Removing Residual Stress and Increasing Fatigue Life by Ultrasonic Method

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Abstract: In this paper, a new method is introduced for evaluating effects of residual stress on fatigue life. The ability of ultrasonic method using longitudinal wave with critical angle of refraction or LCR wave in measuring and removing residual stresses due to welding was used. Two plates of alloy 2024-T351 were welded to each other. To measure their residual stress field acoustoelastic property was used and the changes in the speed of ultrasonic propagation of elastic waves when passing through the residual stress fields was investigated. In order to exert the effects of residual stress on fatigue life, the relations between the coefficients of effective stress intensity (SIF) and Fatigue Crack Propagation (FCP) rate in a state that the parts were welded together with residual stress under cyclic loading were obtained. Finally, ultrasonic waves with a certain frequency were used to remove the residual stresses. Also, the relationships between stress intensity factor and fatigue crack propagation rate were modified to predict fatigue life after removal of residual stresses. This method resulted in a 31% increase in fatigue life. The main reason for the increase in life was the plastic area created by the ultrasound wave. Therefore, it can be said that introduced method are suitable for using to remove residual stress due to welding.

Keywords: Fatigue Life, Longitudinal Ultrasonic Wave, Residual Stress, Stress Intensity Factor

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Biographical notes: Ali Moarrefzadeh received his PhD in Mechanical Engineering from IAU University in 2019. His interest is fatigue, fracture mechanics and computational Mechanics. Also, his current research interest includes study of residual stress effects on fatigue crack propagation. He is currently Assistant Professor at the Department of Mechanical Engineering, Islamic Azad University, Mahshahr, Iran.

1 INTRODUCTION

Welding is a valid and effective method for connecting metals and used in the industry. Despite the advantages of welding such as easy access to caution and high strength, the existing surface at the joint, creating residual stresses of the design is an unavoidable avoidance loss in the construction process. Due to the role of welding in the industry and the ability to require the desired safety factor of welding connections in industries using vehicles such as cars, bridge construction, structures, pressure storage tanks, etc., trying to find methods to measure and control residual stress values, will inevitably be of great importance so that in the next step, by special methods existing residual stresses can be reduced, or destroyed.

Finite element method [1-2] is one of the most commonly used methods in this field to analyze the temperature field and the residual stress caused by welding. In this method, the domain of the problem is divided into smaller sections called elements; the differential Equations governing the system are approximated by a set of algebraic Equations for each element. Residual stresses show their destructive effect during loading and when a piece with residual stress is under external loading, the stresses caused by external load are added to the existing residual stresses and phenomena such as submitting, fatigue and fracture in parts are quickened. One method of decreasing the residual stresses is heating treatment. In this method, the parts are placed in furnaces and the temperature increases in a fixed rate. Then, it is kept in tension at a stress relieving temperature for a period of time expressed in the standard and it is cooled to achieve ambient temperature at the rate of ideal cooling.

The start of development for using ultrasonic method for measuring stress was by Hughes and Kelly [3] based on the results of Morgan’s theory of nonlinear elasticity. They expressed the changes of the speed of ultrasonic wave as a function of the elastic stress and by doing so, they founded the theory of acoustoelasticity. Numerous research has been performed on the effectiveness and efficiency of stress relieving at low frequencies. For the first time, they applied a vibration with a frequency lower than the resonant frequency to the parts with the aim of reducing residual stress from welding. In his study, 10 to 30 Hz frequencies and amplitude of 2.5 to 9.5 mm was used and it was found that the amount of plastic deformation and distortion of the structure as a result of vibrations were negligible and there were no cracks or fractures as a result of vibrations. In his study, no comparison was made between the states of the parts before and after vibration. Research by Wozney and Crawmer [4], had the greatest impact on understanding the mechanism and efficiency of the process of vibration stress relief. In their research, the process of vibration stress relief with resonance frequency was carried on Elman belts and residual tensions were reduced by 33 percent. Lokshin [5] used vibrations with the resonance frequencies for the tension relieving of rings cast out of aluminum and in his research a maximum of 70% of the amount of residual stress in the parts reduced.

Dawson and Moffat [6], used the resonant frequencies of 33, 66 and 92 Hz to further explore the effect of vibrations with lower frequency on various materials, and observed that with the change of frequency, a significant difference was observed in reducing residual stress. In their study, with the increase of the amplitude of cyclic stress, the amount of residual stress also decreased linearly. Walker et al [7], could create tensile residual stresses by rolling in low alloy steel and decrease of 40 percent of initial residual stresses by applying vibrations with a frequency of 100 Hz. Luh and Hwang [8] presented a model in which he described the movement of dislocations by virtue of the combined effect of residual stresses and tensions caused by external vibration loading and used XRD to test his model. Walker et al [9] decreased welded residual stress using vibrating stress relief and compared the results with heat treatment. In his study, the frequency of 25 Hz was used and the result showed that using vibrating stress relief, there was a maximum of 30 percent of stress decrease.

