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Fundamentals of Vibratory Stress Relief

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ABSTRACT

The use of cyclic loading to reduce residual stress levels in mechanical components is a potential alternative to some thermal annealing processes. The application of the vibratory stress relief (VSR) process has been limited in use due to the lack of understanding of the process. From a literature survey the claimed effectiveness of VSR ranges from 0 to 100%. In this study several rectangular steel bars were vibrated at different surface strain amplitudes and different number of cycles. Residual stress distributions in the bars were measured before and after vibration using the hole drilling technique. For the same high surface strain amplitude (plastic zone), the residual stress reductions for one, five and 100,000 cycles were the same. For a low surface strain amplitude (elastic zone), there were no reductions in residual stress for all one, five, or 100,000 cycles. An equation has been developed to help predict the remaining residual stress in the bar after vibration based on the following parameters: the initial residual stress, the yield stress and the applied surface strain amplitude.

Key words: Vibratory stress relief, residual stress, cyclic loading

INTRODUCTION

Manufacturing processes such as casting and welding leave residual stresses within a part which are capable of causing dimensional changes (Qinghua *et al*., 2008). These residual stresses can accelerate corrosion and crackingand reduce strength and fatigue life of the part when combined with service loads (Bonal Technologies Inc., 1992) (Lulgjuraj, 1996; Welding Consultants Inc., 1990). Using Vibratory Stress Relief (VSR) to reduce these residual stresses has many advantages over the heat treatment methods (Landgraf *et al*., 1967; Krempl, 1967; Sandor, 1972). Some of the advantages include: the equipment required for running the process is inexpensive and easy to use, potential saving in cost is associated with the process over heat treatment annealing due to decreased process time and energy consumption, no scaling results from the treatment, any size of part can be relieved using this technology provided that it is isolated, bringing the process to the workpiece minimizes handling costs, the process is cleanand no ventilating or air-scrubber equipment is needed since VSR generates no smoke, fumes, or gases.

VSR studies were done on heavy fabrication (Ohol *et al*., 1988), welded parts (Bouhelier *et al*., 1988), titanium blocks (Volkov and Orzhekauskas, 1988), Vibratory Weld Conditioning (VWC) on welded body valves (Xu *et al*., 2007; Qinghua *et al*., 2008), cyclic loading on stainless steel welded parts proved effectiveness (Rao *et al*., 2007), computer simulation for vibrator stress relief by mean of cyclic loading proved that time has no effect on residual stress relief (Zhao *et al*., 2008)and cyclic loading extended the life of fatigue tests (Tuegel and Brooks, 1997). The most interesting study as far as results and data documentation was done by Wozney and Crawmer (1968). Although, Wozney and Crawmer results were important, there is much more work that can be done in this area to better understand the process. A mathematical model can be developed to help predict the residual stress relief. Commercial VSR equipment can be used instead of a fatigue test machine and fatigue limit of the specimen should be considered as an important factor of VSR.

To help understand the VSR process, fundamentals of cyclic loading such as stress controlled and strain controlled functions, cycle dependent hardening of the materialand the Bauschinger effect were studied in detail (Lubhan and Felgar, 1961; Sachs *et al.*, 1948; Ludwik and Scheu, 1923; Beer and Johnston, 1981; Hebel Jr., 1985; Dieter, 1986; Measurements Group, 1993). The original residual stress distribution in a rectangular bar is known. The distribution of residual stress after bending is analyzed based on superimposing an applied load and its inverse (Sandor, 1972).

Tensile tests were performed to experimentally determine the material properties of the specimens used in the experiments. Using the hole drilling technique, the distribution of the initial residual stress in the specimens was measured before the vibration test. These distributions were identical in form with a small difference in magnitude. Several specimens were vibrated according to different parameters. The final residual stress distributions in these specimens were measured after vibration using the hole drilling technique.

Experimental procedure and equipment

Tensile test: Four specimens of the ASTM A36 hot rolled steel 457.2×25.4×9.52 mm material used in the vibratory stress relief experiments were tensile tested. The yield point and modulus of elasticity were found experimentally using an Instron tensile testing machine and compared to handbook values Table 1.

