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# RELAXATION OF RESIDUAL STRESSES AN OVERVIEW

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ABSTRACT

This paper reviews the various sources for relaxation of residual stresses by thermal and mechanical means. Since residual stresses induced during manufacturing can be detrimental to the integrity and service behaviour of a component, stress relief operations are an integral step in many production sequences. The basic principles of thermal, mechanical and vibrational methods of stress relief are outlined. Beneficial residual stress distributions can relax during service by these same mechanisms, leading to loss of their worth. Special emphasis is placed on fatigue-induced relaxation. A review of the literature shows a copious supply of data with few comprehensive models for predicting specific effects.

## INTRODUCTION

The need for relaxing manufacturing-induced residual stresses encompasses all material types, including metallic, ceramic, glass and polymeric systems, as well as semiconductor and thin film structures. Residual stresses locked in during manufacturing processes are often detrimental to the integrity and service behaviour of components. Stress relief is common in many production operations, often taking place during annealing and other thermal treaments intended for unrelated purposes. For instance, post-weld heat treatments not only relax the high tensile stresses induced by differential thermal contraction, but also improve metallurgical properties such as fracture toughness. While thermal stress relaxation is thought to produce better dimensional stability than other methods, sometimes only modest reduction can be achieved because of microstructural limits on the temperature range allowable, or because of high creep resistance of the material. When microstructural effects of thermal treatments are undesirable, stress relief can be achieved by mechanical means. This is usually accomplished by plastically stretching or overstressing the material above the monotonic yield. Alternative methods that redistribute rather than relieve the residual stress state include vibrational stress relief and explosive or shock loading.

Relaxation of residual stresses can also occur during the life of a component and can lead to altered properties. Cyclic fatigue and creep can result in a redistribution of the initial elastic residual stresses, leading to stress relaxation during service. This is especially true of short-range residual stresses that exist as a consequence of local plastic deformation. These stresses are significantly altered by cyclic or thermal softening that results in dislocation motion and alteration of the elastic stress state. Creep and recovery effects cause time-dependent stress relaxation of statically loaded parts.

These effects are discussed in more detail by separating them into thermal, mechanical and vibratory stress relief operations. Within the limited scope of this review, attention is focused on the mechanisms involved during the individual relaxation processes, while illustrating the use and problems of each technique with enough references to give the reader sources for solutions to specific problems.

## THERMAL STRESS RELAXATION

### Procedures and Mechanisms

Isothermal stress relief involves the uniform heating of a part or section to a suitable temperature, holding at this temperature for a period of time, followed by slow cooling to prevent the reintroduction of thermal stresses. This is usually done in an air circulation furnace with good control over the specified thermal cycle. Crane [1], in an overview of thermal methods, comments on the use of low thermal mass furnaces made of lightweight panels that are assembled on-site. The structure itself becomes the furnace, using radiant electric elements for the heating system and overall thermal efficiencies as high as 55%.

Three primary mechanisms cause relaxation of the locked-in stresses. At temperatures high enough to cause a substantial reduction in the material yield strength, plasticity mechanisms relieve the elastic strain through rapid thermal activation of dislocations. This requires that a component be heated to a temperature where its yield strength approaches a value that corresponds to an acceptable level of residual stress. Unfortunately, this usually approaches or exceeds that of the solution-annealing temperature. Attendant decreases in mechanical properties that remain after slow cooling dictate that this relatively time-independent, high temperature mechanism often cannot be utilized. At lower temperatures, classical diffusional creep enables the counterbalancing regions of tensile and compressive stresses to contract or expand slightly, and thus to redistribute. Precipitation and ageing effects also cause volume changes that can relax elastic stress. These processes are time-dependent, and significant tradeoffs must be made in determining the appropriate temperature and duration required. At low temperatures, microplastic strain that occurs due to thermal glide (rather than climb) of dislocations enables the relaxation of high tensile stresses. This process is only weakly temperature- and time-dependent and does not fully relieve the stress state. It is easily suppressed by ageing treatments that may take place prior to stress relieving.

Typical stress relief temperatures for low alloy ferritic steels are between 595 and 675°C, and 900 to 1065°C for high alloy steels [2]. The duration can be estimated by examining the influence of temperature on the creep and yield strength of the material. However, over many of the temperature ranges employed, both plasticity and creep processes occur simultaneously, making accurate modelling of the behaviour difficult. As a result, determination of the time-temperature range is often accomplished experimentally. While the dwell time is important, creep is a logarithmic process such that most relief obtained at a given temperature is achieved relatively rapidly, as shown by the data in Fig. 1. Heat treatments of 1 to 4 h are typical. Throop et al. [3] have shown that this can be speeded up in certain circumstances by using nonuniform rather than isothermal heating and cooling. In autofrettaged cylinders, the magnitude

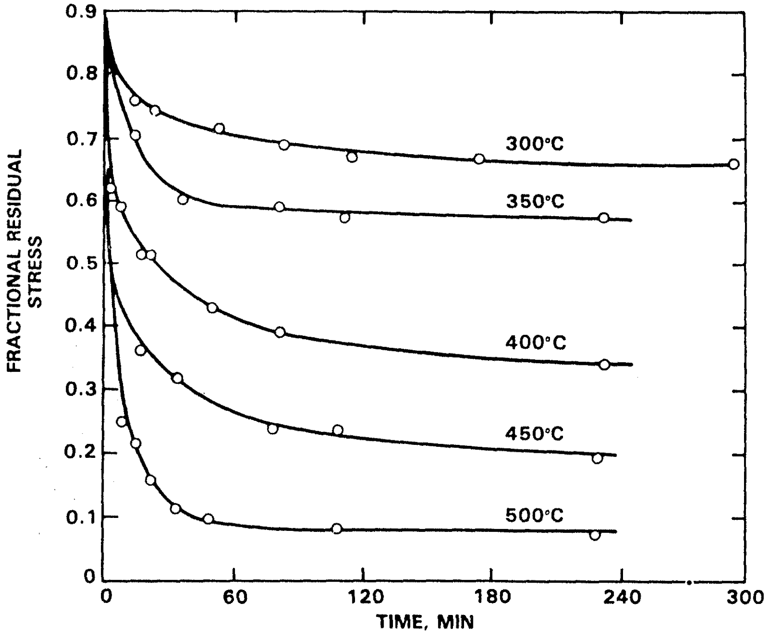


Fig. 1 Effect of annealing time on the fractional residual stress of mild steel [10].

of relaxation was significantly greater in the presence of thermal gradients as compared to uniform heating. This may be unique because of the combined compressive stresses induced during autofrettage and the thermal stresses induced near the bore, but the example shows that uniform thermal exposure may not be necessary. In fact, Woodward et al. [4] report stress relief experiments on Alloy 600 steam generator tubing, using induction heating with thermal exposures of 30 s to 4 min. Obviously, the use of such rapid thermal heating and temperature gradients must be approached with caution. In investigating the relief of residual tensile stresses in injection-molded plastics, Thompson and White [5] found that thermal gradient annealing left tensile stresses at the surface.