Wang et al [10], conducted a similar research on HSLA steel stress reduction and achieved 20 MPa decrease of residual stresses in welded structures of this steel. This amount of reduction was the same as the reduction observed in thermal stress relief. The use of ultrasonic wave for stress relief was presented by Hira and Aoki [11]. This study was performed aiming to prove the effectiveness of high-frequency vibrations to reduce residual stresses in the formation stage (during welding) and the resonant frequency of 17.8 Hz was used. Liqun and Qijia [12] used ultrasonic vibrations at a frequency of 20 kHz and the amplitude of 15 to 19 micron for the stress relief of two photo resist layers. The initial residual stresses in the samples appeared after the thin film deposition of two materials on each other and the difference of their linear expansion coefficient as bending and the amount of bending decreased after stress relief. Ligon’s research showed that by increasing the amplitude of vibrations, the efficiency of stress relief increased and by increasing the time of stress relief to 10 minutes, the efficiency of stress relief increased and then reduced.

In this study, a suitable method for measuring and removing residual stress due to welding using ultrasound is presented. In this regard, a relation was obtained that reflects the changes in the velocity of waves propagating in the metal in the presence of residual stresses. Finally, after calculating the residual stresses of these waves, they were used to eliminate the residual stresses and a modified relationship for the fatigue crack growth rate was presented. The novelty of this study is the use of ultrasonic waves in the calculation and elimination of residual stresses and the modification of fatigue life prediction Equations for this purpose. The proposed method has a good accuracy in removing residual stress, so that based on the modified relationship, this method has led to a 31% increase in fatigue life.

2 RESIDUAL STRESS DUO TO WELDING

2.1. The Measurement of Longitudinal Residual Stress of Welding using Ultrasonic Method

Residual stress measurement using ultrasonic method is based on the acoustoelastic property of the materials and based on this property, the speed of electrical wave propagation in the material depends on the tension in it. The principle to create LCR wave is that when longitudinal wave meets the common border of the two materials with different acoustic resistance part of it returns and the process is called reflection. Some of this wave enters into the material with certain angles and this process is called refraction. The refracted part is divided into two categories of longitudinal and transverse waves that each is spread in the metal with a different angle. As shown in "Fig. 1" , part of the wave at the same angle of radiation θ is reflected to the environment 1.

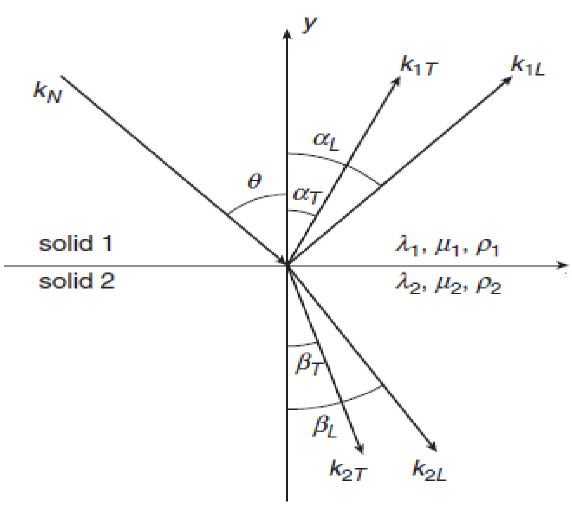

Fig. 1 The result of longitudinal wave collision from one environment to another.

Angles of refraction of longitudinal and transverse waves are respectively shown by θ_L and θ_T . The rest of the wave enters environment 2 and produces two types of longitudinal ultrasonic wave at an angle of β_L and transverse or shear ultrasonic wave at an angle of β_T . The relationship between these angles are shown by Snell Equation or the Equation (1). In this formula, C is the speed of the collided longitudinal wave in the environment 1, C_L is the speed of longitudinal wave in the environment 2 and C_T is the speed of transverse wave in environment 2.

$$\frac{\sin\theta}{C} = \frac{\sin\beta_L}{C_L} = \frac{\sin\beta_T}{C_T} \qquad (1)$$

