ULTRASONIC STRESS MEASUREMENT IN WELDED JOINTS BY USING L_{CR} WAVES: An approach to separate microstructure and stress effects

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Abstract

Welding, which is a largely used process in the mechanical manufacturing, is one of the main sources of residual stresses. The level of residual stresses has a great importance for the life time of welded components used in mechanical engineering industry. The ultrasonic technique may be used to determine residual stresses in industrial components. The technique is based on the acoustoelastic effect, which refers to the change in the velocity of ultrasonic waves propagating in strained solids. Previous studies were carried out to evaluate residual stresses by using ultrasonic methods, but they do not enable to exactly determine the stress values in the heat-affected zone (HAZ) and the melted zone (MZ). The welding process, produces changes in the microstructure of the HAZ and the MZ, which also involve variations in the propagation velocity. These variations in velocity can be more important than those induced by the stresses, and the superposition of both effects involves an over evaluation of the stresses in the different zones.

After a brief review of the theoretical aspects, this paper describes the experimental procedure of ultrasonic stress measurements applied to welded manufactured joints for different steel grades. The variations in velocity are determined by using differential time of flight measurements for L_{CR} waves, which are longitudinal waves refracted near the first critical angle. The determination of the acoustoelastical constants in the parent metal and the MZ is required. It enables to take into account the effect of the microstructure in the different zones of measurement and to avoid the over evaluation of the stress level. The ultrasonic stress measurements are compared with those obtained by the hole drilling method.

1. Introduction

The various operations of transformation of materials used in mechanical engineering industry induce residual stresses. These stresses can be introduced on purpose, in order to improve the mechanical characteristics (shot-penning, surface heat treatments) or out of purpose (welding, grinding,). In this case they are often detrimental to the mechanical resistance of the part and must be taken into account in design in order to increase his lifestime. The knowledge of residual stresses has a real importance in machine elements. There are various techniques making it possible to determine these residual stresses by: X-rays diffraction , hole drilling method, the Barkhausen method based on the ferromagnetic properties of material and ultrasonic method. The first two methods are well established whereas the Barkhausen and ultrasonic methods are always under study.

2. Ultrasonic method for determination of residual stresses

Elastic waves propagate isotropic solids with a velocity which is characteristic of the material under test. The velocity of a longitudinal wave (V_L) and a shear wave (V_T) are given by:

$$\rho V_L^2 = \lambda + 2\mu = K + \frac{3}{4}\mu \qquad (1)$$

$$\rho V_T^2 = \mu \qquad (2)$$

The most widely used model for the description of the acoustoelastic effect, that is, the influence of strain states on the propagation velocities of ultrasonic waves, is given by HUGHES et KELLY [HUGH 53] using MURNAGHAN's [MURN 51] theory of finite deformations and third order terms in the elastic strain ε :

$$\Phi(\varepsilon) = \Phi_0 + gC_{ij} + \frac{1}{2}C_{ijkl}\varepsilon_{ij}.\varepsilon_{kl} + \frac{1}{6}C_{ijklmn}\varepsilon_{ij}.\varepsilon_{kl}\varepsilon_{mn} + \ldots.. (3)$$

if the deformation energy is zero before deformation, Φ_0 is zero.

In an isotropic solid, the strain energy density depends only on the invariants I_1, I_2 et I_3 of the Lagrangian strain tensor since the elastic constants are invariant under arbitrary rotations:

$$\Phi(\varepsilon) = \frac{1}{2}(\lambda + 2\mu)I_1^2 - 2\mu I_2 + \frac{1}{3}(1 + 2m)I_1^3 - 2mI_1I_2 + nI_3 \qquad (4)$$

Differentiating the equation (4) with respect to the strain yield to the stress components. As described in [HUGH 53] and in more detail in [GREE 73], the solution of the wave equation results in three expressions for the propagation of a pure longitudinal and two pure shear waves polarised to one principal direction of each strain.