Often of more importance than the time is the choice of temperature because of the significant microstructural changes that can take place. Stainless steels, for instance, require considerable care so as not to be sensitized to stress corrosion cracking through chromium depletion that occurs as a result of chromium carbide formation. Many industrial and professional societies cognizant of such problems have published recommended specifications for stress-relieving heat treatments. Metals Handbook [6], for instance, provides general data on low carbon and mild steels, austenitic stainless steels, tool steels, and aluminium, copper, lead, magnesium, nickel and titanium alloys. Problems of corrosion sensitization, recrystallization and grain growth, hydrogen embrittlement, ageing and precipitation reactions are elaborated on. In general, however, detailed procedures and estimates of the expected degree of relaxation are not specified. This necessitates the use of experimental studies to determine adequate and useful heat treatments.

## Experimental Studies

Pertainent data are often required to determine the effectiveness of a given thermal treatment. A major problem in these investigations is quantification of the residual stress levels. One of the most accepted methods of residual stress determination involves x-ray diffraction where the near surface stresses are evaluated. Potter and Millard [7] and Diesner [8] have used this technique to study the thermal stability of compressive stresses induced by shot peening. The former demonstrated substantial reduction of compressive stresses in 7075-T6 aluminium at rather low temperatures and long times (225°F for 20 h), and Diesner developed master stress relief time-temperature curves for AISI 52100 and H-11 steels. Diesner measured the through-thickness stress distribution by removal of successive surface layers. Also using x-ray diffraction, Amin and Ganesh [9] showed that thermal relief of cold-rolling induced stresses in Cu-2% Be alloy strips was effective, but mechanical stress relief using roller levelling was not.

The Sachs bore-out method is effective when long-range macrostresses induced by thermal gradients are measured. This technique was used by Adeyemi et al. [10] on mild steel, Bakaev and Vainerman [11] on hardfaced steel shafts, and Anderson et al. [12] on a U-2.4% Ni alloy to determine the degree of relaxation. Layer removal procedures are also often used. Thompson and White [5] evaluated the use of this technique in neat polymers and fibre-reinforced polymers, and concluded that the variation of stiffness with depth typical of composites does not seriously affect the calculations. Thakkar and Broutman [13] calculated the activation energy required to release residual stresses in cold-worked polycarbonate using the layer removal technique. They found that small per cent reductions in thickness (the method used to introduce the cold work) impart only surface tensile stresses that can be relaxed by annealing at 50°C. Large reductions during rolling also cause a high degree of molecular orientation that cannot be substantially relaxed below 125°C ($T_g$ = 150°C).

These techniques, although quantitative, are tedious and time-consuming, and many simpler methods can be used for qualitative determinations. The use of split rings and longitudinal splitting has been described by Brown et al. [14] and Adeyemi et al. [10], respectively, in steel alloys and by Pavarov [15] in Ti alloys. Fox [16] describes a number of simple stress relaxation tests on Cu and Cu alloys, such as vibration of a wire and a tapered beam bending fixture that could be applied to the testing of thermal stress relief. Woodward et al. [4] tested in situ stress relief of steam generator tubing by observing its susceptibility to stress corrosion cracking in a sulfur containing environment. These simple techniques are usually used to determine per cent reductions for time-temperature curves; and when combined with metallographic examination to ensure microstructural stability, they are quite adequate in many circumstances.

Experimental studies on the isothermal stress relief of thin film stresses are often done by measuring the curvature of the film and substrate. Seshan and EerNisse [17] studied the annealing of residual stresses in ion implaned Si layers and found three distinct stages, with the third stage (about 450°C) being the most effective due to epitaxial regrowth of the amorphous layer. They modelled their observations employing the maximum shear stress. Blaauw [18] used sample curvature measured by the beam deflection method and found that temperatures of 500-700°C relieved the tensile stresses in chemical vapour deposited $SiO_2$ films (both doped and undoped) on GaAs substrates. However, plasma-enhanced CVD films of $SiN_x$ could not be stress-relieved at these temperatures. Kinbara et al. [19] also used substrate bending to study stresses in $MgF_2$ films on single-crystal quartz substrates. Noble and Reed [20] found that "baking" at 750°C relieved the residual stresses in Ni- and Cr-plated AISI 8740 hardened steel. Abermann et al. [21] used a cantilever technique for measuring internal stress in thin films and discussed the necessary corrections for thermal effects in the substrate. Parker [22] found that the stress state in electroless Ni coatings was dependent on the phosphorus content of the bath. Eight per cent phosphorus baths resulted in tensile stress, but increasing the content to 12% resulted in compressive stresses. Heat treatment above 250°C increases the tensile stresses due to volume shrinkage that occurs during nickel phosphide precipitation and Ni crystallization. Nir [23] used simple optical microscopy to study the stress relief in diamond-like carbon films that occurred from elastic crack formation. The optical patterns of buckling and cracking were related to the stress distribution. Of course, more complicated measurement techniques have also been appalied to thin films. Moser and Beserman [24] used Raman spectroscopy to monitor strains induced into the Si layer by the thermal mismatch between Si and a sapphire substrate. Vander Straten and Metselaar [25] used x-ray lattice constant measurements to monitor the internal stress in liquid phase epitaxial growth of single crystal oxidic magnetic bubble materials.

Experimental measurements have led to the development of several qualitative models for predicting the degree of stress relaxation. For instance, the studies by Brown et al. [14] showed that the relaxation accompanying tempering of hardened steel results from the local volume change during the precipitation of carbide particles in the martensitic matrix. In this case, the fractional stress relaxation was independent of the magnitude of stress. However, Adeyemi et al. [10] calculated activation energies for stress relief of cold-extruded mild steel bars, and they found these energies to be dependent on stress rather than temperature. Analytical estimates of the effectiveness of residual stress relaxation have also been made. Burger and Sundyrin [26] used strain compatibility equations and plastic flow theory to calculate thermal stress states, and they showed that thermal cycling under load can rapidly decrease the surface stresses in such components as turbine blades. Sundstrom et al. [27] have studied the influence of multiaxiality on thermal stress relaxation using compatibility of strain equations performed on thick-walled tubes. To simulate a weldment where the boundaries are constrained and thus reduce the relaxation rate, one principal stress direction was assumed to be fixed by restraint. They concluded that the rate of relaxation was controlled mainly by the peak stress state. Even in thick weldments of pressure vessel A533B steel, heat treatments corresponding to commercial practice were shown to reduce the residual stess peaks by at least 70%. Fidler and Hepworth [28] have advocated the use of the Larson-Miller parameter to predict the relaxation rate of austenitic stainless steels and Cr-Mo steels. The Larson-Miller parameter is defined by the equation

