VIBRATORY STRESS RELIEF:
A Fundamental Study of Its Effectiveness

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Vibratory Stress Relief: A Fundamental Study of Its Effectiveness

Techniques have been devised for inducing consistent residual stress distributions into cantilever beams and for measuring their variation through the section. Commercial vibratory stress relief procedures have been simulated using a laboratory shaker, and it has been shown that resonant vibration techniques are capable of producing almost complete surface stress relief in specimens of hot rolled mild steel, cold drawn mild steel, and an aluminium alloy. The variables involved in the process are examined and conclusions are reached regarding cyclic strain amplitudes, cycle numbers, and frequency and fatigue effects.

Introduction

Vibratory stress relief (V.S.R.), as an alternative to natural ageing or thermal stress relief for reducing residual stresses in structures, has been debated for some 35 years. Investigations have ranged from tests on simple fatigue type specimens [1-3], with residual stresses induced by shot-peening or plastic bending, to vibration tests on castings and weldments [4-11]. Commercial processes normally involve clamping an eccentric-mass electric motor to the work-piece and vibrating at various resonant frequencies for periods of the order of 15 minutes. Manufacturers claim to achieve greatly increased dimensional stability during machining and subsequent operation of castings and weldments, up to many tons in weight, as a result of applying the V.S.R. process. The evidence that the process does indeed produce increased dimensional stability is impossible to deny. However, the various research investigations, aimed at assessing and explaining the process, have arrived at a variety of conclusions ranging from open skepticism to guarded optimism.

Early work by McGoldrick and Saunders [4] on castings and welded space frames, although giving no useful quantitative data, concluded that vibrational stress relief depended upon the occurrence of plasticity at some time during the treatment, and that to achieve the necessary amplitudes, resonant vibration should be used. These conclusions were supported by the findings of Moore [1] using shot-peened tapered cantilever beams.

In the early 1960's, Buhler and Pfalzgraf contributed four papers [6 and 12-14] on the subject, describing tests on a variety of castings and weldments. Their conclusions were not encouraging, although they did achieve a 20 percent reduction in residual stress when they increased the applied cyclic stress to around the fatigue limit of the steel used. They were clearly restricted by their concern about potential fatigue failures, and hence never attained the stress amplitudes that would be required for significant stress relief. Adoyan, et al. [7 and 8] showed that long term stability of iron castings was much improved as a result of a vibration treatment although, like Buhler and Pfalzgraf, they were concerned about the possible failure of their castings during the vibration process. They proposed a combined annealling and vibration treatment to overcome this problem.

Lokshin [9] obtained up to 70 percent stress relaxation in preloaded cast aluminium rings with a resonant cyclic stress superimposed. In 1971 Sagalevich and Meister [15] claimed success using an eccentric-mass type of vibrator in producing 50 percent reductions in welding deformations in wagon bodies fabricated from welded sheet steel.

Probably the most useful literature on the subject to date is that produced by Wozney and Crawmer [10]. They achieved a 33 percent reduction in residual stress in a shot-peened Almen strip 3 × ¾ × 0.05 in. (76 × 19 × 1.3 mm) thick subjected to cyclic bending between fixed strain limits. The value of their work was that they gave a plausible explanation of the behavior in terms of the cyclic softening characteristics of the material. According to the known monotonic tensile yield strength of the Almen strip, yielding would not have been anticipated during the application of cyclic loading. However, using a derived cyclic stress-strain curve for the material they showed that, with a knowledge of the initial residual stress magnitude, the applied cyclic stress amplitude and the final strain condition, they could predict the residual stress reduction.

Brogden [16] conducted a literature survey of the work prior to 1968. His conclusions as to the value of the process were largely pessimistic. He was not convinced that dimensional stability could be achieved without serious risk of fatigue failure during vibration.

In 1972, Cheever [11] described an extensive investigation on the subject, conducted at the Battelle Memorial Institute. Initially, a series of small scale specimens including flame-hardened castings, welded rings, welded T-beams, welded boxes and welded plates were vibrated on a vibration table using a variety of gripping techniques. The welded rings and T-beams gave the most promising results initially, but on further investigation the additional results were found to be

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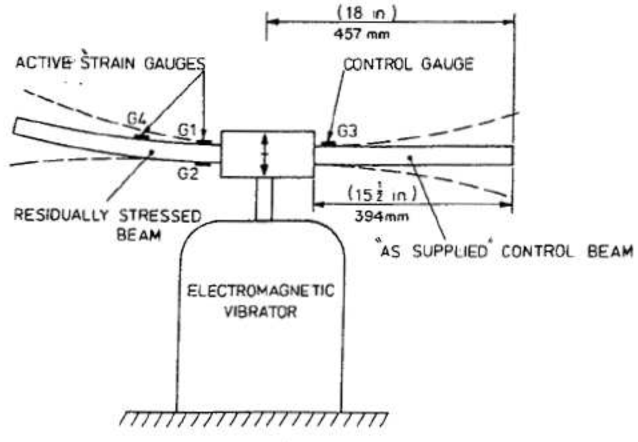


Fig. 1 Arrangement for specimen vibration

Table 1 Material properties

Material	0.2% Proof stress lbf/in^2 (MN/m^2	Ultimate tensile strength lbf/in^2 (MN/m^2)
Hot-rolled mild steel	41,500 (290)	57,000 (393)
Cold-drawn mild steel	88,000 (607)	88,500 (610)
Aluminium alloy	37,600 (262)	40,200 (277)

either discouraging or inconclusive. Very little information was given on the applied cyclic stress levels, although it was implied that the values were low. These tests were followed by a series of tests on a variety of large scale castings and also 24 large valve rings with stiffening ribs. Unfortunately, the scatter in the results prevented the author from reaching firm conclusions on the effects of V.S.R. on dimensional stability. The overall conclusions were disappointing, bearing in mind the extensive scale of the investigation.

