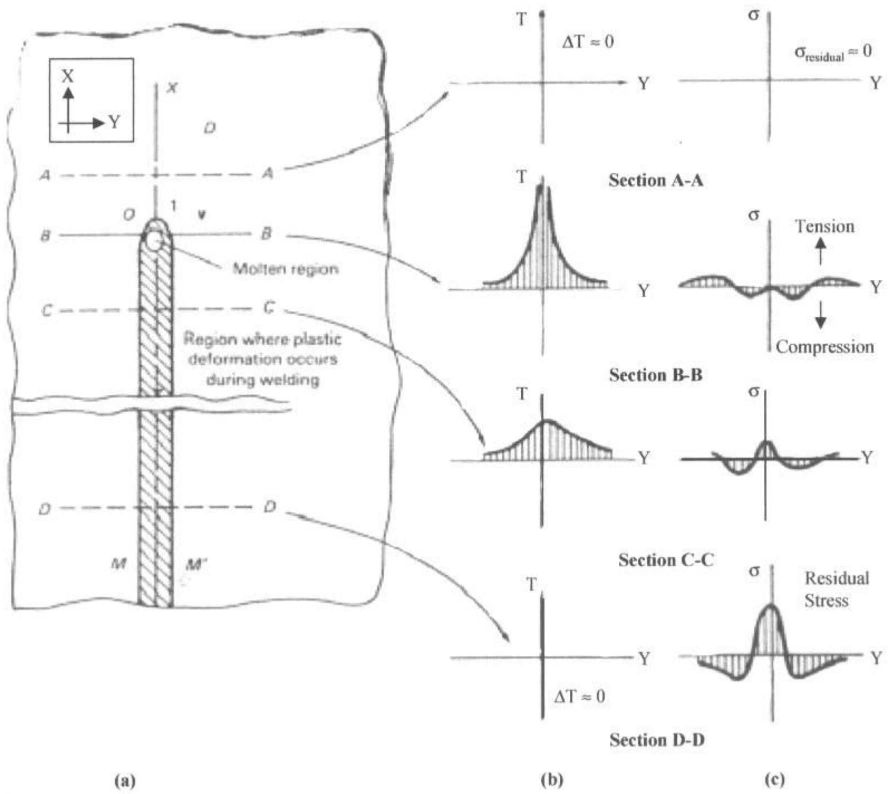


Fig 3 (a) Schematic representation of a single run butt weld and associated (b) temperature and (c) stress changes. (*Courtesy ASM Handbook Vol.6***)**

In fig 3(a) the weld is shown by the shaded area. The molten weld pool region is shown by the origin; O. Fig 3 (b) shows the varying temperature profiles along with different sections with section B-B bisecting the molten region and section C-C being a close distance from the weld pool in the solidified weld. As is to be expected the greatest temperature gradient is at the weld pool as shown in section B-B. Fig 3 (c) shows the residual stresses as a result of the welding. Section A-A ahead of the weld bead on the parent metal shows no residual stresses. In the melted region B-B there are thermal stresses present but they are close to zero because the molten metal is unable to support any load. In regions away from the arc where cooling is taking place, the stresses are larger due to the lower temperature and contraction restraints.

The maximum magnitudes of compressive stresses and tensile stresses occur at D-D where the tensile stresses peak in the cooled weld metal and compressive stresses peak in the surrounding parent metal.

This is more clearly detailed in Fig 4, where the distribution of stresses in a butt welded joint can be easily seen.

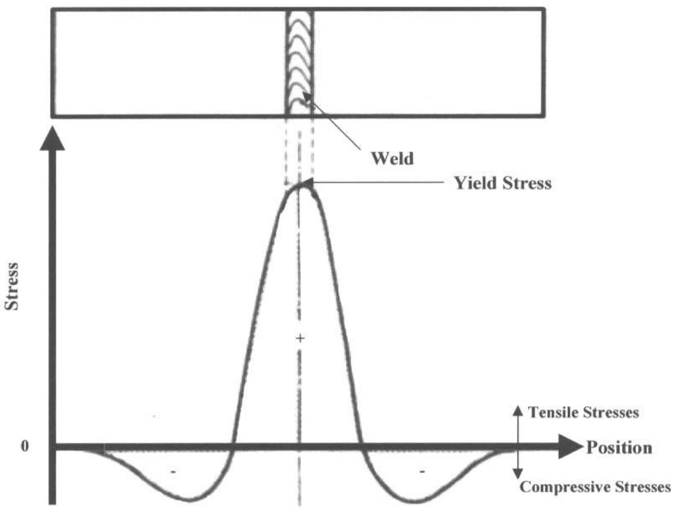


Figure 4: The distribution of stresses in a single pass butt weld (*Lincoln Arc Welding 2004*).

The residual stress pattern in Fig 4 occurs in materials of rather low thicknesses, in thick plates there is a contraction stress at right angles to the plate surface and consequently the stress field may intensify progressively as the joint is filled up with weld deposits. Figure 5 shows residual stresses measured before a short (15mins) and a longer (40hrs) post weld heat treatment, measured by remanent magnetism along the center line of a submerged arc weld in a ±160mm thick plate ±650mm long.
The curves in Fig 5 details the residual stresses in three directions i.e. stress in the longitudinal direction, the transverse direction and the short transverse direction which is perpendicular to the root face.
It also demonstrates that residual stresses can either be compressive or tensile along the thickness of the plate, and a lengthy post weld heat treatment can result in the redistribution of residual stresses to one plane.
This was also established in 2003 in South Africa with test plates welded by the South African Institute of Welding in Johannesburg and the research and testing carried out by Ms. Vanessa Naicker, Technical Manager of Anglo American. A short treatment with Vibratory Stress Relieving brought about the same results. A dramatic reduction in residual stresses was gained with the remaining stresses redistributed through to the longitudinal direction.

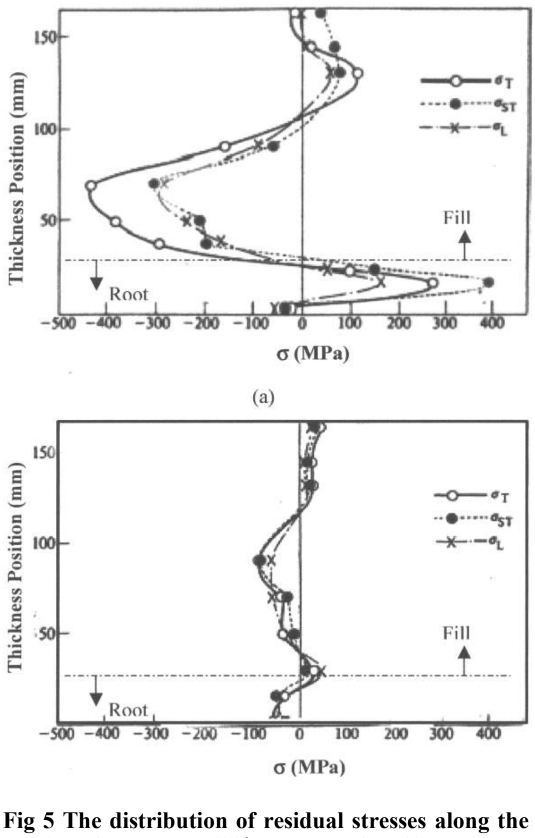


Fig 5 The distribution of residual stresses along the centre line of a single Vee submerged arc weld in 165mm thick plate (a) after 15mins of PWHT at 600˚c and (b) after 40hrs of PWHT at 600˚c (*Suzuki et al, 1978,pp 87-112*).