$$P = T\,[C + \log(t)] \times 10^{-3} \tag{1}$$

where $T$ is the test temperature in degrees Rankine and $t$ is the rupture time in hours. C is a constant whose value is approximately 20 for low alloy steels. This parameter, and others like it [29], are used to relate creep properties at different temperatures and can provide a means of determining the proper time of isothermal heat treatment for alloys where creep data are available. As an example, Dawson and Jackson [30] were able to use creep data to predict the relaxation of residual stress in autofrettaged cylinders. Fidler [31] used creep data in a computer-simulated stress relief of thick weld structures to derive the distribution of residual stress in a CrMoV-2CrMo weld after various periods of heat treatment. They concluded that the British Standard code of 1 h at 700°C per 25 mm of thickness was sufficient to relax the surface axial stress, but that internal hoop stresses greater than that tolerable from a defect assessment were still present, and required at least 2 h thermal treatment to relax sufficiently, as specified by CEGB Standard 23584. Vinckier and Dhooge [32] combined metallurgical and mechanical phenomena taking place during thermal stress relief to describe the development of reheat cracking in high alloy steels. While not in general use, such predictions can be helpful in determining time temperature ranges without expensive testing.

Analytical treatments have also been conducted for ceramics. Evans and Clarke [33] describe methods for calculating the relaxation of residual stresses developed at the microstructural level because of thermal contraction inhomogeneity. The rate of relaxation was shown to be a strong function of the microstructure, with rapid relaxation obtainable in fine grained materials or in materials containing an amorphous boundary phase that provides viscous flow. Tree et al. [34] found that quench tensile stresses in aluminium oxides could not be thermally relieved because of subcritical microcrack growth that takes place at temperatures below that required for diffusional creep. As shown in Fig. 2, the minimum stress intensity $K_O$ required for subcritical crack growth decreases with temperature such that the tensile stress field by itself provides enough energy for crack growth. This results in elastic relaxation of the residual stress state, but in a manner detrimental to the load-bearing capability of a brittle ceramic. Thus, only when the tensile stresses are sufficiently low can high enough temperatures be achieved to enable diffusional creep mechanisms to relax the stresses in a safe manner.

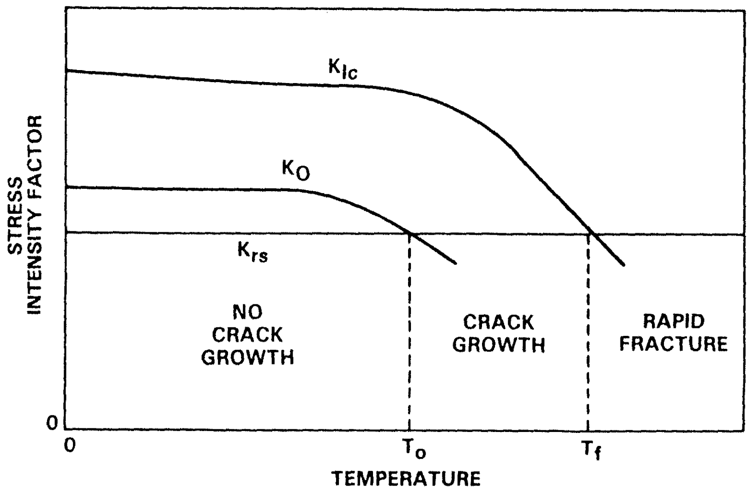


Fig. 2 Schematic of relative magnitude of residual stress intensity factor with corresponding values for fast fracture ($K_{IC}$) and minimum value ($K_o$) required for subcritical crack growth. From Tree et al [34].

## Post-Weld Heat Treatments

Thermal stress relief is perhaps more often used in weldments where peak tensile stresses occur with magnitudes that approach or exceed the nominal yield strength of a material. Simultaneously, the weld metal and heat affected zone often have poor microstructures offering low fracture toughness and ductility. As a consequence, considerable attention has been placed on post-weld heat treatments with a view towards improving the safety of a structure from brittle fracture, making it more tolerant of defects, and reducing the residual stress state for lower fatigue crack growth and stress corrosion cracking rates. Because of the importance of this process to industry, especially the electric power industry, many industrial and professional societies have developed extensive requirements on the rates of heating, soaking and cooling. A partial review of these has been published by Cottrell [35], and many other papers pertinent to residual stress in welds can be found in Ref. 36. Agapakis et al. [37] published a literature survey of stress relieving in structural weldments, so no attempt is made here to summarize these findings. Much information pertaining to microstructural modification, residual stress relaxation, stress relief cracking, and fatigue crack propagation in welded joints can be found in these references.

### Cold Treating

Residual stresses frequently result from nonuniform thermal contraction due to temperature gradients through the thickness. Characteristically, the residual stresses are compressive at the surface and tensile in the interior unless a phase change occurs during quenching. The use of cold treating to induce mild stress relief and to act as a stabilizing treatment has proved beneficial, both in castings and machined parts [2]. Often, this occurs due to stabilization of untransformed products left after the quench. Hill et al. [38] have proposed an "uphill" treatment of such severity as to develop residual stresses that counteract those formed during a high temperature quench. In this case, the part is cooled to liquid nitrogen temperatures and then subjected to a high velocity steam blast to promote thermal gradients great enough to produce local plastic flow. This works well with alloys of low yield strength or when applied to a component before ageing which raises the yield strength. Since low temperatures are used, microstructural and strength changes are negligible. Recent work by Sevimli [39] has shown this to be an effective method to stress relieve the outer shell of large aluminium structures having residual stresses formed both by quenching and by machining. While not of widespread popularity, this technique might be particularly useful on irregular-shaped parts that cannot be stress relieved by other means.

## RESIDUAL STRESS RELAXATION BY MECHANICAL MEANS

A great deal of misunderstanding exists in regard to mechanical effects on stress relaxation. The term mechanical stress relaxation or load relaxation is used to describe an experimental technique to measure inelastic strain properties, at both ambient and elevated temperatures, and these terms do not relate specifically to residual stresses. This type of data is used mainly to predict creep in practical engineering components operating for long times under static and dynamic loads. On the other hand, mechanical residual stress relief refers mainly to overstressing or stretching of a material or component to induce plastic flow in order to redistribute the residual stresses. Yet, it is important to understand load relaxation because of its inter-relation to residual stress relaxation. We begin by examining the deliberate use of mechanical residual stress relaxation and then discuss both stress relaxation testing and service relaxation by fatigue and thermal means.