Recent work by Weiss, et al. [17] using 12 in. (306 mm) diameter by ½ in. (12 mm) thick low carbon steel discs with a 6 in. (103 mm) diameter submerged arc weld, reported substantial reduction in residual welding stresses. The specimens were vibrated on a large laboratory shaker and residual stresses were measured using a modified Sachs boring-out technique.

It will be seen from the above summary of previous work on the subject that, although there has been a considerable effort expended over the years, the pros and cons of the technique are still very much under debate. The researchers are undecided on the whole, and yet many manufacturers claim to be using the technique with positive results. A recent article by Dreger [18] summarizes the manufacturers' claims for the process as follows: "The vibratory method of relieving stresses in castings and weldments does the job faster, cheaper, and more conveniently than thermal stress relieving."

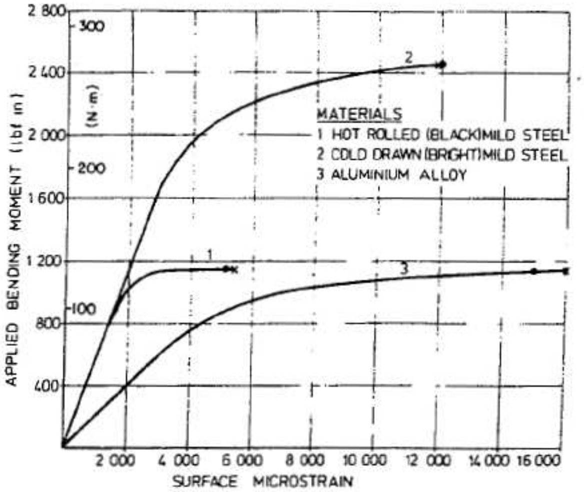
The objectives of the present work were to examine as many of the variables in the V.S.R. process as possible, without the complication of welds or complex castings. To do this simple test specimens were required within the following constraints:

(*a*) Specimens should be readily available in a range of metals as standard stock;

(*b*) For each material, it should be possible to introduce a residual stress distribution that would be consistent from one specimen to another;

(*c*) The residual stress should be capable of being reliably measured;

(*d*) Specimens should be capable of being vibrated in a manner that would relate as nearly as possible to the commercial process. This means that dimensional changes during vibration should be unrestrained;



• MAXIMUM STRAIN ON UPPER SURFACE OF BEAM (NEGATIVE)

× MAXIMUM STRAIN ON LOWER SURFACE OF BEAM (POSITIVE)

Fig. 2 Strain history of typical beams in four point loading

(*e*) Cyclic stress amplitude and frequency should be variable and readily controlled.

The specimen design selected and the test methods adopted to achieve the above objectives, together with the results and conclusions, are now discussed.

Simulation of the V.S.R. Process

The test specimen and vibration technique selected are indicated schematically in Fig. 1. The test specimen is a simple cantilever beam of ½ in. (12 mm) square cross-section with residual stresses induced by plastic bending. The test beam, together with an as-supplied control beam, were clamped to an electromagnetic shaker as indicated, and resistance strain gauges were used for control of the vibration and measurement of residual stresses. This simple arrangement meant that test specimens were obtainable from stock with no subsequent machining requirements and in a variety of materials. Perhaps the most important criterion to be met, and one which previous investigators have often failed to meet, is the need for freedom for the specimen to deform freely as residual stress redistribution occurs during cycling. The present arrangement meets this requirement.

The three materials selected for investigation were:

(*a*) Hot-rolled mild steel to BS 4360 Grade 43A,

(*b*) Cold-drawn mild steel, and

(*c*) Aluminium alloy to BS 1474 HE 30 TF.

The B.S. reference for the cold-drawn mild steel was not available, but a chemical analysis gave the following composition:

Fe	C	Si	Mn	S	P	Ni	Cr	Mo	Cu
Rem.	0.11	0.13	0.62	0.058	0.032	0.055	0.04	0.01	0.05 %

0.2 percent proof stress and ultimate tensile strength values for the materials were measured and the results are tabulated in Table 1.

