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**MODIFICATION OF WELDING
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VIBRATION DURING WELDING**

A. S. M. Y. Munsi
A. J. Waddell
C. A. Walker

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Modification of welding stresses by flexural vibration during welding

A. S. M. Y. Munsi, A. J. Waddell, and C. A. Walker

Flexural vibration was applied to specimens during the welding process to observe its effect on welding residual stresses. The study was carried out in three phases, namely, (i) investigation of the effect of amplitude of vibration, (ii) investigation of the effect of time of vibration, and (iii) investigation of the effect of high frequency vibration. The results of the present study provide a basis for relieving the residual stresses in practice. It has been shown that there is an optimum applied stress that will maximise the reduction in both longitudinal and transverse residual stresses. The effect of time of vibration on residual stresses was found to be negligible. After high frequency vibration, the change in longitudinal and transverse residual stresses showed no consistent trend.

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The authors are in the Department of Mechanical Engineering, University of Strathclyde, Glasgow G1 1XJ, UK (c.walker@mecheng.strath.ac.uk). Manuscript received 25 July 2000; accepted 14 September 2000.

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INTRODUCTION

Welding processes inevitably induce a state of residual stress in materials and products. This poses potential problems in terms of dimensional stability and structural integrity. The conventional method of relieving such residual stresses is post-weld heat treatment (PWHT), which is an effective process, but it suffers from several disadvantages: the cost of treatment in terms of equipment and energy is high; the growth of oxide scale on the surface necessitates subsequent finishing processes to remove the scale; and in many metals annealing relieves residual stresses at the expense of important mechanical properties that are usually achieved during the thermomechanical processes. Vibratory methods have been proposed as alternatives to thermal stress relieving processes. A number of industries¹⁻⁶ have used the vibratory stress relieving (VSR) method to reduce the residual stresses of their components, even though they were unaware of the detailed mechanisms of the vibratory stress relieving process.

The present work is part of a detailed investigation⁷ that was aimed at determining how vibratory methods could be used to relieve welding residual stresses. In the present study flexural vibration was applied to the specimens while the specimens were being welded and cooled and the effect of vibration on welding residual stress was investigated. Controlled flexural vibration can apply a dynamic stress at preselected locations of the specimens. From the work carried out in the early 1960s by Bühler and Pfalzgraf⁸ to the most recent work by Sonsino *et al.*,⁹ most of the publications related to vibrational stress relief have considered flexural vibration. Aoki and Nishimura¹⁰ and Aoki *et al.*¹¹ applied vibratory treatment to their specimens

while the specimens were being welded. In their experiment two mild steel bar samples were welded while a combined mode of vibration (longitudinal and flexural) was applied, and the effect of vibration on longitudinal (parallel to the weld line) residual stresses was investigated. Aoki and Nishimura¹⁰ showed reductions in the residual stresses in the weld and in the weld toe from 300 to 120 MPa and from 120 to 20 MPa respectively. However, Aoki *et al.*¹¹ showed a reduction in residual stresses from 160 to 100 MPa in the weld and an increase in residual stress from 30 to ~150 MPa in the weld toe. In common, neither of the above studies commented on the transverse (perpendicular to the weld line) residual stresses. A similar study (similar configuration, specimens, and vibration conditions) carried out by Munsi⁷ did not establish a similar result. It was observed that owing to a slight difference in the prepared V, the distance between the two plates and the position of the weld line causes large differences in the magnitude and distribution of the weld induced residual stresses. To remove the factors caused by specimen geometry and welding position, a simplified approach was taken, in that a single pass bead weld (perpendicular to the length) was carried out on a solid plate.

To summarise the present study, a pure flexural vibration was applied to the specimens while the specimens were being welded and cooled and its effect on welding induced residual stresses was investigated. The time and amplitude of vibration were varied independently. The effect of high frequency flexural vibration on welding residual stresses was also investigated separately.

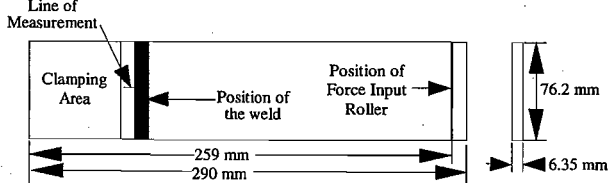
TEST SPECIMENS AND MATERIAL PROPERTIES

The specimens were produced from 0.18 wt-%C steel flat bar of cross-section 6.35 × 76.2 mm. A metallographic study revealed that the bar was hot rolled, quenched, and then cold rolled to obtain the given surface finish and mechanical properties. The specimen size was selected as it could be located on the goniometer of the X-ray diffractometer using a locating jig. The material specification of the flat bar was BS 970 080A15.¹² The composition of the bar is given in Table 1.

