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VIBRATORY STRESS RELIEF – AN INVESTIGATION OF THE UNDERLYING PROCESSES

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Published by University of Strathclyde,
Glasgow, SCT UK

August, 1994

Vibratory stress relief – an investigation of the underlying processes

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The use of vibration to reduce residual stress levels in fabrications is potentially an attractive alternative to thermal annealing. The application of the process has hitherto been limited by the lack of coherent theory of operation. In this study, residual stresses were introduced into a low-alloy steel EN3b by rolling. It was shown that prolonged low-amplitude vibration at 100 Hz induced a stress relaxation of as much as 40 per cent, where the original level was close to yield. A model has been developed to explain the diverse effects resulting from low-amplitude vibration; the model involves the motion of dislocations under the influence of the combined residual and external cyclic stress fields. This model, which has been validated by detailed X-ray line profile analysis and elasticity measurements, is an extension to the currently available explanation for VSR (vibratory stress relief). The standard model, which assumed the need to exceed the local yield stress, only comes into operation at the higher levels of applied stress amplitude. The development of accurate and validated methods for the application of VSR may now be contemplated.

Key words: residual stress, X-ray line profile analysis, vibratory stress relief, EN3b steel alloy, cold rolling

NOTATION

lattice parameter of ferrite in the (110) direction
*n*th Fourier coefficient of reflection order 1
Burger's vector of dislocations
ideal distance within crystal between *n*th neighbour unit cells
Young's modulus of elasticity
angular dependent X-ray polarization factor
order of reflection from ferrite (110) planes
gradient near $d =$ O of $\langle Z^2 \rangle$ versus d curve
index number of Fourier coefficients
number of unit cells having *n*th neighbours in the same subgrain
limits of validity for the approximate strain field surrounding dislocations
deviation of *n*th neighbour unit cells from ideal spacing
dislocation density
denotes a mean value taken over all diffracting unit cells

1 INTRODUCTION

Processes involved in the manufacture of structures and components often result in the formation of residual stresses. These are undesirable for a variety of reasons: they can contribute to accelerated corrosion and cracking of members; machining of residually stressed material results in distortion from the desired final dimensions; in combination with service loading, residual stress reduces strength and fatigue life of affected pans.

Traditionally, the solution to these problems has been to apply a thermal annealing process to residually stressed structures; at elevated temperatures, the yield strength of the material becomes very low, so that it cannot support internal stresses of significant magnitude. Upon slow cooling (to avoid reintroduction of residual stresses by differential thermal contraction) the material is left in a state of negligible residual stress. The process,although effective, suffers from several disadvantages: the cost of treatment in terms of equipment and energy is high; the growth of oxide scale on the surface implies the need for a subsequent finishing process to remove the scale; many materials undergo heat treatment to ensure their suitability for their intended purpose. Clearly, the application of thermal stress relief is impractical in such cases.

1.1 Vibratory stress relief

Vibratory stress relief (VSR) is a general term used to refer to the reduction of residual stress by means of cyclic loading treatments. As commonly applied, a VSR treatment involves vibration of the component at resonance, in order to achieve high stress amplitudes using relatively inexpensive portable equipment. A number of enterprises have been applying a VSR for at least 30 years; the practice has been for operators to attach eccentric mass electric motors to stressed components. It has been claimed that a high degree of stress relaxation may be achieved in a wide variety of mechanical structures by running these motors close to a resonant frequency of the combined assembly. Components subjected to this form of treatment range in size from a few kilograms to large welded assemblies of several hundred tonnes mass (1-16).

This process of VSR, if proven to be effective, avoids the disadvantages of thermal stress relieving. The potential savings in time, equipment and energy costs are substantial; the freedom from many of the side effects accompanying thermal stress relief (distortion, scale formation and degradation of mechanical properties) serves to make the process still more attractive. VSR may be applied at any point during the manufacturing process, although it will clearly be most effective when invoked after the completion of all probable stress-inducing stages; multiple treatments are also feasible,

The MS was received on 2 August 1993 and was accepted for publication on 30 August 1994.

