Experimental Comparison Study on Stress Relief for Welded Low Carbon Steel (St 37) Bar by Vibration Mechanism and Heat Treatment Process

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Abstract. In this paper An Experimental process of vibration stress relief (VSR) and post-weld heat treatment (PWHT) after welding the resonant vibration is implemented. Depending on the vibration frequency as the indications for stress relief for a Welded Low Carbon Steel (St. 37) Bar. The vibration frequency should be applied to the structure and the structure natural frequency should be close each other in vibration mode, and with small vibration amplitude which will be amplified during vibration under a 7 N force of frequency which it close to the natural frequency of the welded bar (at resonance) for 20 mints. When the amplitude of vibration in the stress relief became large, then the treatment will be more effective. The (PWHT) is employed for comparison, and indication that the stress been relief are take place by mean of metallurgical and mechanical properties development and change in the natural frequency before and after treatment lead to change the amplitude for small to larger also indicate that the stress been relived.

Key words: Residual stress, Vibration stress relief, Post-Weld Heat treatment.

1. Introduction
The vibratory stress relieving methods are used in industries to reduce the residual stress in welded components. But the mechanism of vibration stress relief is not well known, so this process is not used in in a weld renege in industries. The difficulties is the vibration applied on a welded structure if it is not adequate, in this case the weld residual stress cannot be reduced. moreover that the cost of the measurement of stress residual is high and time consuming, and a difficult to know the extent of reduction of residual stress by the VSR. With the development of modeling technology, it is possible to model the process of VSR using a commercial finite element code Marc [1]. A finite element model was developed to predict weld residual stress and simulate the vibratory stress relief, in which a resonant vibration stress relief was studied using ABAQUS dynamic analysis on the 2D model [2].

There are many instruments to the measuring residual surface stresses by using the x-ray diffraction or magnetic methods. And we know that the x-ray diffraction methods are taking a long time and cannot used due to safety considerations. And for ferromagnetic materials the magnetic methods are only can be used [3]. The resonance is response of passing of many cases of systems or not meeting performance targets, the vibrating structure has tendency to oscillate with larger amplitude at certain frequencies. Which is known as resonance frequencies or natural frequencies? These resonance frequencies, even a small periodic driving force can result in large amplitude vibration. When resonance occurs, the structure will start to vibrate excessively [4]. Thermal stress relief (TSR) has been proved to be an effective method to relieve residual stress, but it suffers the disadvantages of
oxidizing the heating surface and changing the materials mechanical properties.\[5\]. Research on High-Frequency Vibratory Stress Relief of Small Cr12MoV Quenched Specimens which is an experimental work on 2012 where a comparison was made with a various vibration levels.\[6\] The aim of this work is to investigate the mechanism of the VSR process and the effect of the parameters of VSR, frequency and amplitude, vibration time on the reduction of weld residual stress, comparison with classical heat treatment for better understanding the method and because most of the literature are concentrated on the theoretical and a simulation but there is a little effort in the experimental, sometimes it is so difficult to treat a large or stationary parts after welding using classical heat treatment.

2. Methodology
For a transverse vibration of a bar the general equation of motion is known as \[7\] \[8\]:

\[
\frac{\partial^2 u}{\partial t^2} + \frac{E I}{\rho A} \frac{\partial^4 u}{\partial x^4} = 0 \tag{1}
\]

For small amplitudes it may be assumed that:

\[u(x, t) = U(x)e^{i\omega t}\]

Which is a sinusoidal vibration with amplitude varying along the bar
Substituting in equation (1) it gives:

\[-\omega^2 U(x) + \frac{E I}{\rho A} \frac{\partial^4 U(x)}{\partial x^4} = 0\]

Thus

\[\frac{\partial^4 U(x)}{\partial x^4} = \frac{\rho A \omega^2}{E I} U(x) = 0 \tag{2}\]

And the general form of the solution is:

\[U(x) = A \cos \lambda x + B \sin \lambda x + C \cos h \lambda x + D \sin h \lambda x \tag{3}\]

Where \(\lambda^4 = \frac{\rho A \omega^2}{EI}\)

The constants \(A, B, C, D\) can be found from the boundary conditions (end conditions of the bar). For this conditions i.e. Pinned-fixed bar, and for natural frequencies solution it is known in the literatures that

\[\omega_n = \frac{(\lambda_n l)^2}{\xi^2} \left(\frac{EI}{\rho A}\right)^{\frac{1}{2}} \tag{4}\]

| End condition | \(\lambda_1 l\) | \(\lambda_2 l\) | \(\lambda_3 l\) |
|---------------|----------------|----------------|----------------|
| Pinned –Fixed  | 3.926602       | 7.068583       | 10.210176      |

Table 1: Transverse [7]

Then for the first frequency, where the following beam parameters are:
Table 2: Bar Parameters.

| Length L[m] | Modulus of elasticity E [N/m²] | Polar Area Moment of inertia I [m⁴] | Density kg/m³ | Cross sectional area A[m²] |
|-------------|--------------------------------|-----------------------------------|---------------|--------------------------|
| 0.825       | 210 E09                        | 2.08 E-09                         | 7800          | 0.00025                  |

Then for 0.825 m length (Span) the theoretical fundamental frequency can be calculated as:

\[ \omega_n = 373.22 \text{ rad/s} \quad \text{or} \quad f = 59 \text{ Hz} \]

The maximum amplitude of vibration can be calculated experimentally from [7]:

\[ X = \frac{x}{\omega_n} \quad \text{where} \quad \omega_n = 2\pi f \]

Where the acceleration will be taken from the experimental resulted as shown later.

