The Influence of Vibratory Treatment on the Fatigue Life of Welds: A Comparison with Thermal Stress Relief

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Abstract: *A comparison has been made between the fatigue lives of welded specimens a) in the as welded condition b) after heat treatment, and c) after post-weld vibration. By comparison with the as-welded specimens, the fatigue lives of the thermally relieved specimens were found to decrease by 43%, while the vibration treated specimens showed an increase of between 17% and 30%. While these findings are interesting in that they offer a way of extending the fatigue lives of welded joints, they confirm the view that the mechanism of residual stress relieving in the vibratory stress relief (VSR) method, and its relationship with fatigue life is poorly understood.*

Key words: *Residual stress, X-ray diffraction analysis, vibratory stress relief, fatigue life, post-weld treatment.*

Introduction

Residual stresses in components and structures pose a potential problem, in terms of dimensional stability and structural integrity. Although compressive residual stress causes an increase in the fatigue life, tensile residual stress causes the fatigue life to decrease. If the residual stress is not relieved or redistributed in a suitable manner, the fatigue life of the component may be decreased significantly, or the component may distort to some degree.

The conventional way to relieve residual stresses is by annealing, 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 implies the need for a subsequent finishing processes to remove the scale; in many metals annealing relieves residual stresses at the cost of important mechanical properties which are usually achieved during prior thermomechanical processes. An alternative way to relieve the residual stresses is "Vibratory Stress Relief" (VSR) treatment. Different researchers [1-8] have studied VSR to determine its effectiveness and to understand the underlying processes. The majority of investigations have yielded positive findings, reporting the reduction of residual stress levels or improved dimensional stability as a result of vibratory treatment. Some of them found an increase in residual stress or no change due to the treatment. One should recall that residual stress is self-equilibrating and so may increase in some areas due to a reduction in others with no net reduction in the total residual strain energy. In certain situations the stress may not change without a radical redistribution. This explains why there is so much disagreement between the researchers about the subject. The findings and comments from different experimenters depended on the position of the points that they measured.

A similar disagreement between different investigators is observed about the fatigue life of the VSR treated specimens. Some investigators have commented on an increase in fatigue life and some have found quite the opposite. Bühler and Pfalzgraf [1-2] Balasingh [3] and Wozney and Crawmer [4] commented that fatigue damage due to the VSR treatment could not be neglected. However, no detailed experimental data were presented to support their comment. Sonsino *et al* [5] reported that VSR dangerously decreases fatigue life. Jesensky [6] found no damage in fatigue life due to VSR treatment. Fenghua and Dexin [7] found higher fatigue life in vibrated samples. Ankirskii [9] found that the fatigue life was decreased in both cases (tempered and vibrated) compared to unwelded parent metal, but the vibratory treated samples showed higher fatigue life than the tempered samples. Lutes and Sarkani [10] found significant increase in fatigue life due to an application of cyclic higher stresses.

The current investigation is part of a detailed study [8] aimed at finding out the underlying processes of vibratory stress relief (VSR) and also to find out if the vibratory method could be used to relieve residual stresses after welding. It was observed in different investigations that the residual stress decreased due to the VSR treatments. An assessment of the effect of VSR treatment on fatigue life was the aim of the work reported in this study. A comparison of the fatigue lives of welded specimens that have been a) untreated, b) annealed, or c) VSR treated represents an important aim, since the whole intention of VSR in welded structures is to prolong component lifetime under load. In this study unvibrated, thermally treated and vibratory treated specimens were fatigued to provide a comparison between their fatigue lives. Some specimens were also processed with a view to seeking a relationship between the residual stresses and corresponding fatigue lives of the specimens, since it was believed that higher residual stress would decrease the fatigue life and that lower residual stress would result in extended fatigue lives.

Test specimens and material properties

The specimens were made from 0.18% carbon steel flat bar of cross-section 6.35 mm x 76.2 mm. A metallographic study revealed that the bar was hot rolled and then cold rolled to obtain surface finish and mechanical properties. This cross-section was chosen because it was easy to locate on the goniometer of the X-ray diffractometer using a locating jig. The material specification of the flat bar was BS970 080A15. The amounts of carbon and other alloying elements in the bar are shown in Table 1.