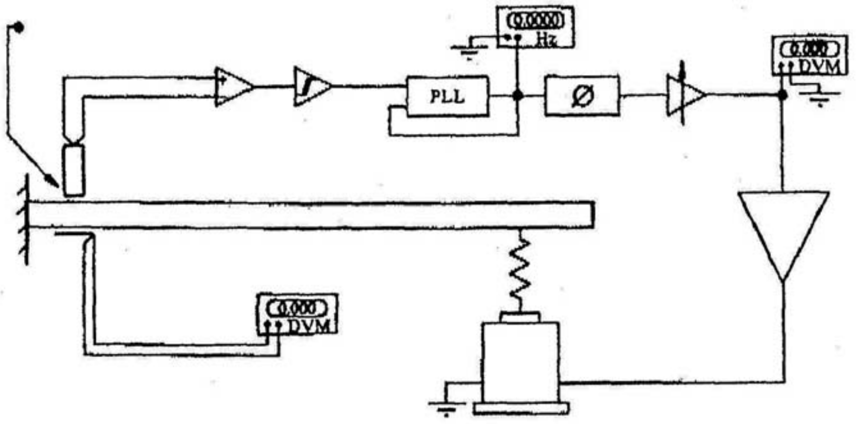

Fig. 1 Schematic diagram of resonant vibration feedback control loop

given the low overheads associated with the process. The most important sources of concern relating to VSR involve the possibility of adverse effects upon fatigue life and uncertainty as to the actual parameters necessary to achieve effective stress relief.

Over the past years, the use of VSR has become widespread throughout industry, despite a lack of scientific data concerning the phenomenon. The results of laboratory-scale investigations to date have been inconclusive; although VSR has been shown to be effective in some circumstances, its range of applicability to certain classes of material is, as yet, uncertain.

It should be noted that residual stress patterns are overall in balance over a structure--tension in some areas balanced by compression in others. Whether achieved by annealing or by VSR, residual stress reduction implies the operation of plastic deformation mechanisms--usually in the form of intragranular microplastic processes as individual dislocation segments move to positions of lower energy.

1.2 The need for a validated theory of VSR

This investigation has been targeted upon the problem of providing a rational explanation of VSR effects. Two models have been proposed by earlier researchers. A simple theory of bulk plastic flow due to the combination of residual with applied stresses is often cited [see Klotzbucher and Kraft (17)] this is referred to hereafter as the 'standard model'. The standard model postulates that VSR works by combination of residual and vibrating stress exceeding the yield strength of the material; the presumption is that the subsequent plastic flow is such that when the vibrational amplitude is removed, the previously stressed area can now return to a low level of residual stress. Plainly, this implies that VSR should be almost instantaneous, once the correct level of vibration had been reached; such an effect has not been reported (1, 2, 6). Several other authors write in general terms of an alternative theory (18), although details of this are omitted; the rather vague term dislocation effects' is commonly used in such literature, the authors providing little or no further explanation.

The need for a validated theory may be stated in the following terms. If the operation of VSR is not well understood, then its application is based simply upon experience. In the case of complex engineering components, the creation of this experience must of necessity be slow, and so the application of VSR will only extend by cautious steps. On the other hand it is entirely possible that with this scenario, elements of the components treated by VSR will be under- or over-treated, leading on the one hand to dimensional instability and on the other to fatigue cracking. Given a quantitative understanding, then VSR treatment may be specified with a degree of confidence, and applied in a quantitative and controlled manner.

1.3 Experimental approach

In the present work, experimentation was undertaken based upon several complementary approaches to the problem. Specimens of simple geometry (rectangular bars) and known residual stress distribution were subjected to cyclic loading treatments (Fig. 1). The material selected for the study was mild steel, EN3b (properties are given in Table 1). Briefly, a residual stress regime was induced by cold rolling (see Section 2.2). Standard specimens, in the form of thin beams, were clamped and vibrated (Fig. 1) by an electromagnetic shaker that was driven by a resonance-seeking phase-locked loop controller. This controller both maintained resonant conditions and gave an accurate measurement of the resonant frequencies (~100 ± 0.001 Hz). Changes in the resonance could be monitored with the same system. The effects of treatment were characterized by a variety of methods: direct measurement of residual stress was achieved by a destructive sectioning technique; small changes in mechanical properties (elastic modulus and internal friction) were monitored by the use of the electronic instrumentation in the vibration controller; a detailed analysis of X-ray diffraction line profiles provided information concerning the internal microstruc-

Table 1 Composition and properties of EN3b

	C	Si	Mn	Ni	S	P
%	0.25	0.35	1.0	--	0.06	0.06
Ultimate tensile strength	450 MPa					
Uniaxial yield strength	250 MPa					

ture and dislocation density within materials before and after treatment.

