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FINITE ELEMENT MODELING OF VIBRATION STRESS RELIEF AFTER WELDING

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Finite Element Modeling of Vibration Stress Relief after Welding

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Abstract

A finite element model was developed to simulate the vibratory stress relief after welding. Both resonant and non-resonant vibrations can relieve residual stresses in welded structures by creating plastic deformation around the weld area. For the non-resonant vibration, the stress reduction strongly depends on the vibration amplitude. For the resonant vibration, the vibration frequency is the key for stress relief. The vibration frequency should be close to the structure natural frequency for the desired vibration mode. Only small vibration amplitude is needed, which will be amplified during vibration. Vibration time does not have a major impact on the vibration stress relief. The larger the amplitude that the vibratory stress relief has, the better the treatment.

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 materials mechanical properties. Vibratory stress relief has been proposed as an alternative to relieve weld residual stress for many years.

Munsi did very detailed experimental work of vibration stress relief during welding and after welding [1, 2, 4]. 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 was not paid enough attentions, which is critical for relieving residual stress for large structures because the required vibration amplitude is too big.

More recently, a number of industries have used the vibratory stress relieving methods to reduce the residual stress in large welded components [3, 5, 7-9]. Because of a lack of understanding of the mechanisms of a vibratory stress relieving, this process was not 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 the vibration stress relief. With the development of modeling technology, it is possible to model the process of vibration stress relief. Kuan 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 [6]. So far there are no any finite-element model that can be used to model both a welding process and a vibration stress relief process.

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

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 into 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 paper only vibration stress relief after welding was studied. Both non-resonant frequency (25Hz) and resonant frequency vibration was studied using this setup.

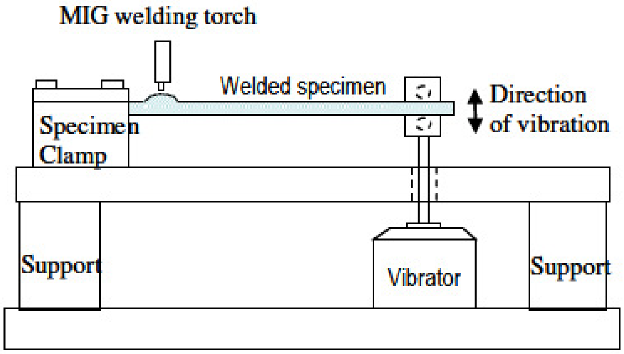


Figure 1: A setup forvVibration stress relief [1]

The weld specimen, as shown in Fig. 2, was produced from 0.18 wt-%C steel flat bar of cross-section 6.35 by 76.2 mm. The total length of the specimen was 290 mm, which included the clamping area and the free length for applying a dynamic load. Weld bead was deposited near the clamping area with a MIG welding process. The mechanical properties of the specimen are shown in Fig. 3. The 0.2% offset yield stress is 607 MPa at ambient temperature [1].

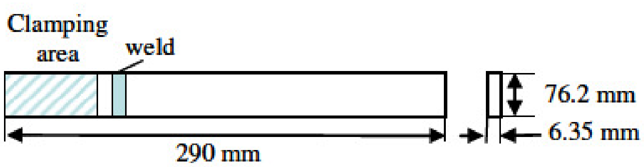


Figure 2: A weld specimen [1]

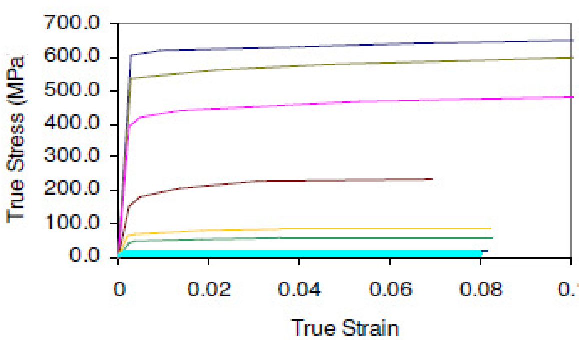


Figure 3: Temperature Dependent materialproperties

Weld Residual Stress Modeling

Welding was conducted after the specimen was tacked and put in the setup with a MIG welding process. The voltage and current in the welding process were 25 v and 195 A respectively. The travel speed is 5.63 mm/s.