The total length of the specimen was 290 mm, which included the clamping area and the free length for applying dynamic stress. A single pass metal inert gas (MIG) bead weld line was deposited near the clamp of the specimen (Fig. 1) to induce welding residual stresses. The position of the weld line near the clamp was selected to ensure that the vibration amplitude would be low in that area, because a high amplitude of vibration causes the molten metal to

Table 1 Alloying elements of specimen, wt-%

C	Si	Mn	P	S	Fe
0.18	0.23	0.88	0.013	0.011	Bal.



1 Cantilever beam specimen

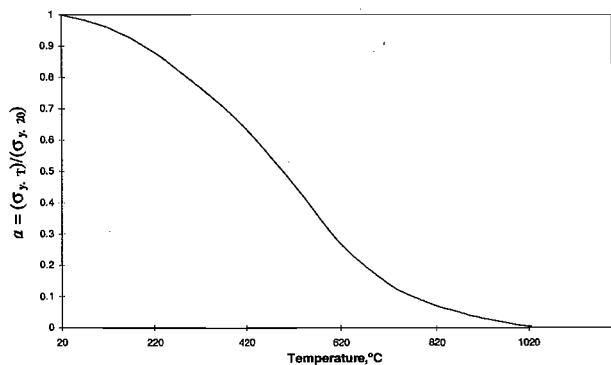
move from its deposited location and results in distortion in the weld.

The ambient mechanical properties of the flat bar were determined via a tensile test, for which a 0.2% offset yield stress of 607 MPa and an ultimate tensile strength of 611 MPa were recorded. Owing to the welding process, the area surrounding the weld experienced a heating and cooling cycle in that it was heated from 20°C (room temperature) to high temperatures (~1530°C on the fusion line) and then returned to 20°C. As an effect of the high temperature the yield stress was reduced to a very low value, and then increased as the temperature decreased. Typical high temperature yield properties for mild steel are presented in Fig. 2,¹³ where the dimensionless yield stresses are shown in the temperature range 20–1200°C. To verify the high temperature properties of the test material, a tensile test at 700°C was carried out, which showed that the yield stress of the metal was ~70 MPa.

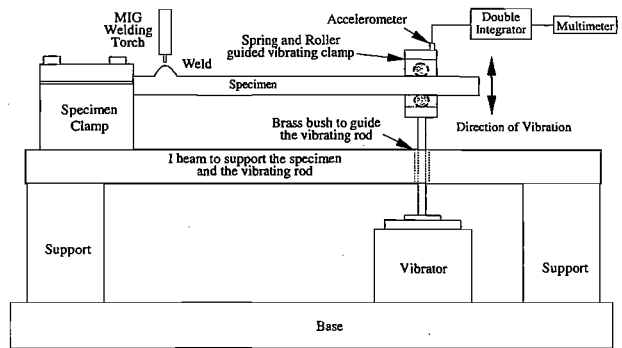
EXPERIMENTAL PROCEDURE

The specimens were subjected to a flexural vibration during welding, at a non-resonant frequency of 25 Hz (the natural frequency of the specimens was approximately 115 Hz). This frequency was selected to maximise the amplitude of vibration of the system. The experimental configuration is shown in Fig. 3.

One end of the specimen was inserted into the vibrating clamp, where it was clamped by two rollers. The rollers were loaded by compression springs, which were tightened with screws. The springs were used to capacitate the translational and rotational movement of the specimens during vibration. The other end of the specimen was rigidly clamped to a fixed frame. The roller clamp was connected to the vibrator using a 10 mm diameter steel rod, which was guided by a brass bush. A single pass bead weld was performed on the specimens while they were being vibrated under preselected conditions, the details of which are described in the 'Experimental results' section below. It is arguable that a bead weld on a solid plate does not represent a real weld where two or more pieces of metal are joined together in a multipass welding process. In the present study, a simplified approach was taken to reduce the number of variables due to the changes in the specimen geometry, a brief description



2 Variation of yield stress (dimensionless) with temperature for typical low carbon steel (after Ref. 13)



3 Experimental configuration for flexural vibration treatment of cantilever beam

of which is presented in the introduction above. This will not model a welded joint, but it will model the residual stresses and reduction in residual stresses due to the vibratory treatments. A MIG welding set was used in the welding process. The voltage and current in the welding process were 25 V and 195 A respectively. A stepper motor driven weld torch carrier controlled the welding speed to 338 mm min⁻¹, i.e. the duration of welding was ~13.5 s.