2 METHODOLOGY

2.1 Residual stress measurement

In order to study the effect of mechanical treatments upon residual stress levels within materials, it was necessary to find a method by which these stresses could be quantified. Towards this objective, a programme of experimentation was initiated, culminating in the selection of a simple technique by means of which the variation of residual stress throughout the thickness of cold rolled metallic specimens could be investigated. The method thus developed was a variation of the layer removal technique (19), in which the residual stress within a thin surface skin of the object under investigation is inferred from the change in strain occurring in the remaining material upon removal of this layer.

Various methods of material removal were tested to determine their influence upon the observed strain readings in specimens having a known residual stress distribution. It was ultimately decided that a single-point fly-cutter, under conditions of controlled feedrate, gave the most convenient and least stress-inducing method of removing the material layers. Measurements were taken at 0.1 mm intervals through the thickness. Strain changes were measured using resistance strain gauges and analysed using a customized software package. This allowed rapid calculation of residual stress profiles from observed data, with the facility to display experimental results in graphical form (20).

2.2 Stress induction

The destructive nature of the chosen residual stress measurement technique clearly precluded experimental studies of stress changes within individual specimens as a result of vibration. Instead, it was necessary to develop a method by which controlled, reproducible stress patterns could be introduced into test pieces: statistical methods could then be applied to the results of experiments conducted using similarly treated materials.

Various stress induction processes were considered before a decision was made in favour of a controlled cold rolling treatment. Annealed samples of the metal under consideration were reduced in cross-section by 5 - 10 per cent in several stages in a twin-roll mill: the exact degree and pattern of reduction were determined by experiment for the chosen material (EN3b steel alloy). It was found that the level of surface residual stress varied inversely with the degree of reduction at each stage (Fig 2): repetition of low reduction processes caused cumulative effects, resulting in high residual stress levels after 2 - 5 rolling passes at 1 per cent reduction per pass.

The pattern of residual stress induced by such treatment was considered to be ideal for the intended purpose. Specimen and rolling apparatus geometry ensured that the resulting stress field was, to a good approximation, uniaxial (directed along the specimen long axis) throughout the material. In addition, the magnitude of residual stress depended only upon the depth within the material, neglecting the small boundary effects at the specimen edges. These features precisely match the assumptions made in the classical analysis of layer removal stress measurement techniques (19), thus increasing confidence in the chosen method.

Peak stress levels introduced by rolling techniques were found to be considerably greater than those caused by other mechanical treatments, in particular the plastic bending methods adopted by Dawson (8, 21). Indeed, typical surface residual stresses in rolled specimens were found to be close to the ultimate tensile strength of the untreated (annealed) material, This observation was

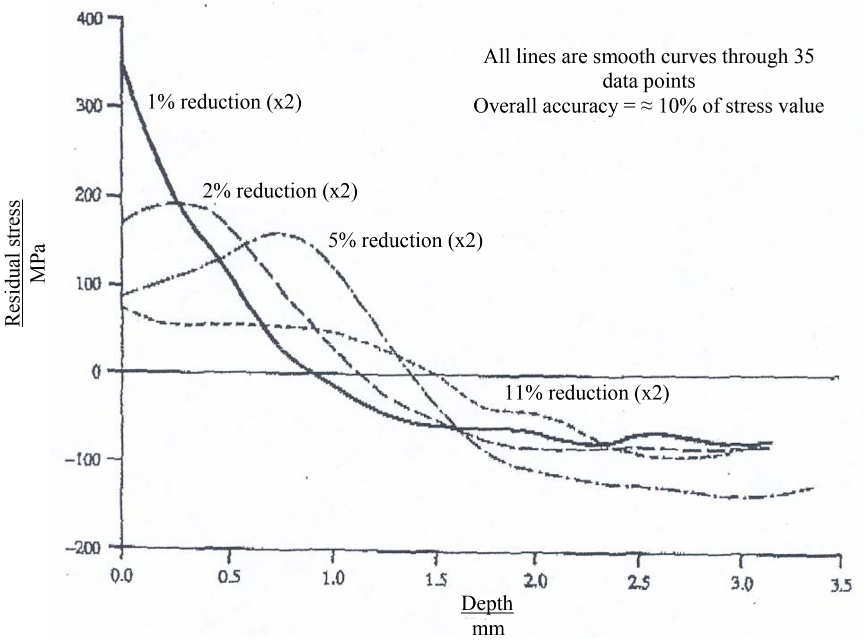

Fig. 2 Residual stress profiles induced by cold rolling.

attributed to work hardening or surface layers during the rolling process.

