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Understanding of Vibration Stress Relief with Computation Modeling

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A finite element model was developed to predict weld residual stress and simulate the vibratory stress relief. Both resonant and nonresonant vibration stress relief were studied to better understand the mechanism of vibration stress relief. The effect of process parameters, vibration amplitude and frequency, of vibration stress relief on weld residual stress reduction was investigated with the developed model. It was found that both resonant and nonresonant vibration stress relief can relieve weld residual stresses. For the nonresonant vibration, the stress reduction strongly depends on the vibration's amplitude. For the resonant vibration, the vibration's frequency is essential to stress relief. The vibration's frequency should be close to the structure's natural frequency for the desired vibration mode.

Keywords fabricated metal, modeling processes, welding

1. Introduction

Welding processes inevitably induce residual stress into welded structures. This creates potential problems in terms of dimensional stability and structural integrity. Traditionally, post-weld heat treatment (PWHT) was used to relieve residual stress, which is an effective process, but it suffers from a number of disadvantages: oxidizing the heating surface and changing the materials mechanical properties. Vibratory stress relief has been proposed as an alternative to relieve weld residual stress for many years.

Munsi (Ref 1-3) did very detailed experimental work of vibration stress relief during welding and after welding. Significant residual stress reduction was achieved in a laboratory environment by applying large vibration amplitudes. But the importance of structure resonance on vibration stress relief, which is critical for relieving residual stress for large structures because the required vibration amplitude is too big, did not receive enough attention.

More recently, a number of industries have used the vibratory stress relieving methods to reduce the residual stress in large welded components (Ref 4-8). Because of a lack of understanding of the mechanisms behind vibratory stress relieving, this process has not been widely used in industries. If the vibration applied on a welded structure is not the desired one, the weld residual stress cannot be reduced. Furthermore, since the cost of weld residual stress measurement is high and time consuming, it is difficult to know how much reduction of weld residual stress is obtained by vibration stress relief. With the development of modeling technology, it is now possible to model the process of vibration stress relief. Kuang (Ref 9) modeled the vibration stress relief using a commercial finite element code ANSYS by assuming a stress distribution without modeling the development of weld residual stress. So far there is not a finite element model that can be used to model both a welding process and a vibration stress relief process.

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In this article, a finite element model was developed to investigate the mechanisms behind vibratory stress relief process and the effect of the parameters, frequency and amplitude, of vibratory stress relief on the weld residual stress reduction. A three-dimensional solid model was used to simulate the weld residual stress development and a two-dimensional (2D) plain strain model was used to simulate the vibratory stress relief process after welding. Both the nonresonant vibration and the resonant vibration were studied to better understand the mechanism of vibration stress relief. The results show that the weld residual stress can be reduced using both resonant and sub-resonant vibrations.

2. Setup of Vibration Stress Relief

The setup of vibration stress relief is shown in Fig. 1, which is similar to the experimental setup used in Ref 1. One end of the specimen was rigidly clamped in a fixed frame and the other end of the specimen was inserted into a vibrating device. This setup can be used to study the vibration stress relief during welding and after welding. In this article, only vibration stress relief after welding was studied. Both nonresonant frequency (25 Hz) and resonant frequency vibrations were studied using this setup.

The weld specimen, as shown in Fig. 2, was produced from a 0.18 wt.% C steel flat bar of cross section 6.35×76.2 mm. The total length of the specimen was 290 mm, including the clamping area and the free length for applying a dynamic load. The mechanical properties of the specimen are shown in Fig. 3. The 0.2% offset yield stress is 607 MPa at ambient temperature (Ref 1).