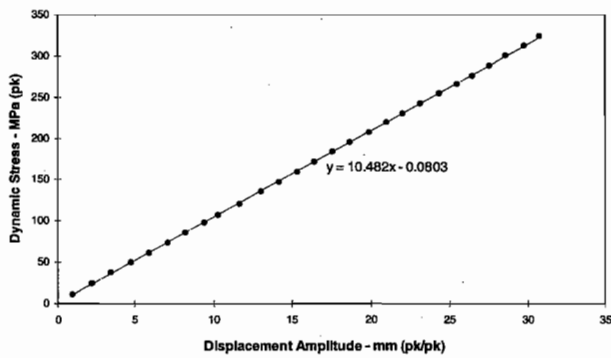
When the specimens cooled to room temperature, the longitudinal and transverse directional residual stresses were measured on the as rolled surface (the selected line is shown in Fig. 1) using a scanning X-ray diffractometer. The residual stress measurement line was selected to lie in the heat affected zone (HAZ) of the weld, which was also near the rigid clamp, to ensure that it would experience a relatively high dynamic stress with a lower amplitude of vibration.

APPLIED STRESS CALIBRATION

The dynamically applied stress at room temperature was calibrated using a P-3500 digital strain indicator, an accelerometer, a double integrator, and a multimeter. The calibration was carried out on the apparatus shown in Fig. 3. In the calibration process the dynamically applied stress (at room temperature) in the investigation area was determined in terms of vibration amplitude at the vibrating clamp (Fig. 3). The calibration curve is shown in Fig. 4. It should be noted that owing to welding, the weld and adjacent area were highly heated, which caused the material properties (yield stress, modulus of elasticity, etc.) to change. Thus the actual applied stress to the weld and surrounding area would certainly be different from the calibrated values. The aim of this calibration was to ensure that repeatable levels of dynamic stress would be applied to all the specimens (even if the detailed stress distribution was unknown owing to the high temperatures). The calibration constant was found to be as follows: a displacement amplitude of 1 mm (peak-peak) equals an applied stress of 10.5 MPa (peak).

RESIDUAL STRESS MEASUREMENT

The longitudinal and transverse residual stresses (with respect to the weld line) were measured using a scanning X-ray diffractometer. The X-ray diffractometer was calibrated and the material elastic constant was determined to obtain the absolute value of the measured residual stresses. The error band of the diffractometer was considered to be ±20 MPa as specified by the manufacturer. A verification of the error band was carried out by measuring the same point in a sample a number of times, and the differences in the measured values of the residual stress were found to vary within a range of ±5 MPa.



4 Calibration plot for applied dynamic stress

In the X-ray diffraction measurement the single exposure technique (SET) was used, where a line map was generated along the selected line of the specimens (Fig. 1). The measurements were carried out using a fixed position X-ray head, with the goniometer table moved to locate the measurement point under the head. The movement of the goniometer under the X-ray head was controlled by a computer. The specimens were located on the goniometer table using a positioning jig, where six point supports were used to locate the specimens precisely in position each time. The specimens were levelled using a precision dial indicator. After positioning the specimens on the jig they were clamped using a clamping screw, which prevented any movement of the specimens relative to the goniometer table and clamping jigs. Since the specimens were prepared from bright mild steel there was no scale on their surface. After completion of welding the surface was cleaned using soft tissue paper and then the residual stress measurement was carried out, i.e. no further surface treatment was carried out. The conditions of the X-ray measurements are given in Table 2. The longitudinal residual stress measurements were carried out at intervals of 0.2 mm, i.e. 26 points were measured over a 5 mm length. The transverse residual stress measurements were carried out at intervals of 0.1 mm, i.e. 31 points were measured over a 3 mm length. This spatial resolution should be compared with e.g. hole drilling, where the sampling area is of the order of several millimetres.