Weld residual stress was modeled with a developed modeling procedure, which has been validated through many industrial and government projects. This procedure has been successfully used in predicting and control welding-induced distortion [10-12] in industries. In this study, a moving-arc solution was used to simulate the welding process with ABAQUS commercial code. The weld cross section was accurately modeled as shown in Fig. 4, in which a v-groove was included in the model as shown in Fig. 4.

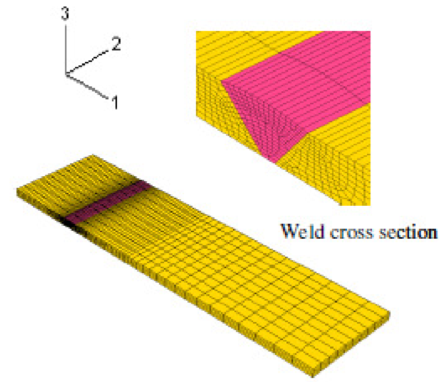


Figure 4: A finite element mesh for the weld specimen

Thermal Analysis

Goldak's ellipsoid model was implemented into an ABAQUS subroutine DFLUX to perform a moving-arc thermal analysis [13]. The heat flux distribution was expressed in Equation 1:

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

where a, b, and c are the semi-axes of the ellipsoid as shown in Fig. 5, η is the heat efficiency, and Q is the power (welding current multiplying by voltage).

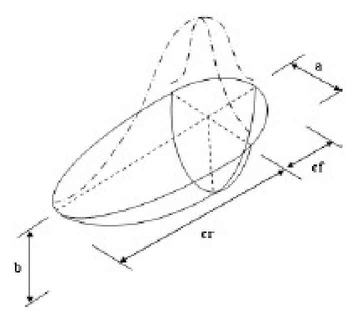


Figure 5: A sketch of Goldak's ellipsoid model

Fig. 6 shows a predicted temperature distribution when arc is moving to the middle of the plate. The entire temperature histories which include heating and cooling were saved into a database for stress analyses.

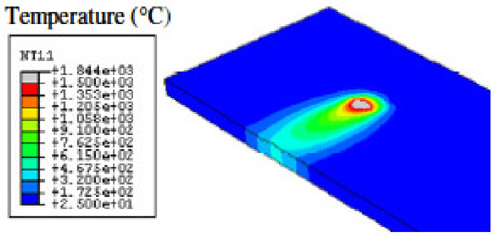
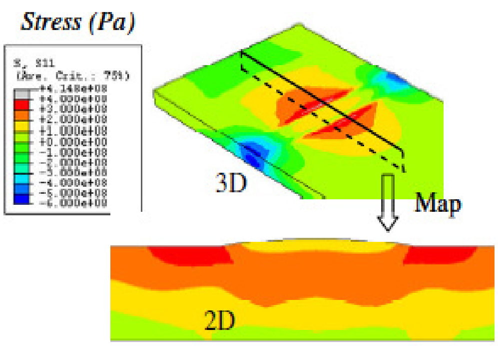


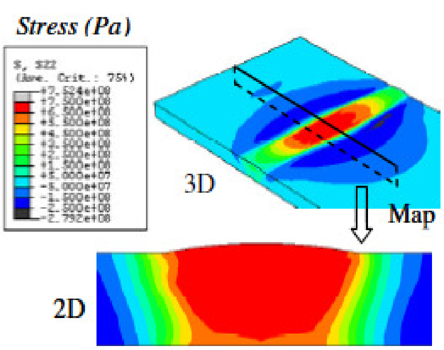
Figure 6: Temperature distribution (time = 6.75 second)

Weld Stress Analysis

The temperature histories predicted in the thermal analysis were inputted to a thermal-mechanical model to perform weld stress analyses. Proper boundary conditions were included in the stress model to simulate the clamp of the fixed end. Metal deposition and melting/remelting effect were considered in the thermal-mechanical model. Isotropic hardening was used in the simulation. Figure 7 shows the predicted transverse and longitudinal residual stress distribution. To save the computation time for the vibration stress relief, the residual stress was mapped to a two-dimensional (2D) model.