Stress Relieving - Various Means of Reducing Residual Stresses

The most well known method of stress relieving is by heat treatment. Other equally effective methods of stress relief are typically mechanical.
These include localised peening (sound operator experience required) shot blasting (up to 8% stress relief owing to surface compressions), hydrostatic testing (monotonic overload situations for small pressure vessels) and vibratory stress relieving (results equal to and in some cases better than heat treatment).
All of these techniques are discussed along with their possible drawbacks in the following sections.

Heat Treatment (furnace methods)

Thermal stress relieving involves heating a component to a temperature at which the material yield strength has fallen, allowing creep to take effect. Large residual stresses are no longer supported and, if the temperatures are high enough the stress redistribution will become more uniform across the component. Typically on most carbon steels this temperature would be around 570˚c - 650˚c although local codes or specifications often dictate otherwise as indicate below in Figure 6.

	ANCC(3)	ASME(4)	BS(5)	DnT(6)
Plain C/C-Mn	600-650	>593	580-620	550-600
C-½Mo	620-670	>593	650-680	580-620
1Cr-½Mo	630-680	>593	630-670	620-660
2¼Cr-½Mo	660-710	>677	680-720	625-750
5Cr-½Mo	680-730	>677	710-760	670-740
3½Ni	550-610	>593	580-620	550-590
9Ni	By agreement	Not specified	Not required	Not specified

Figure 6 the variation in the temperature requirements of different codes!

From these details it can be deducted that considerable variations exist between the different codes of practice, reflecting their diverse origins and the arbitrary nature of their derivation. For this reason care has to be exercised in applying the recommendations of codes of practice. Whatever the specific requirements, control of temperature at all stages of heat treatment is essential, and to achieve this, the heat flux / temperature of the items must be reliably monitored.
The ease of control of temperature distribution depends greatly on the method of heating, e.g. electric radiant elements, gas-fired radiant elements, or gas fired with forced circulation.
The last method is able to overcome one of the most common problems, i.e. convention, which causes the roof of the furnace to become significantly hotter than the floor. This can be overcome in other methods, e.g. electric elements, by suitable distribution of the heating units to bias the heat flux preferentially towards the lower part of the furnace. Ideally, each heating unit should be independently controllable and linked to the monitoring system.
The number, position, and mode of attachment of the thermocouples are important in the generation of confidence in the achievement of the required thermal cycle.
In this respect at least the top and base of large items should be monitored, as should any attachments of substantial thickness.

Disadvantages of furnace treatment are many the most common being that commercial heat treater's operate on tonnage as it would be obscenely expensive to fire a furnace for only one component, although this would produce far superior results.
A typical furnace may hold 40 ton of components of varying shapes size and mass coupled with many different material compositions. This results in many components obtaining too much "soak time" and others undergoing improper cooling cycles as the treatment time is normally calculated upon the mass of the largest item.
Where temperatures are too high or soak times are prolonged, undesirable loss of material properties can occur e.g. hardness, yield strength, fatigue life and the tensile properties. Codes of practice provide only general guidance and many practical aspects of heat treatment receive only scant attention. Two of these, which deserve special consideration, are the physical support and the importance of the correct temperature measurement.
The loss of strength with increasing temperature upon which effective heat treatment depends, can lead to distortion if the item is not properly supported, or if its own natural stiffness is insufficient to support its own weight.
Thin walled, large diameter, vessels without internal stiffening are particularly susceptible to the latter, and the provision of temporary internal stiffening for the purposes of heat treatment is advisable in such conditions.
Large furnaces are normally only available in the major centres and this often results in high transport costs and excessive component downtime.
Lastly but by no means least with the ever increasing environmental concerns one must mention the high energy consumption and pollutions associated with the large heat treatment furnaces. In 2001 The US Department of Energy estimated that through the use of VSR a total of almost 1,6 million tons of carbon emissions were reduced and in excess of $300 million were saved from the reduced natural gas usage associated with large furnaces.(*US facts and figures courtesy Bonal Technologies*)

Localised Heat Treatment

There are frequent occasions when the item requiring thermal treatment is part of a larger fabrication which is either too large, or inconvenient, to heat as a whole for financial or technical reasons. In such circumstances local heat treatment is preferred.
This is done using ceramic elements surrounding the resistance heating wire. The cheapest kind are the finger element heaters. By connecting a series of these elements in parallel a flexible pad is produced, which may be wrapped around a cylindrical surface and they are covered with an insulating material to conserve heat.
The power source is often from a welding unit or an auxiliary transformer at 60-80v. These tend to be most suitable for piping applications and control of welding interpass temperatures.
Braided heaters are rather more costly and much less durable, but they offer great advantages in terms of size range, power ratings, and temperature control.
The above types are being overtaken slowly by the flexible ceramic panel type of heater, which combines the more important advantages of both at the expense of initial cost.
Where the items to be heat-treated are large in number and are of invariate shape, the use of custom-built heating units becomes economically viable and offers the additional advantages of greater technical control and reproducibility.
The circumferential joints in pipelines are a good example of such an application as shown below in Fig. 7

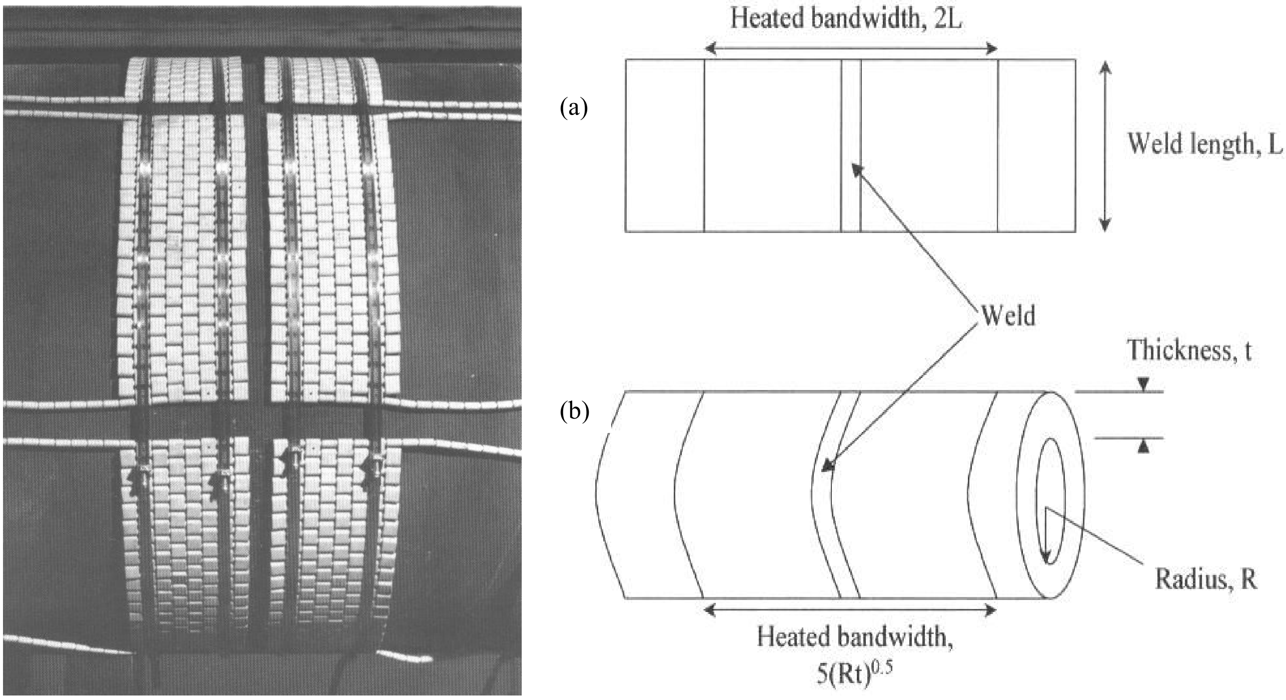


Fig 7. Localised heat treatment showing flexible ceramic heating pads in position on a 1.2m diameter vessel with a wall thickness of 25mm and (a) butt welded plate (b) butt welded pipe showing the correct bandwidth for the heating elements