VSR equipment: VSR equipment as shown in Fig. 1

- An eccentric mass electric motor is bolted to a steel bed. The angle between the weights (θ) can be manually adjusted to produce varying degrees of rotational imbalance. Thus the forcing vibration amplitude can be controlled

Table 1: Handbook and experimental values of ASTM-A36

Parameters	Yield stress	Modulus of elasticity
Handbook values	250 MPa (36 10^3 psi)	200 GPa (28.810^6 psi)
Experimental values	290 MPa (41.8 10^3 psi)	206 GPa (29.6910^6 psi)

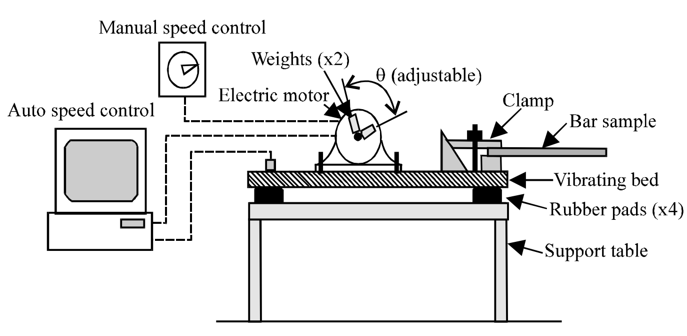

Fig. 1: VSR equipment

- Four rubber pads are used to separate the bed from a steel table
- An accelerometer (α) is magnetically clamped to the vibrating bed or sample. The signal is sent to a computer. The signal is used to obtain the response amplitude of the vibrating bed or sample
- The computer automatically adjusts the speed of the motor. The speed of the motor is proportional to the forcing vibrating frequency and can also be manually controlled

VSR tests: A resistance strain gage was installed on the top surface of each bar, 127 mm from the end as shown on ure 2. This strain gage was used to monitor the cyclic strain amplitude during vibration. A SOMAT field computer system was used to display and record the strain data for each sample in real time. A length of 76.2 mm of the specimens is clamped to the vibrating bedand the remainder of the specimen was cantilevered. A manual regulator was used to control the speed of the motor. A strobe light was used to record the vibrating frequency of the bar at the desired surface strain amplitude.

Tests to determine influence of No. of cycles: In these tests the specimens were vibrated with the following parameters as the surface strain amplitude is fixed at±1050 με for 20,000 and 100,000 cycles Table 4.

Tests to determine influence of cyclic strain amplitude: In these tests the specimens were vibrated with the following parameters as the number of cycles is fixed based on the results of the previous test and the surface strain amplitude used, were 550, 1050 and 1550 με Table 5.

Table 2: Reduction in residual stress in the X and Y directions after VSR

Bars(με; cycle)	Percentage reduction X direction (%)	Percentage reduction Y direction (%)
High strain low cycle		
Bar 1 Face 1 (1550; 1)	36.75	51.04
Bar 1 Face 2 (1550 ; 1)	37.73	34.02
Bar 2 (1550; 1)	31.26	56.16
Bar 1 (1550; 5)	33.34	54.05
Bar 2 (1550; 5)	34.77	56.67
Bar 1 (1350; 1)	19.02	28.71
Bar 2 (1350; 1)	15.89	30.2
Low strain low cycle		
Bar 1 (550; 1)	-1.37	0.21
Bar 2 (550; 1)	2.11	-3.61
High strain high cycle		
Bar 1 (1550;100k)	35.59	44.92
Bar 2 (1550;100k)	38.79	53.71
Bar 3 (1350;100k)	23.83	34.41
Bar 4 (1350;100k)	17.99	33.31
Low strain high cycle		
Bar 5 (550;100k)	5.16	-0.29
Bar 6 (550;100k)	6.66	-1.41

Table 3: Percentage stress reduction

Strain με	Experimental 100 k cycle (%)	Perfect plastic (%)	$\sigma = k\varepsilon^n$ (%)	Experimental 1 cycle (%)
1350	16.87	19	22	17.6
1550	34.31	36	33	39.67

Table 4: Test to determine influence of No. of cycles

Parameters	Values
Vibration frequency:	$\omega_{VSR} \approx \omega_n$ (60 Hz-estimated)
Surface strain amplitude:	±1050 με (or closest convenient amplitude)
No. of cycles:	Test 1a: 20,000 cycles Test 1b: 100,000 cycles
Clamping method:	Cantilevered with overhang = 15 in. (381 mm)

Table 5: Tests to determine influence of cyclic strain amplitude

Parameters	Values
Vibration frequency	$\omega_{VSR} \approx \omega_n$ (60 Hz-estimated)
Surface strain amplitude	Test 2a: ±550 με, Test 2b: ±1050 με, Test 2c: ±1550 με
No. of cycles	To be decided based on results of test 1
Clamping method	Cantilevered with overhang = 15 in. (381 mm)

Tests to determine the influence of VSR on residual stress reduction: A total of fourteen specimens were used to determine the influence of VSR on residual stress reduction Table 6.

Theory and analysis: Prediction of remaining residual stress after one half strain cycle:

Measured Young's modulus E	=	197067 MPa
Measured yield stress σ_y	=	335 MPa
Original residual stress at the surface $\sigma_{Initial}$	=	-100 MPa is taken as an average from the experimental work

Loading and unloading between the two strain ranges ±1550με and ±1350με is shown in Fig. 2.