### Overstressing and Stretching

Plastic deformation and subsequent relief of locked-in internal stresses begins in those regions in which conditions of yielding under the combination of applied and residual stress are satisfied. As a load is applied, yielding will occur first in the regions of high residual tension with the dislocation motion decreasing the amount of misfit, as explained by Rosenthal [40]. Investigating the effect of preload on fatigue strength in 2024-T3 Al, Nawwar and Shewchuk [41] found that tensile stresses are quite easily relieved by a preload or overload, but that compressive stress can be sustained at high preloads without loss of their beneficial effect. In fact, Fuchs and Stephens [42] describe this as a method to deliberately induce beneficial compressive stresses. Potter and Millard [7] have shown in 7075-T6 Al that static loads approximating yield must be attained before relaxation of compressive stresses induced by shot peening can occur. Their data, Fig. 3, indicate that the residual stress

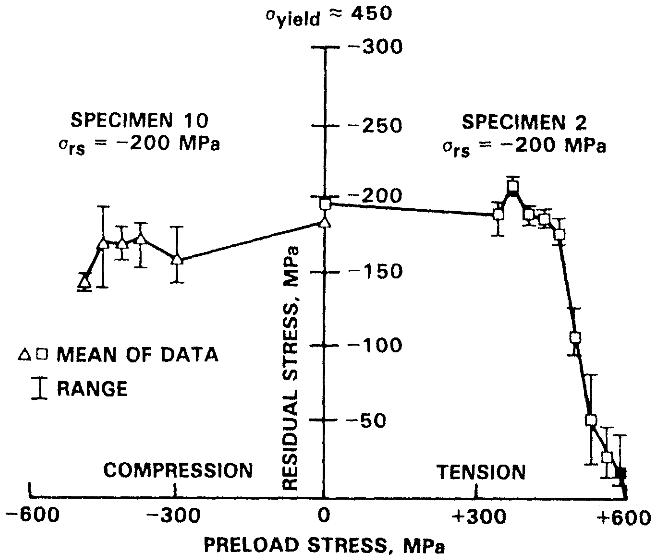


Fig. 3 The effect of static load stress on the surface residual stress level (reprinted from Potter and Millard, Ref. 7).

has no effect on the threshold stress for relaxation. This is consistent with Rosenthal's [40] view that it is the maximum shear stress that must exceed the yield strength, since shot peening introduces an isotropic distribution.

Many age-hardening, high strength aluminium alloys undergo a stretching operation after solution treatment and prior to tempering and ageing as a standard means to relieve quench stresses. Thermal annealing treatments cannot be used because they cause coalescence of precipitates from solid solution that must be done during the ageing treatment. The ANSI standard designation for this is the Tx51 temper where x represents the temper treatment. The Tx52 designation applies to products that are stress relieved by compression after solution treatment to produce a permanent set of 1 to 5%. Forged Al products are sometimes restruck in the die while cold to produce stress relief, and are designated Tx54.

Aside from high strength Al alloys, stretching as a usual means of achieving stress relaxation is done only on cold-drawn tubing. Cold-drawn tubes tend to have high levels of longitudinal tensile stress in the outer surface. While stretches of up to 5% longitudinal plastic strains are sometimes used, even small amounts of homogeneous tensile strain will significantly reduce the tensile residual stresses created by the inhomogeneous deformation during drawing of the tube.

## Stress Relaxation Testing

If a component at constant temperature is loaded and held at constant strain, the stress decrease with time due to subsequent inelastic deformation is called stress relaxation. Stress relaxation is defined as the initial stress minus the remaining stress [43], and tests are usually conducted in tension by loading a sample to a predetermined strain and holding the strain constant over time by decreasing the applied load. Standard practices have been prescribed by ASTM

[43]. Other experimental techniques, phenomenological modeling of the inelastic processes, and development of governing constitutive equations, as well as the interrelation of stress relaxation and residual stress are reviewed in an ASTM special technical publication [44]. Manjoine [45] discusses how stress relaxation data can be used to evaluate the reduction of residual stress upon thermal exposure, and Laflen and Jaske [46] use relaxation data to predict creep rates in three alloy steels. As already mentioned, creep data can be used in a number of different models to determine time-temperature relationships for thermal exposure, and stress relaxation studies are a convenient method to obtain the necessary data. Alderman and Webster [47] have used a two-element composite model to describe the relationship of creep and stress relaxation to the redistribution of internal stresses within materials, thus unifying the phenomena.

## Fatigue Induced Residual Stress Relaxation

Proposed mechanisms for the relaxation of residual stress due to cyclic loading can be separated into three regimes that occur at cyclic stress amplitudes (i) above the macroscopic yield strength, (ii) below the endurance limit, and (iii) in between.

Fatigue Above the Yield Strength. A complete redistribution of the residual stress state occurs when gross yielding takes place. This happens if the entire net section stress exceeds the yield strength, or if only the surface yields such as in bending or torsion. As mentioned previously, this is sometimes taken advantage of in overstressing operations to induce compressive stresses at the surface. When macroscopic yielding of the surface takes place in fully reversed loading, the surface stress should, after unloading, be opposite in sign to the direction of loading due to the constrained influence of the subsurface [48-51]. Quesnal et al. [50] measured the surface residual stress after each half cycle during cyclic loading and found the stress to be dependent on the direction and magnitude of unloading. This effect has also been seen by Kodama [48] and by Ziegeldorf [51], the latter suggesting that the sequence of unloading also affects the stress. Kodama [48] noted that, for some materials, significant microscopic yielding on the surface may take place below the bulk yield strength and lead to this same type of behaviour.

Boggs and Byrne [52] investigated the relaxation of shot peened residual stresses in Ni-Co alloys. For Ni-20% Co and Ni-60% Co cycled at amplitudes just above the yield strength in fully reversed cantilever bending, rapid relaxation took place in the first 100 cycles before equilibrating to a constant decay slope. The reduction in the higher strength, higher stacking fault energy Ni-60% Co alloy was much less than in the lower Co content alloy, as would be expected. Measurements of surface hardness during fatigue showed no change, from which the authors concluded that the stress relief process was due to dynamic recovery in the same sense as the recovery produced in thermal stress relief prior to any recrystallization.

Significantly different behaviour has been observed for samples cycled in tension-tension loading. Weiss et al. [53,54) have shown that in 304L and 316 stainless steels cycled in axial tension-tension loading above the monotonic yield strength, rapid relaxation of the initial compressive residual stress takes place and subsequent development of a tensile stress occurs. Voskamp et al. [55] have reported that during overrolling in the inner ring of a deep-groove ball bearing, the initially tensile residual stresses just below the surface decrease progressively with fatigue and then change to compressive stresses, which continue to increase in magnitude with further deformation. McClinton and Cohen [56] have shown that tensile residual stresses develop within the plastic deformation bands of an annealed mild steel, even at loads close to the fatigue limit in tension-tension fatigue. These cases of residual stress generation under cyclic loading can be ascribed to inhomogeneous plastic deformation due to mechanical or structural changes that take place. Changes in the yield strength due to work hardening may set up conditions where the surface, which initially plastically deforms before the subsurface and thus hardens to a greater degree, undergoes more elastic deformation than the subsurface and subsequently is held in tension on unloading. In a 52100 ball bearing steel, Voskamp et al. [55] showed that decomposition of the austenite is primarily responsible for the development of the compressive residual stresses. It is obvious that such changes in the residual stress state depend on the specific material and loading conditions. Because of this, use of the development of the residual state to determine fatigue damage [53] is limited to specific situations and has not become a general purpose tool.