The total length of the specimen was 290 mm, which included the clamping area and the free length. A single pass bead weld line was created near the clamp of the specimen to induce the welding residual stresses. The specimen is shown in Figure 1. The ambient mechanical properties of the flat bar were determined by a tensile test where the properties were recorded as: 0.2% offset yield stress = 607 MPa and ultimate tensile strength = 611 MPa. It should be kept in mind that the heat affected zone of the weld underwent a heating and cooling cycle, which would modify the mechanical properties of the heat affected zone to a large degree, so that they would be lower than the above figures.

Table 1 - Alloying elements of the specimen

% C	% Si	% Mn	% P	% S
0.18	0.23	0.88	0.013	0.011

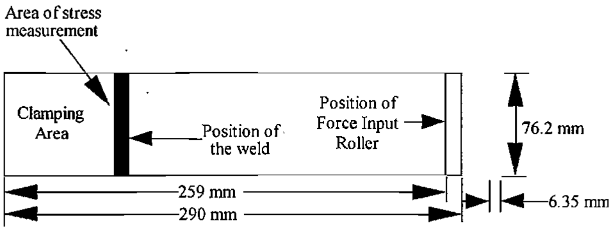

Figure 1: Schematic cantilever beam specimen

Experimental procedure

This investigation was carried out by processing three types of specimens - i.e. (a) as-welded, (b) annealed, and (c) vibratory treated. The bar specimens were mounted on the experimental set-up and a single pass bead weld was carried out using a MIG welding set. In the welding process a constant speed of 338 mm/min of the welding torch was maintained using a stepper motor driven torch carrier. After welding, the specimens were divided into three different groups. The details of the treatments are provided in the description of the relevant batches. The specimens were fatigued by applying a constant dynamic stress until they failed. In one batch of specimens, the residual stresses were measured before carrying out the fatigue tests to investigate the relationship between the fatigue life and the residual stress. The residual stresses were measured using an X-ray diffractometer.

The fatigue test was carried out in the set-up shown in Figure 2. One end of the specimens was clamped with a rigid frame while the other end was inserted into the force-input roller. The force-input roller was attached to a vibrator to produce sinusoidal controlled cyclic load to the specimens. The force-input roller was designed such that it did not induce any axial load in the specimens. The set-up also made sure that the force-input rollers did not produce any bending load in the specimens in the static condition. This was done to make sure that during the fatigue test there would be no loading asymmetry, which may cause either early failure or extended life of the specimens. The nominal stresses applied to the specimens were determined by measuring the displacement amplitudes of the force-input roller. An accelerometer was placed on the top of the force-input roller clamp and was set to measure the displacement amplitudes of the clamp (Figure 2). The displacement of the roller clamp was calibrated in terms of applied stresses by

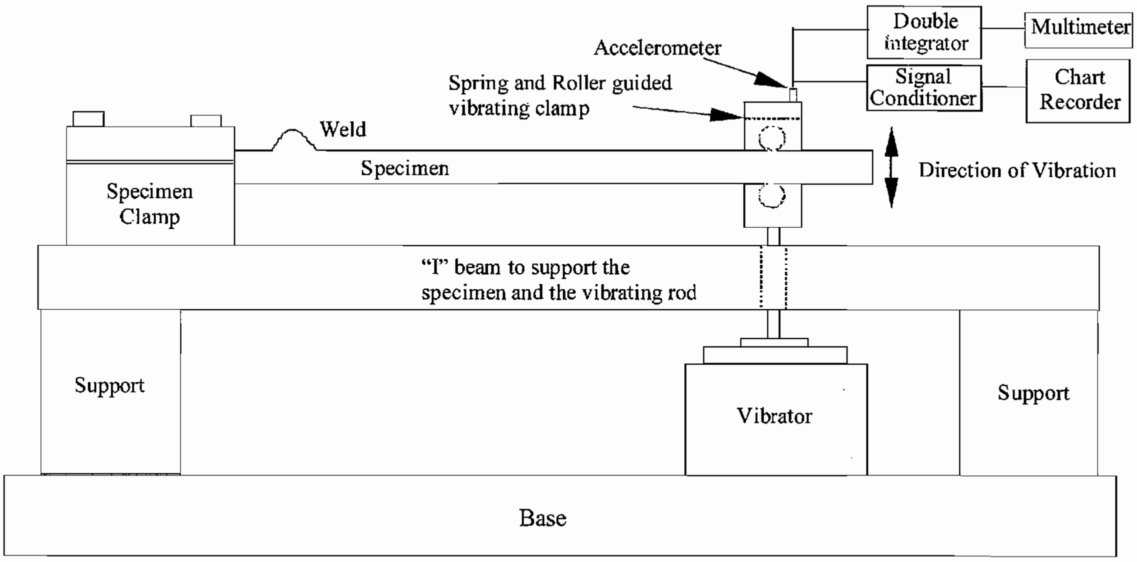

Figure 2: Schematic set-up for VSR treatment and fatigue test

attaching a strain gauge at the mid-width in the HAZ of the weld. The calibration is shown in the section below.