(a) Transverse residual stress



(b) Longitudinal residual stress

Figure 6: Weld Residual Stress distribution

Non-Resonant Vibration Stress Relief

Using the 2D model and loading conditions shown in Fig. 7, non-resonant vibration analysis was performed with ABAQUS dynamic analysis. The residual stress and effective plastic strain were inputted as initial conditions in the dynamic analysis. A low frequency, 25 Hz was selected for these analyses. The effect of vibration time and the effect of vibration amplitude on weld residual stress reduction were studied. In the dynamic analysis, displacement load was applied near the end of the plate with a sin wave as shown in Fig. 7.

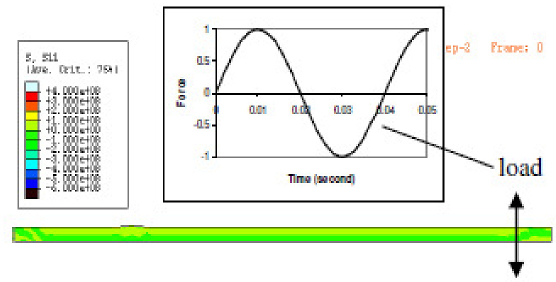


Figure 7: Vibration Stress Relief in a 2D model

Effect of Vibration Time on Stress Reduction

Fig. 8 shows the effect of vibration time on the longitudinal residual stress reduction. Residual stress was reduced most in the first cycle (0.04 seconds). Small reduction happened in the second cycle (0.08 seconds) and little reduction was in the third cycle. After the third cycle, it is hardly to see any further reduction of stress. Munsi observed the similar phenomena during the experiment of vibration stress relief [1]. This means that stress reduction depends on the amplitude of the vibration rather than the vibration time for the non-resonant vibration stress relief.

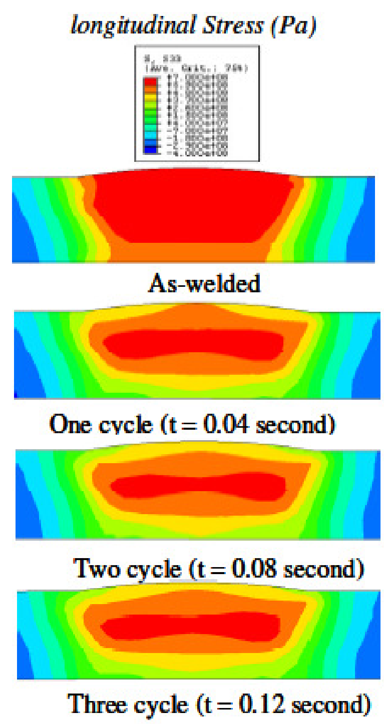


Figure 8: Effect of Vibration Time on longitudinal Residual Stress Reduction

Effect of Vibration Amplitude on Stress Reduction

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

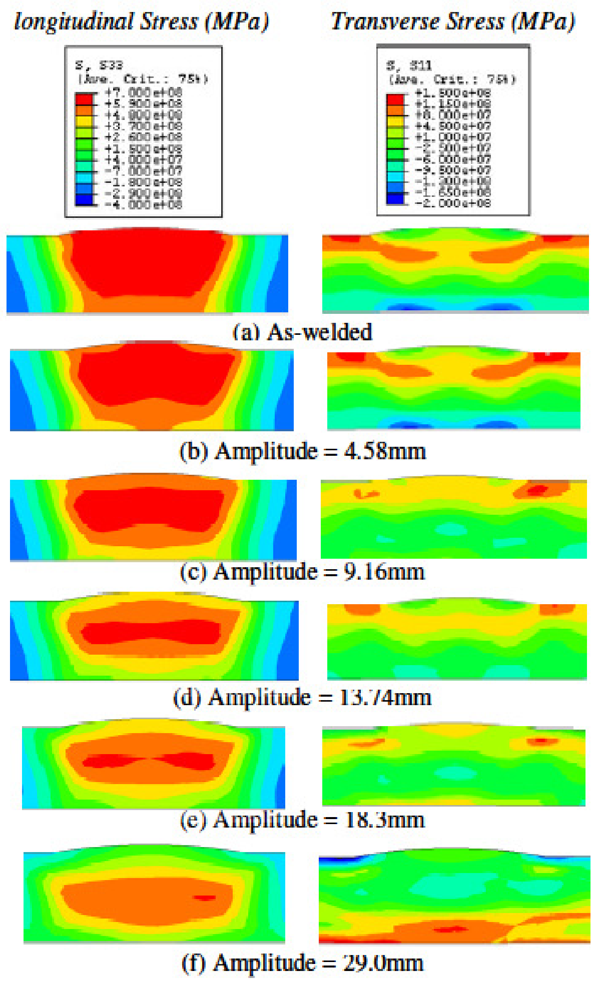


Figure 9: Effect of Vibration Amplitude on Residual Stress Reduction

The longitudinal residual stress reduction is in a good agreement with Munsi's results [1], but 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 to10mm, and then decreased when the vibration amplitude was larger than 10mm. When the vibration amplitude reached to 29 mm, the transverse residual stress near the weld toe area became compressive. This is in a good agreement with the model predicated results.