If the goal is that refracted longitudinal wave in the environment 2 falls on the surface of the metal and moves along the surface of the part, the angle of refraction of longitudinal wave in the environment 2 should equal 90 degrees. So, according to the Equation of Snell, the radiation angle of the longitudinal wave in the environment 1 must be a certain amount and this radiation angle is called first critical angle or θ_{cr}. To obtain this radiation angle, it is sufficient to replace the amount of θ_L in Snell's relation with 90 degrees, then the obtained θ is the first critical angle and the Equation is (2):

$$\theta_{cr} = \sin^{-1}(\frac{C}{C_L}) \qquad (2)$$

The longitudinal wave generated on the surface of material 2 that is released parallel to the surface is called the longitudinal wave with critical angle of refraction or LCR. The Equations of motion of a particle with physical coordinatesx_i, regardless of the volumetric force can be written as:

$$\frac{\partial\sigma_{i,j}}{\partial x_j} = \rho_0 \frac{\partial\sigma_{i,j}}{\partial x_j} \quad i, j = 1,2,3 \qquad (3.1)$$

Where σ_{ij} is the component of the stress tensor at point, ρ□ is the density in a state without deformation and u_i is the components of the displacement of x_i to coordinates x_i. Total contract on the repetitive index is established and $x_i = x_i(X_1, X_2, X_3), U_i = x_i - X_i$ are the components of stress tensor derivative of elastic strain energy density function of the substance without deformation (ϕ) in terms of Lagrangian finite strain component (E) written as Equation:

$$[\sigma] = [J][\frac{\partial\varphi}{\partial E}] \qquad (3.2)$$

Lagrangian finite strain tensor is written based on Jacobian (J) and tensor unit (I) as the Equation (4):

$$E = \frac{1}{2}(J^T J - I) \qquad (4)$$

Jacobian matrix can be calculated by the Equation (5):

$$[J]=[\frac{\partial x_i}{\partial X_i}] \tag{5}$$

The density of strain energy for a solid isotropic elastic is written as a function of the three constant values of I_3, I_2, I_1 Lagrangian tensile strain:

$$[\varphi]=\frac{l+2m}{3}I_1^3+\frac{\lambda+2\mu}{2}I_1^2-2mI_1I_2-2\mu I_2+nI_3 \tag{6}$$

Where, J, m and n are three new fixed values of the substance called third order elastic constants which must be determined by testing. According to "Fig. 2", Hughes and Kelly [3] expressed the Equations of the relations of the speeds of ultrasonic wave with elastic strain in isotropic object as Equations (7-15).

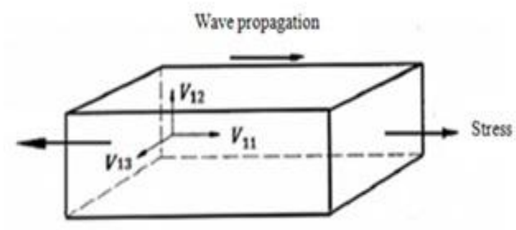

Fig. 2 Speeds used in acoustoelasticity relations [3].

$$\rho_0 V_{11}^2=\lambda+2\mu+(2l+\lambda)\theta+(4m+4\lambda+10\mu)\alpha_1 \tag{7}$$

$$\rho_0 V_{12}^2=\mu+(m+\lambda)\theta+4\mu\alpha_1+2\mu\alpha_2-\frac{1}{2}n\alpha_3 \tag{8}$$

$$\rho_0 V_{13}^2=\mu+(m+\lambda)\theta+4\mu\alpha_1+2\mu\alpha_3-\frac{1}{2}n\alpha_2 \tag{9}$$

$$\rho_0 V_{21}^2=\mu+(m+\lambda)\theta+4\mu\alpha_1+2\mu\alpha_2-\frac{1}{2}n\alpha_3 \tag{10}$$

$$\rho_0 V_{22}^2=\lambda+2\mu+(2l+\lambda)\theta+(4m+4\lambda+10\mu)\alpha_2 \tag{11}$$

$$\rho_0 V_{23}^2=\mu+(m+\lambda)\theta+4\mu\alpha_2+2\mu\alpha_3-\frac{1}{2}n\alpha_1 \tag{12}$$

$$\rho_0 V_{31}^2=\mu+(m+\lambda)\theta+4\mu\alpha_3+2\mu\alpha_1-\frac{1}{2}n\alpha_2 \tag{13}$$

$$\rho_0 V_{32}^2=\mu+(m+\lambda)\theta+4\mu\alpha_3+2\mu\alpha_2-\frac{1}{2}n\alpha_1 \tag{14}$$

$$\rho_0 V_{33}^2=\lambda+2\mu+(2l+\lambda)\theta+(4m+4\lambda+10\mu)\alpha_3 \tag{15}$$