A chart recorder was used to record the fatigue lives of the specimens. Prior to use of the chart recorder in the experiments the chart speed was calibrated. The fatigue lives of the specimens were determined by measuring the length of the chart. The chart length was converted to the time of vibration then to a number of cycles.

Calibration of applied stresses

The dynamic applied stress was calibrated using a strain gauge, a P-3500 digital strain indicator, an accelerometer, a double integrator and a multimeter. In the calibration process, the applied stresses in the selected area of the specimen were determined in terms of the displacement amplitudes of the force-input rollers. The calibration was carried out on the experimental set-up shown in Figure 2, and resulted in the calibration curve of Figure 3. The calibration gave 1 mm (pk/pk) displacement amplitude equal to 23.9 MPa applied stress.

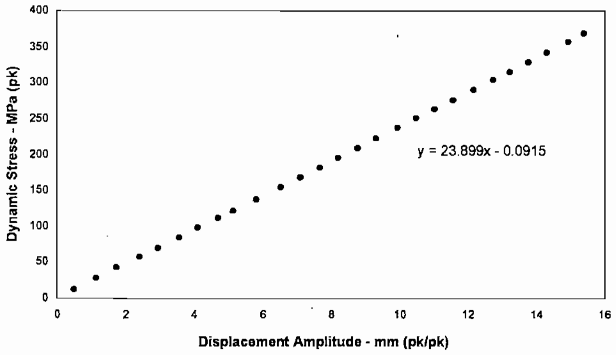

Figure 3: Calibration plot - applied dynamic stress

Residual stress measurement

The transverse residual stresses (with respect to the weld line) were measured using an X-ray diffractometer. The X-ray diffractometer and the material elastic constant of the mild steel were calibrated before carrying out the residual stress measurements. This was done to ensure absolute stress measurement. The error band of the diffractometer was measured to be ±10 MPa.

In the X-ray measurement the single exposure technique (SET) was used. 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 points 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/clamping jigs. The conditions of the X-ray measurements are shown in Table 2.

Table 2 - X-ray measurement conditions

X-ray type	Cr K-Alpha
Bragg angle	156.1 degree
Measurement plane	(211)
X-ray beam diameter	1 mm
Measurement angle, β	30 degree
Oscillation of β angle	0 degree
Peak fit	Gaussian
Number of exposures	2

Experimental details and results

Batch 1

In batch 1, the test was carried out on three groups of specimens (six in a group). In all three groups, cold rolled flat bar specimens were bead welded. The conditions of welding and removal from the welding rig were controlled carefully to ensure that the specimens went through similar situations. The first group of specimens were not treated at all, but were left as they were welded to make a control sample. The next group was annealed before carrying out the fatigue test. Before annealing, the specimens were coated with anti-oxidant paint to prevent oxidation at higher temperatures. In the annealing process, the specimens were heated to 913°C in ~70 minutes, then the furnace was turned off and the specimens were cooled down with the furnace. The third group was vibratory treated with an applied dynamic stress of ±365 MPa for 5 seconds. The frequency of vibration was 25 Hz. Vibratory treatment was carried out on the set-up in Figure 2. The specimens were mounted on the set-up and a controlled sinusoidal vibratory stress was applied.