Welding was conducted after the specimen was tacked and put into the setup with a MIG welding process. A weld bead

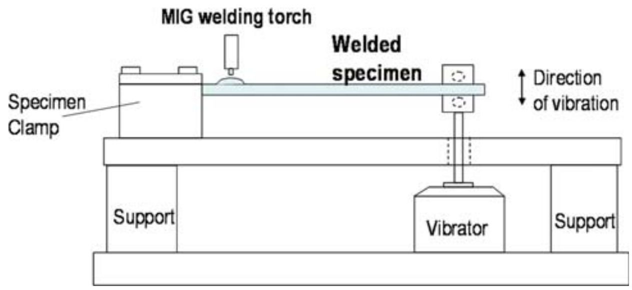

Fig. 1 A setup for vibration stress relief (Ref 1)

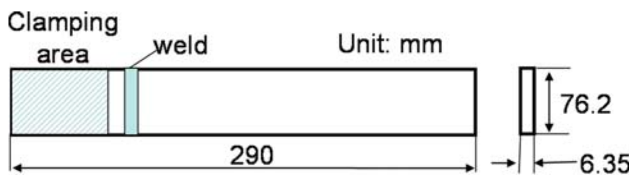

Fig. 2 Dimensions of a weld specimen

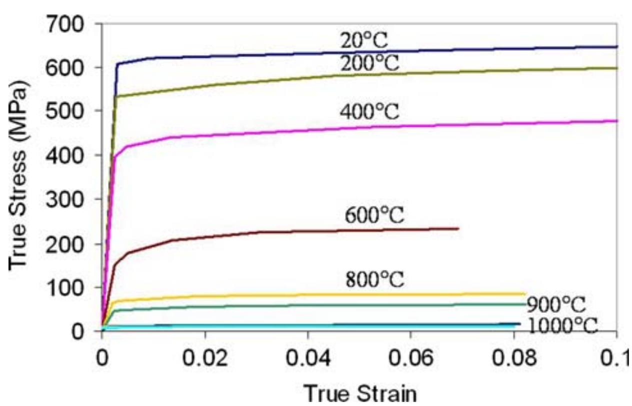

Fig. 3 Temperature-dependent material properties

was deposited near the clamping area. The welding parameters are voltage, 25 V, current, 195 A, and travel speed, 5.63 mm/s.

3. Weld Residual Stress Modeling

Weld residual stress was modeled with a developed modeling procedure, which has been validated through many industrial and government funded projects (Ref 10, 11). This procedure has been successfully used in predicting and controlling welding-induced distortion (Ref 12) in industries. In this study, a moving-arc solution was used to simulate the welding process with ABAQUS commercial code.

Figure 4 shows the finite element mesh created on the weld specimen shown in Fig. 2 for weld residual stress analysis. The weld cross section was accurately represented with fine mesh. In the finite element mesh, direction Y is the welding direction which often refers to the longitudinal direction, direction X is the transverse direction which is perpendicular to the welding direction, and direction Z is the through thickness direction.

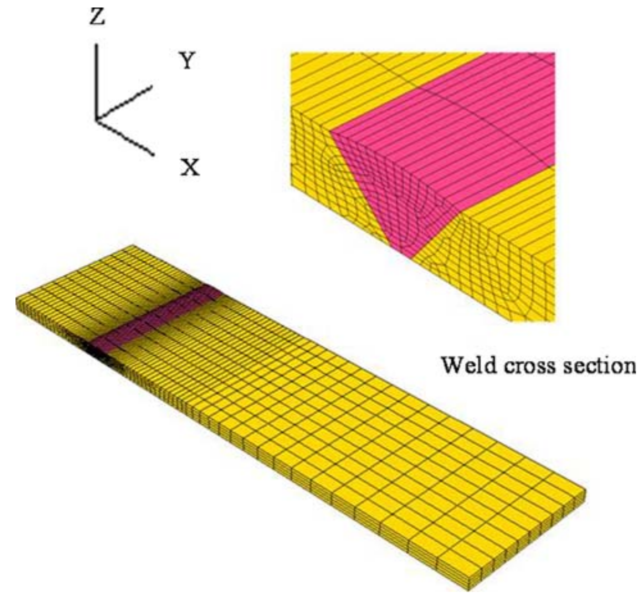

Fig. 4 A finite element mesh for the weld specimen

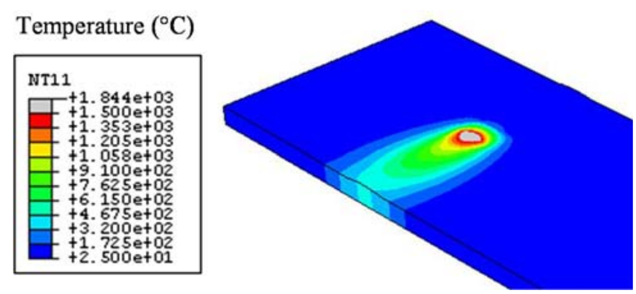

Fig. 5 Temperature distribution (time = 6.75 s)