In the above relations, $\alpha_3, \alpha_2, \alpha_1$ represent the major strains, ρ_0 is the initial density (density of the piece changes with stress), μ and λ are second-order elastic constants; m, n and l are third-order elastic constants, v_{ij} is the ultrasonic wave speed. In case of uniaxial tension that stress is inserted on the part in direction 1 and strain in his direction is ε and v is Poisson's ratio, the Equations of speed mentioned above will be as the Equations (16-21) [3]:

$$\alpha_1=\varepsilon,\ \alpha_2=\alpha_3=-v\varepsilon \tag{16}$$

$$\rho_0 V_{12}^2=\rho_0 V_{13}^2=\mu[4\mu+m(1-2v)+v(\frac{n}{2})]\varepsilon \tag{17}$$

$$\rho_0 V_{11}^2=\lambda+2\mu[4(2\mu+\lambda)+2(\mu+2m)+v\mu(1+\frac{2l}{\lambda})]\varepsilon \tag{18}$$

$$\rho_0 V_{22}^2=\lambda+2\mu+[2l(1-2v)-4v(m+\lambda+2\mu)]\varepsilon \tag{19}$$

$$\rho_0 V_{21}^2=\rho_0 V_{31}^2=\mu+[(\lambda+2\mu+m)(1-2v)+v(\frac{n}{2})]\varepsilon \tag{20}$$

$$\rho_0 V_{23}^2=\rho_0 V_{32}^2=\mu+[(\lambda+m)(1-2v)-6\mu+v(\frac{n}{2})]\varepsilon \tag{21}$$

To calculate the changes of the speed of wave to strain, it is enough to derive the parties of the above Equations to the strain to obtain the Equations (22-26):

$$\frac{dV_{11}/V_{11}^0}{d\varepsilon}=2+\frac{\mu+2m+\mu v(1+2l/\lambda)}{\lambda+2\mu}=L_{11} \tag{22}$$

$$\frac{dV_{12}/V_{12}^0}{d\varepsilon}=2+\frac{nv}{4\mu}+\frac{m}{2(\lambda+\mu)}=L_{12} \tag{23}$$

$$\frac{dV_{21}/V_{21}^0}{d\varepsilon}=\frac{\lambda+2\mu+m}{2(\lambda+\mu)}+\frac{nv}{4\mu}=L_{21} \tag{24}$$

$$\frac{dV_{22}/V_{22}^0}{d\varepsilon}=-2v[1+\frac{m-\mu l/\lambda}{\lambda+2\mu}]=L_{22} \tag{25}$$

$$\frac{dV_{23}/V_{23}^0}{d\varepsilon}=\frac{m-2\mu}{2(\lambda+\mu)}+\frac{n}{4\mu}=L_{23} \tag{26}$$

Using one-dimensional stress-strain relationship in elastic material, the amount of stress changes could be obtained with the change of Equation (22) to Equation (27) as the following:

$$d\sigma = \frac{E(dV_{11}/V_{11}^{0})}{L_{11}} \quad (27)$$

In the above formula $d\sigma$ is stress changes and E is the elastic modulus.

2.2. Stress Intensity Factor of Residual Stress Field

When there is residual stress in a substance, the effective stress intensity factor (K_{eff}) according to the principle of superposition is defined as a sum of the stress intensity factor due to cyclic loading and residual stress according to Equation (30).

$$K_{eff} = K_{ext} + K_{res} \quad (28)$$

Where, the stress intensity factor due to cyclic loading is defined as Equation (29):

$$K_{ext} = f(\frac{a}{w})\sigma_{ext}\sqrt{\pi a} \quad (29)$$

And the stress intensity factor due to residual stress using the appropriate weight function is obtained via Equation (30):

$$K_{res} = \int W(x,a)\sigma_{res}(x)dx \quad (30)$$

2.3. Fatigue Crack Propagation Rate in The Field of Tensile Residual Stresses

Walker used the Equation (31) for the calculation of fatigue crack growth rate:

$$\frac{da}{dN} = c(K_{\max}(1-R)^{m})^{n} \quad (31)$$

Where, R represents the cycle ratio. If there is residual stress in the substance, changes in stress intensity can be obtained as the following Equation (34):

$$\frac{da}{dN} = c(\Delta K_{ext}(1-R_{eff})^{m-1})^{n} \quad (32)$$

According to Equation (33), the following Equation is possible:

$$\frac{da}{dN} = c(\Delta K_{ext}(1-R_{eff})^{m-1})^{n} \quad (33)$$

Where, the ration of the affective cycle is defined as Equation (34):

$$\Delta K_{tot} = \Delta K_{eff}^{\max} - \Delta K_{eff}^{\min} = (K_{ext}^{\max} + K_{res}) - (K_{ext}^{\min} + K_{res}) = \Delta K_{ext} \quad (34)$$