This study shows that non-resonant vibration stress relief strongly depends on the amplitude of the vibration. The larger the amplitude of the vibration, the larger reductuon of the residual stress. At the maximum amplitude of the vibration, residual stress can not be completely removed from the plate for this knid of loading methods. 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 methods (bending). If a tension load is applied at the free end of the plate in the direction perpendicular to the welding direstion, the residual stress relief could have much better results. But due to the limitation of the load magnitude, the tension loading method is not practical in a real application.

The study of the non-resonant vibration stress relief implys that the reduction of the weld residual stress is induced by the plastic deformation around weld area. The plastic deformation is induced by bending load applied to the free end of the plate.

Resonant Vibration Stress Relief

Natural Frequency Analysis

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

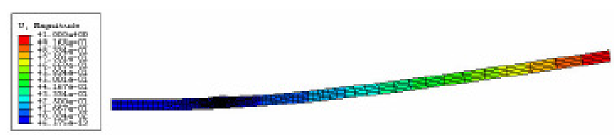


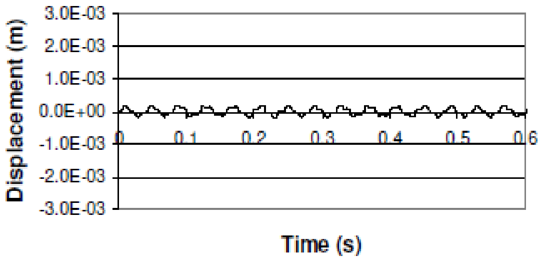
Figure 10: Mode shape of natural frequency

Load-Frequency Effect on Displacement Amplitude

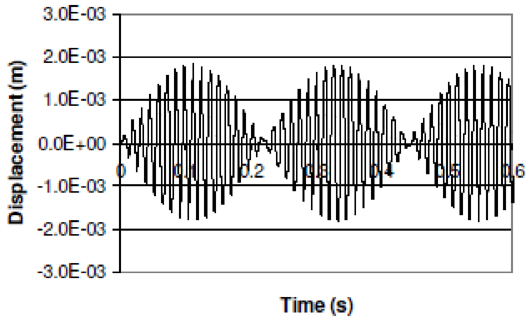
A force, 100 N, was applied at the free end of the plate with three frequencies: 25 Hz, 74.3 Hz, and 75.928 Hz. Weld residual stress was not included in the analysis for simplicity. Fig. 11 shows the displacement induced by this load. The displacement amplitudes are 0.19 mm for frequency 25 Hz, 0.17 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 keeps constant in the following loading cycles, but for the cases with frequency 74.3 Hz and 75.928 Hz, the displacement amplitudes are amplified in the following 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 natural frequency (75.928 Hz), the bigger the amplified displacement amplitude.

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

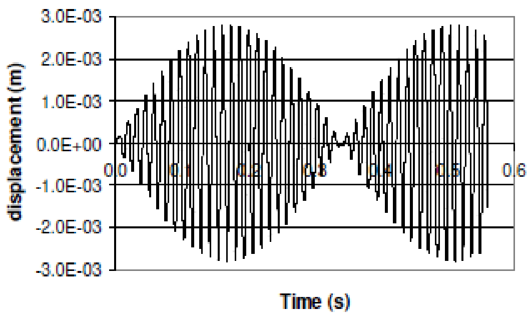
This study implies that the resonant vibration stress relief can be used in large structures. A small load is applied on the large structures with sub-resonant frequency or resonant frequency. Then the load induced displacement is amplified to the required level so that the weld residual stress can be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