The temperature in localised heating, which usually does not exceed 250˚c, should extend for at least 75-80mm on each side of the welded joint. Post weld heat treatment temperatures, usually in the range of 590-760˚c, reduce internal stresses and help to soften hardened areas in the heat affected zones. The work is heated to a given temperature, held at this temperature for a given soaking time, and then allowed to cool, both heating and cooling being subject to a controlled temperature gradient such as 100-200˚c per hour for thicknesses up to 25mm and slower rates for thicker plates
The technical limitations of such treatment by definition give rise to thermal strains and, since a change in temperature of 100°c in ferritic steel causes a change in length equivalent to yield strain, the thermal gradients occurring during such treatment must be controlled to avoid the introduction of another pattern of residual stress following cooling. Most codes of practice give recommendations concerning limitations to be applied to temperature gradients during local treatments by specifying minimum heated band widths and lagging etc.
Despite such general guidelines care has to be exercised in applying heat treatment to complex items, particularly box shaped structures with internal members that may be shielded from the primary heat flux. ASME VIII, Div.1 specifically draws attention to this type of structure and the need to monitor temperature gradients much more closely. Other configurations, which require additional consideration, are multiple thick walled penetrations into a vessel.

Radiant Heating

This exploits the heating properties of infrared radiation which may be generated either by firing ceramic elements with gas, or from a tungsten quartz lamp. The efficiency of the method depends on the absorpitivity / emissivity of the item which is dependant both on the material being treated and on its surface condition. The method has an immediacy of control, which can be used in conjunction with quite complex feedback systems without problems of hunting about the desired level. This technique also has the advantage that the heating units may be contoured to shape as required, and is also able to cope adequately with local variations in heat sink. Further advantages are its general applicability to preheat type operations and comparatively low operating costs.

The alternative quartz lamp method has a better heating efficiency, but is much less robust, needs careful control to keep down heating rates to acceptable levels, and involves high capital costs. It is generally better suited to low emissivity materials such as stainless steel in clean controlled conditions.

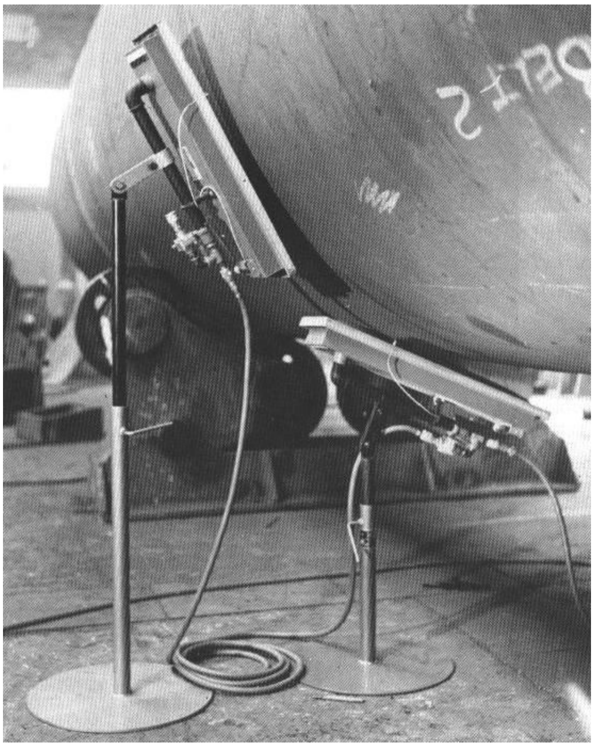


Fig 8 Radiant heating with surface combustion using propane or natural gas to maintain an even interpass weld temperature control

Reliable temperature measurement is vital to all heat treatment operations, and without it such exercises are almost worthless. Where the exact temperature attained is not critical, temperature-indicating crayons may be used to establish a range within which the heat treatment has been carried out. Similarly, radiation detecting pyrometers are being increasingly used to monitor the temperature of items passing through metal forming operations requiring inter stage heat treatment. The preferred and generally only suitable method to monitor the temperature of stress relief heat treatment is by a thermocouple attached to the workpiece. Furnace thermocouples are of little benefit unless the parts being heat treated are of a standard size and shape, and are always distributed within the furnace in the same manner, and reliable correlations between furnace temperature and item temperature have been established for all parts of the furnace. The method of attachment of the thermocouple to the workpiece is most important.

The junction of the two wires should be at the surface and not some distance from it, and should be protected from direct radiation from the heating elements and from the circulating atmosphere of the furnace. Similarly the number and distribution of thermocouples on the item(s) must be sufficient to monitor the greatest variations in temperature that are likely to arise. If attention to these details is inadequate the heat treatment will not be reliably monitored, and the consequences of this can be severe.

In addition to the benefits that heat treatment confers in reducing residual stresses and improving the mechanical properties of HAZ’s, it can cause deterioration if incorrectly applied.

A common problem in thick structures is that yield strength is reduced if treatments are extended. In this respect it is essential to avoid heat-treating tempered steels above their tempering temperature; otherwise degradation of the mechanical properties is a certain unwanted factor.

Creep properties may also be affected in this way. Heat treatment also has a variable effect on weld metal fracture toughness, which in many instances is reduced by the modification of retained phases.

A potentially serious problem associated with postweld heat treatment is its side effect on the results of ultrasonic tests. Often the plastic strain that accompanies stress relaxation causes small fissures or other minor weld defects to open up slightly during heat treatment. This tends to raise the intensities of reflected signals and cause indications, which passed the acceptance standard prior to heat treatment to become unacceptable to the relevant code following heat treatment.

Monotonic Overloading.

Overloading techniques involve the relaxation of stresses by permanent yielding via the hydrostatic test or the warm pressure test. Overloading techniques combine loading generated by external pressure together with the presence of residual stresses. A single overloading above the yield stress results in a decrease of any residual stresses. The overloading technique generates compressive residual stresses around existing defects with a beneficial effect upon brittle fracture.
During the increase of pressure, external loads are added to the existing residual stresses causing localised plastic deformations. As the pressure is released, the elastic retention produces residual stresses that play the favourable role of prestressing (*International Institute of Welding, 1987*).
The hydrostatic test is a mandatory test for pressure vessels conforming to AS1210 or AS 4458. Limitations to the suitability of the process for stress relief include:

- The question of compensating pads and attachments receiving adequate stress relief.
- Reaching the required stress levels for conservatively designed road tankers (*Epselis, 1996*).

Monotonic Overloading is generally achieved by simple mechanical loading, either by pressure in a vessel or a closed pipework system, or by a weight in lifting gear or a simple framework.
Most critical fabrications are subjected to such an overload treatment in a proof test prior to being put into service, and may be subjected to further tests during service to ensure that degradation of performance has not occurred.
The reduction of residual elastic stress is effected by the conversions of stored elastic strain to plastic strain, (see Fig 9).
This method however has two major disadvantages:

1. The first is that it can be applied only to closed pressure-containing systems or simple fabrications of comparatively small size.
2. The second is that the stressed regions may not be able to withstand the extent of plastic strain involved and may require some prior treatment to eliminate any brittle behaviour.

This is particularly so for welded structures where maximum tensile residual stress levels tend to occur in areas of greatest metallurgical deterioration. For this reason most codes of practice require structures above a certain thickness, which depends on material type, to be thermally treated prior to proof testing, and the avoidance of brittle fracture is one of the principal reasons for carrying out a postweld heat treatment.