So, the Equation (33) can be rewritten into Equation (35):

$$\frac{da}{dN} = c(\Delta K_{ext}(\frac{\Delta K_{ext}}{K_{ext}^{\max} + K_{res}})^{m-1})^{n} \quad (35)$$

3 REMOVING RESIDUAL STRESS AND ESTIMATION OF FATIGUE LIFE

3.1. Remove Residual Stress by Ultrasonic Waves

Ultrasonic waves can be used to remove residual stress so that stress field caused by the waves with residual stress are accumulated in the substance and the bulk of them exceed the limit of plastic and a significant portion of tensile residual stress is released and finally removed and turned to the compressive residual stress. For this purpose, the longitudinal ultrasonic waves are used as multi-pulse. The created stress field can be obtained by Equation (36):

$$U = 2A\cos\{0.5\Delta Kx - 0.5\Delta wt\}.\cos(kx - wt) \quad (36)$$

Or as a total of the sentences, the Equation (37) would be as following:

$$U = \sum_{i}^{n} A_i \cos(k_i x - w_i t) \quad (37)$$

Based on the Hooke's Law, according to Equation (38):

$$\sigma_{ij} = \lambda e\delta_{ij} + 2\mu E_{ij}$$
$$\sigma_x = (\lambda + 2\mu)\frac{\partial U}{\partial x} \quad (38)$$

Therefore, the Equation (38) can be written:

$$\sigma_x = (\lambda + 2\mu)\sum_{i}^{n} iA_i k_i e^{(k_i x - w_i t)} \quad (39)$$

Since LCR wave is a longitudinal wave, according to the Navier Equations and the Helmholtz decomposition in accordance with Equations (39), it could be written:

$$(\lambda + \mu)\nabla\nabla.U + \mu\nabla^2 U = \rho\frac{\partial^2 U}{\partial t^2} \quad (40)$$

$$\nabla[(\lambda+2\mu)\nabla^2\phi-\rho\frac{\partial^2 U}{\partial t^2}]+ \\ \nabla\times[\mu\nabla^2 H-\rho\frac{\partial^2 U}{\partial t^2}]=0 \quad (41)$$

Since each term of the Equation (42) is equal to zero:

$$\begin{cases}(\lambda+2\mu)\nabla^2\phi-\rho\frac{\partial^2 U}{\partial t^2}=0\rightarrow\nabla^2\phi=\frac{1}{C_L^2}\frac{\partial^2 U}{\partial t^2}\\ \mu\nabla^2 H-\rho\frac{\partial^2 U}{\partial t^2}=0\rightarrow\nabla^2 H=\frac{1}{C_T^2}\frac{\partial^2 U}{\partial t^2}\end{cases} \quad (42)$$

On the other hand, it is clear the LCR wave as shown in "Fig. 3" is released parallel to the surface, and in the environment 2, there is only transverse wave and this wave is reflected at collision in every level in material 2 as shown in "Fig. 4" as longitudinal and traverse waves. As this process continues, there will be a set of waves that move together.

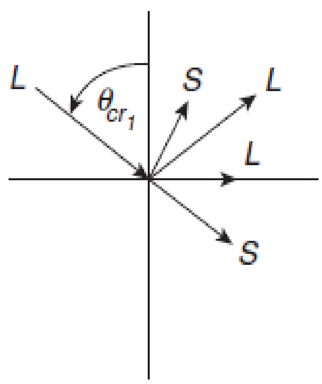

Fig. 3 LCR wave profile.