2.3 X-ray diffraction studies

The application of mechanical treatment to reduce residual stress levels was expected to cause changes in the internal microstructure of the specimen. Such changes may be monitored both qualitatively and quantitatively by analysis of the angular dependence of the intensity of X-ray beams diffracted from the material. This evaluation of the internal microstructure has been extensively analysed, but has not before been used to quantify the effects of VSR in a precise manner.

The method used in the course of this work was a variation of the Fourier transformation technique developed by Warren and Averbach (22). This procedure involved the detailed observation of diffraction line profiles corresponding to two or more orders of reflection from a single set of atomic planes. From these data, complex Fourier coefficients were calculated after making corrections for angular-dependent instrumental factors. Division of these coefficients by those measured using an annealed reference specimen of the same material implemented the 'Stokes' correction' described by Warren (23), compensating for peak broadening due to instrumental imperfections.

A comparison between different reflection orders of corresponding corrected Fourier coefficients allowed the broadening coefficient to be expressed as a product of two factors:

$$_1A_n = KN_n \langle c^{2n11Zn} \rangle \tag{1}$$

where

1 = reflection order
$_1A_n$ = *n*th Fourier coefficient of (*001*) line profile
N_n = number of unit cells having the *n*th neighbours in the same column/subgrain
Z_n = displacement of the nth unit cell from its undeviated position in perfect crystal
K = a slowly varying angular-dependent factor
$\langle \quad \rangle$ indicates a mean value taken over all cells within the diffracting region

Order-independent factors, N_n, were attributed to the finite site of coherently diffracting regions ('crystallites' or 'subgrains') within the material; order-dependent broadening arose from internal microstresses due to defects within these regions, and also from stresses acting uniformly throughout the body of each crystallite but varying from one to another. Denton (24) classified such stresses into distinct categories, referred to as type II and type III microstresses respectively.

A careful study of the order-independent factors revealed that, in the case of cold-rolled materials, the dominant influence upon peak profiles arose from internal defects (mainly dislocations). A relationship was derived between the corrected Fourier coefficients and the dislocation density within the material (20):

$$M = \frac{a\langle b^2 \rangle}{8\pi} \left(\frac{r_{max}}{r_{min}} \right) \rho_d \tag{2}$$

where

M = gradient of $\langle Z^2{}_n \rangle$ versus d (= na) plot near $d = 0$
a = lattice parameter, 2 Å, of ferritic steel (basis vector in cubic [110] direction)
$\langle b^2 \rangle$ = mean squared Burger's vector of dislocations $\approx a^2$
ρ_d = dislocation density within material
r_{min} = 10a, lower limit of approximation for the strain field around dislocations
r_{max} = half the mean crystallite size, upper limit of strain field around dislocations

Calculations using observed data yielded a plausible value for the dislocation density of 6×10^{11} cm $^{-2}$.

3 DISCUSSION OF RESULTS

3.1 Residual stress measurement

Residual stress profiles were recorded for test specimens after stress relief annealing and stress induction (cold rolling): a comparison of these data allowed the effects of each treatment to be evaluated,

Analysis of material in its annealed condition provided verification that the chosen material removal method introduced negligible amounts of residual stress into material ($\leq$ 15 MPa). Statistical analysis of surface residual stress levels in material after the stress induction process revealed some variation between individual samples. The mean value of the underlying distribution was determined to be 450 M Pa; its standard deviation was ±50 MPa. No systematic variation of residual stress with position along the length of rolled bars occurred within the region of observation. Reliability of the stress measurement method haying been established by the tests upon annealed material, the scatter in results was attributed to true variability between specimens of similar material, rather than to uncertainty in the measurement process.

The results of observations made upon the low-carbon steel samples (BS 970:EN3b) subjected to cyclic loading treatments are illustrated in Figs 3 and 4. In essence the surface residual stress after treatment decreases with increasing cyclic stress amplitude, and also with the number of cycles applied. The dependence upon treatment duration is non-linear, becoming weaker as the dynamic stress amplitude is increased. Surface stress levels tend towards a limiting value which is dependent upon treatment amplitude. The rate of convergence towards this value is also determined by the amplitude: at 250 MPa, stress reduction is essentially complete after 10 000 cycles (Fig. 4).