3.1 Thermal Analysis

Goldak's ellipsoid model was implemented into an ABAQUS subroutine DFLUX to perform a moving-arc thermal analysis (Ref 13). The heat flux distribution was expressed in Eq 1.

$$q(x,y,z,t) = f\,\frac{6\sqrt{3}Q\eta}{abc\pi\sqrt{\pi}}\,e^{\frac{-3x^2}{a^2}}\,e^{\frac{-3[y+v(\tau-t)]^2}{c^2}}\,e^{\frac{-3z^2}{b^2}} \qquad \text{(Eq 1)}$$

where a, b, cf, and cr are the parameters to define a ellipsoid, η is arc efficiency, and Q is the power calculated by welding current multiplying by voltage, v is traveling speed, t is welding time, and τ is the holding time before the welding torch moving.

Figure 5 shows a predicted temperature distribution when the arc is moving toward the middle of the plate. The entire temperature histories, which include heating and cooling, were saved into a database for subsequent stress analysis.

3.2 Stress Analysis

The temperature histories predicted in the thermal analysis were inputted into a thermal-mechanical model to perform a weld stress analysis. Proper boundary conditions were included in the stress model to simulate the clamping of the fixed end. Metal deposition and melting/re-melting effect were considered in the thermal-mechanical model. Isotropic hardening was used in the simulation. Figure 6 shows the predicted transverse and longitudinal residual stress distribution. Both the longitudinal and transverse residual stresses were mapped into a 2D model which was used in the subsequent analysis of vibration stress relief to reduce the computational cost.

4. Non-Resonant Vibration Stress Relief

Nonresonant vibration stress relief was simulated using ABAQUS dynamic analysis on the 2D model shown in Fig. 6. Weld residual stress and effective plastic strain were inputted before the dynamic analysis. Figure 7 shows the loading cycle. A low frequency, 25 Hz, was selected for the analysis. The effect of vibration time and the effect of vibration amplitude on weld residual stress reduction were studied.

4.1 Effect of Vibration Time on Stress Reduction

Figure 8 shows the effect of vibration time on the longitudinal residual stress reduction. Residual stress was reduced most in the first cycle (0.04 s). Small reduction occurred in the second cycle (0.08 s) and little reduction occurred in the third cycle. After the third cycle, further cycles produced only minimal reductions of stress. Similar phenomena were observed by Munsi (Ref 1) in the experimental study of vibration stress relief. This implies that stress reduction from nonresonant vibration stress relief depends on the amplitude of the vibration rather than the vibration time.