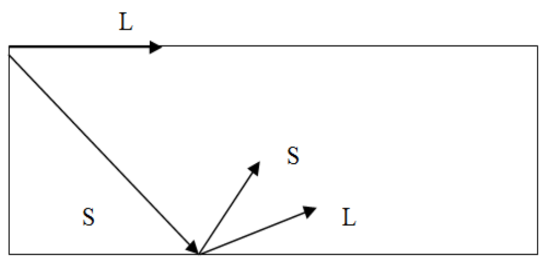

Fig. 4 Wave reflection in environment 2

3.2. Predicting the Fatigue Life (In Case of Residual Stress Being Removed)

As mentioned, tensile residual stresses will be gradually removed by ultrasonic waves. Therefore, the stress intensity factor due to residual stress is changing according to Equation (30) due to the change in residual stress distribution. As a result, according to Equation (34) due to the change of residual stress distribution and according to Equation (35) fatigue crack growth rate is declining. Therefore, in every step of removing residual stress, fatigue crack growth rate is obtained as the Equation (43):

$$\frac{da}{dN}=c(\Delta K_{ext}(\frac{\Delta K_{ext}}{K_{ext}^{\max}+K_{res}^{t}})^{m-1})^{n} \quad (43)$$

Where, K_{res}^{t} is stress intensity factor due to momentary residual stress field. After complete removal of tensile residual stresses, a plastic zone is formed which leads to the creation of compressive residual stresses. Therefore, stress intensity factor due to tensile residual stress K_{res} is completely removed, and stress intensity factor due to compressive residual stresses K_{res}^{C} will be replaced by it. So, the relationship between effective stress intensity factories can be modified as the Equation (44).

$$K_{eff}=K_{ext}-K_{res}^{C} \quad (44)$$

And thus the relationship between fatigue crack growth rate is modified as Equation (45):

$$\frac{da}{dN}=c(\Delta K_{ext}(1-R_{eff}^{C})^{m-1})^{n} \quad (45)$$

Where effective compression cycle is modified as the Equation (46):

$$R_{eff}=\frac{K_{ext}^{\min}-K_{res}^{C}}{K_{ext}^{\max}-K_{res}^{C}}$$
(46)

3.3. The Case Study

As mentioned, LCR wave is a longitudinal wave and in case of the entrance of uniaxial tension in the direction of (1) to the part as shown in "Fig. 2" , the relation of LCR wave speed with elastic strain can be obtained by Equation (17). In "Table 1" , for this alloy the second and third order elastic constants are provided.

Table 1 The second and third order elastic constants for alloy 2024-T351 in terms of GPa

L	m	n	λ	μ	E	υ
-310	-400	-408	60	27	73	0.34

In addition, "Fig. 5" shows butt welding of the two sheets of this alloy along with its geometric and mechanical properties. According Equs. (22) and (29), the changes in the speed of wave to strain and stress are shown in the “Figs. 6-7” respectively.

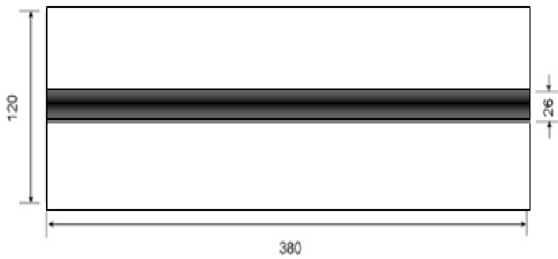

Fig. 5 The butt welding of the two sheets of alloy 2024-T351 $(\sigma_y = 325MPa,\ \sigma_u = 470MPa)$.

Residual stress distribution in this connection along the weld line is obtained as shown in “Fig. 8”. The placement of the crack is also shown in “Fig. 9”.

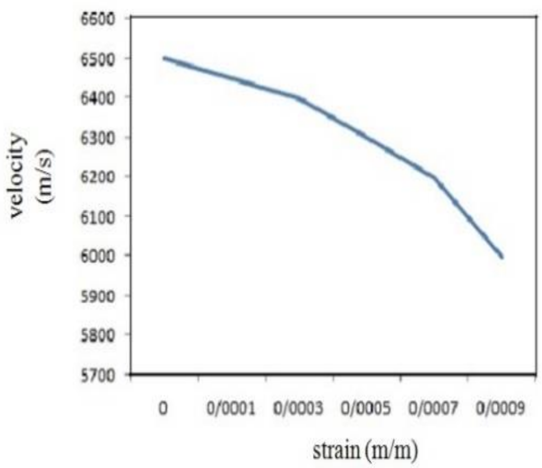

Fig. 6 Speed changes in longitudinal waves in alloy 2024-T351 (when the wave moves along the tension).