Fatigue Near the Endurance Limit. Several investigators have shown that residual stress relaxation occurs during fatigue for peak cyclic stresses well below [57,58] and near [59] the endurance limit. It has been suggested that stress concentrators may provide the mechanism for relaxation in this regime [60-63], although definitive results are lacking. Pattinson and Dugdale [57], for example, found that relaxation did not begin until $10^7$ cycles in an Al alloy L65 (4-1/2% Cu) cycled below the nominal endurance limit. Possibly, defects or microcracks generated during the latter phase of the cycling process may have initiated an elastic relaxation. Also, local temperature increases during fatigue at high rates of cyclic loading may induce relaxation. There will always be some form of stress concentrations, such as at grain junctions, dislocation pileups and phase boundaries. With the exception of large stress concentrations such as notches [60], relaxation at cyclic loads below the endurance limit takes place, if at all, only late in the fatigue life of a component, and probably by mechanisms completely different from those important for larger cyclic stress amplitudes.

An additional factor in strain hardening materials is that early in fatigue, microplastic deformation takes place below the fatigue limit until strain hardening occurs in deformed grains. Relaxation is certainly possible during this period.

Fatigue at Intermediate Stress Amplitudes. High performance components are commonly designed to operate in a cyclic stress regime that exceeds the material endurance limit, but which is less than the yield strength. Considerable data have been generated on the relaxation phenomenon in this regime, but a complete model explaining relaxation behaviour has not yet been suggested. In general, relaxation begins rapidly within the first few cycles and decreases in rate with increasing fatigue. In discussing internal stresses, Valluri [64] suggested that the situation is analogous to creep. In such a thermally activated process, rate theory is often applicable and generally predicts an exponential decrement of residual stress with the number of fatigue cycles. Several investigations [65,66] have used rate process theory to describe the relaxation rate empirically, but they have not attempted to separate the influence of important variables such as the material's properties and cyclic stress amplitude. However, data do support an exponential decay rate.

Studies using surface residual stresses (measured by x-ray diffraction) to investigate the relaxation process have illuminated certain aspects of the problem. Taira and Murakami [67] have shown that the amount of relaxation is a function of the applied cyclic stress amplitude. Potter and Millard [7] observed only minor relaxation in cycling Al 7075-T6 at R = 0.5 with the maximum cyclic stress amplitude of 0.78 $\sigma_{yield}$, well above the fatigue limit, because the cyclic stress range was only 0.39 $\sigma_{yield}$; the cyclic stress (or strain) range is therefore also an important variable. James and Morris [68] showed that compressive machining stresses decay during fully reversed loading of Al alloys, but that in tension-tension loading, both compressive and tensile stresses can be introduced depending on the particular microplastic and hardening response of the alloy [69], as illustrated by the curves of Fig. 4.

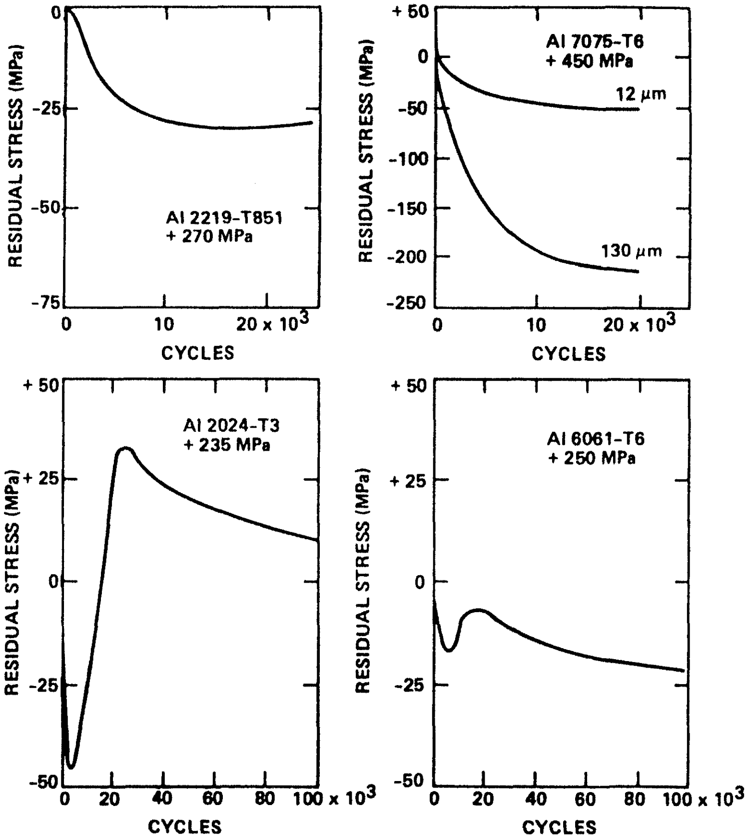


Fig. 4 Fatigue-induced residual stresses in four aluminium alloys. Samples were cycled at constant amplitude in zero-tension bending.

Esquivel and Evans [70] have shown that the degree of relaxation increases with increasing stress gradient in shot-peened 4130 steel, and both Esquivel and Evans [70] and Hayashi and Doi [58] found that the greatest relaxation takes place on the surface. Leverant et al. [71] have shown that not only is the strain amplitude and range important, but also that cycling about a mean strain significantly affects the relaxation (as long as the cyclic strain range is large enough). A mean strain of -0.3% was shown to induce greater relaxation in shot-peened Ti-6Al-4V than a mean strain of +0.3% (cyclic strain range +0.6%). This was expected, since a compressive surface stress was induced by shot peening, and therefore the sum of residual and applied stresses was greatest with a compressive mean strain.

Both residual stress and hardness distributions can change with repetitive rolling contact. Muro et al. [72,73] found that compressive residual stress values and degree of work hardening increase as the contact stress and number of contact cycles increase. In sliding-rolling, Fujita and Yoshida [74] also found a gradual increase in the compressive residual stress with rolling cycles in both annealed and case-hardened rollers. Relaxation of the circumferential compressive stresses was assumed to be due to the initiation of microcracks in the roller surface along the axial direction. Ho et al. [75] found that the sliding wear process in AISI 1018 and 4340 steels rapidly altered the initial stress distribution produced by heat treatment or peening.

A convenient experimental approach to the study of residual stress relaxation is to use an externally imposed mean stress. Some basic characteristics of the relaxation process are found to be similar. Mean stresses relax at an exponential rate with cycles [76] and by a power law dependence [77], the rate of relaxation becoming smaller with increasing fatigue. Higher strain amplitudes produce faster rates of relaxation [76-79]. The rate of relaxation does not depend on the sign of the mean stress [77].