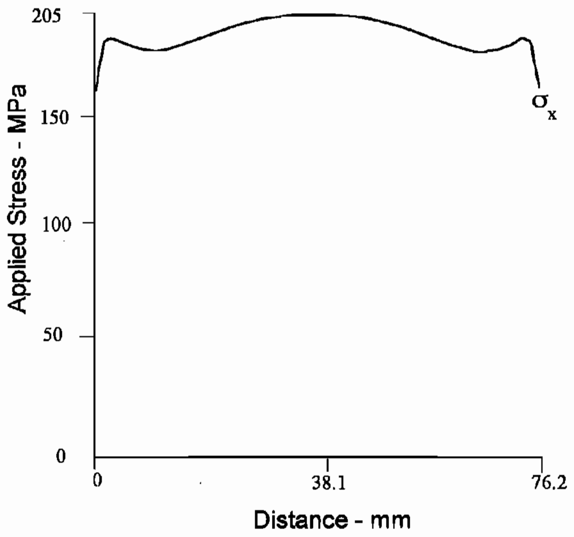

Figure 4: Applied dynamic tensile stress on the weld toe of the specimen. This was determined from a harmonic analysis of the specimen using FE software ANSYS

The fatigue test was carried out at a vibration frequency of 25 Hz applying a dynamic stress of ±205 MPa. The specimens were vibrated until they failed. It was observed that the crack initiated at the mid-width of the specimen (at the weld toe) and propagated

Table 3 - Fatigue lives of the as-welded and annealed samples - batch 1

As-welded sample				Annealed sample				Difference		
Max	Min	Avg	St dev	Max	Min	Avg	St dev	Min	Max	Avg
cycles	cycles	cycles	cycles	cycles	cycles	cycles	cycles	%	%	%
279,000	233,000	260,800	19,200	212,500	85,170	147,000	52,500	-63	-24	-43

Table 4 - Fatigue lives of the as-welded and VSR treated samples - batch 1

As-welded sample				VSR treaded sample				Difference		
Max	Min	Avg	St dev	Max	Min	Avg	St dev	Min	Max	Avg
cycles	cycles	cycles	cycles	cycles	cycles	cycles	cycles	%	%	%
279,000	233,000	260,800	19,200	412,900	238,500	304,600	69,200	2	48	17

Table 5 - Fatigue lives of the as-welded, and VSR treated samples - batch 2

As-welded sample				VSR treaded sample				Difference		
Max	Min	Avg	St dev	Max	Min	Avg	St dev	Min	Max	Avg
cycles	cycles	cycles	cycles	cycles	cycles	cycles	cycles	%	%	%
282,800	216,200	241,100	27,000	414,000	256,000	314,500	55,800	2	46	30

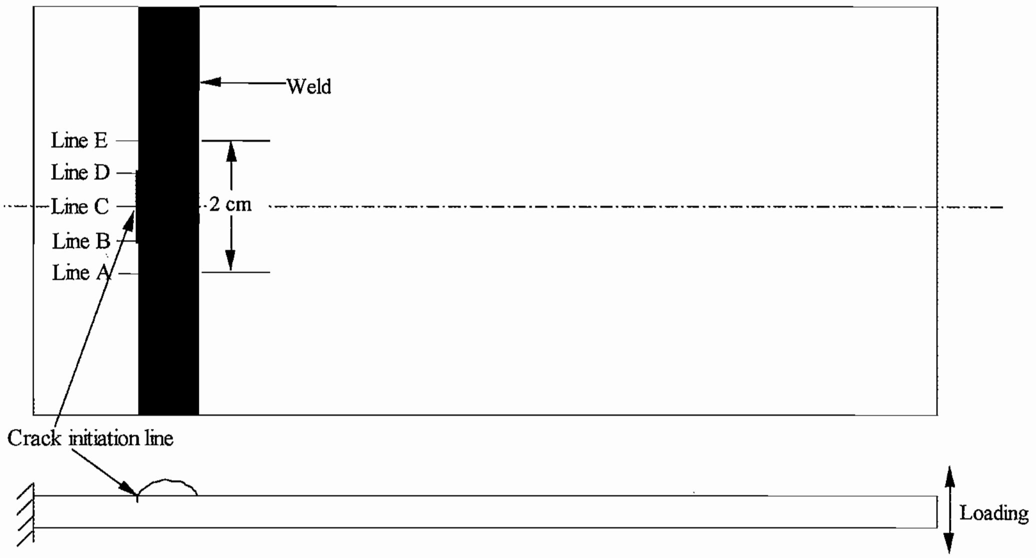

Figure 5: Schematic location of residual stress measurement lines

towards the edges. This observation was in agreement with the dynamic stress distribution in the Finite Element analysis shown in Figure 4, where it was found that the direct stress was maximum at the mid-width and minimum near the edges. The fatigue lives of the annealed, as-welded, and vibratory treated specimens of this batch are shown in Tables 3 and 4. Tables 4 and 5 show the statistical analysis of the data and a comparison between the fatigue lives of annealed, as-welded and VSR treated samples.