(a) Frequency = 25 Hz



(b) Frequency = 74.3 Hz



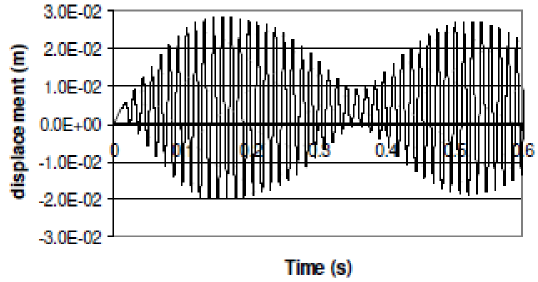
(c) Frequency = 75.9 Hz

Fig. 11 Load-Frequency Effect on Displacement

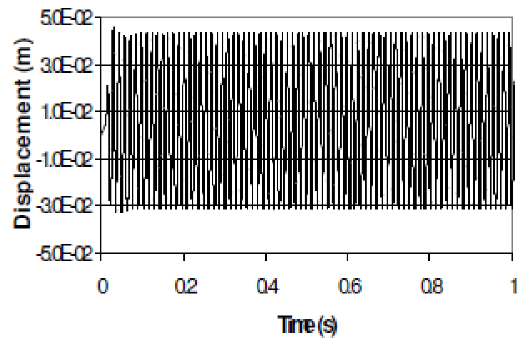
Load-Magnitude Effect on Displacement Amplitude

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 is 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. Fig. 12 shows the load-magnitude effect on displacement amplitude. The weld residual stress was included in the analysis.

Fig. 12 shows the displacement amplitude is amplified to 28 mm for the case with a 1,000 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 stress. Note that the amplified displacement amplitude is no longer decreased 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 force is smaller than the case with a 1000 N force.



(a) Force = 1,000 N



(a) Force = 10,000 N

Figure 12: Force magnitude effect on displacement amplitude

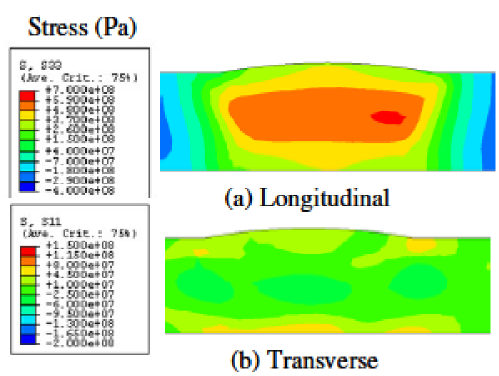


Fig. 13 Weld Residual Stress with resonant vibration stress relief

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

A application example of vibration stress relief modeling

The developed vibration stress relief model was applied on a shift to reduce the residual stress around toe to improve the fatigue life. Using the methods proposed in Ref. 5, a torsional loading was applied on the shift as shown in Fig. 14. Four kinds of torsional loading were studied. Fig. 15 shows that the weld residual stress was reduced by vibration stress relief.

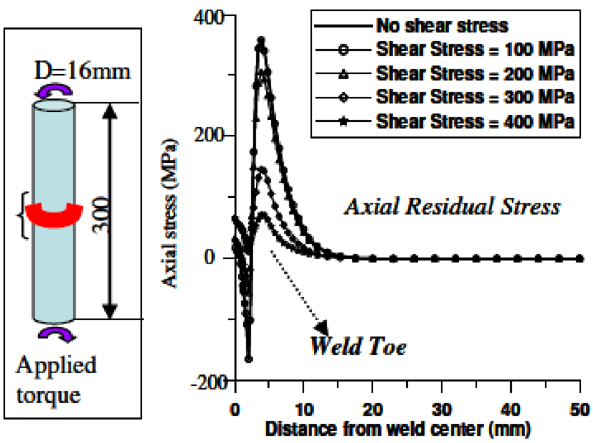


Fig. 14 Residual Stress on a shift with and without vibration stress relief

Conclusion

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

- Load amplitude is the key parameter for reducing weld residual stress. For the non-resonant vibration stress relief, large amplitudes are needed. But for the resonant vibration stress relief, only a small excitation load is needed, which will be amplified so that enough load amplitude can be reached for relieving weld residual stress.
- The time for vibration stress relief is not critical. For the non-resonant vibration stress relief, most stress relief happened in the first loading cycle. For the resonant residual stress relief, more loading cycles are needed for load amplification. The time can be calculated by a vibration analysis.
- To reduce weld residual stress, a proper vibration mode must be selected.

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