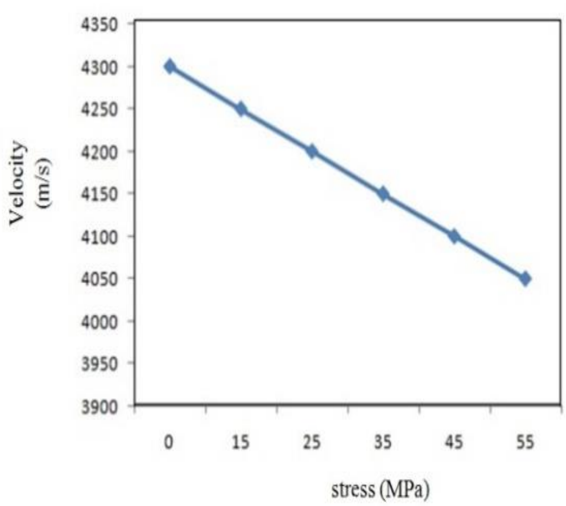

Fig. 7 Speed changes in longitudinal waves in alloy 2024-T351 (when the wave moves along the tension).

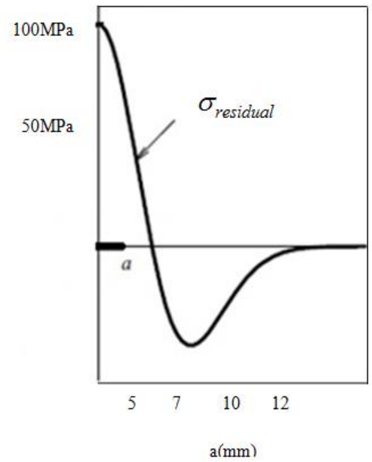

Fig. 8 Longitudinal residual stress distribution.

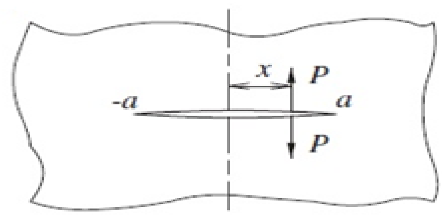

Fig. 9 Crack in the middle of the plate.

Based on “Fig. 9”, the weight function can be obtained by Equation (47) and the tensile residual stresses caused by field of tensile residual stressed from the Equation (30).

$$W(a,x) = \frac{1}{\sqrt{\pi a}}\left(\frac{a+x}{a-x}\right)^{\frac{1}{2}} \tag{47}$$

In “Table 2”, for different lengths crack is intended. The stress intensity factor due to cyclic loading $(\Delta\sigma = 40MPa,\ R = 0)$, effective stress intensity factor based on the Equations (28 and 29) and the crack growth rate are obtained based on the Equation (48):

$$\frac{da}{dN} = 1.8\times10^{-10}(\Delta K_{eff})^{3.5} \tag{48}$$

Table 2 Results of applied research

a (mm)	K_{ext} $(MPa\sqrt{m})$	K_{res} $(MPa\sqrt{m})$	K_{eff} $(MPa\sqrt{m})$	$\frac{da}{dN}$ $(m/cycle)$
5	5.1	9	14.011	1.89×10^{-6}
7	5.9	11.5	16.43	3.91×10^{-6}
10	7.1	12.3	19.38	5.68×10^{-6}

12	7.7	18.6	26.36	9.94×10^{-6}

In this case, "Figs. 10-11" show the effect of the field of residual stress on the stress intensity factor and fatigue crack growth rate. In these Figures, the changes of stress intensity factor and fatigue crack growth rate for different lengths of crack in different states indicating the presence or absence of residual stresses are shown. To reduce residual stress by ultrasonic wave and based on the relationships described in section (4), with natural frequency of the intended part during 10 minutes, the residual stress is reduced by 20 percent. In "Table 3" , the effective stress intensity factor and crack growth rates calculated in this case for 5 mm crack length and supposed cyclic loading is shown. The results show that the fatigue life increases by 31 %.

Table 3 Stress intensity factor and fatigue crack growth rate after 20 percent reduction of the residual stress

a(mm)	K_{res}(MPa $\sqrt{\square m}$)	$\frac{da}{dN}$ (m/cycle)	Fatigue Life
5	7.2	1.1×10^{-6}	+31%

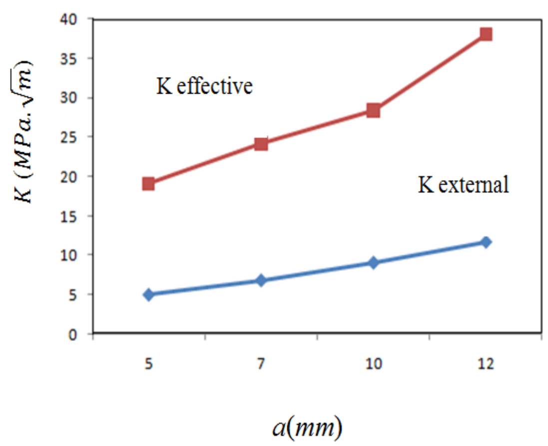

Fig. 10 The changes in stress intensity factor.