Mean stress relaxation tests are done by cycling the sample in strain control at a constant strain range, usually above the 0.2% offset yield point, until an equilibrium hysteresis loop is obtained; a mean stress is then imposed (by adjusting the strain limits) and its decay rate is followed with further cycling. Because of the constant strain amplitude cycling and uniform net section stress inherent in these tests, the mean stresses relax to zero except at small strain amplitudes. (From our previous discussion, the surface residual stress would be expected to change sign with each half cycle because of the different values of the yield strength on the surface and in the bulk.) Surface residual stresses, however, often relax to some asymptotic nonzero value during fatigue cycling in the load regime under discussion. In this regime, macroscopic yielding of the bulk does not take place; but, of course, localized yielding at the surface is still present. This gives rise to a redistribution of the residual stress state to some nonzero magnitude rather than simply an exponential decay to zero. The residual stress state is a highly localized disturbance in an elastic continuum, and hence is an unstable condition. The degree of stability must be dictated by the surrounding matrix and should depend on such features as the residual stress gradient, initial stress state, prior fatigue history, and hardening or softening behaviour - problems not encountered in mean stress relaxation tests. For instance, Jhansale and Topper [77] have shown that strain amplitude and number of cycles seem to be the primary variables influencing mean stress relaxation behaviour, and to a first approximation, the influence of other variables is negligible; one cannot be certain that such conditions are applicable during relaxation of surface residual stresses. Even so, material dependent properties can be easily studied in this way. For instance, Morrow et al. [79] found that the amount of relaxation occurring in martensitic steels was a function of their heat treatment, with the decay being less pronounced for harder materials, indicating a dependence on the material ductility. Landgraf [80] attributed similar results to an increase in the cyclic yield strength with increasing hardness.

Empirical relaxation laws to describe certain limited data have been proposed. Impellizzeri [81] used a simple exponential decay function and Neuber's rule to calculate the cyclic-dependent local stress at a notch, which predicts relaxation even below the endurance limit at the notch. Potter [82], in studying the effects of overload behaviour, used the nonequilibrium component of the residual stress (i.e., the difference between the initial and equilibrium value of the residual stress) and an exponential rate of decay based on the cycles to equilibrium to determine the transient value of the residual stress. James and Morris [68] used a model of microplastic strain to describe the effect of stress amplitude on the decay rate in Al 2219. None of these models adequately describes the influence of the cyclic stress or strain range, the endurance limit, the stress gradient, or possible work hardening of the surface.

In summary, relaxation of surface residual stress is known to occur at or near the fatigue limit. Well above this region, i.e., in low cycle fatigue, the residual stress state is dependent on the direction and magnitude of loading. Below the fatigue limit, relaxation may still take place, in that there will always be stress concentrators, but definitive studies are lacking. These regimes are only intended to define a separation in the apparent behaviour of the surface residual stress and are not to be taken as definitive separations between the mechanisms responsible. However, the influence of compressive residual stresses in increasing fatigue life is recognized to be highly dependent on stress stability, since relaxation may take place early in the fatigue process.

## VIBRATORY STRESS RELIEF

Probably no technique has polarized opinions more than vibratory stress relief (VSR). A literature survey of work prior to 1968 was published by Brogden [83], who remained largely unconvinced of the technique's merits. Since then, however, a number of investigations have shown improvements in dimensional stability and lowered residual stresses [84-95]. Undeniably, when applied properly, the method can relax the distribution of residual stresses. The questions to be answered are how does relief in stress take place; and, is any damage induced?

Commercial processes normally involve clamping an eccentric mass electric motor to the component of interest and vibrating it at resonant frequencies (usually 10-100 Hz) for periods up to 15 min. The workpiece, of course, must be free to move, but castings up to many tons have been relieved [87]. Resonant frequencies are used to impart the largest stress amplitude with small inputs of energy, but require control of the vibrator's frequency. The necessary feedback control and proper instrumentation to record and display pertinent data have been elaborated on by Klauba and Adams [92-93]. The resonant frequency varies with the internal state of stress and changes by small amounts during the stress relieving process. Monitoring shifts in the resonant frequency enables the relaxation process to be quantified and verified. Instrumentation sold by Bonal Technologies operates just below the resonant frequency, which is supposed to induce more absorbed energy into a component.

An understanding of the mechanism behind VSR can be obtained by reviewing a previous section, where examples were given of stress relaxation during cyclic loading. The types of stress or strain amplitudes used in successful VSR are equivalent to cyclic loading above the endurance (fatigue) limit. Relaxation takes place by microplastic deformation, in which the movement of dislocations redistributes the residual elastic stresses and the microstresses. The dislocation experiences a force equal to the sum of the vibratory and static stresses. The vibrations of dislocation segments are highly damped so that in the low frequency range there is no possibility of storing energy from one cycle to another. Natural frequencies of vibration of dislocations are in the gigacycle range. Thus, VSR is simply a low cost method of cyclically loading a component to relax the residual stresses through microplastic deformation. Small-scale deformation takes place above a threshold usually equivalent to the fatigue limit. As shown in a previous section, the relaxation is dependent on the cyclic amplitude and is modified by cyclic hardening or softening, but it is exponential in rate. Thus, the major relief occurs in $10^3$-$10^4$ cycles, within 10 min or so at the normal frequencies used. Accumulation of cyclic damage must also occur during this process. If damage accumulates at rates predicted by a Coffin-Manson type relationship, as suggested by Cooper and Fine [96], the rate of damage accumulation is considerably slower than the exponential rate of residual stress relaxation. James and Morris [68] found that the majority of relaxation in Al 22198 took place far before the initiation of surface microcracks. Dawson and Moffat [97] concur, stating that although the fatigue limit must be exceeded for VSR to work, the accumulated fatigue damage should be minor.

By analogy of the VSR process to that of microplastic deformation, we can also understand why the method is relatively ineffective in bent tubing and other components having undergone cold-work processes. These processes raise the threshold limit (fatigue limit) at which VSR is effective by pinning the dislocations and making slip processes more difficult. VSR techniques combined with low thermal treatments have been shown to be very effective in stress relieving welded structures [91], as would be expected by the thermal enhancement of plastic flow. The authors developed a finite-difference model and used the von Mises yield criterion to model the VSR process numerically. As a point of interest, it is well known that surfaces microplastically yield at lower stress levels than the bulk due to lack of three dimensional constraints and environmental effects. Thus, surface measurement techniques to monitor residual stress should be most senitive to the VSR technique.

## CONCLUSIONS

This perspective on relaxation of residual stress offers insight into the many ways residual stress can be relieved and redistributed, both deliberately or unintentionally during service. Appropriate research on stress relieving should focus on correlating creep resistance to thermal relief and models of microplastic deformation to mechanical stress relieving. Many techniques have been used to monitor the degree of relaxation with that of dimensional stability of a part being the most simple and most used. Recognition of the decay of beneficial residual stresses during service should lead to the use of more sophisticated nondestructive measurement techniques to monitor the distribution. Finally, robust models, whether analytical or numerical, would be of great value in quantitatively predicting the relaxation rate, a prediction that currently is as much art as science.