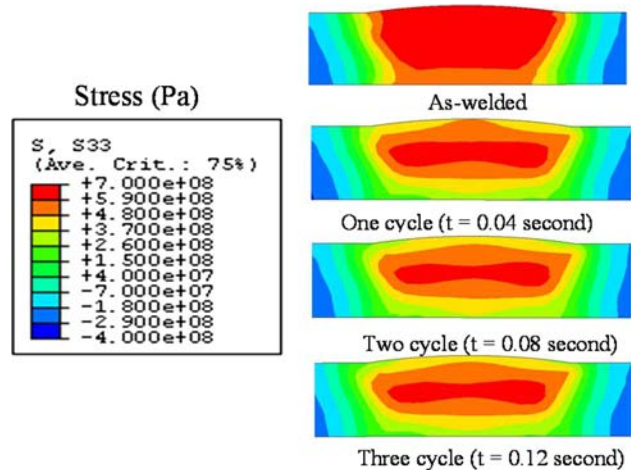

Fig. 8 Effect of vibration time on longitudinal residual stress reduction

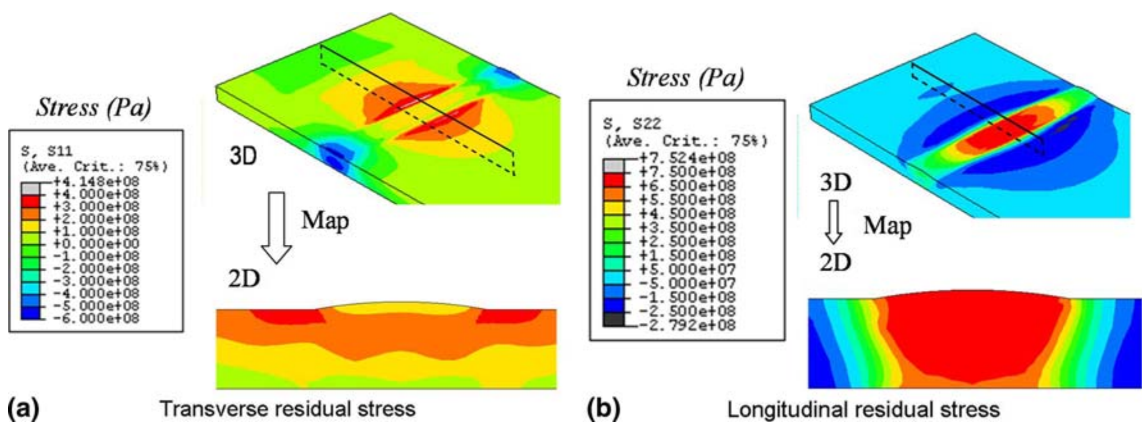

Fig. 6 Weld residual stress distribution: (a) transverse residual stress and (b) longitudinal residual stress

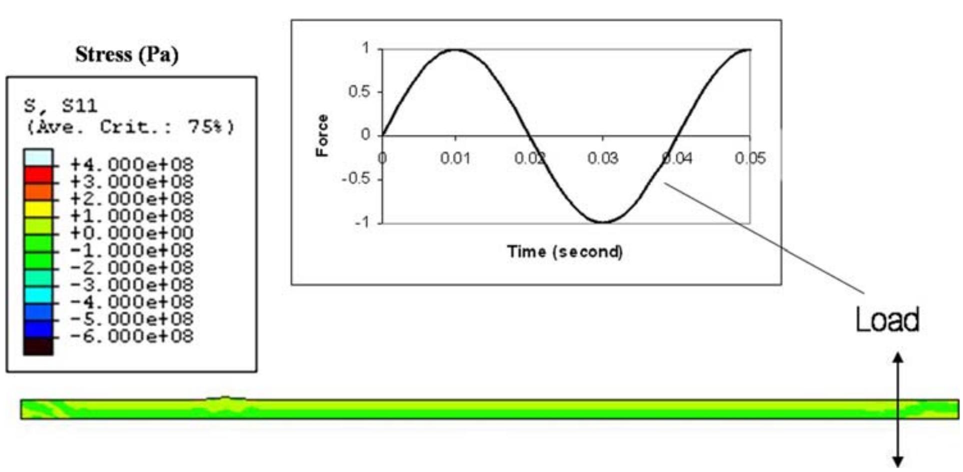

Fig. 7 Vibration stress relief in a 2D model

4.2 Effect of Vibration Amplitude on Stress Reduction

The frequency of vibration was kept constant (25 Hz) while the amplitude of vibration was varied to investigate the effect of vibration amplitude on residual stress reduction. As shown in Fig. 9, with the increase of vibration amplitude, both longitudinal and transverse residual stresses were reduced. More significantly, when the vibration amplitude reached 29 mm, the tensile transverse residual stress near the weld toe changed to compressive as shown in Fig. 9(f).

The longitudinal residual stress reduction is in a good agreement with Munsi's results (Ref 1), while the transverse residual stress reduction shows a different trend. In Munsi's results, the transverse residual stress increased when the vibration amplitude increased from 0 to 10 mm, and then decreased when the vibration amplitude was larger than 10 mm. When the vibration amplitude reached 29 mm, the transverse residual stress near the weld toe area became compressive. This is in agreement with the model predicated results.