The experimental setup was as in Figure (1). The bar weight is 1.95 kg and made of cast iron with 0.825 m in length 0.025 m in width and thickness of 0.01 m which is pinned-fixed mounted on the TID devise, an integrated electronic accelerometer is attached near the force set on the bar figure (2) this sense is connected to the remain set of vibration and frequencies measuring. The excitation force is taken from a vibration shaker which weight of 2.715 kg is used to vibrate the beam and is placed in the middle of the beam. The vibration shaker is capable to vibrate the beam structure up to 5000 rpm which approximately 83 Hz or \( \omega = 525 \text{ rads}^{-1} \) as a sinusoidal wave which is as a result of unbalance rotating.

![Figure 1: Experimental set](image-url)
Figure 2: The integrated electronic, accelerometer, and the force set.

2.1 Before welding bar properties

Table 3: Chemical Composition

| C%  | Si%  | Mn%  | P%  | S%  | Cr%  | Ni%  | Al%  | Cu%  | Fe%  |
|-----|------|------|-----|-----|------|------|------|------|------|
| 0.014 | 0.012 | 0.252 | 0.005 | 0.011 | 0.014 | 0.025 | 0.018 | 0.017 | Bal. |

2.2 Weld Residual Stress Preparation

In order to verify and confirm the pattern of longitudinal residual stress distribution in welded sample, a Mug machine of (DCRP) polarity was used after weld joint preparation made as shown in figure (3) with the following parameters:

Table 4: Welding conditions

| Parameter       | Used gas | Join angle degree | Current [Amp.] | Voltage [Volt.] | Flow gas L/min. | Feeding speed m/min. | Filler metal | Filler metal Die. [mm] | Metal the [mm] |
|-----------------|----------|-------------------|----------------|----------------|------------------|----------------------|--------------|------------------------|---------------|
| Data            | Ar.      | 45                | 210            | 30             | 10               | 10                   | ER705-6      | 1.2                    | 10            |

Figure 3: Schematic of weld-joint preparation.
3. Results and discussion

3.1. Natural frequency analysis
By applying the fixed boundary at the end of the bar, free natural vibration analysis was performed. Figure 5 shows the desired mode shape with first natural frequency 64 Hz. This is the mode used for the following study of resonant vibration.

3.2. Frequency effect on displacement amplitude
After welding take place free natural vibration analysis was performed. Figure 6 shows the desired mode shape with fundamental natural frequency 72.8 Hz. This is the mode used for resonant frequency treatment. Where a centrifugal force of 7 N in a sin wave was applied at the middle of the bar with a frequency of 72.8 Hz the be subjected to the force at resonance for 20 minutes [2], as shown table (6) which show that the displacement induced by this load. The displacement amplitudes is $2.66 \times 10^{-3}$ mm for frequency 64 Hz, $2.4 \times 10^{-6}$ mm for frequency 72.8 Hz and $2.1 \times 10^{-3}$ mm for frequency 66.3 Hz as shown in figures (5,6,7) respectively in addition to results of mechanical properties from laboratory test shown in table (5). From the displacement it can be deduce that after it been restricted from welding effects it retreated close to the normal after vibratory treatment. This means that when load frequency is closer to the structure natural frequency, the amplified displacement amplitude will be higher. With resonant, displacement required level so that the weld residual stress can be relieved.

![Figure 5: As received fundamental frequency](image-url)

**Figure 4:** Welded bar

**Figure 5:** As received fundamental frequency
Figure 6: After welding fundamental frequency.

Figure 7: After Vibratory treated fundamental frequency.

Table 5: Mechanical properties before and after treatment

|                        | As received | After welded | Fully Annealed | After Vibratory treated |
|------------------------|-------------|--------------|----------------|------------------------|
| Yield strength [MPa]   | 225         | 215          | 260            | 241                    |
| Tensile strength [MPa] | 360         | 315          | 330            | 310                    |
| Elongation %           | 30          | 24           | 29             | 28                     |

Table 6: Results before and after treatment

|                             | As received | After welded | After Vibratory treated |
|-----------------------------|-------------|--------------|------------------------|
| fundamental frequency /[Hz] | 64          | 72.8         | 66.3                   |
| Amplitude X [mm]            | $2.66 \times 10^{-3}$ | $2.4 \times 10^{-6}$ | $2.18 \times 10^{-3}$ |

4. Conclusion
An experimentally VSR & PWHT are used to make the mechanism of VSR is to be clear and reaching to optimize the parameter of VSR process. It can say that the resonance VSR process is an effective compared with PWHT, and to reduce weld residual stress, a proper vibration mode shape should be selected. The displacement amplitude as will the mechanical properties can be playing as a major factor to indicate that the thermal stress be relieved.

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