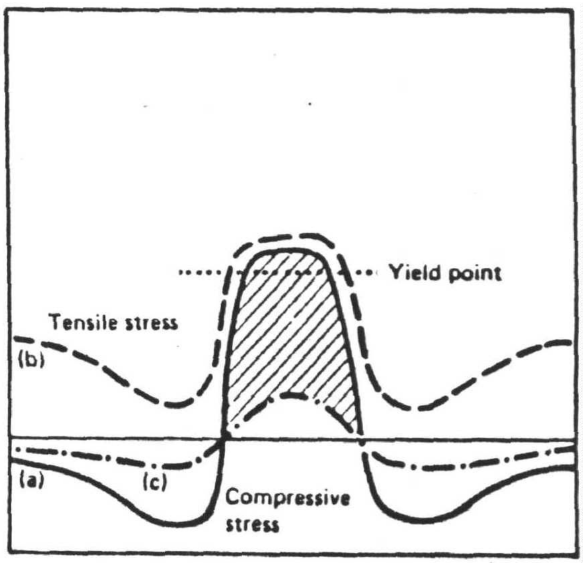


Figure 9

Mechanical relaxation of residual stress by application of tensile force: (a) initial residual stress field, (b) apply tensile force causing plastic deformation in regions of peak stress and converting elastic strain to plastic strain, and (c) remove tensile force leaving a small residual stress field. ______ AW; _ _ _ _ proofloaded; _ . _ . . unloaded stress relieved; shaded area indicates the region of conversions from elastic strain to plastic strain.

Shot Peening

A local form of overload can be applied in the form of peening. This can be employed to reduce general residual stress levels in as-welded welds or to control distortion, but is used principally to improve the fatigue strength of welded joints by the introduction of a local compressive stress field close to the weld toes.

Shot peening is a surface cold worked process that is used to minimise the potential for fatigue, stress corrosion cracking and other modes of failure. Peening works on the principle of introducing residual compressive stress into the surface layer of the material by bombarding it with small very high velocity media more commonly called shot.

It is well known that cracks will not initiate or propagate in compressively stressed zones. This delays the initiation and the early growth of cracking, thereby achieving a significant increase in fatigue life. However excessive peening can result in the formation of many small cracks, but in practice these have not been observed to affect the components fatigue life.

Since numerous failures are initiated at the surface of components, compressive stresses induced by shot peening can considerably enhance the life of a component.

Shot peening has made considerable advancements over the years but a lot further work is required in the area of shot media, shot velocity measurements, engineering models and non destructive testing to measure residual stress profiles to avoid such pitfalls as irrelevant applications and inappropriate and incorrect peening methods.

The object of controlled shot peening is to produce a compressively stressed surface layer so that the magnitude and uniformity of stress and depth of layer, can be constant over the whole of a component and between components. Control of the process becomes essential where it is impossible or impractical to inspect the stress distribution on a finished part.

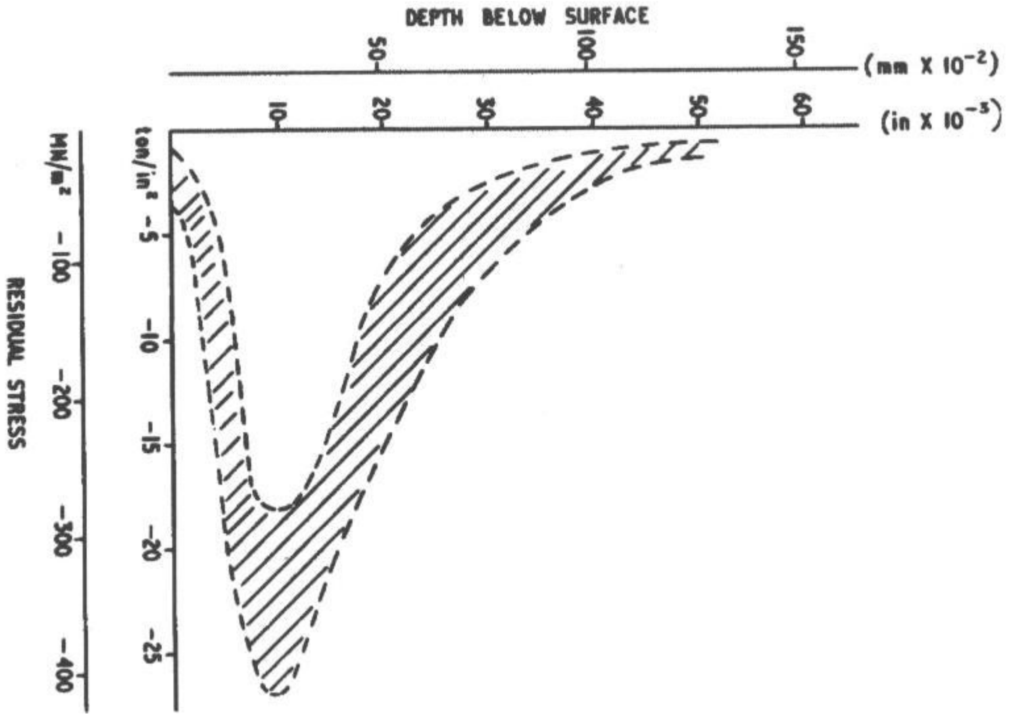


Fig 10 Residual Stress versus depth curve for shot peening for a variety of joint designs and for an unwelded sample

Other forms of surface mechanical treatments are as follows:

- Needle Peening
- Hammer Peening.
- Roller Burnishing.
- Roto Peening.
- Grit Blasting.

All of the above methods if correctly applied would give results equal to that of shot peening, but one must remember that any form of peening is a localised surface treatment only, with its effects more suited to welding induced residual stresses.

Peening combined with a thermal or vibratory treatment upon completion of welding would produce exemplary results in terms of low residual stresses, even stress redistributions and complete component stability in service. This method is of particular benefit to critical tolerance fabricated and then machined items such as bases and jigs as used in the automotive and aerospace industries worldwide.

Vibratory Stress Relieving.

Effective vibratory stress relieving treatment can be carried out on a production basis, providing that changes in the workpiece's resonance pattern are carefully monitored. Stability of the new resonant pattern is indicative of completion of the vibration treatment. These changes are consistent with the workpiece's increased mechanical response to dynamic loading.

An ever increasing number of manufactures of precision components use vibratory stress relief from many diverse industries such as vehicle manufactures, armament manufactures through to heavy mining industries reveals regular applications of the technology upon wide ranges of workpiece's, materials and various component configurations.

In many applications vibratory stress relieving completely replaces thermal stress relieving particularly upon components that respond marginally to thermal treatment, stainless steels weldments being one of the most common examples.

Often thought of as "new technology" the origins of vibratory stress relieving are far distant. The history of which can be traced back to the late 1930's. It was first developed as a fatigue test during World War 2 and was used by both the German Air force and the US Navy as a means of testing aircraft wings and boat hulls.

Vibratory Stress Relieving is a natural resonant / sub resonant treatment process for neutralizing unwanted stresses from metal structures, fabrications or castings. It may be helpful to relate Vibratory Stress Relieving as being similar to the natural ageing stress relieving concept. The ageing concept however has been generally discontinued for industrial use because of the lengthy time required to obtain the desired result. VSR however will do in approximately 30 minutes what ageing took two years to accomplish.

With the exception of the practice of "ageing" the traditional method of stabilizing engineering components has been to treat them thermally. For over sixty years, engineers have been attempting to obtain equivalent or better results with diverse vibratory treatments; this need was partly met by using dc rotating mass systems. These systems largely gave way to the ac rotating mass systems in the early seventies, more so where the requirements called for supreme stability and accuracy. The superiority of ac VSR systems coupled with the ease of application has become widely accepted by industry and researchers alike. With the latest VCM 905 systems developed in the late nineties with enhanced force and frequency ranges traditionally difficult areas can be tackled, further reducing the role of thermal stress relief.