More detailed insight into the nature of stress reduction attained by cyclic loading may be obtained from Fig. 3. At intermediate amplitudes (<300 MPa), stress relief is confined to regions close to the surface, where original residual stress levels art highest and applied stress amplitudes greatest. As amplitudes arc increased beyond these levels, stress relief effects penetrate farther into the body of the material; changes also occur in the shape of the stress profile, dramatically reducing the stress gradient close to the surface. Further increase of the stress amplitude to 550 MPa results in massive plastic deformation of the test specimen, accompanied by almost complete stress relief throughout the material: the final stress pattern h simply that due to static overload bending of the annealed material.

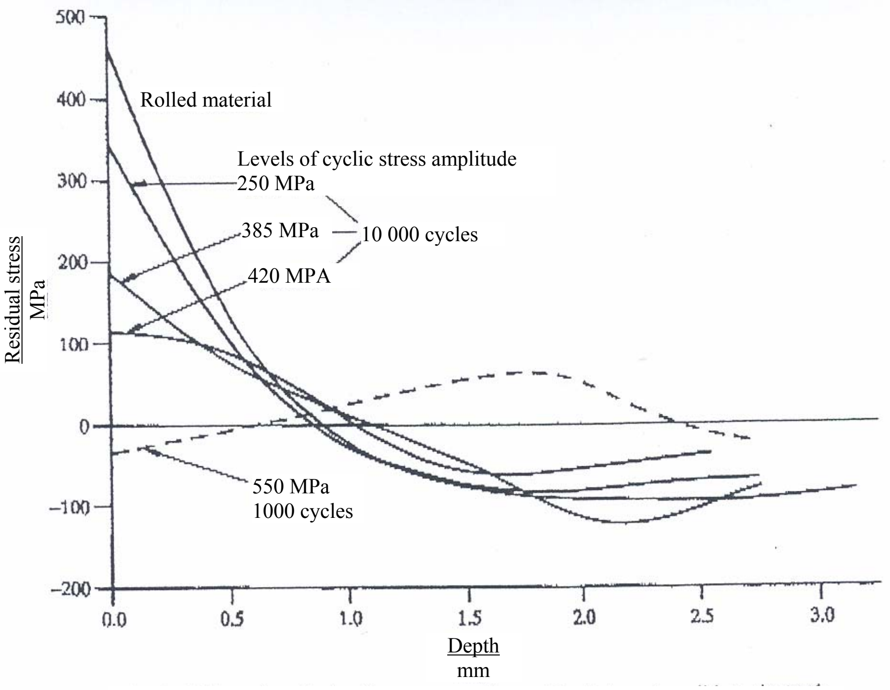

Fig. 3 Effect of cyclic loading upon surface residual stress in mild steel EN3b

Stress profile resulting from low-amplitude treatmenu are highly significant, as they are in direct contradiction with the predictions of the simplistic mechanism proposed by Klotzbucher and Kraft (17) and others to explain mechanical stress relief. In this model, residual stresses within the material combine vectorially with externally applied cyclic stresses, to a level at which they exceed the yield strength of the material. At this point, bulk plastic flow occurs, limiting the combined stress amplitude. Upon removal of the external load, the internal stress returns to a level determined by the relationship

$$(\text{residual stress}) + (\text{externally imposed stress}) \le (\text{material yield strength})$$

Thus stress changes are expected to occur in well defined regions of the material. Within these regions, the predicted stress distribution is determined only by the applied load. According to this model, also, complete stress relief should occur within the first few cycles, as opposed to the observed asymptotic behaviour. Only