This study shows that nonresonant vibration stress relief strongly depends on the amplitude of the vibration. The larger the amplitude of the vibration, the larger the reduction of the residual stress. At the maximum amplitude of the vibration, residual stress cannot be completely removed from the plate utilizing this kind of loading method. There are quite large residual stresses left in the middle area along the plate thickness direction. This is the limitation of this kind of loading method (bending). If a tension load is applied to the free end of the plate perpendicular to the welding direction, more stress could have been relieved during vibration stress relief. But, due to the limitation of the load magnitude, the tension loading method is not practical in real application.

The study of the nonresonant vibration stress relief implies that the reduction of the weld residual stress is induced by plastic deformation around the weld area. The plastic deformation is induced by applying a bending load to the free end of the plate.

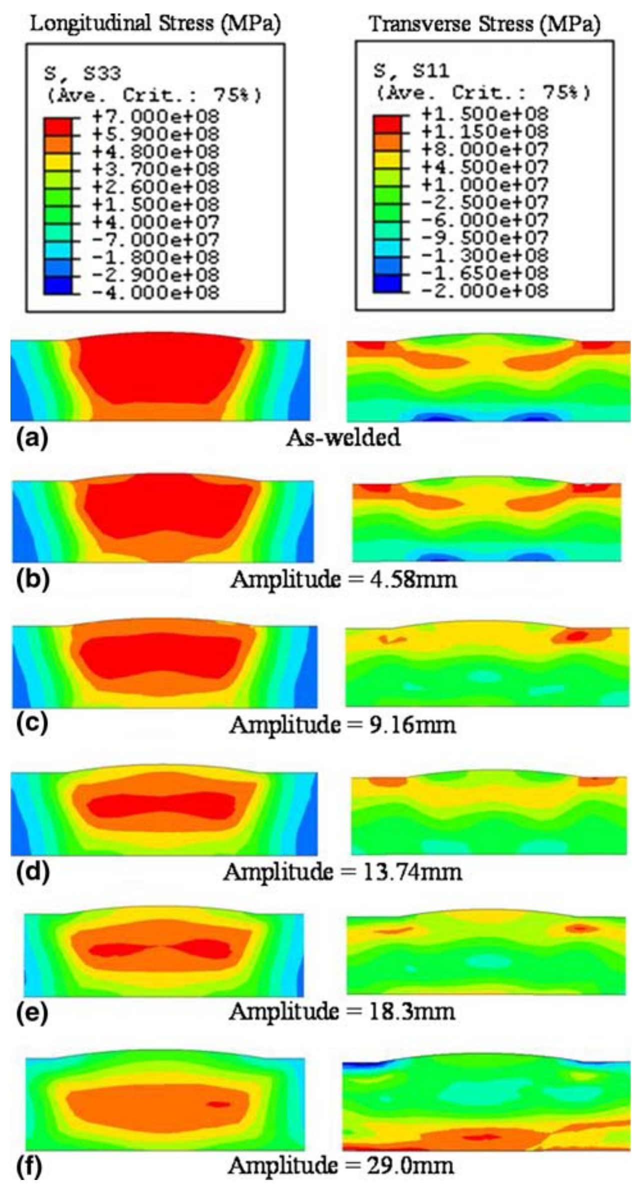

Fig. 9 Effect of vibration amplitude on residual stress reduction

5. Resonant Vibration Stress Relief

Resonant vibration stress relief was studied using ABAQUS dynamic analysis on the 2D model shown in Fig. 6. For the resonant vibration stress relief, it is critical to know the natural frequency of the structure. Thus, a natural frequency analysis was performed first, and then the effect of load frequency and load magnitude on displacement amplitude of vibration stress relief was studied.

5.1 Natural Frequency Analysis

By inputting the weld residual stress as the initial condition and fixing the left end of the plate, free natural vibration analysis was performed with the ABAQUS finite element code. Figure 10 shows the desired displacement mode (bending) with a natural frequency 75.928 Hz. This is the mode used for the following study of resonant vibration stress relief.