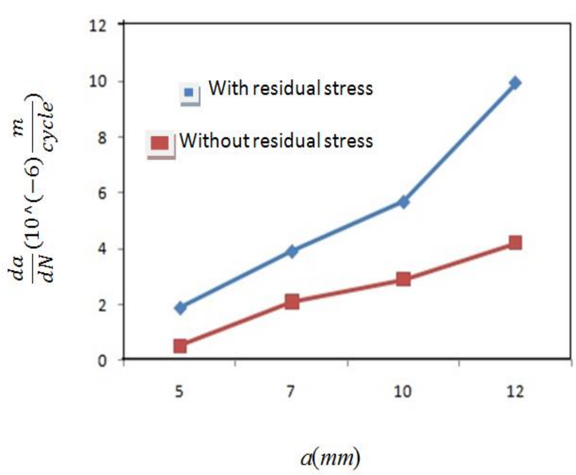

Fig. 11 The changes in fatigue crack propagation rate

4 CONCLUSION

In this paper, the ability of the ultrasonic wave method using the longitudinal wave with refractive angle or LCR to measure and eliminate residual stress due to welding was investigated. The results are as follows:

1- The results show that this method is very suitable for calculating and removing residual stress. If the tensile and stress waves are along each other, in the tensile state, the longitudinal wave velocity decreases.

2- Changes in wave velocity are greater for longitudinal waves propagating along the stretch than in other modes. To de-stress at a certain frequency by increasing the amplitude, a larger plastic area can be created, which leads to softer sound of the material.

3- Modified relationships have been introduced to calculate the stress intensity factor and the rate of fatigue crack growth if the residual stress field is reduced. This relationship can be used to calculate the instantaneous growth rate of cracks based on the percentage of reduction in residual stress.

REFERENCES

[1] Yaghi, Y., Becker, A., Weld Simulation Using Finite Element Methods, University of Nottingham, UK, 2004, pp. 7–11.

[2] Zubairuddin, M., Albert, S. K., Vasudevan, M., Mahadevan, S., Chaudhari, V., Suri, and V. K., Numerical Simulation of Multi-Pass GTA Welding of Grade 91 Steel, Journal of Manufacturing Process, Vol. 27, 2017, pp. 87–97.

[3] Hughes, D. S., Kelly, J., Second-Order Elastic Deformation of Solids, Physical Review, Vol. 92, 1953, pp. 1145-1953.

[4] Wozney, G. P., Crawmer, G. R., An Investigation of Vibrational Stress Relief in Steel, Welding Journal, Vol. 479, 1968, pp. 411-418.

[5] Lokshin, I., Vibration Treatment and Dimensional Stabilization of Castings. Russian Castings Production Journal, Vol. 7, 1965, pp. 454-456.

[6] Dawson, R., Moffat, D. G, Vibratory Stress Relief: A Fundamental Study of Its Effectiveness, Journal of Engineering Materials and Technology, Vol. 102, 1980, pp. 169-178.

[7] Walker, C. A, Waddell, A. H, and Johnston, D. G., Vibratory Stress Relief, an Investigation of the Underlying Processes, Journal of Process Mechanical Engineering, Vol. 209, 1995, pp. 51-58.

[8] Luh, G. C., Hwang, R. M., Evaluating the Effectiveness of Vibratory Stress Relief by a Modified Hole-Drilling

Method. International Journal of Advanced Manufacturing Technology, Vol. 14, 1998, pp. 815-823.

[9] Munsi, S. M., Waddell, A. J., and Walker, C. A., The Influence of Vibratory Treatment on the Fatigue Life of Welds: A Comparison with Thermal Stress Relief, International Journal of Strain, Vol. 37, 2001, pp. 141-149.

[10] Sun, M. C., Sun, Y. H., and Wang, R. K, Vibratory Stress Relieving of Welded Sheet Steels of Low Alloy High Strength Steel, Material letters, Vol. 58, 2004, pp. 1396-1399.

[11] Hira, S., Aoki, S. H., Reduction of Residual Stress by Ultrasonic Surface Vibration. Advances in Vibration Engineering, Vol. 7, 2005, pp. 207-216.

[12] Liqun, D., Qijia, W., Experimental Study on Ultrasonic Stress Relief for Cured SU-8 Photo resist Layer, Microelectronic Engineering, Vol. 87, 2010, pp. 2555-2560.