The compressive stress (Sandor, 1972) increases from its initial value $\sigma_{initial}$ to the yield strength. Since the fixed strain is higher than the elastic strain, plastic flow occurs. On unloading from the compression half of the cycle, the behavior will be elastic and σ_{final} is reached.

Using a straight line equation with the slope equals to Eq. 1

$$E = \frac{\sigma_{final} - \sigma_{flow}}{0 - \varepsilon_{applied}} \quad (1)$$

And by simple calculation from the geometry of Fig. 3 we can obtain the following equations:

$$\sigma_{final} = \sigma_{flow} - E\varepsilon_{applied} \quad (2)$$

$$\sigma_{remaining} = \sigma_{initial} - \sigma_{final} \quad (3)$$

$$\sigma_{remaining} = \sigma_{initial} - \sigma_{flow} + E\varepsilon_{applied} \quad (4)$$

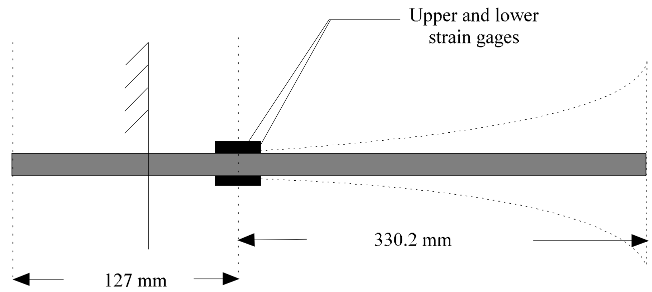

Fig. 2: Strain gages locations

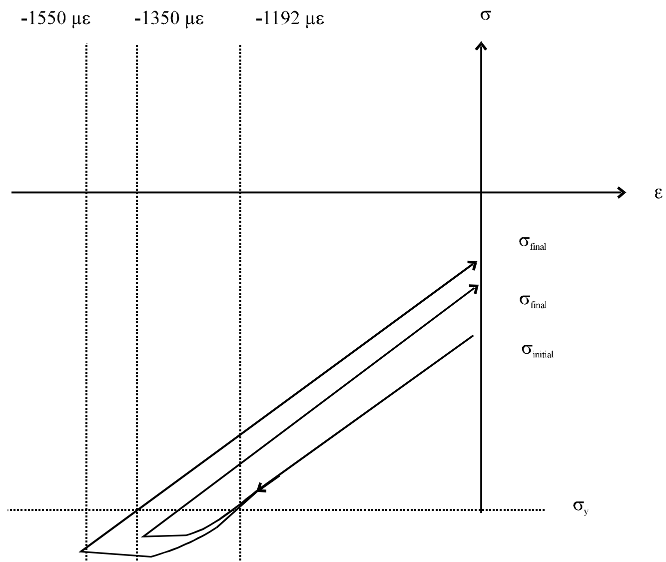

Fig. 3: Bending the bar in the first half cycle

where $\sigma_{flow} = \sigma_y$ for perfectly plastic materials and $\sigma_{flow} = k\varepsilon^n$ for strain hardening materials.

Calculation of residual stress reduction in the X and Y directions, along the length 457.2 mm and the width 25.4 mm of the bar are the three strains ε_1, ε_2 and ε_3 at 0, 60 and 90° angles, respectively, were read directly from the strain gage indicators for every increment of the hole drilling. Data reduction sheets were used to calculate the maximum stresses σ_{max} and σ_{min} and their directions (Measurements Group, 1993). From these maximum stresses the principle stresses σ_1 and σ_2 were calculated along with their directions. Finally σ_x and σ_y were calculated from σ_1 and σ_2.

RESULTS

The residual stress distribution was measured before and after vibration (hole drilling technique). The results of reduction of residual stress are summarized in Table 2 and 3 and shown in Fig 4. The calculation of reduction of residual stress in the X and in the Y directions is based on the average reduction of each of the seven data points. These data points are stresses calculated from the incremental hole drilling data (Measurements Group, 1993).

Comparison of experimental and theoretical data: The average reductions in residual stress in the X direction for the 1550με and 1350 με (100,000 cycles) from the experimental data were 37.2