## REFERENCES

[1] Crane, L. W. (1979) Heat Treatment-Methods Media, Inst. Metall. Tech., London, 1-10.
[2] Metals Handbook, (1971) Ninth Edition, Vol. 4, B.P. Bardes, ed., American Society for Metals, 3-5.
[3] Throop, J. F., J. H. Underwood and G. S. Legar (1982) Residual Stress and Stress Relaxation, ed. E. Kula and V. Weiss, Plenum Press, 205-226.
[4] Woodward, J., D. van Rooyen and A. R. McHee (1984) In-Situ Stress Relief of Expanded Alloy 600 Steam Generator tubing, DoE Contract No. DE-AC02-76CH00016, Report No. DE84-014560.
[5] Thompson, M. and J. R. White (1971) Polymer Eng. and Sci. 24, 227-241.
[6] Metals Handbook (1971) Ninth Edition, V1-V4, ed., B. P. Bardes, American Society for Metals.
[7] Potter, J. M. and R. A. Millard (1977) Advances in X-Ray Analysis, V20, ed., H. G. McMurdie, Plenum Press, 309-319.
[8] Diesner, R. W. (1969) The Effect of Elevated Temperature Exposure on Residual Stresses, SAE Report 710285, Soc. of Automotive Engineers.
[9] Amin, D. E. and S. Ganesh (1980) Experimental Mechanics 21, 473-476.
[10] Adeyemi, M. B., R. A. stark and G. F. Modlen (1980) Heat Treatment '79, Metals Society, 122-125.
[11] Bakeav, A. N. and A. E. Vainerman (1976) Autom. Weld. 29, 24-16.
[12] Anderson, R. C., T. G. Kollie and C. A. Reeves (1981) Dimensional Stability, Annealing, Stabilization and Residual Stress Analysis of Alpha-Phase Extgruded Chromium - 2.4 Wt. Percent Niobium Alloy, Union Carbide Corp., Nuclear Div., Oak Ridge Y-12 Plant, Oak Ridge, TN, Report No. Y-2251.
[13] Thakker, B. S. and L. J. Broutman (1981) Polymer Eng. and Sci. 21, 155-162.
[14] Brown, R. L., H. J. Rack and M. Cohen (1975) Mater. Sci. and Eng. 21, 25-34.
[15] Pavarov, I. (1980) Metals Sci. Heat Treat. 22, 433-438.
[16] Fox, A. (1982) Residual Stress and Stress Relaxation, ed., E. Kula and V. Weiss, Plenum Press, 181-204.

[17] Seshan, K. and E. P. EerNisse (1978) Appl. Phys. Lett. 33, 21-23.
[18] Blaauw, C. (1983) J. Appl. Phys. 54, 5064-5068.
[19] Kinbara, A., S. Baba, N. Matuda and J. Takamisawe (1982) Thin Solid Films 89, 125-129.
[20] Noble, H. J. and E. C. Reed (1974) Exp. Mechs. 14, 463-467.
[21] Abermann, R., H. P. Martinez and R. Kramer (1980) Thin Solid Films 70, 127-137.
[22] Parker, K. (1981) Plating and Surface Finishing 68, 71-77.
[23] Nir, D. (1984) Thin Solid Films 112, 41-49.
[24] Moser, F. and R. Beserman (1983) J. Appl. Phys. 54, 1033-1036.
[25] Vander Straten, P. J. M. and R. Metselaar (1978) Mat. Res. Bull. 13, 1143-1151.
[26] Burger, I. A. and V. G. Sundyrin (1980) Strength of Materials 12, 135-142.
[27] Sundstrom, R., K. Maleu and R. Otterberg (1983) Res. Mechanica 6, 215-232.
[28] Fidler, R. and J. K. Hepworth (1982) Residual Stresses in CrMoV-2CrMo Pipe Welds, Central Electricity Generating Board TPRD/M/1259/R82.
[29] Smith, G. V. (1975) Evaluation of Elevated temperature Tensile and Creep-Rupture Properties of 3-9% Chromium-Molybdenum Steels, DS58, Am. Soc. Testing and Materials.
[30] Dawson, V. C. D. and J. W. Jackson (1969) Trans. ASME-J. Basic Eng. 91, 63-66.
[31] Fidler, R. (1983) Int. J. Pres. Ves. and Piping 14, 181-195.
[32] Vinckier, A. and A. Dhooge (1979) J. Heat Treating 1, 72-80.
[33] Evans, A. G. and D. R. Clarke (1980) Residual Stresses and Microcracking Induced by Thermal Contraction Inhomogeneity, in Proc. Int. Conf. on Thermal Stresses in Materials and Structures in Severe Thermal Environments, Blacksburg, VA; and Lawrence Berkeley Lab #LBL-11568.
[34] Tree, Y., A. Venkateswaran and D. P. H Hasselman (1983) J. Matls. Sci. 18 2135-2148.
[35] Cottrell, D. J. (1978) An Examination of Postweld Heat Treatment Techniques, Residual Stresses in Welded Construction and Their Effects, The Welding Institute VI, 195-209.
[36] Residual Stresses in Welded Construction and Their Effects (1978) ed., R. W. Nichols, The Welding Institute, Cambridge.
[37] Agapakis, J. E., V. J. Papazoglou, A. Imakite and K. Masabuchi (1982) Study of Residual Stresss and Distortion in Structural Weldment of High Strength Steels, Final Report of Contract N00014-75-C-0469, ONR.
[38] Hill, H. N., R. S. Barker and L. A. Wiley (1959) Am. Soc. Metals 52, Preprint No. 132.
[39] Sevimli, E. (1985) Removal of Residual Stresses by Cold Stabilization, submitted to Metal Progress.
[40] Rosenthal, D. (1959) Influence of Residual Stress on Fatigue, in Metal Fatigue, eds., G. Sines and J. L. Waisman, McGraw-Hill, 1970-196.
[41] Nawwar, A. M. and Shewchuk, J. (1983) Expt. Mech. 23, 409-413.
[42] Fuchs, H. O. and R. I. Stephens (1980) Metal Fatigue in Engineering, John Wiley & Sons, New York.
[43] Standard Recommended Practices for Stress-Relaxation Tests for Materials and Structures, Annual Book of ASTM Standards (1982) E328-72, Am. Soc. Testing and Materials, Phil.
[44] Stress Relaxation Testing, ASTM STP 676 (1979) ed., A. Fox, Am. Soc. Testing and Materials, Phil.
[45] Manjoine, J. M. (1982) in Residual Stress and Stress Relaxation, eds. E. Kula and V. Weiss, Plenum Press, 519-530.
[46] Laflen, JH. H. and Jaske, C. E. (1979) Stress Relaxation Testing ASTM-STP 676, ed. A. Fox, Am. Soc. test. Mater., 182-206.
[47] Alderman, R. L. and G. A. Webster (1973) J. Strain Analysis 8, 99-107.
[48] Kodama, S. (1972) in Mech. Behavior of Metals 2, Soc. of Materials Science, Japan, 111-118.
[49] Nagao, M. and V. Weiss (1977) Trans. Asme-J. Eng. Mat. Tech. 99, 110-113.
[50] Quesnel, D. J., M. Meshii and J. B. Cohen (1978) Matls. Sci. Eng. 36, 207-215.