5.2 Load-Frequency Effect on Displacement Amplitude

A 100-N force with three frequencies, 25, 74.3, and 75.928 Hz, was applied at the free end of the plate. Weld residual stress was not included in the analysis for simplicity. Figure 11 shows the displacement induced by this load.

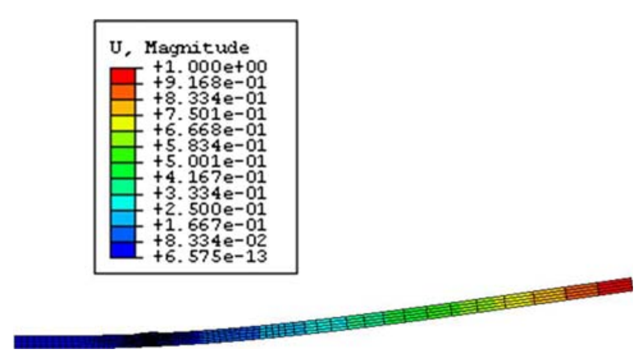

Fig. 10 Mode shape of natural frequency

The displacement amplitudes are 0.19 mm for frequency 25 Hz and 0.17 mm for both frequency 74.3 Hz and frequency 75.928 Hz in the first load cycle. For the case with the frequency 25 Hz, the displacement amplitude stays constant in the subsequent loading cycles, but for the cases with frequency 74.3 and 75.928 Hz, the displacement amplitudes are amplified in the subsequent cycles. The maximum amplified displacement amplitude is 1.8 mm for the case with the frequency 74.3 Hz and 2.7 mm for the case with the frequency 75.928 Hz. This means that the closer the load frequency to the structure's natural frequency (75.928 Hz), the larger the amplified displacement amplitude.

Another interesting phenomenon was observed in Fig. 11. For the cases with the frequency 74.3 and 75.928 Hz, the displacement amplitude was amplified, and then de-amplified periodically. The cycle time was different between these two cases (74.3 and 75.928 Hz). These phenomena could be induced by structure damping.

This study implies that the resonant vibration stress relief can be used in large structures. A small load is applied on the large structures with sub-resonant frequency or resonant frequency. Then the load-induced displacement is amplified to the level to alter weld plastic strain so that the weld residual stress can be relieved.

5.3 Load-Magnitude Effect on Displacement Amplitude

The study on the load-frequency effect on displacement amplitude shows the maximum displacement achieved is 2.7 mm for resonant frequency 75.928 Hz, which was not enough to reduce residual stress based on the previous study. To reduce the weld residual stress, the load is increased by 10 times and 100 times. Figure 12 shows the load-magnitude effect on displacement amplitude. The weld residual stress was included in the analysis.

Figure 12 shows the displacement amplitude is amplified to 28 mm for the case with a 1000 N force and 41.2 mm for the case with a 10,000 N force. Because of weld residual stress, the cycling curve is shifted up since the top plate surface has a tension transverse residual stress and the bottom surface has a compression transverse residual stress. It is important to note that the amplified displacement amplitude no longer decreases for the case with a 10,000 N force. This could be due to the large load magnitude overcoming the effect of structure damping. The amplified ration for the case with a 10,000 N force is smaller than the amplified ration for the case with a 1000 N force.

Figure 13 shows the final weld residual stress after resonant vibration stress relief (1000 N and 75.928 Hz). Both longitudinal and transverse residual stresses were reduced. These results are very similar to the results in Fig. 9(f). This means that weld residual stress can be reduced by both nonresonant vibration stress relief and resonant vibration stress relief. To reduce weld residual stress, the only requirement is that the displacement amplitude has to be sufficient enough to create plastic deformation around weld area. The only difference