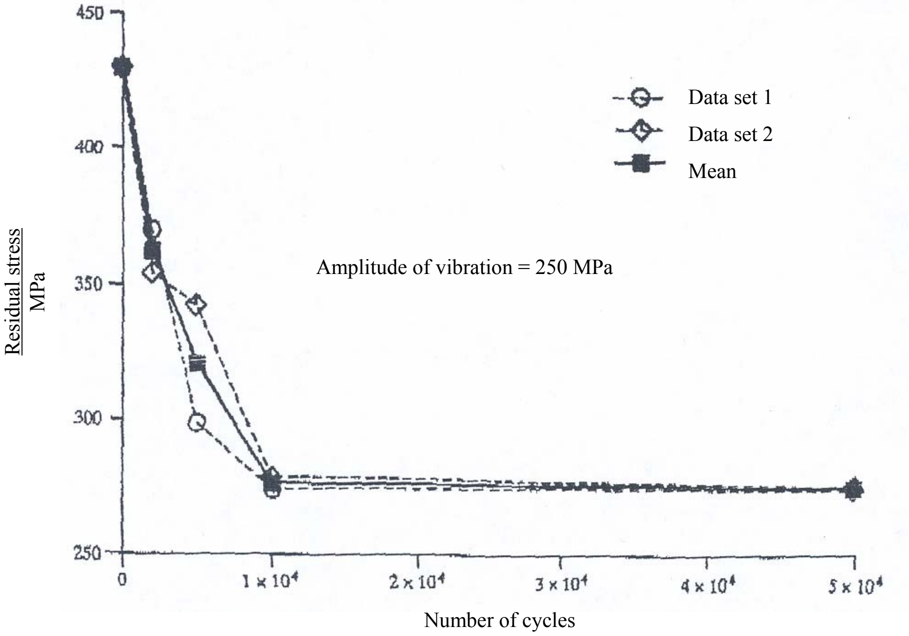

Fig. 4 Effect of vibration at 250 MPa upon surface residual stress in mild steel EN3b

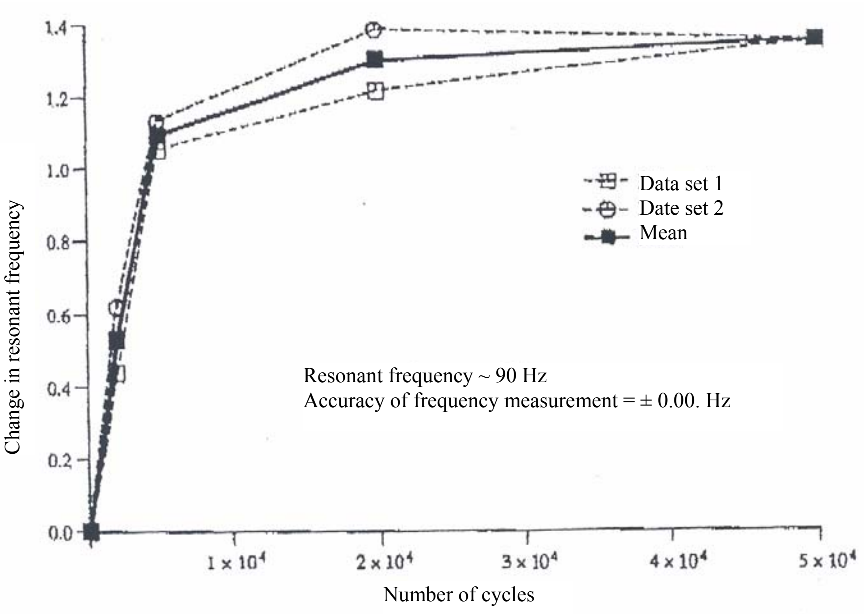

Fig. 5 Effect of vibration at 250 MPa upon resonant frequency in mild steel EN3b

as applied stress levels increase towards the yield point of the material (≥450 MPa) does the expected behaviour begin to manifest itself. Clearly the standard model has some relevance at these amplitudes, but it cannot be successfully applied to lower levels of vibration.

3.2 X-ray diffraction studies

As described earlier, the corrected Fourier series coefficients associated with related orders of diffraction from specimen material may be manipulated to yield order-independent ('subgrain size') and order-dependent ('disorder') factors [equation (1)]. These quantities may be analysed independently of one another to yield information concerning domain size and lattice imperfections respectively.

Derived crystallite size coefficients were not subjected to further analysis beyond a graphical extrapolation method used to estimate the mean crystallite size in each specimen; this was found to be ≈ 600 Å in all cases. A comparative plot of size coefficients before and after vibration of a typical specimen (Fig. 6) is sufficient to demonstrate that no significant changes occur in the crystallite size distribution as a result of vibration. This