These principal solutions can be generalised for the case of sound propagations in each of the three principal directions of a strained solid with cubic structure:

$$\rho_0 V_{11}^2 = \lambda + 2\mu + (2\ell + \lambda)\theta + (4m + 4\lambda + 10\mu)\varepsilon_1 \quad (5)$$

$$\rho_0 V_{12}^2 = \mu + (\lambda + m)\theta + 4\mu\varepsilon_1 + 2\mu\varepsilon_2 - \frac{1}{2} n\varepsilon_3 \quad (6)$$

$$\rho_0 V_{13}^2 = \mu + (\lambda + m)\theta + 4\mu\varepsilon_1 + 2\mu\varepsilon_3 - \frac{1}{2} n\varepsilon_2 \quad (7)$$

The first index of V represents the direction of sound propagation, the second the direction of vibration. 1, 2 and 3 are the axes of a Cartesian coordinate system. l, m and n are the third order elastic constants of the material under consideration. V_{ii} is the velocity of a longitudinal wave propagating in the i- direction; V_{ij} and V_{ik} are the velocities of two shear waves polarised perpendicular to each other. The equation (5) to (7) are the fundamental equations for the ultrasonic evaluation of load or residual stress states. They describe the acoustoelastic effect. It should be noted that these equations can only be used if the sound wave propagates and vibrates along principal axes.

In the case of a tensile stress (σ=E.ε) according to 1, we can write: $\alpha_1 = \varepsilon$, $\alpha_2 = \alpha_3 = -\nu.\varepsilon$, by injecting into the equation (7) the values of the principal deformations, we obtain: $\rho_0 V_{11}^2 = \lambda + 2\mu + [4(\lambda + 2\mu) + 2(\mu + 2m) + \nu\mu(1 + \frac{2l}{\lambda})].\varepsilon$

(8)

Then we can write the relative variation of velocity according to the deformation for each mode, the following expression corresponds to the longitudinal mode:

$$\frac{\frac{dV_{11}}{V_{11}}}{d\varepsilon} = 2 + \frac{(\mu + 2m) + \nu\mu\left(1 + \frac{2l}{\lambda}\right)}{\lambda + 2\mu} = A_{11} \quad (9)$$

where A_{11} is the acoustoelastic constant corresponding to the longitudinal mode.

3. Experimental procedure

Two P460 HLE and P265 sheets having a 30 mm thickness are welded with a chamfer in X. Manual welding for P460 sheet steel is performed while automatic welding under flow is carried out in the case of sheet P265 steel. Figure 1 presents the experimental procedure.

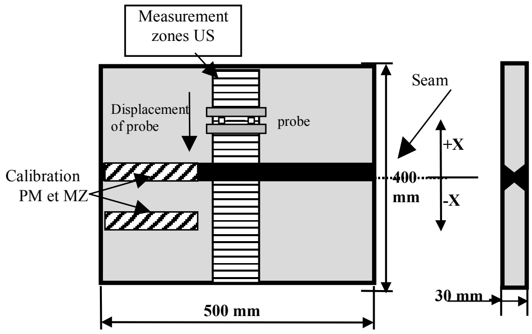

Figure 1 : welded plates, probe

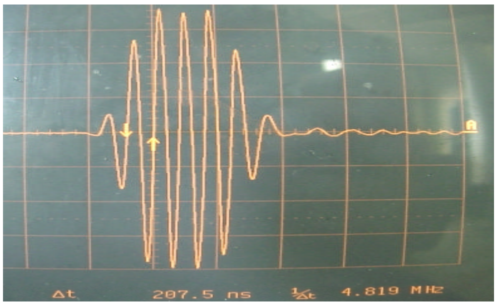

Figure 2 : longitudinal wave Lcr

3.1 *The Lcr Ultrasonic technique for stress measurement*

As research on the non-destructive measurement of stress has evolved over the years, it has become clear that the critically refracted longitudinal (L_{cr}) wave technique offers some distinct advantages over other methods. The L_{cr} wave may be generated with critically refracted, angle beam transducer as shown in figure 1 for a PMMA (poly methyl methacrylate) and steel combination. Since the Lcr wave is a bulk wave which travels just below the surface of the material, it is sensitive to a stress field in a finite thickness and not just at the surface. Additionally, stress gradients may be measured since the depth of penetration may vary with the choice of the excitation frequencies[BRAY00]. Also important is that in comparison with the shear wave, the Lcr wave is more sensitive to stress and, yet, it is less sensitive to material texture.