In all three specimen groups, the same applied stress was used (±205 MPa). The average fatigue life of the as welded specimens was 260800 (±19200) cycles. The annealed specimens showed an average fatigue life of 147100 (±52500) cycles. The vibratory treated specimens showed an average life of 304600 (±69200) cycles. In Tables 3 and 4, comparisons have been shown between the minimum to minimum and the maximum to maximum fatigue lives of the as-welded, annealed and vibratory treated samples. The annealed samples showed a decrease in the fatigue lives of 63% (min-min) and 24% (max-max) respectively, while the average decrease was 43%. On the other hand the VSR treated specimens showed increases in fatigue lives of 2% to 48% respectively over the as-welded samples, while the average increase was 17%.

Here, the VSR treated specimens showed the maximum fatigue life, with an increase of 17% in comparison to the as-welded specimens. The annealed specimens showed the least fatigue life, where the reduction in the fatigue life was 43%.

Batch 2

In this batch, two groups of specimens (six in a group) were processed. The first group was fatigue tested as-welded and the second group was vibratory treated prior to the fatigue test. The specimens were vibratory treated at a frequency of 25 Hz using an applied stress of ±370 MPa for 5 seconds. The fatigue test was carried out using an applied stress of ±205 MPa and using the same frequency. The fatigue lives of the as-welded and vibratory treated specimens are shown in Table 5, where the maximum, the minimum and the average values of the fatigue lives and also the standard deviation are included for each group of samples.

In this batch the average fatigue life of the as-welded specimens was 241100 (±27000) cycles. On the other hand the average fatigue life of the VSR treated samples was 314500 (±55800) cycles. A comparison between the minimum to minimum and the maximum

Table 6 - Fatigue lives of the as-welded and VSR treated samples - batch 3

As-welded sample				VSR treated sample				Difference		
Max	Min	Avg	St dev	Max	Min	Avg	St dev	Min	Max	Avg
cycles	cycles	cycles	cycles	cycles	cycles	cycles	cycles	%	%	%
391,300	307,500	346,800	34,100	500,900	298,500	408,100	80,300	-3	28	18