EXPERIMENTAL RESULTS

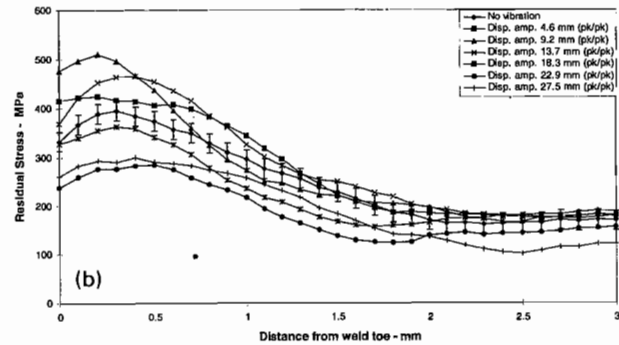
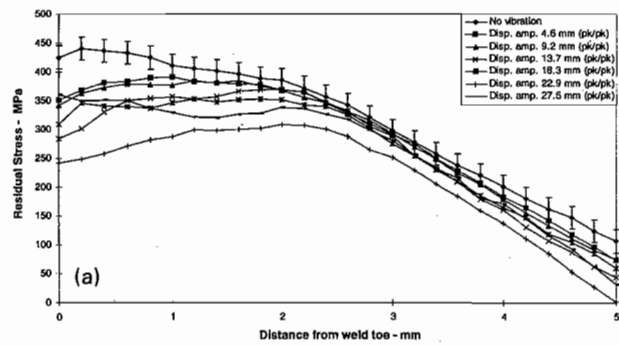
The effects of variable vibration amplitude, time of vibration, and high frequency vibration were investigated. The results are described in the following sections.

Effect of amplitude of vibration

In this investigation the frequency of vibration was kept constant and the amplitude of vibration was varied. In total, 28 specimens were processed; grouping four in a sample, seven samples were created. The first sample was welded without any vibration, and therefore acted as the control sample. The other six samples were vibrated while they were being welded, applying different amplitudes of vibration. The width of the HAZ of the weld was 0.6–0.8 mm. The longitudinal and transverse residual stresses of the samples

Table 2 X-ray measurement conditions

X-ray type	Cr K_{α}
Diameter of X-ray beam	1 mm
Bragg angle	156.1°
Measurement plane	211
Measurement angle β	30°
Oscillation of β angle	0°
Peak fit	Gaussian
Number of exposures	2



5 Residual stress distribution *a* parallel to weld line (longitudinal) and *b* perpendicular to weld line (transverse)

were measured. The residual stresses of the four specimens of each sample were averaged to reduce error in the analysis and are shown in Fig. 5. The displacement amplitude at the vibrating clamp and corresponding nominal dynamic applied stresses in the investigating area, as well as the resulting residual stress range in different batches are presented in Table 3.

In the longitudinal stress plot (Fig. 5a), the residual stresses in and near the weld toe (distance range 0–2 mm) decreased by ~65 and ~71 MPa owing to application of vibration amplitudes of 4.58 and 9.16 mm (all amplitudes given are peak–peak) respectively. With increases in the vibration amplitude to 13.74 and 18.3 mm, the residual stresses decreased by ~119 and ~95 MPa respectively. Vibration amplitudes of 22.9 and 27.48 mm showed a decrease in residual stresses of ~166 and ~79 MPa respectively. Away from the weld toe the residual stresses also decreased, but to a lesser degree.

The transverse residual stresses on and near the weld toe (distance range 0–1 mm) increased by ~52 MPa on application of a vibration amplitude of 4.58 mm (peak–peak), as shown in Fig. 5b. An increase in the vibration amplitude to 9.16 mm caused an increase in residual stresses by ~88 MPa. A further increase in the vibration amplitude to 13.74 mm caused an increase in the residual stresses by ~68 MPa. The vibration amplitude of 18.3 mm showed a decrease in residual stresses by ~31 MPa. Further increases in vibration amplitudes to 22.9 and 27.48 mm caused the residual stresses to decrease by ~98 and ~79 MPa respectively. Away from the weld toe (distance range 2–3 mm), no reductions in residual stresses were observed until the vibration amplitude level of 13.74 mm was reached. The vibration amplitudes of 22.9 and 27.48 mm showed a decrease in residual stresses by ~25 and ~50 MPa respectively.