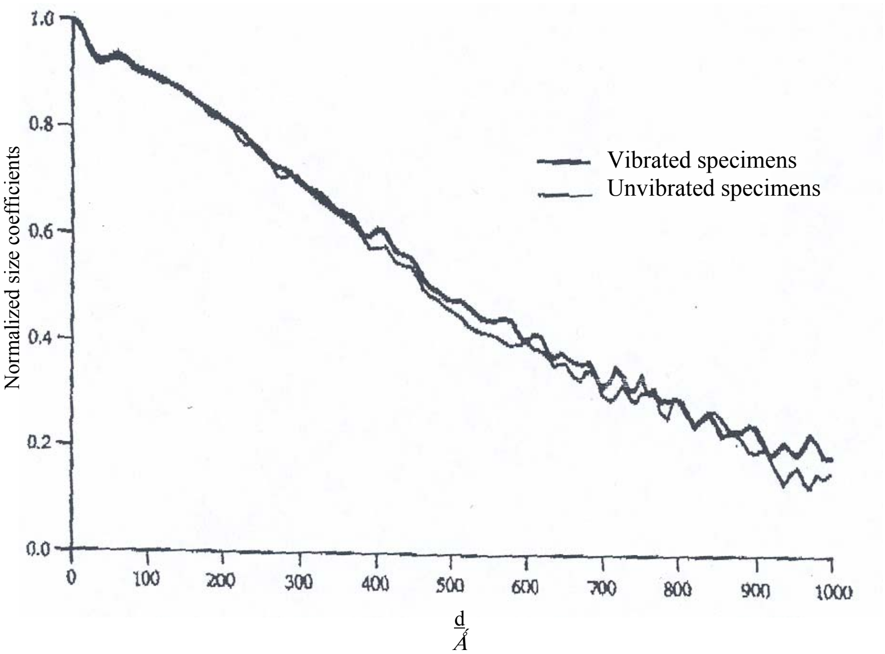

Fig. 6 Effect of cyclic loading upon crystallite size coefficient in mild steel EN3b

result contrasts sharply with the effects of thermal annealing, in which the mean domain size is greatly increased.

Analysis involving the order-independent factors consisted of a calculation of the dislocation density within the material. A least-squared error method was used to calculate the gradient of the straight line which best fitted the disorder coefficients close to their origin. This quantity was found [equation (2)] to be directly proportional to the required density; the mean crystallite size entered the calculation weakly, as a logarithmic term contributing to the constant of proportionality, Figure 7 represents the effect of resonant cyclic loading at 250 MPa upon the dislocation density within cold-rolled low-carbon steel. Although the relative change in this quantity is not large (≈30 per cent) it is significant, since the uncertainty was estimated by statistical methods to be $\pm 5 \times 10^{10}$ cm^{-2} or ± 8 per cent.

These results support the conjecture that mechanical stress relief occurs by a process of plastic deformation upon a microscopic scale. The increase in dislocation density indicates that irreversible slip has taken place within the material, causing dislocation multiplication by the Franck-Read mechanism. There is no indication that cyclic loading is a low-temperature analogue of thermal annealing (other than where residual stress reduction is concerned), which causes crystallite growth and a massive reduction of the dislocation density by several orders of magnitude.

3.3 Elastic property changes

Throughout the course of resonant loading treatments, the system of Fig. 1 allowed precise monitoring of the cantilever specimens' natural frequencies and response amplitudes. In all cases, the resonant frequency was observed to fall as a result of cyclic loading. This was attributed to a reduction in the stiffness (Young's modulus of elasticity, *E*) of the material. Since this behaviour has been considered as evidence of the efficacy of the VSR treatment, further investigation of this phenomenon was instigated.

The time dependence of elastic property changes exhibited clear similarities with that of stress reduction (Fig. 5), approaching a limiting value as the number of applied cycles increases. Statistical analysis of all available data indicates a weak correlation between changes in residual stress and material stiffness: this connection, however, is not sufficient to merit the claims that have been made. In particular, significant reductions in resonant frequency were observed in many cases with no concomitant reduction in residual stress.

Tests performed using annealed material induced frequency shifts similar to those occurring in cold-rolled specimens. Since no stress reduction was possible in these cases, the change in elasticity could not be attributed to this cause. Observation of strain amplitudes developed in response to a standard low-amplitude excitation signal revealed accompanying increases in material internal friction; these changes exhibited spontaneous reversal at room temperature over a period of 24 hours. At elevated temperatures, the recovery period was substantially reduced (1 hour at 400 K). This analysis of the elastic property changes suggests that they cannot be relied upon as an indicator of stress reduction; changes occur even in the absence of residual stress. It is unlikely, however, that stress reduction can be achieved without causing some alteration in these properties, so that their occurrence is a necessary, but not sufficient condition for stress relief by vibration.