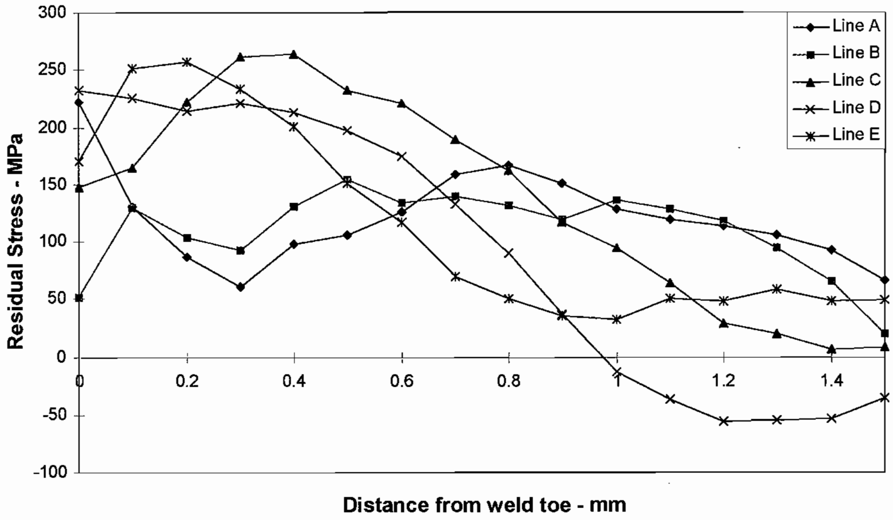

Figure 6: Transverse residual stresses plot – specimen 1

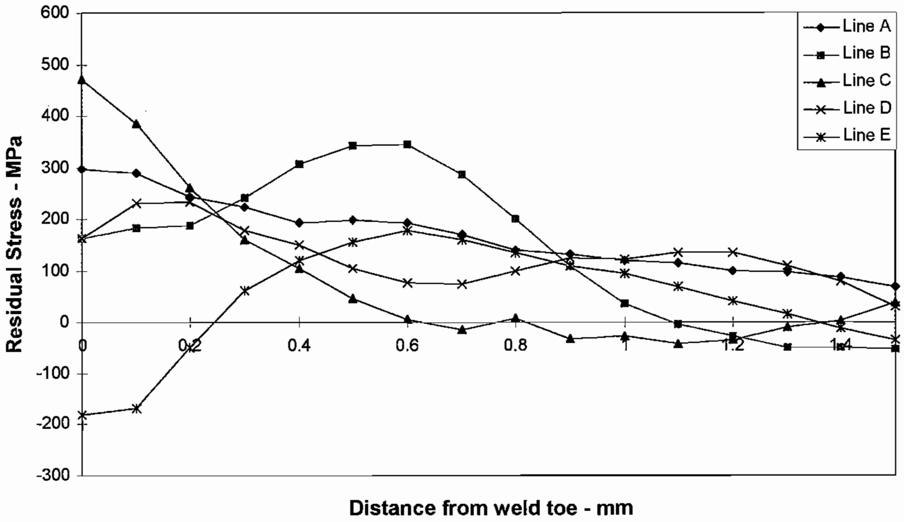

Figure 7: Transverse residual stresses plot – specimen 2

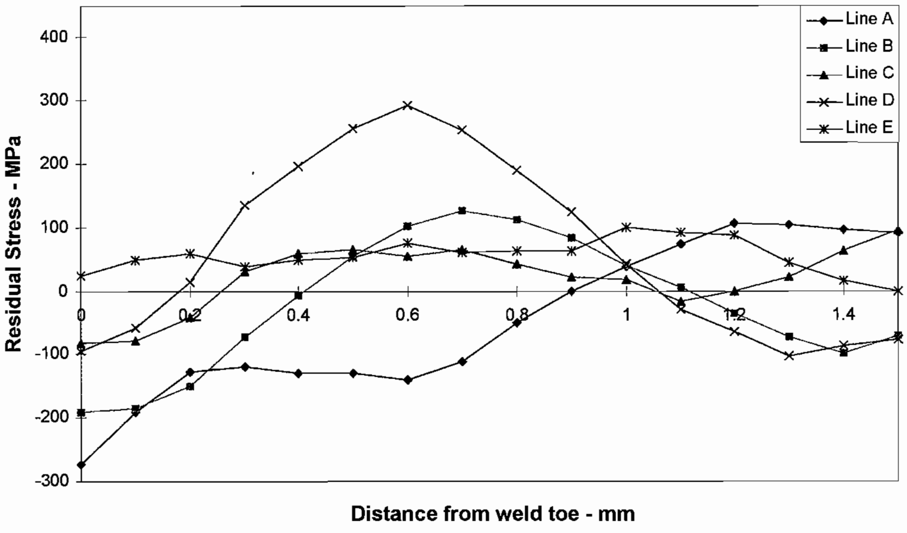

Figure 8: Transverse residual stresses plot – specimen 3

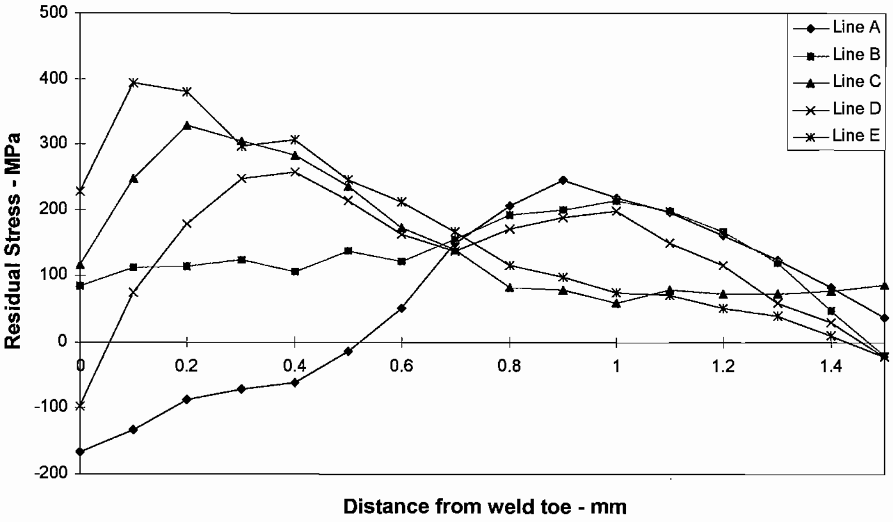

Figure 9: Transverse residual stresses plot – specimen 4

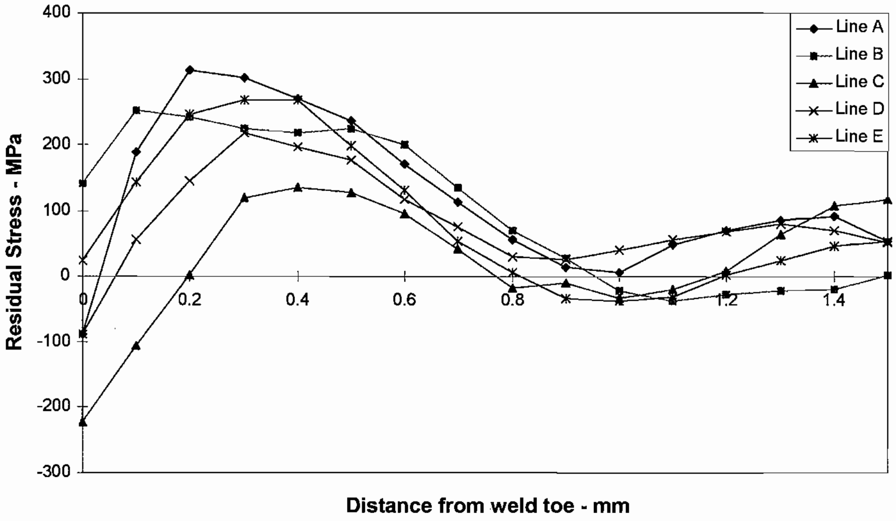

Figure 10: Transverse residual stresses plot – specimen 5

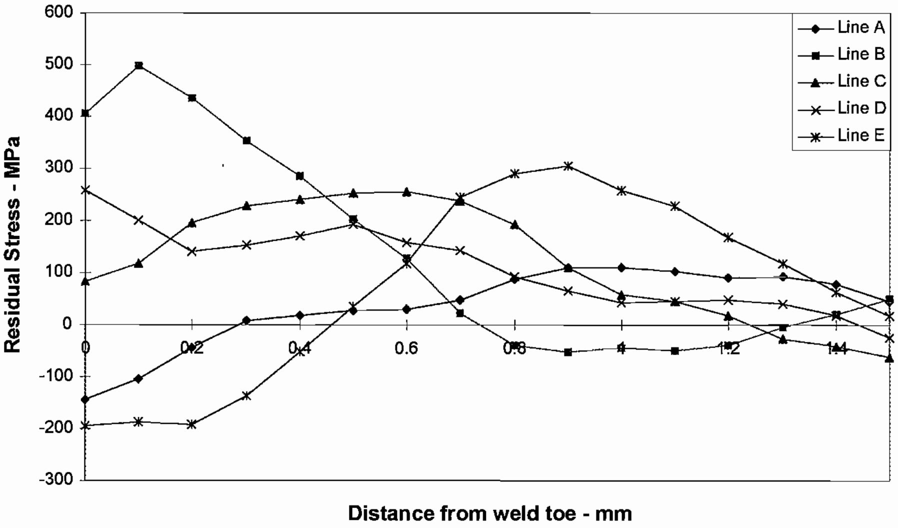

Figure 11: Transverse residual stresses plot – specimen 6

to maximum fatigue lives showed the increase in fatigue lives of 2% and 46% respectively, while the average increase was 30%. Thus, it can be said that the fatigue life of the VSR treated specimens was increased by 30%.

Batch 3

In this batch, two groups (six in a group) of specimens were fatigue tested. The first group was tested as-welded and the second group was vibratory treated for 5 seconds with an applied stress of ±370 MPa. The transverse residual stresses of the specimens were measured before carrying out the fatigue test. The measurement lines were located within a distance of ±10 mm from the specimen axis and the distance from one line to the next line was 5 mm, i.e. stresses along a total of 5 lines were measured (Figure 5). The lines were selected in that area because it was observed that the crack initiated from the middle of the specimen. The residual stresses of the vibratory treated specimens are shown in Figures 6 to 11. Fatigue lives of all twelve specimens were tested using an applied stress of ±164.4 MPa at a frequency of 25 Hz. The fatigue lives of the vibratory treated and as-welded specimens are shown in Table 6, where the maximum, the minimum, and the average values of the fatigue lives and also the standard deviation are included for each group of samples.