Effect of time of vibration

In this investigation two different levels of vibration amplitude were applied to the specimens, namely 15.26

and 22.89 mm (peak–peak). The vibration amplitude levels were kept constant and the time of vibration of the specimens was varied. Some specimens were welded without any vibration as a control. The vibration started before welding and continued for 2, 4, 6, or 8 min. The vibration conditions and resulting residual stress ranges are given in Tables 4 and 5 for the longitudinal and transverse residual stresses respectively.

At both amplitude levels of vibration, the longitudinal residual stresses in the HAZ were found to decrease by ~75 MPa in the first 2 min of vibration. Increases in vibration time to 4, 6, and 8 min for both amplitude levels of vibration did not decrease the residual stresses any further (Fig. 6). Away from the weld toe the reductions in residual stresses for both amplitude levels were small.

The transverse residual stresses (Fig. 7) in the HAZ for the vibration amplitude of 15.26 mm (peak–peak) were found to increase by 60 MPa, and for the amplitude level of 22.9 mm no particular trend was observed for the change in the residual stresses (both increases and decreases were

observed). Away from the weld toe, the displacement amplitude of 15.26 mm did not show any decrease in the residual stresses, but the amplitude level of 22.9 mm showed a decrease of 35 MPa after 2 min of vibration. With an increase in vibration time the transverse residual stresses were found both to increase and to decrease without showing any particular trend.

Effect of high frequency vibration

In this investigation a high frequency vibration was applied to the specimens to observe its effect. A frequency of 341.5 Hz was applied to the specimens. Due to the high frequency, the amplitude was very small. The recorded amplitude of vibration of the vibrating clamp was 0.2 mm (peak–peak). Vibration was started before welding and was continued for 5 min from the welding start time. The resulting average residual stresses are shown in Fig. 8.

At and near to the weld toe (distance range 0–2.7 mm) the longitudinal residual stresses were found to be similar to

Table 3 Comparison of peak longitudinal and transverse residual stresses

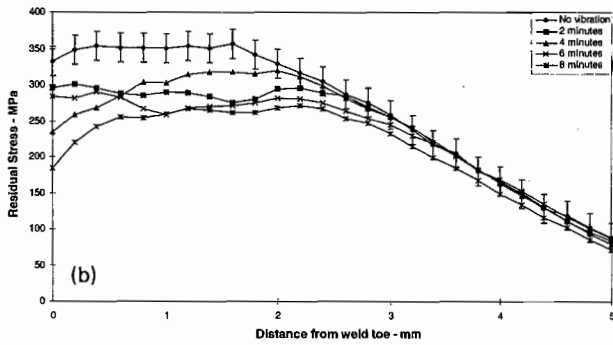
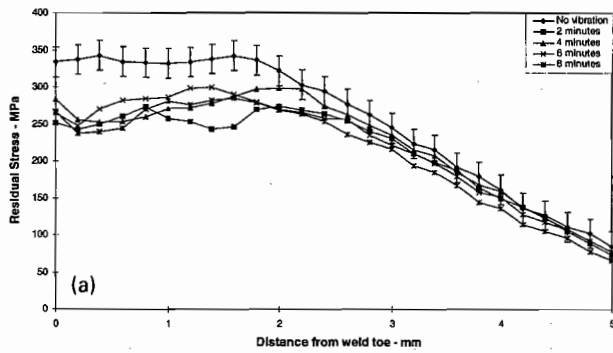
Vibration time, min	Displacement amplitude at vibrating clamp, mm (peak–peak)	Nominal applied stress, MPa (peak)	Peak residual stress range, MPa (error band ± 20 MPa)	
			Longitudinal	Transverse
0	0	0	441	395
1.5	4.58	± 48	390	425
1.5	9.16	± 96	384	511
1.5	13.74	± 144	368	466
1.5	18.3	± 192	353	362
1.5	22.9	± 240	308	284
1.5	27.48	± 288	361	299

Table 4 Comparison of peak longitudinal residual stresses for 15.26 and 22.9 mm (peak–peak) displacement amplitudes