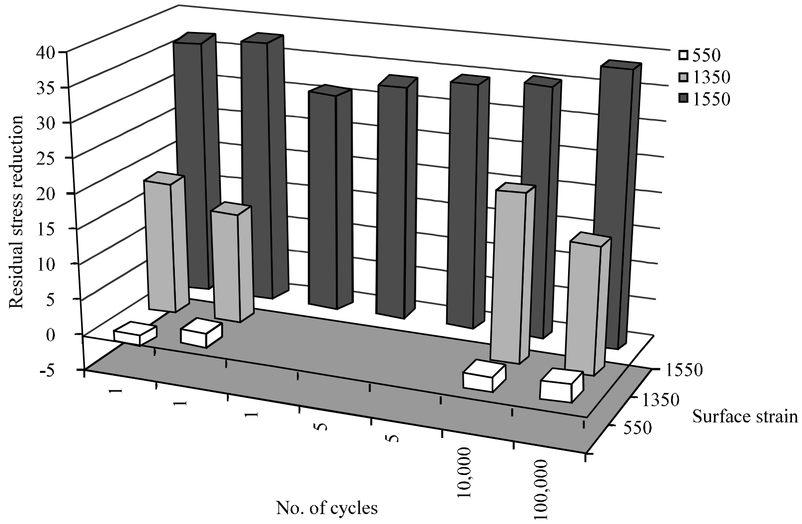

Fig. 4: Residual stress reduction in the X and Y directions

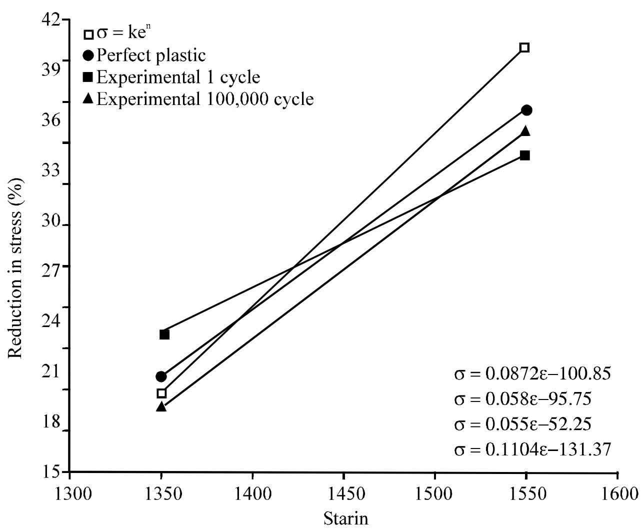

Fig. 5: Comparison of stress reduction between experimental and theoretical data.

Table 6: Tests to determine the influence of VSR on residual stress reduction.

Parameters	Low strain	High strain με
Low cycle (1 and 5 cycles)	XX550 με	XXXXXX1350 and 1550
High cycle (1350 and 1550 cycles)	XX550 με	XXXX1350 and 1550

and 20.9%, respectively. The reductions in residual stress in the X direction for the same strains but for 1 cycle were 36 and 17.5%, respectively. These reduction values form two straight lines Fig. 5.

Following the theoretical section the predicted average reduction in residual stress in the X direction was 36% for the strain of 1550 με and 19% for the strain of 1350 με in the case of a perfect plastic curve. In the case where the plastic portion of the stress strain curve is $\sigma = k\varepsilon^n$, the reductions were 33% for the 1550 με and 22% for the 1350 με. Figure 5 shows the plots of the four straight lines corresponding to the reduction in residual stress for the two cases, measured and predicted.

- **550με:** Low strain low cycle (550με; 1 cycle) and low strain high cycle (550με; 100,000 cycles) gave similar results. There was no noticeable reduction in residual stress in these two cases. The 550με surface strain amplitude is in the elastic zone.
- **1350 με:** High strain low cycle (1350 με; 1 cycle) and high strain high cycle (1350 με; 100,000 cycles) gave similar results. The average residual stress reductions in the X and Y directions were 19 and 32%, respectively. The 1350με applied strain is in the plastic zone when taking into consideration the initial residual stress Fig. 4.
- **1550 με:** High strain low cycle (1550 με; 1 cycle and 5 cycles) and high strain high cycle (1550 με; 100,000 cycles) also gave similar results. The average residual stress reduction in the X and Y directions were 35 and 53%, respectively.

It is obvious from these results that the reduction in residual stress is directly related to the magnitude of the surface strain amplitude or the applied strain range. This relationship is linear as shown in Fig. 5. The threshold that has to be exceeded for any reduction to occur is the elastic limit of the material. The number of cycles is not an important variable in the VSR process since one cycle and 100,000 cycles for the same strain gave similar results. According to the Bauschinger effect study (Sandor, 1972; Lubhan and Felgar, 1961), during cycling, most of the change occurs in the first cycle.

CONCLUSIONS

As a result of the VSR tests the following conclusions can be reached:

- VSR is capable of producing reduction in initial residual stress
- For stress relief to occur, a critical cyclic strain amplitude (elastic limit) must be exceeded, below this there is no change, above this the change is linear. This complies with the studies done by Dawson (1975) and Dawson and Moffat (1990)
- The number of cycle is not a critical variable in VSR
- The magnitude of the residual stress reduction may be predicted from the initial residual stress, the applied loadand the flow stress value using the model equation:

$$\sigma_{remaining} = \sigma_{Initial} - \sigma_{flow} + E\varepsilon_{applied}$$

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