The relationship of measured Lcr wave travel-time change and the corresponding uniaxial stress is given by EGLE and BRAY [EGLE76]:

$$\Delta\sigma = \frac{E}{K_{11} t_0}\left(t - t_0 - \Delta t_T\right) \quad (10)$$

where $\Delta\sigma$ is change in stress, E is Young's modulus, K_{11} is the acoustoelastic constant for longitudinal waves propagating in the direction of the applied stress field and Δt_T is travel- time effect of the temperature difference at time of measurement from a standard temperature.

3.2. *Determination of acoustoelastic coefficient in Parent Metal and Melted Zone*

To use the ultrasonic method, it is necessary to determine the acoustoelastic constants of the material. These constants are obtained by a tensile test.

The welding operation is characterized by a great and localized heat flux on the welded plate. It appears that, if we consider the weld from the fusion line to the parent-metal, we meet typical microstructures which nature depends on the maximum temperature reached. We may identify from the parent metal to the weld axis, a microstructure evolution from a ferrito-perlitic structure, in parent metal, to a bainitic microstructure, respectively, in the heat affected zone(HAZ) and the melted zone[WALA02].

So, in the case of welding, it is necessary to determine the constant K (figure 3) in the parent metal (PM) and the melted zone (MZ), the double calibration is due to the dependence of the acoustoelastic constants and the microstructure of material.

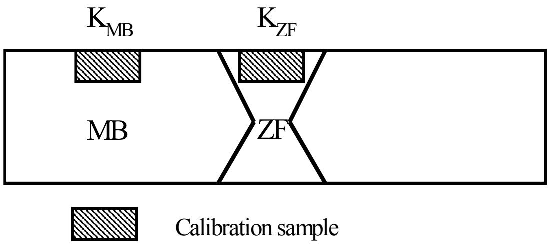

Figure 3 : samples in parent metal and melted zone (P460 HLE steel) to determine the acoustoelastic constant

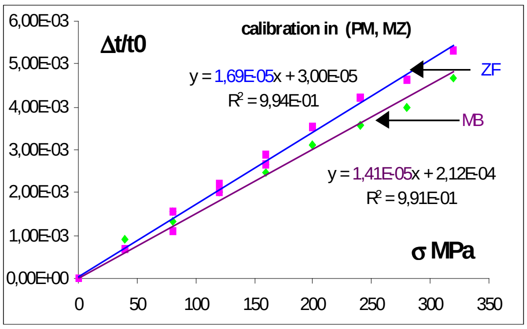

Figure 4 : Tensile test to determine the acoustoelastic constant in parent metal and melted zone (P460 HLE steel)

There is an effect due to the microstructure since we obtain two distinct values for acoustoelastic constants.

K_{11PM} (MPa)$^{-1}$	K_{11MZ} (Mpa)$^{-1}$
$1.41\ .10^{-05}$	$1.69\ .10^{-05}$

4. Experimental results and discussions

The probe used to measure the travel-time of the Lcr waves has one transmitting transducer(T) and one receiving transducer (R) Figure 1. Two probe sets were manufactured, one on each for exciting 2 MHz and 5 MHz waves, respectively.

Results of longitudinal residual stresses versus distance from the weld centreline for the welded plates (P460 and P265), before and after correction of microstructure effect (acoustoelastic constant and velocity V_0 in unstressed material), are shown in figs, 5 and 6. Data were obtained from both sides of the welded plates.