Residual Stress Induction

The cantilever beam specimen shown in Fig. 1 had electrical resistance strain gauges attached as indicated. Single, axial gauges with a guage length of 0.25 in. (6 mm) and self-temperature compensated for the relevant material, were used. Residual stresses were induced using a 4-point bending

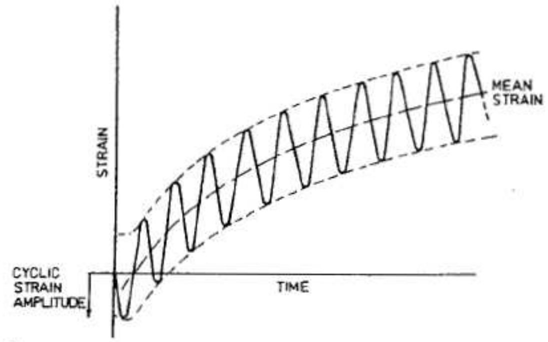


Fig. 3 Schematic output from strain gauge during vibration

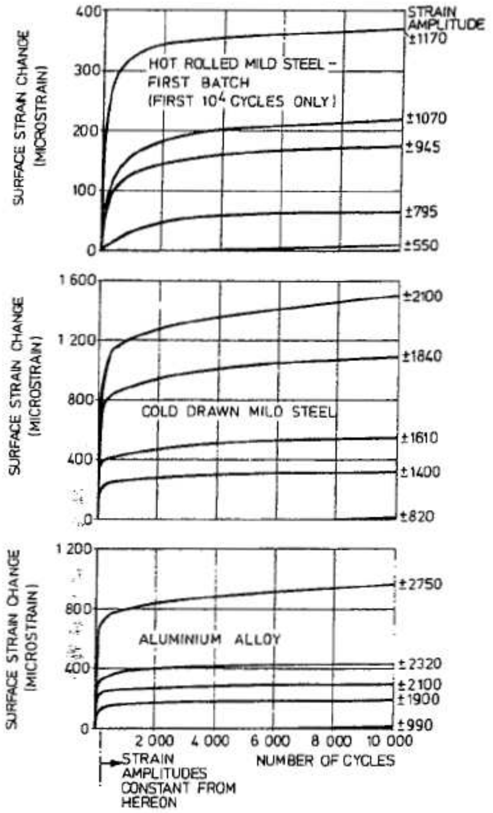


Fig. 4 Surface strain changes during vibration

system with roller bearings incorporated at the load points to ensure pure bending. Moment/strain relationships for the three materials are illustrated in Fig. 2. The loading was strain-controlled using the upper (compressive) surface gauges, and variation in applied bending moment to achieve the maximum stipulated strain values was within ± 3 percent of the mean over approximately 15 specimens of each material. As can be seen in Fig. 2, each material was loaded to approximately four times the elastic yield strain. The strain histories on both the tensile and compressive faces of the beams were essentially identical. Strain measurement was by means of a null-balance type strain indicator with a resolution of 1 microstrain.

The Vibration Process

Since the frequency range used by commercial operators of the V.S.R. process is normally in the range 0-100 Hz, the dimensions of the beams were selected to give resonance within this range. The resonant frequency achieved was 63 Hz. One particular advantage was that the resonant frequency was the same for both the steel and aluminum beams. [Resonance depends on the ratio (E/ρ) which is approximately constant for most engineering metals.]

Using the test arrangement shown in Fig. 1, it was possible to test a residually stressed specimen simultaneously with a non-residually stressed specimen at exactly the same vibrating conditions. Strain gauges 1 and 2, and the control gauge 3, all underwent high cyclic strain amplitudes, being near the root of the cantilever, while gauge 4 experienced lower values. Each run therefore gave results for two cyclic strain amplitudes. The control gauge 3 was important as a check on any gauge drift that might occur during cycling. In the event, drift was negligible and thus any changes in the output from gauges 1, 2, and 4 were associated with residual stress changes during cycling.

Use was also made in the vibration set-up of the fact that the resonant frequency could be raised by shortening the cantilever, or lowered by adding weights to the cantilever tips. Using this adjustment, tests were conducted at 33 Hz and 92 Hz in addition to the main bulk of the tests at 63 Hz.

The electronics associated with the shaker excitation and strain gauge output were arranged to provide a "closed loop" system of control. The form of the strain gauge output during vibration consisted of a constant cyclic strain amplitude and a variable mean strain, the latter being due to stress redistribution. By using a purpose-build filter system, the output from gauge 1 was split into its a-c and d-c components (shown simply in Fig. 3) such that a continuous recording of both could be obtained on an ultraviolet chart recorder.

Strain gauge readings from each of the four strain gauges were also noted before and after the vibration process using the static strain gauge bridge, which had a better resolution than the U.V. recorder.

Vibration Tests

A range of cyclic strain amplitudes was applied to the three batches of residually stressed beams-10^4 cycles for both the cold drawn mild steel and aluminium alloy materials, and either 10^5 or 3×10^5 for the hot rolled steel. Since the beams were effectively straightening during the vibration treatment, strain changes on opposite faces could be expected to be of equal magnitude but of opposite sign. This was found to be so, with maximum variations of 14, 4 and 10 percent for the hot-rolled M.S., cold-drawn M.S., and aluminium alloy, respectively, although in most cases the values were much closer than this. In the results that follow therefore, the data relates to changes in the upper, tensile residually stressed, surface.

In Fig. 4 the variations of surface strain change during cycling are presented for gauge 1 up to 10^4 cycles of vibration. Figure 5 shows the gauge 1 surface strain changes which occurred between start and finish of the vibration treatment for the three materials. As anticipated, most of the overall strain change took place during the initial period of cycling but, as can be seen, changes did continue right up to 10^4 cycles – and beyond in the case of the hot rolled steel. Unfortunately, the initial build-up of vibrator excitation signal meant that the intended cyclic strain amplitude was not attained until around 250 cycles of vibration. The question then arose as to what effect a more elaborately controlled "step" increase in vibrator amplitude would have. In an effort to answer this question, without resorting to complex signal control gear, the first few cycles were examined more closely using the slow bend tests described in the following section.