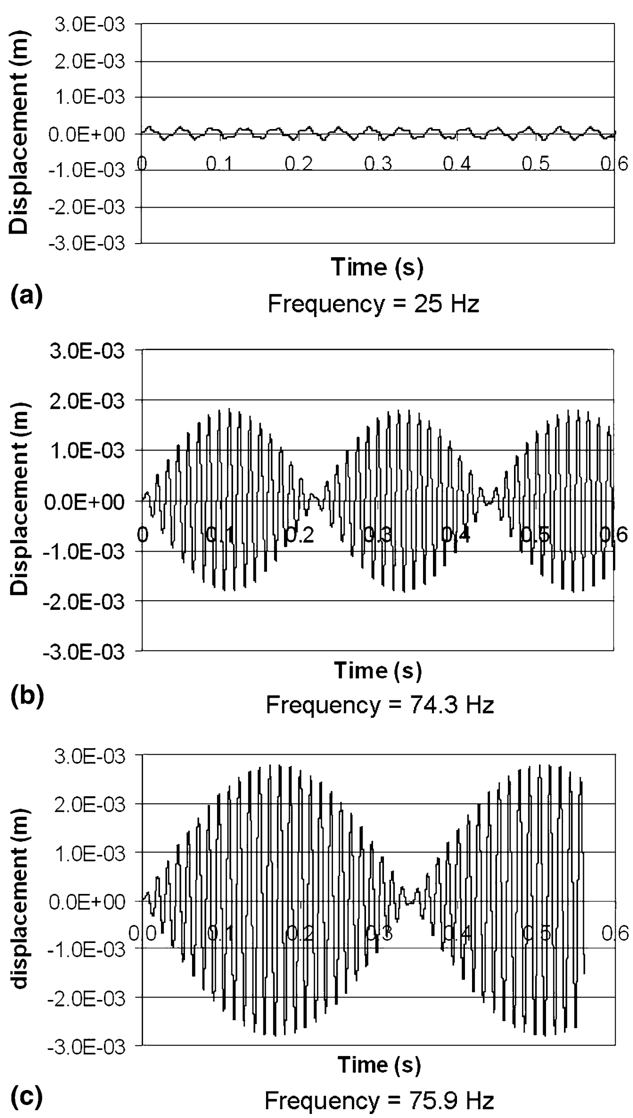

Fig. 11 Load-frequency effect on displacement: (a) frequency = 25 Hz, (b) frequency = 74.3 Hz, and (c) frequency = 75.9 Hz

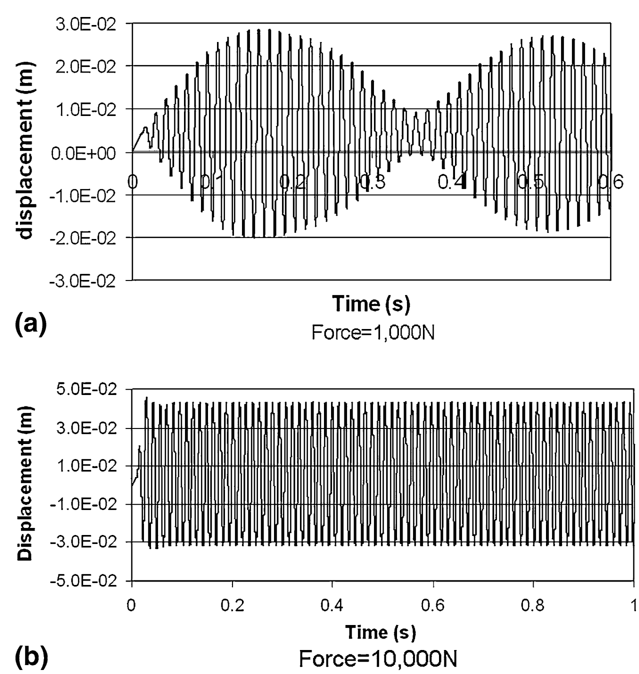

Fig. 12 Force magnitude effect on displacement amplitude: (a) force = 1000 N and (b) force = 10,000 N