Many attempts have been made to establish what happens inside material during the vibratory process.

With few exceptions research at universities was carried out using tensile test machines, rotary bending fatigue rigs, or oscillatory electromagnetic vibrators.

Some closely simulated a VSR system, others bore no relationship at all, and unfortunately the results obtained were referred to as Vibratory Stress Relieving, and this caused grave misunderstandings and distrust of the process.

Conclusions reached included: nothing at all, cyclic versions of a simple stress overload and the beneficial effects of vibration on the distorted lattice of the material.

More recently, with the advent of the 5-240 Hz VCM systems, both private research and other papers have shown reductions ranging from 40 – 87 %, all using the resonant approach. While the high imposed cyclic stresses are elastic and kept well within safe limits by the natural damping of the component, they do not permit the imposed strains to add to the residual strains and cause local plasticity at points or areas of stress concentration.

Following a series of such resonance's each within a different imposed strain pattern, very substantial lowering and redistribution to low levels of the overall stress field is achieved.

Generally, academic and industrial research indicates that where VSR is applied and, or in the case of supreme accuracy and stability re-applied a second time at near finished machine size, the results have been better stability and accuracy than is available using thermal stress relief.

The use of vibratory stress relieving has increased dramatically over the last three decades. The reasons for this rapid growth include:

- The finding that thermal stress relief is, in practice less effective on certain types of workpiece configurations. Large variations in wall thicknesses of a workpiece or its topography characterise two such types.
- Stress relieving before and after rough machining improves dimensional stability. This is practical with VSR but often impractical, if not in many cases, totally impossible with thermal treatment.
- Weldments made out of 300 series, austenitic stainless steel, and all non-ferrous materials which require good dimensional stability, are more effectively stabilised with VSR than with post weld heat treatment.
- The ever increasing use of low-carbon, high strength steel, post weld heat treatment of these steels risks either reduction in strength or toughness. Certain grades also suffer an increased risk of cracking as a result of PWHT. Of the 141 ASTM grades of steel listed in the International Steel Group Plate Steel Specification Guide, 43 carry the warning that PWHT "may degrade heat affected zone strength and toughness"; whilst 11 others also "may be susceptible to cracking in the heat affected zone of welds during PWHT or elevated temperature service"!
- The time taken to VSR treat a component is only a fraction, (normally 30:1) of that required to thermally treat the same component or to carry out PWHT, plus the ability to treat virtually any size or weight of component on site.
- The ability to treat components at the client's premises further reducing downtime and large costs as transport costs are eliminated with the usage of VSR
- The increased cost of fuels and their environmental consequences (pollution) which is associated with furnaces of which more and more countries and international organisations are expressing their concern about.

VSR Equipment.

VSR machines drive high-performance rotating mass vibrators. The equipment is portable and can be divided into ac and dc motor types. At low frequencies either can be used, but with dc types the frequencies are limited to 100Hz due to poor service durability. Over the years work pieces have been re-designed to be stiffer, thereby increasing resonant frequencies. Many components need treatment at frequencies well in excess of 100Hz. British made ac equipment can produce frequencies of up to 250Hz with high "g" force tolerances.

Manufacturers of dc equipment have tended to make a virtue out of a necessity by emphasizing non-resonant vibration, particularly in the United States. This low frequency, non-resonant approach has applications on fairly solid castings and for vibration during welding where it can reduce distortion, lower stresses, refine weld material, improve dilution, reduce cracking and increase deposit rates.

Either type of equipment can be used for such applications but only ac systems have the frequency range to treat at resonance, particularly at higher frequencies and higher 'g' forces. As a guide, the frequency range is 10-240Hz and the range of vibrators available produces a top force of 1700kgf.

Drive units weigh as little as 20kg and vibrators 24-28kg dependant upon the type.

Drive modules can have phase-phase, phase-earth output protection, and the supply is typically 15A, single-phase, 220/240V, 50Hz. 110V units are also available on special order.

For quality control purposes, chart recorders are available which can provide a permanent record of treatment. The wide speed range makes it ideal for frequency response testing as well as for stress relieving.

A recent survey indicated that 96% of VSR units in the UK are ac units. In South Africa the number of ac units in comparison with dc units is 98%, certainly testimony to their effectiveness.

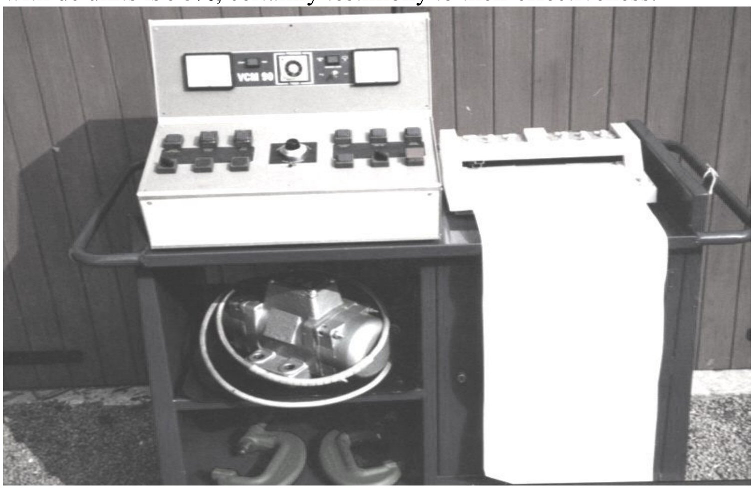


Fig 11 A Typical British made ac system two exciters are supplied as standard

Equipment Development.

Rotating mass vibrators have been used for vibratory stress relieving since before 1940. Oscillatory vibration was thought to be a feasible alternative and in the USSR components have been treated, strapped to rams of oscillatory vibrators. These were of fixed frequency and non-portable. Results were poor and latterly the Russians have been importing modern ac VSR systems. Generally, it has been the attainment and maintenance of resonance or a succession of sweeps through resonant conditions that have been sought. Early equipment had limited scope and, because of the size of the vibrators and associated control gear, units were non-portable. In the early sixties, advances in electronics made it possible to create portable control consoles. Lightweight 1hp dc motors had weights added to their spindles and were called vibrators – the whole process became fully portable, but the systems lacked any finesse and the vibrator life was short.

Soon, real vibrators were harnessed to hand-portable control consoles and advantages resulted, but components were being redesigned to be stiffer. Many were made of fabricated mild steel instead of cast iron. The equipment was found wanting with respect to lack of frequency range for the stiffer components that resulted. To deal with this an Anglo-American company tried to stretch the dc standard motor beyond 80Hz but without success. In 1970, a London company produced a 0-150Hz dc system, which failed after only two sales-the vibrators shook themselves to pieces. Meanwhile, dc equipment manufactures were emphasising vibration at relatively low frequencies and high forces during welding. This had two attractions for them (1) it was unnecessary to exceed the 80Hz threshold and (2) vibration during welding required more vibrations for longer periods. The method, when optimally applied, had some merit in that it reduced distortion, lowered stresses, refined the weld material, reduced cracking and increased the deposit rates by virtue of the lower bead profile produced. However, then as of now, it was difficult to optimise.

A lot of research and development is needed before it can be generally applied and research is currently underway (2005) at The University of Cape Town to determine the merits of vibration during the welding process or as it is commonly called "weld conditioning". To date no benefits have been found on butt welds in normal carbon steels although the process may have its applications on non ferrous steels and certain brittle castings.

Procedure.