[51] Ziegeldorf, S. (1976) Abhangigkeit der Rontgenografisch gemessenen Oberflachen-eigenspannungen von vorangegangenen Wechselbeau spruchungen in Kohlenstoffstahlen, Dissertation, Tech. Univ. Munchen.
[52] Boggs, B. D. and J. G. Byrne (1973) Met. Trans. 4A, 2153-2157.
[53] Weiss, V., Y. Oshida and A. Wu (1979) Fatigue Eng. Matls. Structures 1 333-341.
[54] Weiss, V., Y. Oshida and A. Wu (1980) Nondestructive Eval. 1, 207-213.
[55] Voskamp, A. P., R. Osterlund, P. C. Becker and D. Vingsbo (1980) Metals Tech. 7, 14-21.
[56] McClinton, M. and J. B. Cohen (1982) Matls. Sci. and Eng. 56, 259-263.
[57] Pattinson, E. J. and D. S. Dugdale (1982) Metallurgia 66, 228-230.
[58] Hayashi, K. and S. Doi (1971) in X-Ray Study on Strength and Deformation of Metals, Soc. of Matls. Sci., Japan, 49-57.
[59] Gould, R. W. and C. F. Pittella (1973) in Adv. in X-Ray Analysis 16, 354-366.
[60] Nelson, D. V., R. W. Ricklefs and W. P. Evans (1970) in Achievement of High Fatigue Resistance in Metals and Alloys, ASTM STP 467, Am. Soc. Testing and Materials, 228-253.
[61] Ericsson, T., P. Spiegelberg and L. Larsson (1971) in X-Ray Study on Strength and Deformation of Metals, Soc. of Matls. Sci., Japan, 67-73.
[62] Turovskii, M. L., V. V. Belozerov, I. M. Shifrin and Y. M. Fuks (1976) Strength of Mater. 8, 104-109.
[63] Taira, S., T. Abe and T. Ehiro (1969) Bull. JSME 12, 947-957.
[64] Valluri, S. R. (1963) Acta Metal. 11, 759-775.
[65] Kodama, S. (1971) in X-Ray Study on Strength and Deformation of Metals, Soc. of Matls. Sci., Japana, 43-47.
[66] Radhakrishwan, V. M. and C. R. Prasad (1976) Eng. Fract. Mech. 8, 593-597.
[67] Taira, S. and H. Murakami (1960) JSME 26, 1348.
[68] James, M. R. and W. L. Morris (1981) in Residual Stress for Designers and Metallurgists, ed., L. J. VandeWalle, Am. Soc. Metals, 169-188.
[69] James, M. R. and W. L. Morris (1983) Scripta Met. 17, 1101-1104.
[70] Esquival, A. L. and K. R. Evans (1968) X-Ray Diffraction Study of Residual Macrostresses in Shot-Peened and Fatigued 4130 Steel, Boeing Rep. D6-23377.
[71] Leverant, G. R., B. S. Langer, A. Yuen and S. W. Hopkins (1979) Metal Trans. 10A, 251-257.
[72] Muro, H. and N. Tsushima (1970) Wear 15, 309.
[73] Muro, H., N. Tsushima and K. Nunome (1973) Wear 25, 345.
[74] Fujita, K. and A. Yoshida (1977) Wear 43, 301-313.
[75] Ho, D., C. Noyan, J. B. Cohen, D. Khanna and Z. Eliezer (1983) Wear 84, 183-202.
[76] Morrow, JoDean and G. M. Sinclair (1959) in Basic Mechanisms of Fatigue, ASTM STP 237, Am. Soc. Testing and Materials.
[77] Jhansale, H. R. and T. H. Topper (1973) in Cyclic Stress-Strain Behavior - Analysis, Experimentation and Failure Prediction, ASTM STP 519, Am. Soc. Testing and Materials, 246-270.
[78] Ross, A. S. and JoDean Morrow (1960) Trans. ASME-J. Basic. Eng., Sept.
[79] Morrow, JoDean, A. S. Ross and G. M. Sinclair (1960) SAE Trans. 68, 40-48.
[80] Landgraf, R. W. (1977) in Proc. of Fatigue-Fundamental and Applied Aspects Seminar, Saabgarden, Remforsa, Sweden.
[81] Impellizzeri, L. F. (1970) in Effects of Environment and Complex Load History on Fatigue Life, ASTM STP 462, Am. Soc. Testing and Materials, 40-68.
[82] Potter, J. M. (1973) in Cyclic Stress Strain Behavior-Analysis, Experimentation and Failure Prediction, ASTM STP 519, Am. Soc. Testing and Materials, 109-132.
[83] Brogden, T. (1969) Machine Tool Research, April, 27-35.
[84] Kellar, D. S. (1970) Metal Treating 21, 14-15.
[85] Wozney, G. P. and G. R. Crowner (1968) Welding Res. Sup. 23, 411-419.
[86] Sagalevich, V. M. and A. M. Meister (1971) Svar. Proiz. 9, 1-4.

[87] Claxon, R. A. (1974) Heat Treatment of Metals 1, 131-137.
[88] Weiss, S., G. S. Baker and R. D. DasGupta (1976) Welding Res. Sup. 31, 47-51.
[89] Saunder,a G. G. (1978) in Residual Stess in Welded Construction and Their Effects, The Welding Institute, 173-179.
[90] Irving, R. R. (1978) Iron Age, April, 56-57.
[91] Wahi, K. K. and D. E. Maxwell (1979) Trans. 5th Int. Conf. Structural Mechanics in Reactor Technology, Vol. L, Rep. 13/3.
[92] Klauba, B. B. and C. M. Adams (1982) in Production Applications of Mechanical Vibrations, ASME, 47-58.
[93] Klauba, B. B. (1983) Tooling and Prod. 49, 64-66.
[94] Sutyrin, G. V. (1983) Welding Prod. 30, 27-28.
[95] Olenin, E. P., A. S. Averin, E. V. Dobrotina and O. K. Alekseev (1983) Welding Prod, 30, 19-21.
[96] Cooper, C. V. and M. C. Fine (1984) Scripta Met. 18, 593-596.
[97] Dawson, R. and D. G. Moffat (1980) J. Eng. Matls. and Tech. 102, 169-176.