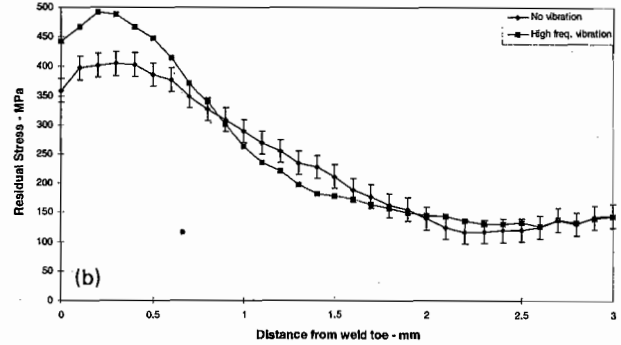
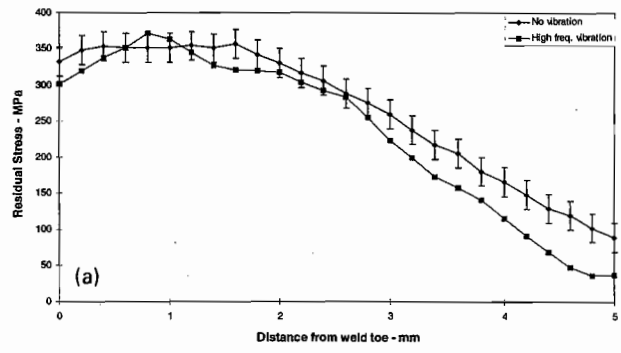
Vibration time, min	Displacement amplitude at vibrating clamp, mm (peak–peak)	Nominal applied stress, MPa	Peak residual stress range, MPa (error band ± 20 MPa)
0	0	0	342
2	15.26	160	273
4	15.26	160	299
6	15.26	160	299.5
8	15.26	160	285
0	0	0	357
2	22.9	240	300
4	22.9	240	317
6	22.9	240	290
8	22.9	240	271

Table 5 Comparison of the peak transverse residual stresses for 15.26 and 22.9 mm (peak–peak) displacement amplitudes

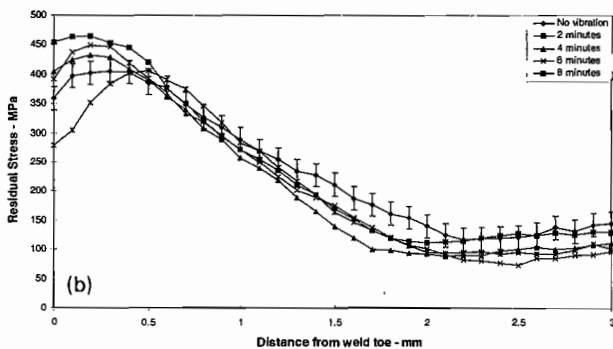
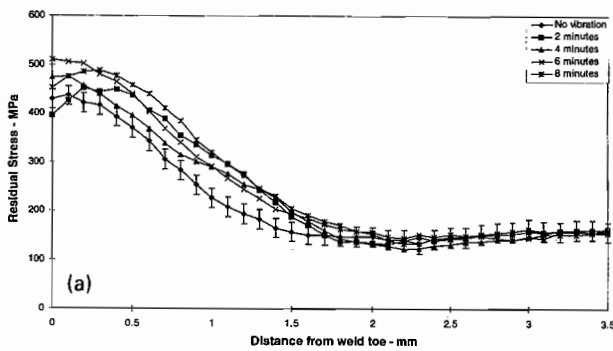
Vibration time, min	Displacement amplitude at vibrating clamp, mm (peak–peak)	Nominal applied stress, MPa	Peak residual stress range, MPa (error band ± 20 MPa)
0	0	0	436
2	15.26	160	452
4	15.26	160	475
6	15.26	160	511
8	15.26	160	488
0	0	0	405
2	22.9	240	465
4	22.9	240	432
6	22.9	240	449
8	22.9	240	407



6 Residual stress distribution parallel to weld line (longitudinal) for vibration amplitude of *a* 15.26 and *b* 22.9 mm (peak-peak)

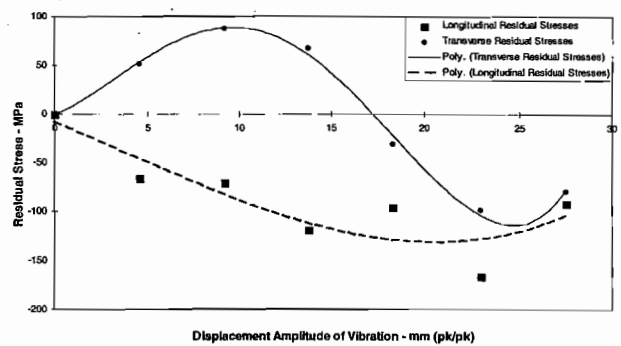


8 Residual stress distribution *a* parallel to weld line (longitudinal) and *b* perpendicular to weld line (transverse) for vibration frequency of 341.5 Hz