Research has consistently shown resonant treatment to be the most effective. Depending on accuracy, stability required and convenience, VSR is normally applied before machining. Ideally, for maximum stability and accuracy, VSR is applied after rough machining as it then also reduces the machining stresses. If greater accuracy and stability are required than what can be achieved using thermal stress relieving alone, VSR can be applied just prior to the finish machining. The component is supported on rubber isolators and the vibrator is attached at the edge of the component. A sensor mounted on the component will identify the resonant conditions as the frequency range is scanned. A resonant peak occurs when the induced frequency of the vibrator coincides with the structure's natural frequency and this can be seen, felt, heard and displayed on meters and chart recorders. During this initial scan the exact node lines can be identified easily by touch, or visually with the aid of a granular medium such as shot blast, grit or sand, and many may be permanently marked on the surface for reference. The optimum position of the supports is beneath the node lines (still areas) shown during the scan.

Peaks are approached slowly, with a pause at the foot to allow any critically high stresses to diminish, prior to treating at the actual peak for the number of minutes specified for the component type, weight and material.

As many of the natural frequencies as possible are sought and sometimes the vibrator is re-positioned to alter the resonant mode shape.

The greater the frequency range, the better the treatment, as more loading patterns (modes) are established and different areas are affected. More loading patterns means that fewer cycles per mode are needed. The higher the frequency, the more complex is the loading pattern and the more uniform is the treatment as panels and limbs are resonated. There is no need to calculate these resonant peaks as they occur spontaneously when the scanning induced frequencies coincides with the natural frequency of the structure.

The frequency scan takes only ten minutes. It is normal for two or three of the many natural frequencies of most structures to lie in the 0-100Hz range of the vibrator and it are these which are utilised during treatment. It follows, therefore, that the effectiveness of VSR depends heavily on the type of structure treated. Factors such as weight, dimensions, and stiffness are all critical in the determination of the natural frequencies and forces required to induce resonance in the various bending and torsional modes of vibration. A further important factor is the freedom of the structure to vibrate within its own limits as opposed to being restrained. If the allowable strain is restricted the localised plastic strain is thereby limited, and the degree of stress relief is less than if the allowable movement was constrained only by the natural damping characteristics of the structure.

The rubber isolators, placed at or near node lines, allow freedom of vibration which is vital for optimum treatment. Rigid clamps are used to make the vibrator and component as one item.

At resonance, the amplitude of vibration increases until it is limited by the natural damping characteristics of the vibrating mass. When the induced frequency is altered, resonance ceases and the amplitude drops. VSR is carried out at or near resonance. The effect of the high amplitude resonant vibration is to induce an overall elastic distortion into the structure, similar to that which may be achieved by mechanical overloading.

The advantages of vibration as a means to achieve this end are that a variety of loading patterns (modes) can be obtained in complex structures which would be very difficult or impossible with a direct mechanical loading device. This is done by using as many of the natural frequencies as possible and, in some cases, by varying the position of the vibrator. Thus vibration at resonance can be considered to be a convenient means of effecting mechanical stress relief.

Important features of true VSR operation are that the component is supported during treatment on rubber isolators which allow complete freedom of vibration and that a high force, infinitely variable vibrator is used, attached firmly to the component and having at least a 0-200Hz frequency range.

Although the overall stresses applied to the structure undergoing VSR are in the elastic range, points of stress concentration or fields of internal stress cause lowering and redistribution of residual stresses. The cyclic behavior of the material also has a bearing.

The Often Asked Question of Fatigue following Vibratory Treatment.

Fatigue is the lowering of strength or a failure of a material due to repetitive stresses which may be above or below the yield strength. It is a common phenomenon in load bearing components such as in cars and aeroplanes, turbine blades, springs, crankshafts and other machinery, biomedical implants and in many other consumer components e.g. shoes, that are subjected constantly to repetitive stresses in the form of tension, compression, bending, vibration, thermal expansion and contraction and many other stresses. The possibility of fatigue failures is one reason why many aircraft components have a finite life calculated through many hours of fatigue testing then often applying the average rule.

Fatigue is a very interesting phenomenon in that the load bearing components can often fail whilst the overall stresses applied may not exceed the material yield stress.

Fatigue failures typically occur in three stages, firstly, a tiny crack initiates normally at or close to the surface where the stress is often at the maximum because of surface defects such as scratches or pits, sharp corners or weld undercut. Next the crack slowly propagates as the loading continue to cycle. Finally, a sudden fracture of the material occurs when the remaining cross section of the material is too small to support the applied load. Therefore the components will often fail through fatigue even though the overall applied stresses may remain below the yield strength but often because the material strength / cross section has been reduced through crack propagation. For a fatigue failure to occur, at least part of the stress in the material has to be tensile in nature.

Fig.12 shows a reduction of around 45% in the cross section of material caused by fatigue crack propagation.

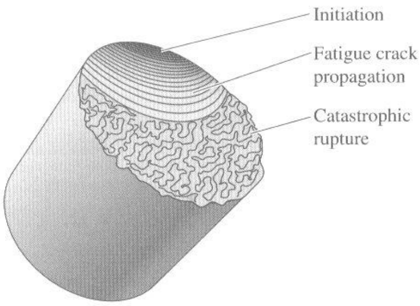


Fig 12
Schematic representation of a fatigue failure fracture surface in a steel shaft, showing the initiation region, the propagation of a fatigue crack and the catastrophic rupture that occurs when the crack length exceeds a critical value at the applied stress.

Courtesy. The Science and Engineering of Materials Fourth Edition

Temperature can also influence the fatigue life of materials. As the materials temperature increases so the fatigue life often decreases. A cyclic temperature change encourages failure by thermal fatigue; when the material heats in a nonuniform manner, some parts of the structure expand more than others. This nonuniform expansion introduces a stress within the material, and when the structure cools and contracts stresses of the opposite nature are then imposed and as a consequence of the thermally induced stresses and strains fatigue failure may eventually occur.
Fatigue failures can also be brought on by **stress corrosion cracking**. This is a phenomenon in which materials react with corrosive chemicals in the environment and this then leads to the formation of cracks and the lowering of strength. Stress corrosion can occur at stresses well below the yield strength of the material due to attack by a corrosive medium. Stress corrosion failures can be identified by microstructural examination of the nearby material. Extensive branching of the cracks is observed along the grain boundaries (Fig 13). The location at which the cracks initiated may be observed by the presence of a corrosive product in the immediate area.

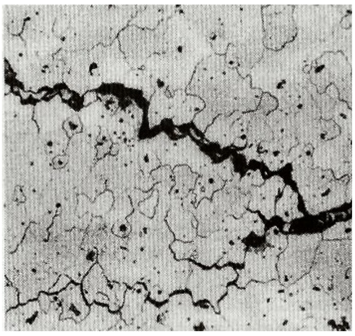


Fig.13
Photomicrograph of a metal near a stress corrosion fracture, showing the many intergranular cracks formed as a result of the corrosion process (x200)