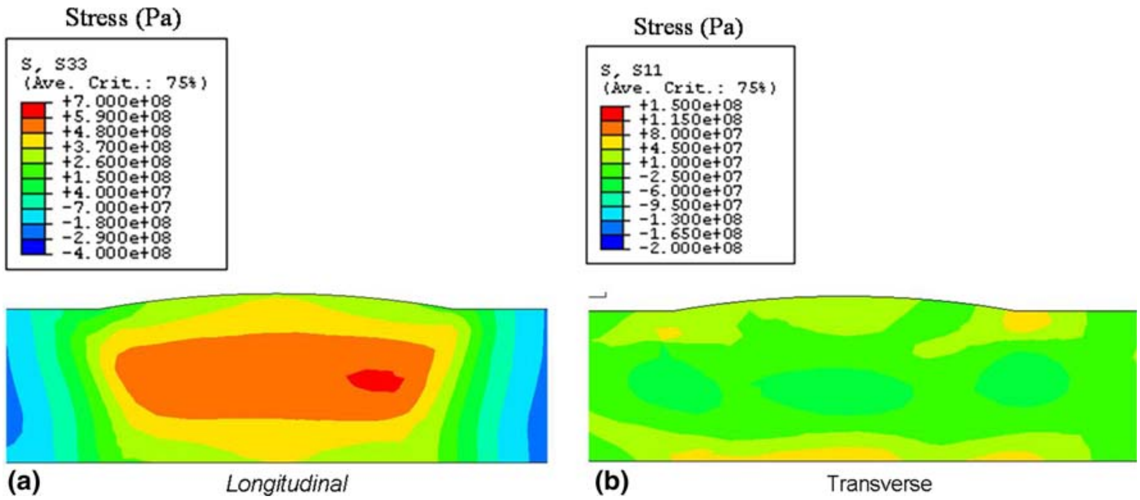

Fig. 13 Weld residual stress with resonant vibration stress relief: (a) longitudinal and (b) transverse

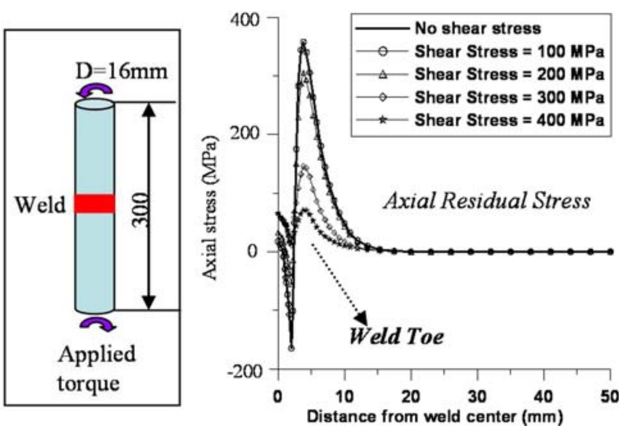

Fig. 14 Residual stress on a shaft with and without vibration stress relief

between nonresonant vibration stress relief and resonant vibration stress relief is that resonant vibration stress relief has an amplification effect. This is why the resonant vibration stress relief can be used in large structures to relieve residual stress.

5.4 An Application Example

The developed vibration stress relief model was applied on a shaft to reduce the residual stress around the weld toe to improve the fatigue life. Using the methods proposed in Ref 5, a torsional loading was applied on the shaft as shown in Fig. 14. Four kinds of torsional loading were studied. Figure 14 shows that the weld residual stress was reduced by vibration stress relief.

6. Conclusion

A vibration stress relief model was developed, which can be used to better understand the mechanism and to optimize the parameters of vibration stress relief to mitigate weld residual stress. The major findings from the studies of the nonresonant vibration stress relief and the resonant stress relief are as follows:

- Vibration amplitude is the key parameter for reducing weld residual stress. For the nonresonant vibration stress relief, large amplitudes are needed to alter weld plastic strain. But for the resonant vibration stress relief, only small excitation vibration amplitude is needed, which will be amplified so that sufficient vibration amplitude can be reached to alter weld plastic strain for relieving weld residual stress.
- The time for vibration stress relief is less critical. For the nonresonant vibration stress relief, most stress relief occurs in the first loading cycle. For the resonant residual stress relief, more loading cycles are needed for load amplification. The time can be calculated through vibration analysis.
- To reduce weld residual stress, selecting a proper vibration mode is important. The select vibration mode should be able to change the weld plastic strain distributions. Finite element model can be used to help select the vibration mode.

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