The first result relates to a sheet thickness 30 mm welded with a chamfer in X made out of P460 HLE steel. Measurements were carried out 4 times in order to ensure its reproducibility of the results. As we specified before, it proves to be necessary to use different acoustoelastic constants for the two zones, this in order not to over-estimate the level of constraint in the molten zone. This method involves a reduction in the value of the stress of about (70 to 150 MPa) in the molten zone, respectively for P460 and P265 plates.

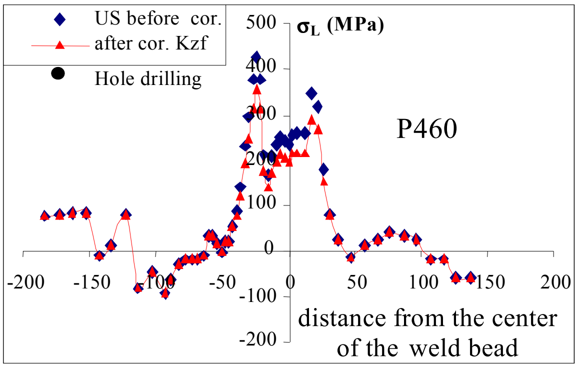

Figure 5 : Longitudinal residual stress in welded plates before and after correction, validation with the hole drilling method (P460).

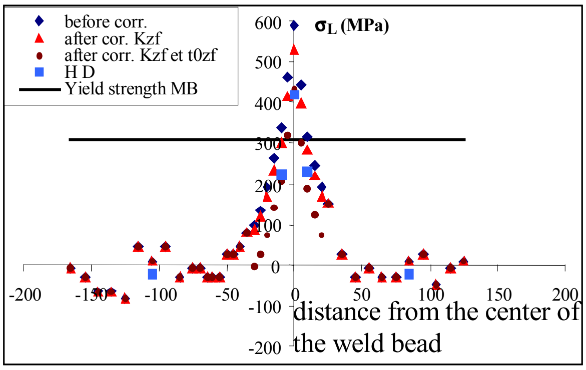

Figure 6 : Longitudinal residual stress in welded plates before and after correction, validation with the hole drilling method (P265).

CONCLUSION

This paper shows the possibility of evaluating the residual stresses induced by welding using the ultrasonic method. The hole-drilling technique was used to verify the results obtained by the Lcr waves technique. When the microstructure of material evolves, the propagation velocity of the waves also undergoes variations which come to cumulate with those induced by the presence of the stresses. To obtain a correct evaluation of the welding stresses, it is necessary to take into account these various effects. The levels of stresses found in the melted zone remain higher than the elastic limit of the base metal. However, it is necessary to take into account the elastic limit of the melted zone which is more important than that of the base metal. Our step will be validated soon on other cases, such as for example welded curved surfaces. Comparative measurements of stresses will be taken soon on various sheets tested by the method of diffraction of x-rays and by the method of the hole. They are well in this case comparative measurements because the various methods do not integrate the same depth of investigation.

References

[MURN51] T. D. Murnaghan, Finite Deformation of an elastic solid, John Wiley, New York (1951)

[HUGH53] D. S. Hughes and J. L. Kelly, Second-order elastic deformation of solids, Phys. Rev, 92, 5, (1953), pp 1145-1149

[EGLE76] D. M. Egle and D. E. Bray, Measurement of acoustoelastic and third-order elastic constants for rail steels, J.A.S.A, 60, 3, (1976), pp 741-744

[WALA02] H.Walaszek, H.P. Lieurade, C. Peyrac, J.Hoblos, J. Rivenez, Potentialities of ultrasonics for evaluating residual stresses : Influence of microstructure, Journal of Pressure Vessel Technology, Vol. 124, August 2002, pp349-353

[BRAY00] D. E. Bray, Current directions of Ultrasonic Stress Measurement Techniques, 15th WCNDT, Rome, 2000, http://www.ndt.net/article/wcndt00/papers/idn647/idn647.htm

[GREE73] R.E. Green Jr., Ultrasonic Investigation of Mechanical Properties, Treatise on Materials Science and Technology, H. Herman (ed.), Academic Press, New York and London (1973) Vol. 3, 73-126.