Courtesy ASM handbook Vol.7

To minimize the effects of fatigue, components must be designed as such that the load on the material may not be enough to cause permanent deformation. However when we do load and unload the material thousands of times, (cyclic loading), small cracks may begin to develop and materials will fail as these cracks propagate. This is known as a fatigue failure and in designing load bearing components, the possibility of fatigue failures must be allowed for in the choice and selection of the materials. Of particular importance is quality control as most materials are notch sensitive, with the fatigue properties particularly sensitive to surface flaws. Manufacturing defects will concentrate stresses and reduce the fatigue strength and subsequently the fatigue life. Often highly polished surfaces are prepared in order to minimse the likelihood of a fatigue failure, particularly upon rotating shafts.
An important and largely unanswered question is the matter of how the vibratory treatment affects the fatigue life. Dawson and Moffat concluded that some amount of fatigue damage, although small, might accompany vibratory treatment. Others have claimed that the VSR process uses up to 1% of the fatigue life of the component. Walker, Waddell and Johnstone, however showed that effective stress relieving took place at lower induced stress levels in mild steel (250mpa) than previously observed a level most unlikely to cause fatigue damage. Jesensky et al have stated that VSR does not cause fatigue. It is clear that the more effective the treatment, the more remote the probability of fatigue. With the many loading patterns produced by a wide frequency range, fewer cycles per mode are required. As little as a 1000cycles are needed for many components.
Whichever is true a possible slight reduction of the fatigue life is certainly offset by the huge gains incurred by the reduction in stresses and redistribution of the critical strains that are inherent in the component.
The author knows of no such failures of good welds. The rare failures that have occurred would not be classed as fatigue failures as they were instantaneous with loading. These were explained either as pre-existing microstructural damage caused by critical stressing during the cooling of highly constrained fabrications, or as cases where little or no weld preparation was carried out and the bead had been ground off leaving a weak joint. VSR is however capable of causing fatigue or sudden fracture if it is misused, or it is applied to structures which contain severe welding defects in brittle regions, e.g. HAZ areas. It has been noticed that, where the normal precautions against hydrogen embrittlement are taken, cracking during VSR treatment does not occur. Failure has also been observed, albeit very rarely, in cases where severe surface defects have been present but have gone unnoticed at the time of treatment. These defects would however have certainly caused catastrophic failures in service if not highlighted (by failure) during the VSR process. In many respects the VSR process is a valuable tool in regard to fitness for purpose testing and as such it is used by many companies for such purposes.

Industrial Examples of Vibratory Stress Relieving.

The widespread use of, and the general satisfaction with vibratory stress relieving has been shown by the extent to which it has been accepted by virtually all sectors of the industry; so extensive in fact that it is impossible to truly represent the entire spectrum in this paper. No specific example of mild steel fabrications or cast iron / cast steel castings is given here as it is well accepted that where no metallurgical changes are required, vibratory stress relieving is as good as thermal stress relieving for stabilising and stress relieving beams, bases, columns, gearboxes, bedplates etc. But it is quicker, cleaner and cheaper as witnessed by thousands of regular users over the last 45 years in virtually every applicable engineering field. The acceptance and usage of VSR in South Africa alone has increased by an average of 69% annually since 1992.

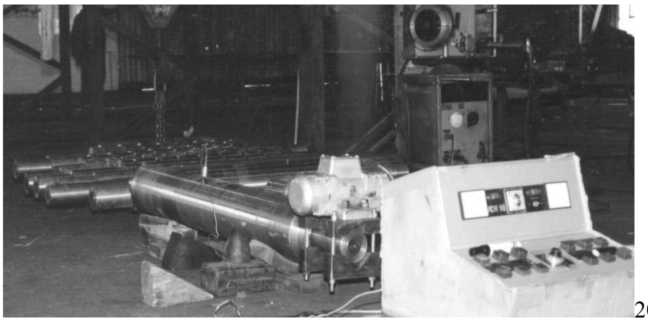
Fan Impellors and Rotating Equipment:

Vibratory Stress Relieving is used to stabilise fans and impellors ranging in size from 800mm diameter x 100mm to 3m diameter x 900mm in fabricated mild steel and stainless steel. Sometimes these are repaired components, and sometimes replacements. After fabricating, but prior to dynamic balancing, the components are subjected to VSR. Since introducing this treatment, no fans or impellors have gone out of balance in service, even under hot conditions – hitherto a troublesome area. Installations are now much quieter and last longer between overhauls. Novenco Aerex, the UK's largest fan and impellor manufacturer, have had their own VSR unit for many years and endorse the benefits stated above. In most cases the system has paid for itself in 4 – 5 months. Rubber coated, steel fan blades have also been treated to overcome instability.

Impellors treated before balancing *Courtesy Rotary Machine Equipment*

Solid Rolls, Bars and Shafts.

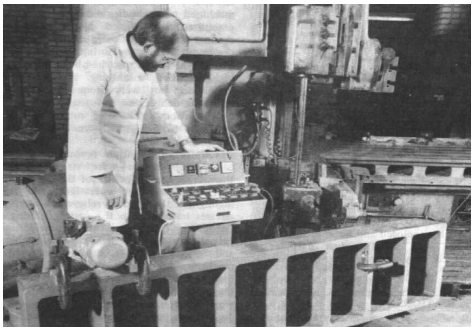
Bowing of shafts whether during machining, weld depositing of worn items or in service had proved to be a virtually insurmountable problem. Particularly difficult materials such as duplex stainless steel, nitronic50, E4340PQ etc. are stabilised using this method, saving companies a fortune in material, time and labour costs. The following photograph shows one of twenty-four unstable EN19 condition T steel, forged drive shafts, being VSR treated and monitored using surface strain gauges. The results showed that VSR reduced surface stress to safe limits, stabilising the component while not reducing fatigue life or altering material properties.



20 off EN19 (T) shafts treated prior to final machining

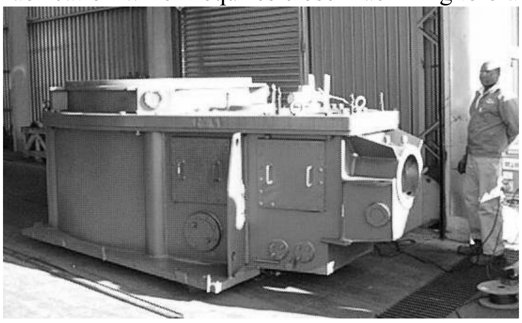
Machine Tools and Baseplates

Some twenty four years ago, Dean Smith & Grace (UK) became disillusioned with thermal stress relieving when cast iron saddles, consistently in tolerance on final inspection in the UK, were 20% out on arrival in the USA, necessitating rework. VSR solved the problem and today, DSG rely on it solely to stabilise saddles, beds, etc. Before that time QA records showed that, using thermal stress relief 98% of beds were reworked in-house after final machining due to movement during handling. Subsequently, only one of 533 beds was reworked – 0.2%. Dean Smith & Grace's subcontract machine shop also finishes mild steel fabricated beds up to 10m long and 1m x 900mm section, basically in 12mm plate, but with sideway sections up to 100 x 300mm and weight up to 12 tons. A 10m bed has a welding time of approximately 50 hours. The fabrication is solely VSR treated. Operation procedure is to fabricate, apply VSR, inspect, rough machine removing up to 35mm to produce sideway profile, ship to Dean Smith & Grace, apply VSR and finish machine to five microns in 6m by grinding. No machinability problems are encountered at any stage, despite the extensive machining of flame cut edges up to 100mm thick.


VSR being carried out on a cast iron precision machine bed. *Courtesy VSR Co. (UK)*

Gearbox Casings.

In this example the manufacturer had a reclamation problem involving the re-welding and finish machining of heavyweight gearboxes already in a part machined condition. The components had already undergone one heat treatment prior to the reclamation operation, during which distortion had taken place sufficient to indicate that a further thermal treatment would render them suitable only for scrap. After consultation VSR was attempted on a reclaimed sample of the weakest component, the gearbox hood, following a rigorous dimensional check. The hood was satisfactorily crack detected and finish machined and all other items successfully treated, thereby avoiding complete remanufacture. VSR is used extensively for this type of fabrication which requires close machining tolerances.