Before concluding this section, however, a statement is necessary on the effect of varying the resonant frequency: the three frequencies of 33, 63 and 92 Hz produced no significant difference in results and in fact no distinction has been made in the results presented in Fig. 4.

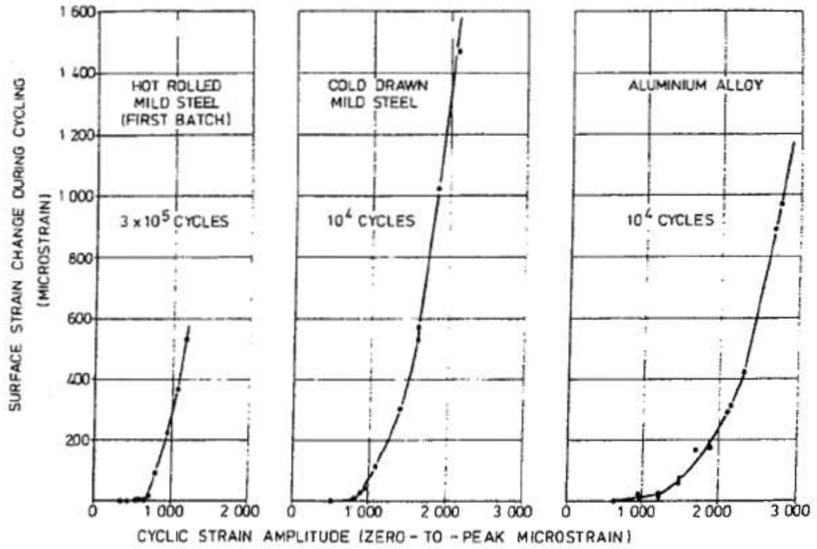


Fig. 5 Strain changes in upper surface of cantilever during cycling

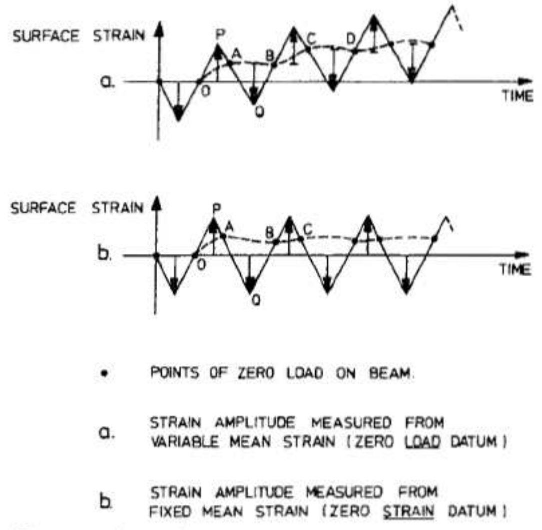


Fig. 6 Methods of strain control for the slow-bend tests

Slow Bend Tests

The objective here was to investigate the behavior of the test beams during the first ten cycles by devising a slow bend test that would reasonably simulate the desired vibration process.

Shorter beams of 10 in. (250 mm) length were used for these tests, with axial strain gauges on the top and bottom surfaces. Residual stresses were induced as before, and the beams were then cycled using the same 4-point loading rig, the straining direction being reversed by simply inverting the beams. In this way cycling was achieved as a series of half cycles. In all cases the direction of the first half cycle of loading was such that it opposed the existing surface residual stresses.

Fig. 6(*a*) illustrates the initial method of strain cycling, and Fig. 7 presents a sample of the moment/strain behavior obtained using the hot-rolled mild steel. In Fig. 7 the amplitude of the cyclic component was ± 1150 microstrain which matched reasonably with one of the vibration test amplitudes of 1170 microstrain in Fig. 5. Because of the tensile residual stress on the upper surface there was no yielding during the initial application of bending moment. Thereafter the loading sequence was:

1. Apply + 1150 microstrain from point 0 to point *P*.
2. Unload, giving residual strain at point A.

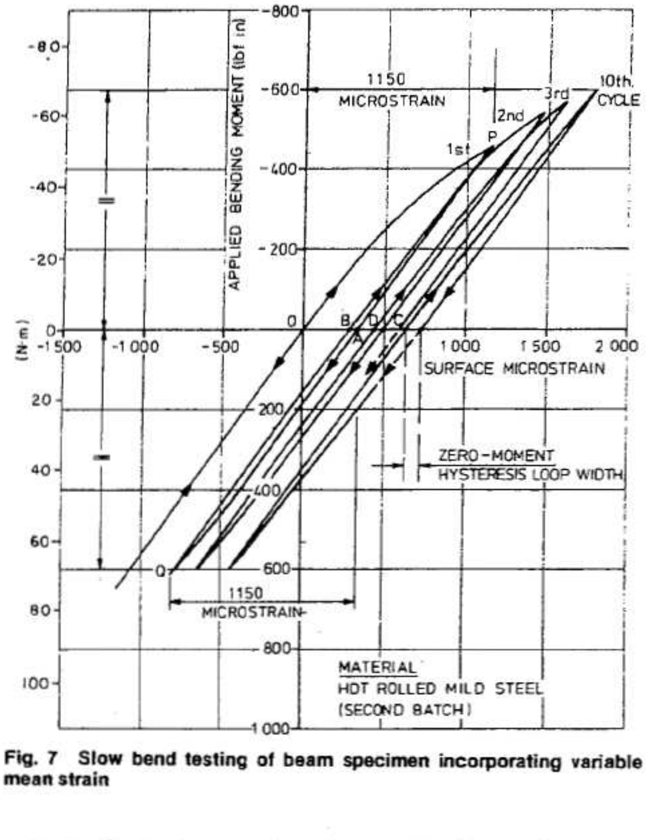


Fig. 7 Slow bend testing of beam specimen incorporating variable mean strain

3. Invert the beam and apply − 1150 microstrain. Hence point *Q*.
4. Unload to give residual strain at point *B*.
5. Apply + 1150 microstrain . . . . . . etc.