7 Residual stress distribution perpendicular to weld line (transverse) for vibration amplitude of *a* 15.26 and *b* 22.9 mm (peak-peak)

the residual stresses for the unvibrated specimens (Fig. 8a). Away from the weld toe (distance range 2.7–5 mm), the residual stresses were found to decrease significantly. The transverse residual stresses at and near to the weld toe (distance range 0–0.5 mm) were found to increase by ~85 MPa on application of high frequency vibration (Fig. 8b). Away from the weld toe no change in the residual stresses was found.



9 Possible variation of longitudinal and transverse residual stress as function of amplitude of vibration

DISCUSSION

A significant reduction in longitudinal (parallel to the weld) residual stresses was observed in the specimens as a result of a small amplitude of vibration. With increases in the amplitude of vibration the residual stresses were found to decrease further. The transverse residual stresses showed a different characteristic, where the residual stresses were found to increase on application of a small amplitude of vibration. With an increase in the amplitude of vibration the residual stresses were found to increase further. However, the residual stresses were found to decrease at higher amplitudes of vibration. The pattern of change in the residual stress states (longitudinal and transverse) as a function of vibration amplitude is summarised in Fig. 9.

The above results strongly indicate that there may be a relationship between the amplitude of vibration and decreases in the residual stresses. Figure 9 indicates that there may be an optimum amplitude of vibration (and hence the applied dynamic stress) which is capable of reducing both the longitudinal and transverse residual stresses. In the

present study, the approximate optimum amplitude of vibration was determined as ~24 mm (peak–peak), which is equivalent to an applied nominal stress of ~250 MPa in the investigated region.

The reduction in longitudinal residual stress in the HAZ in the present study agrees entirely with the study carried out by Aoki and Nishimura¹⁰ and also agrees partially with the results of Aoki *et al.*¹¹ The effect of vibration on transverse residual stresses cannot be compared with their^{11,13} results because those reports did not include the effect on transverse residual stresses.

The effect of time of vibration on residual stress was found to be small or negligible. For both vibration amplitudes (15.26 and 22.9 mm peak–peak) a similar result was found in that the longitudinal residual stresses were reduced in the first 2 min of vibration, and further increases in time of vibration did not cause any further reduction.

The transverse residual stresses were found to increase for both levels of amplitude of vibration near the weld toe. At the vibration amplitude of 15.26 mm (peak–peak), the residual stresses were found to increase near the weld toe, but were found to be unchanged (i.e. they remained within the error band) away from the weld toe. Conversely, for the vibration amplitude of 22.9 mm the residual stress showed no clear trend in that region, but some reduction in residual stresses was observed in the distance range 1.3–3 mm. Both vibration amplitude levels, however, showed no relation between residual stress reduction and the time of vibration. From the above result, it can be concluded that the time of vibration has no effect on residual stress.

In the high frequency vibratory treatment, both longitudinal and transverse residual stresses were found to increase and decrease without showing any particular trend. This result, as well as the results for the effect of time of vibration, contradicts the comments of some researchers (e.g. Claxton *et al.*¹⁴ and Hebel¹⁵ who explained that in the VSR method the specimens absorb the vibration energy and the absorbed energy causes relief of the residual stress. At a given frequency and amplitude of vibration, an increase in the time of vibration implies an increase in the energy input to the specimens. In the present study, the time of vibration was increased to observe its effect, and a high frequency vibration was also applied to the specimens, which required the maximum power from the amplifier for the vibrator. In both instances no reduction in residual stresses was observed as a result of the increase in the energy input. Thus it can be concluded that the energy concept of VSR is not supported by the present observations.

CONCLUSIONS

1. Residual stress reduction using the vibratory method is a function of amplitude of vibration (and hence the applied stress).
2. There is an optimum amplitude of vibration (i.e. applied dynamic stress) which can be used to maximise the reduction in both longitudinal and transverse residual stresses of the specimens.
3. An increase in the time of vibration did not increase the reduction in residual stresses, and high frequency vibration also did not result in any particular trend of change in residual stresses. This observation tends to contradict the energy absorption concept of VSR.

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