11,000kg casing undergoing VSR treatment before machining

Picture courtesy Sasol Synthetic Fuels South Africa

The Treatment of Large Fabrications

Treatment of the tippler cage and its associated components was carried out on behalf of Saldanha Steel. The tippler cage weighed 119,000kgs and treatment was in the range of 2 hours at both sub resonant and resonant frequencies, the complete assembly including the end rings was in excess of 400,000kgs all items of which was VSR treated. A modern VSR system has the capacity to treat a singular component of up to 200ton, though normally restricted owing to workshop lifting facilities.
Opencast dragline buckets with weights of up to 70,000kgs are treated on a regular basis. Many are treated after a major repair some are treated after fabrication at the OEM suppliers. VSR has been proven to reduce cracking and some manufactures in the USA are claiming an increase in service life of 400% a figure suspected to be grossly exaggerated although it was published in a leading welding publication. Feedback received from many mines in South Africa would suggest a figure of around 45% to be more realistic as VSR could in no way influence the wear and tear and the operational characteristics of a bucket with the exception of no softening of the materials occurring during the stress relief process.


Dragline Bucket treatment *Courtesy VR Steel South Africa*


Tippler cage VSR after welding. *Courtesy DCD Dorbyl South Africa*

Treating the parts that thermal stress relieving cannot treat.
There are thousands of components in need of stabilising that cannot be thermally stress relieved but can be treated using a VSRS. Here follow some typical examples:

- Precision conveyor rolls for nuclear waste disposal, having an outer 304L stainless-steel shell, of 819mm diameter x 884mm face, welded to 789mm-diameter mild-steel end plates and bosses with integral En8 120mm-diameter shaft. AC-VSRS was specified by Sandvik and approved by British Nuclear Fuels and NIS based on Sandvik's twelve years of complete satisfaction with the AV-VSRS.

- Mild-steel rolled hollow-section (RHS) fabricated 'A' Frames with reinforcements for a vehicle front chassis, with integrally-welded cast steel "Rose" universal joints are manufactured in a jig to tight tolerance. Prior to VSRP being applied, 106 sets were produced and all distorted in service, causing wear. For over 1000 sets, VSR treating at three resonances between 35 and 180Hz has rendered all of them completely stable

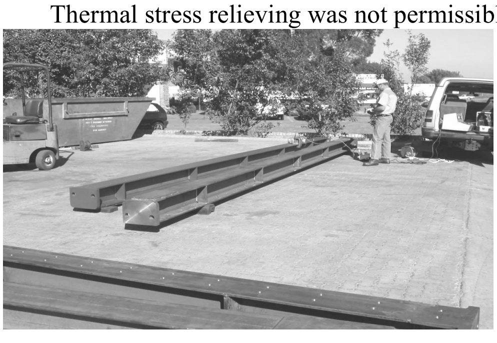
- Three designs of steel amour-grade investment casting, one with a welded-on tie-bar in the fully heat-treated and final metallurgical condition, were found to be grossly unstable during machining. The largest had a 300 x 400mm picture-frame face, associated bore and pad faces 400mm apart, in the first batch of four, movement continued for two months after machining. TIR allowable in all planes is better than 3 microns. A special VSR process was applied, prior to machining, by mounting the component at its center of gravity on a small pad on a 400 x 400mm jig table with a vibrator mounted on the underside.

- A VCM80 AC-VSRS was specified by Short Bros. For their work at their subcontractors and they have used their own VCM80 for stabilising mild-steel and aluminium composite fabrications for many years.

- A failure rate of approximately 40% has been reduced to zero on parts of mining and quarrying equipment since Trellex (Trelleborg Group) and Skega introduced VSR to complex mild-steel fabricated components, often only 14mm x 2mm in section x 4m long. In the same industry, some vibrating screens now carry a three-year guarantee, thanks to the AC-VSRP.


A Vibrating Screen VSR after assembly *Courtesy Bateman SA*

- Typically, screens are mild-steel fabrications from 1m x 3m to 3m x 10m and 100 to 1200mm deep – usually a complex lattice of RHS, angle and tubular members. If thermally stress relieved, they usually distort badly and need mechanical or thermal straightening, often defeating the object of the original thermal treatment.
- When no stress relief or thermal treatment was used, butt welds that lacked preparation and had their bead ground off, leaving a weak joint, failed in service. Now, with the introduction of VSR, welders know that a poor joint will break in the welding shop so they ensure good joints. This 'fitness for purpose' testing is regarded by Goodwin Barsby, Parker, Kue Ken, Pegsons, Babcock Power, etc. as a good reason to use the VSR process as in-service life has, on average, tripled.
- Beams, 8m long x 140 x 300mm section, fabricated from RTQ60 material, bowed 2mm during rough machining. Thermal stress relieving was not permissible on metallurgical grounds. VSR has completely solved the problem.


Treatment of crusher support beams *Courtesy Bomax Engineering.*

- Deloro Satellite uses an AC-VSR system at both their UK and Canadian plants to stabilise carpet knife blades. These are typically mild-steel bars, 5m x 150 x 10mm, grooved out and deposited with satellite along one long edge. This edge is ground to expose the satellite and to form a cutting edge. The mild-steel section behind is slotted to give adjustments for the holding screws. Up to ten year ago, it was common for 50% of the wear tolerance to be lost due to movement taking place during transport (typically from UK to Italy). Since introducing VSR, no movement has occurred and tighter tolerances are now maintained.

- Thousands of examples are on file: large copper plates fully machined, screwed and dowelled; flow-brazed aluminum instrument frames; powder-coated enameled 25mm x 25mm mild-steel angle instrument frames for Marconi; mixed-metal fabrications for Helio (UK) and Dennel (South Africa) tank turrets and a wide variety of materials such as Inconel, Zeron, duplex stainless steel, Ferraliu, titanium, P20 (1.7% Cr steel), aluminum in TF condition, composite metal / plastic, metal / rubber fabrications, etc. for these and many other applications, the VSR system is invaluable. To its benefit VSR can be used on all non-ferrous materials and on the many hardened materials that are commonplace on most mining and quarrying components. No reduction or softening or degradation of the material properties will occur with the correct treatment.

The terms Stress and Strain

One of the interesting adjectives that is often used to describe residual stress is “insidious”. This is because residual stresses are present in virtually every solid material or component but, because we can’t see them and without some careful and complex measurements we don’t know how severe they might be. We sometimes forget or even ignore the fact that they are there, yet their effects can at times be catastrophic.
The term “stress” refers to load or force per unit area. “Strain” refers to elongation or change in dimension divided by the original dimension.
Application of stress causes strain. If the strain goes away after the load or applied stress is removed, the strain is said to be elastic. If the strain remains after the stress is removed, then the strain is said to be plastic.
There are different types of forces or “stresses” that are commonly encountered when dealing with the mechanical properties of materials. In general, we define stress as a force acting upon the unit area over which the force is applied. Stresses are normally tensile, compressive, shear or bending. Strain is defined as the change in dimension per unit length. Stress is typically expressed as either psi (pounds per square inch) or Pa (Pascals). Strain has no dimensions and therefore is often expressed as in/in or cm/cm.
When considering stress and strain it may be useful to think about stress as the cause and strain as the effect.

Conclusion.

The foregoing sections have in no way been an attempt to put the vibratory stress relieving fraternity to rights. Rather it has been a genuine attempt to jolt engineers out of the simplistic complacency that is commonly encountered owing to the misunderstanding between the different types of stress relieving processes that are available, each of which has its own applications and benefits.
As proven by its many years of application there is a genuinely effective vibratory stress relieving process that if used intelligently, treats much that was previously stress relieved by other sometimes more costly and time consuming methods.
The paper has been a genuine attempt to assist both the researcher and the practising engineer and designers, the existing and potential future users of vibratory stress relieving.
No doubt many questions have been left unanswered and some areas of interest have not been covered in this paper. The author is always ready to give advice on vibratory stress relieving or any of the other processes mentioned to existing equipment users and to those contemplating using the process.

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