3.4 Towards a revised theory of VSR mechanisms

The time and temperature dependences of recovery processes in annealed material are indicative of a process of dislocation movement (activation energy ~0.25 eV). It is postulated that dislocation segments, freed from weakly pinning point defects by cyclic loading, migrate towards a more stable configuration under the influence

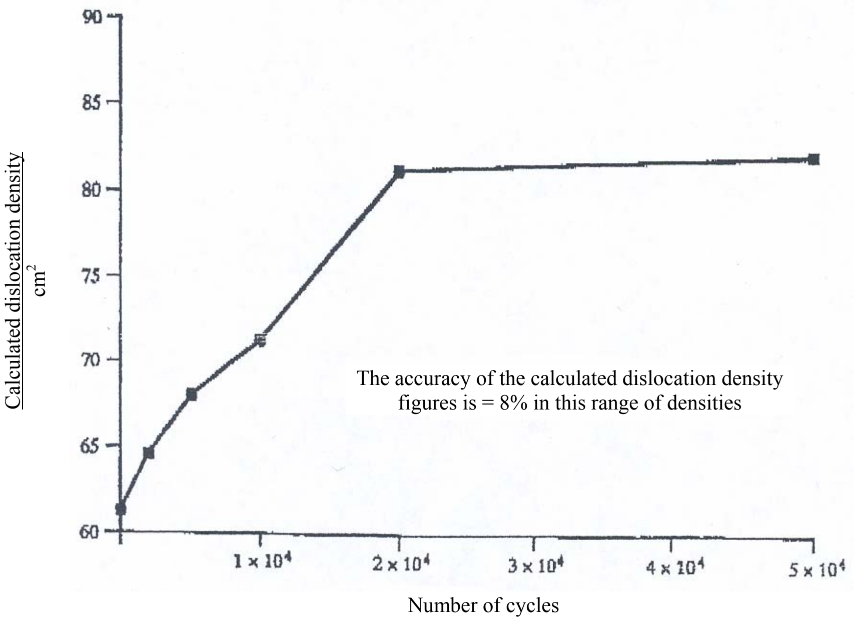

Fig. 7 Effect of resonant vibration upon dislocation density in cold-rolled mild steel EN3b

of internal stresses and thermally excited lattice vibrations. It is this microplastic process of the minimizing of the energy associated with the dislocation system that is responsible for the reduction in the observed residual stresses. Elastic modulus and internal friction are affected by the internal dislocation arrangement in the manner described above [see Granto and Lucke (25, 26)], Nowick (27) refers to reversible and irreversible changes caused by low-amplitude loading as the Koster effect. Permanent changes in elastic properties may be attributed to dislocation multiplication during vibration; this is in accordance with the results of X-ray line profile analysis, presented earlier.

4 CONCLUSIONS

It has been demonstrated that resonant cyclic loading of cold-rolled mild steel is capable of effecting reductions of up to 40 per cent in peak residual stress magnitudes. The level of applied stress required to produce such effects is relatively low: a typical value of 250 MPa represents less than half of the material's ultimate strength. At this level the estimated fatigue limit of the material is not exceeded, so that the treatment may be expected to have a negligible effect upon fatigue life. Similar effects may be induced by non-resonant loading, although considerably more difficulty is experienced in achieving the required stress amplitude. The number of load cycles required for maximum stress relief varies inversely with the dynamic stress amplitude: at 250 MPa the process continues at a decreasing rate for up to 10 000 cycles.

Considerable evidence has been accumulated to suggest that the mechanism of stress relief is one of dislocation motion on a microscopic scale. The standard model of bulk plastic flow in response to overloading becomes applicable only as the applied stress amplitude approaches or exceeds the yield point. A model has been postulated in which dislocation loops pinned by point detects are broken free by cyclic stress. Thermal processes then allow freed dislocations to move under the influence of internal stress fields until stability is reestablished. The time dependence of this microscopic slip is similar to that of diffusion processes; thus the possibility of VSR being expedited by moderately elevated temperature (~ 400 K) must be seriously considered.

It is significant that the material used successfully in this investigation is one that has been reported in much of the available literature to be unresponsive to mechanical stress relief. A logical conclusion is that even more effective results may be achieved in conjunction with different materials, such as castings, welded components or heat-treated alloys. The latter, in particular, offer exciting possibilities, since thermal annealing is often precluded for such materials by the necessity of avoiding untoward effects upon their mechanical properties.

Vibratory stress relief may now be considered to be an established phenomenon, with a validated theoretical basis. Future developments in this area will concern engineering application of this process. In particular, effective treatment parameters should be established for materials in various initial conditions. Engineering of loading methods is required to ensure that those parts of a given structure requiring treatment are subjected to adequate stress levels, while no region is damaged by excessive loads.

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