In this way the necessary freedom of the beams to deform without constraint was achieved. The progression towards symmetric bending moment amplitude in Fig. 7 should be noted.

As a comparison, similar tests were conducted with a fixed mean strain, and the technique and sample results for hot rolled steel are illustrated in Figs. 6(*b*) and 8, respectively. Figure 9 presents sample "no-load" surface strain histories for all three materials, for both the fixed mean and variable mean strain slow bend tests. Figure 10 shows the variation of mean strain with cycle number for cold drawn steel, for three

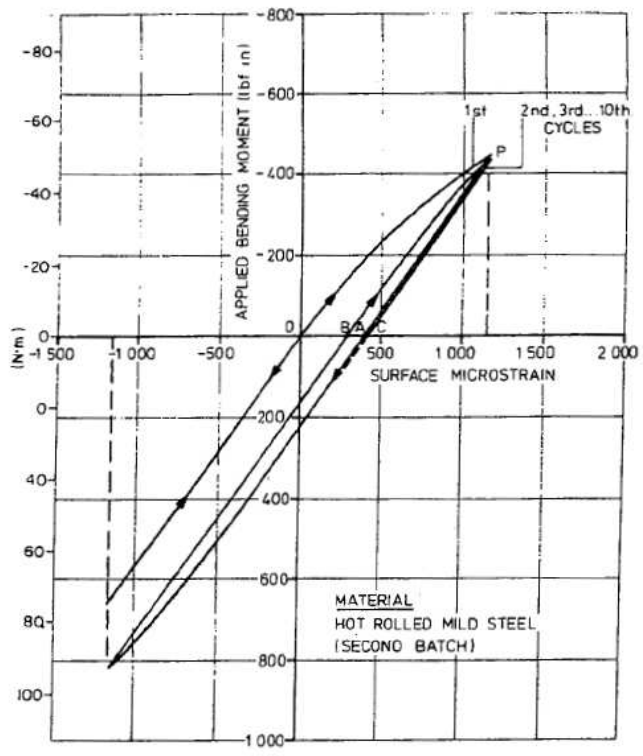


Fig. 8 Slow bend testing of beam specimen incorporating fixed mean strain

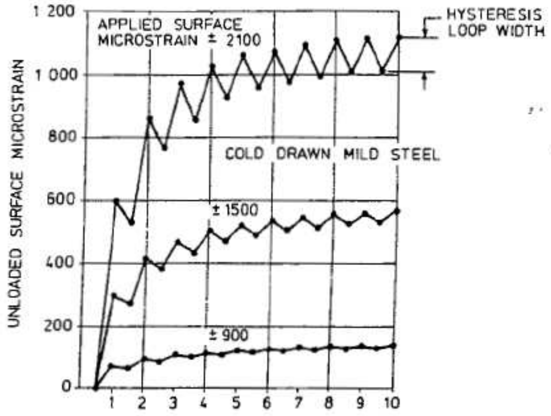
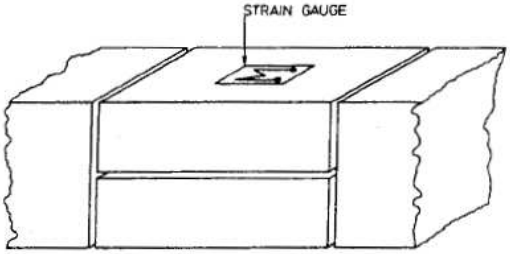
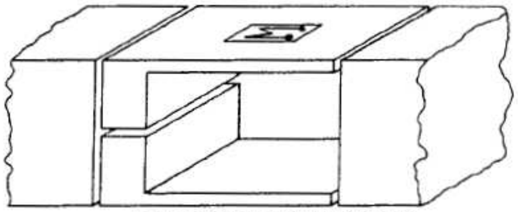


Fig. 10 Unloaded surface strains in beams - slow bend tested with variable mean strain