Due to decrease in the applied dynamic stresses in the fatigue test, the fatigue life of the specimens increased in this batch in comparison to the previous two batches. The average fatigue life of the as-welded specimens was 346800 (±34100) cycles. On the other hand the average fatigue life of the VSR treated specimens was 408100 (±80300) cycles. A comparison between the minimum to minimum and the maximum to maximum fatigue lives showed a decrease of 3% and an increase of 28% respectively, while the average increase was 18%. Thus, in this batch the fatigue lives of the vibratory treated specimens were increased by 18%. This result was similar to the results of the previous two batches.

From Figures 6 to 11, the maximum tensile residual stresses in the distance range 0 to 0.4 mm (from the weld toe) of the six specimens were 260 MPa, 470 MPa, 200 MPa, 395 MPa, 310 MPa, and 500 MPa. The corresponding fatigue lives of the six specimens were 298500, 452400, 320600, 500900, 426700, and 449100 cycles respectively. It was clear from the above data that the peak residual stresses were not related to the fatigue lives of the specimens.

Discussion

Because only two levels of stresses were applied in the fatigue test the σ-N curve was not drawn. In the first batch it was found that the average fatigue life was decreased significantly (by 43%) due to annealing. This was quite certainly because, due to heating the cold rolled mild steel bar to 913°C, the fine grains of the bar found scope for recrystallization which finally resulted in coarse grain development and hence a reduced level of yield strength. The annealing reduced the mechanical properties which were achieved during the production process of the steel bar. On the contrary, the average fatigue life of the VSR treated specimens was found to increase by 17% in the first batch, 30% in the second batch and 18% in the third batch over the untreated specimens. The increase in the fatigue lives due to the VSR treatment was found to be varied from 0% (neglecting changes less than 5%) to 48%. Out of 18 VSR treated samples, 4 samples did not show any significant effect of the treatment. The reason of that is unknown. A clear trend of increase in fatigue life, however, was observed in this investigation.

Thus, if the vibratory treatment is carried out with application of a high dynamic stress (higher than the designed load) and a small number of cycles, it does not decrease the fatigue lives, instead it is likely to cause the fatigue lives to increase. This result agrees with the findings of the work carried out by Ankirskii [9] and Lutes and Sarkani [10], and contradicts the experiments carried out by Sonsino *et al.* [5]. The fact that these results are not in agreement with the work of Sonsino *et al.* [5] is worthy of further reflection. Both studies used very similar low carbon steel alloys for their specimens. However, the mechanical properties in Sonsino's study were much higher (Yield stress 777 MPa and Ultimate stress 829 MPa) than those measured in this study. The specimen design in reference [5] was a T-butt weld, on a base plate of 25 mm thickness. As a result, the heat input to the weld was much higher, and the residual stress distribution (Figure 3 of reference [5]) shows that it reached a peak of 260 MPa at a distance of 4 mm from the weld toe. In contrast, in this study the peak welding stress levels were reached within 0.3 mm of the weld toe. Thus, it may be concluded that detailed weld design and heat input will have a major influence on the residual stress distribution and, consequently, on how it will react to vibratory stress relief. The detailed vibratory treatment condition in Sonsino's study was not provided, and this in fact, is the main key to increasing or decreasing the fatigue lives of the specimens [10]. Although the details of the mechanism of residual stress relieving in the vibratory method is not yet generally agreed, it can be said that the applied dynamic stress of ±370 MPa used in this study certainly caused a localised plastic deformation at the sites of potential cracks. As a result of that the fatigue lives were increased.

The second objective of this experiment was to define a relationship between the residual stresses in the specimens and the fatigue life. The residual stress on the weld toes were compared with the fatigue life values, where it was assumed that higher residual stresses would show a lower fatigue life. The measured residual stresses (Figures 6 to 11) did not correlate with the tested fatigue lives of the specimens.

Conclusions

From the investigation the following conclusions were made.

1. Vibratory treatment increases the fatigue lives of the specimens if the treatment is carried out applying a few number of cycles at high dynamic stress (±370 MPa) and the applied stress in the fatigue test is smaller than the applied stress in the VSR treatment. On the other hand the annealing process reduces the fatigue life by altering the material properties.
2. It is generally held that high tensile residual stress will reduce the fatigue life. In the mild steel specimens tested there was no correlation between the residual stresses and the fatigue lives. This finding confirms that the residual stresses and their effect on fatigue life is not well understood in general terms.

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