a. SECTIONED BY SAWING



b. SHIM THICKNESS REDUCED BY FILING

Fig. 11 Side view of beam specimen showing sectioning method

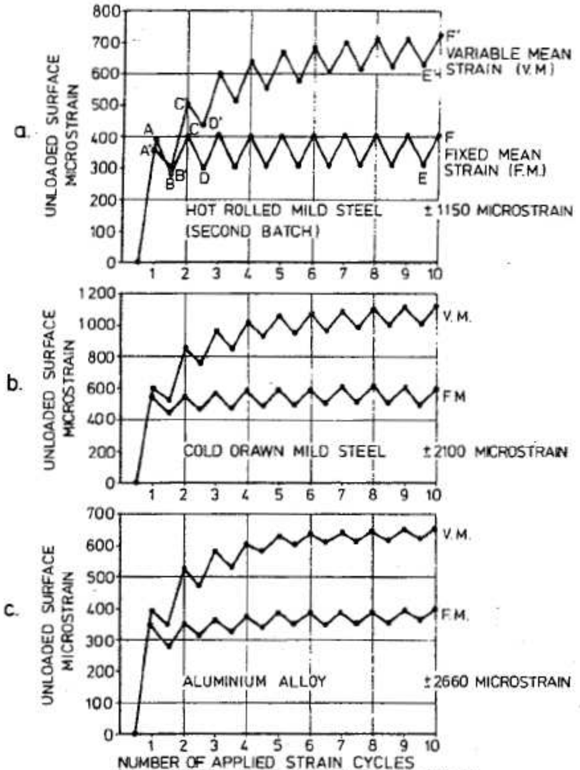


Fig. 9 Unloaded surface strains in slow-bend tested beams (for tensile residual stress)

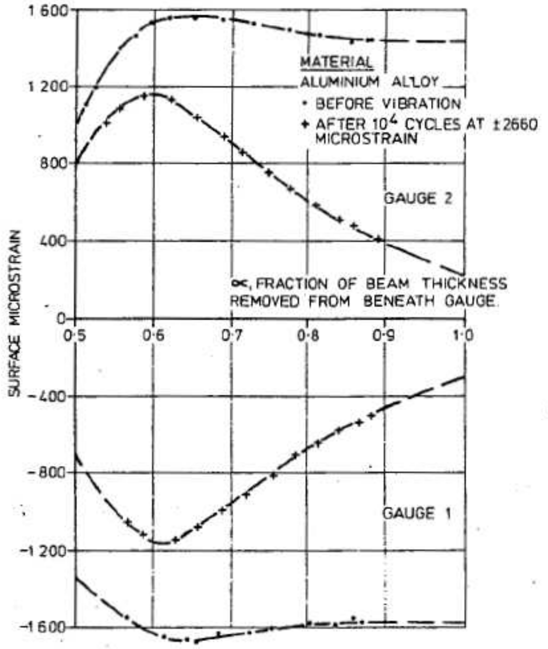


Fig. 12 Strain changes during progressive sectioning

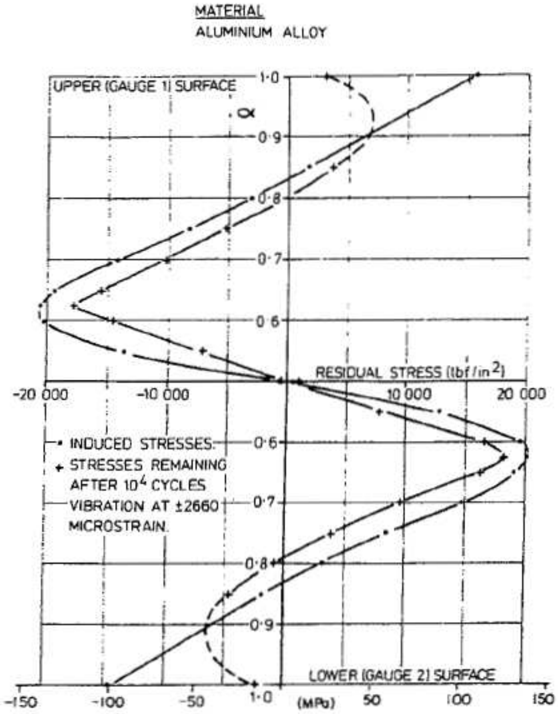


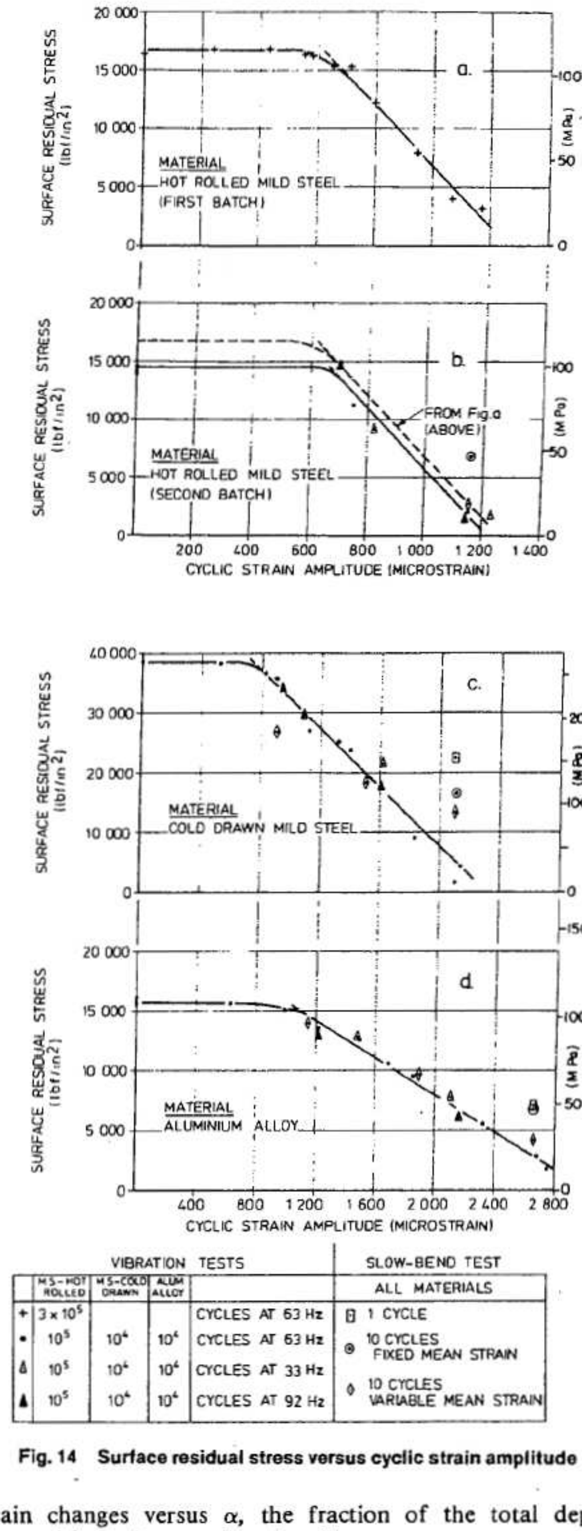
Fig. 13 Residual stress distribution before and after vibration

levels of cyclic strain amplitude. Similar results were obtained for the other two materials. In both the vibration and slow bend tests, it was found that there was a threshold level of cyclic strain amplitude below which no changes in mean strain, and therefore by implication, no changes in residual stress, occurred. This is discussed later.

Residual Stress Measurement

The method employed for measurement of residual stresses was destructive, entailing measurement of surface strain changes as metal was removed from beneath the gauge. Using a method originally devised by Rosenthal and Norton [9], the complete distribution through the beam section could be deduced from the surface strain changes. In all cases the strain gauges used for residual stress measurement were the same as those used in the earlier stages of residual stress induction and subsequent testing. Figure 11 illustrates the procedure adopted.

Initial top and bottom surface strain gauge readings were noted, and the test bar was then sawn across at a section ½ in. (12 mm) from the centre of the strain gauges. The beam was then sawn along the neutral axis to a depth of about 1 in. (25 mm) and the gauge bearing blocks were then separated from the remainder of the beam. On completion of each stage, the stable surface strains were noted – after allowing a sufficient period for cooling. Metal was now progressively removed from the inner faces by careful hand filing (a milling procedure had been previously tried, but in accord with results by Leaf [20], this was found to be unsatisfactory). The filing was done in small increments to prevent overheating of the remaining shim. At each stage, stable strain readings were noted after sufficient cooling to restore the gauge to within its self-temperature-compensating range. The modified method of Rosenthal and Norton required three sets of information to determine the complete residual stress pattern through the beam cross-section. The first was the change in gauge readings after the beam had been sectioned on both sides of the gauges (this was zero in all cases for these tests). The second quantity was the strain change after making the longitudinal slit between the two gauges. The third was a continuous plot of strain changes versus α, the fraction of the total depth removed from the gauge bearing shim.



	VIBRATION TESTS				SLOW-BEND TEST
	M.S-HOT ROLLED	M.S-COLD DRAWN	ALUM ALLOY		ALL MATERIALS
+	3 × 10⁵			CYCLES AT 63 Hz	⊡ 1 CYCLE
•	10⁵	10⁴	10⁴	CYCLES AT 63 Hz	⊛ 10 CYCLES FIXED MEAN STRAIN
△	10⁵	10⁴	10⁴	CYCLES AT 33 Hz	
▲	10⁵	10⁴	10⁴	CYCLES AT 92 Hz	◊ 10 CYCLES VARIABLE MEAN STRAIN

Fig. 14 Surface residual stress versus cyclic strain amplitude

Residual stress measurements were made on virgin bar material, residually stressed beams, and residually stressed beams after vibration and slow cycling. A sample of the surface strain variations as the section was reduced is given in Fig. 12 for the aluminium alloy, before and after one of the higher amplitude vibration treatments. As can be seen, a certain amount of extrapolation was required to allow for the saw blade and final shim thicknesses. Both the aluminum and hot rolled mild steel gave symmetric distributions, whereas the cold drawn steel was somewhat unsymmetric due to the existence of initial residual stresses in the as-received bar.

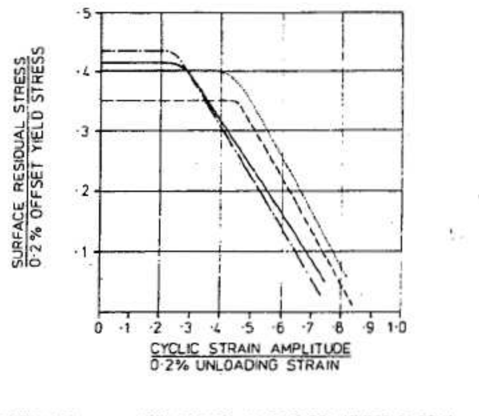


Fig. 15 Non-dimensionalised residual stress reduction curves

The strain distributions in Fig. 12 were used in the Rosenthal and Norton technique to give the residual stress distributions before and after vibration as presented in Fig. 13. Similar distributions were obtained for the other two materials, although again the cold drawn steel was somewhat unsymmetric. In all cases the *before* and *after* distributions complied with the necessary criterion of self-balancing of axial forces and bending moments.

Summary of Results

The results are best summarized in the form of plots of residual surface stress versus cyclic strain amplitude. This is done for the two batches of hot rolled mild steel in Figs. 14(*a*) and (*b*). All results are inserted, including the vibration results involving varying cycle numbers and varying frequency, and the slow-bend tests with both fixed and variable mean strain. Similarly the results for the cold drawn mild steel and the aluminum alloy are summarized in Figs. 14(*c*) and 14(*d*), respectively.

Discussion

A proper understanding of the mechanism behind the V.S.R. process will involve consideration of such contributory factors as cyclic hardening and softening, strain rate effects and variation of material properties during cycling. Attention has been given to these topics by Dawson in his doctoral thesis [21] and this will form the basis for a later contribution on the subject. The present discussion is restricted to those aspects of the work that will be of interest to potential users of the V.S.R. process.

The main results arising from the test programme are undoubtedly those presented in Figs. 14(*a-d*) from which it can be concluded that initial surface residual stresses of the order of half the yield stress can be significantly reduced, and in fact virtually eliminated, by a careful choice of cyclic strain amplitude and the number of cycles applied. This is so for all three materials involved in the tests, notwithstanding the reputation that cold drawn mild steel has of being difficult to treat using commercial V.S.R. processes. It is clear from Figs. 14(*a-d*), and also from Fig. 5, that there is a threshold value of cyclic strain for each material below which no residual stress reduction can be achieved. Above this threshold there is an essentially linear reduction in residual stress with increasing cyclic strain amplitude. To completely stress relieve surface residuals of 0.4 × 0.2 percent proof stress required cyclic strains of the order of 0.85 × 0.2 percent proof strain. In other words, the combined stress level had to be well in excess of the 0.2 percent proof stress.

In view of the similarity in the behavior of the three materials, the results have been nondimensionalized in terms of the 0.2 percent proof stress values and the 0.2 percent unloading strain (i.e. the elastic strain on unloading from the proof stress in the uniaxial tensile test) and the results are presented in Fig. 15. It is interesting that, even with such a diversity of materials, the results should be so similar. Particularly striking is the comparibility of the cold drawn mild steel and aluminium alloy curves. It would appear to be reasonable to conclude from these results that most structural metals will respond to vibratory stress relief treatment provided the necessary care is taken with the vibrating process.

A common method of modifying residual stresses in practice is to apply a single overload to the structure. This is a well-proven technique and is backed up by the present results. Combining the results of the slow bend tests and the resonant vibration tests, it is found that stress relief occurs to a large extent (50-70 percent) in the first cycle, to a moderate extent (25-30 percent) over the next 10 cycles and to a lesser extent (10-25 percent) over the remaining cycles up to 10^4. The important point, however, is that, while substantial stress relief occurs in the first cycle, further reductions do occur continuously as cycling progresses. It is interesting to note that the cold drawn mild steel showed by far the greatest stress reduction (25 percent) between 10 and 10^4 cycles.

Attention has been focussed on "surface" residual stress levels up till now. Surface residual stress reduction is beneficial for a number of reasons. Firstly it is normal for maximum applied stresses to be surface stresses and since these are superimposed on residual stresses, then "first yield loads" can be increased. Secondly, machining distortion, which is due to the removal of residually stressed surface layers, can be reduced, and thirdly, stress corrosion which is a surface phenomenon dependent on residual stress level, can also be reduced. Figure 13 shows the "before" and "after" residual stress distributions through the depth of the beam for the aluminium alloy. Similar results are available for the other two materials, and it is clear that a stress redistribution has occurred as a result of the vibration process. The peak residual stresses near the centre have been reduced, but to a much lesser extent than the surface stresses.

In the summary of previous work on the subject, attention was given to the concern that previous investigators had expressed over the possibility of fatigue damage to the structure resulting from the V.S.R. process. While the present authors have not included fatigue tests in their investigation, empirical strain range v. number of cycles fatigue curves have been produced for the three materials, using Manson's Method of Universal Slopes [22]. From these curves it has been found that the Fatigue Limit for each of the three materials corresponds closely to the threshold value of strain discussed above. Hence it must be concluded, contrary to a recent statement on the subject [18], that vibratory stress relief cannot be achieved without some degree of fatigue damage. However, an approximate assessment of the fatigue damage corresponding to complete surface stress relief suggests that it will only be a few percent. Many industrial applications of the V.S.R. process are mainly concerned with reducing distortion with no subsequent concern about possible fatigue failures. However, the question of fatigue damage is one that requires further consideration.

Conclusions

As a result of the tests described above, the following conclusions can be reached:

1. Mechanical vibration is capable of producing almost complete surface stress relief in components made of hot rolled mild steel, cold drawn mild steel and an aluminium alloy.

2. Stress reduction is indicated by a permanent strain change at the surface. Strain gauges could thus be used to monitor the progress of vibratory stress relief.

3. For stress relief to occur, a critical cyclic strain amplitude must be exceeded – below this there is no change.

4. Above the critical amplitude, and for a given number of cycles, the reduction in residual stress is linear with increase in applied cyclic strain amplitude.

5. For full advantage of the vibratory stress relief process, the component must be allowed to freely deform during the treatment.

6. Vibrational frequency variation, within the range normally applied using commercial methods, has little effect on the resulting stress relief.

7. For any stress relief to occur during vibration, the fatigue limit of the material has to be exceeded and fatigue damage must therefore occur, although this is likely to be small.

Acknowledgment

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