Ultrasonic Stress Measurement: Application to Welded Joints

H. WALASZEK, J. HOBLOS, P. BOUTEILLE, CETIM, Senlis, France
G. BOURSE, C. ROBIN, Ecole des Mines de Douai, France

Abstract: When a material is under mechanical load, the stresses modify the velocity of acoustic waves. This consists in acoustoelastic effect. This property can be exploited for stress measurement in the material itself when the stress concerns the surface of the material, or in the bulk material, as in bolts.
Residual stress measurement. In the welding case, ultrasonic velocity varies not only by the acoustoelastic effect, but also in a smaller part with the microstructure variations produced in melted zone and heat affected zone. This may lead to overestimation of stress level. The work performed gives an answer to this measurement restriction. To achieve this aim, the velocity was measured on unstressed samples extracted from the different zones of the weld. The experimental study performed on P460 HLE and P265 X welded sheets lead to the validation of the method. This is encouraging for the use of the method in some cases for stress measurement of pressure equipment. This study was lead in collaboration between Cetim and Ecole des mines de Douai.

1. Theoretical Basis of Ultrasonic Stress Measurement

The ultrasonic method of stress measurement is based on the application of the theoretical results developed in the articles [1] and [2]. The elastic waves which are propagated in isotropic solids are characterized by their propagation velocity in material (Fig. 1). The velocity variation versus stress is given for the waves of compression (longitudinal) and transverse (shear) modes by linear equations. The following expression gives the velocity dependence for the longitudinal mode:

$$(1)\quad \frac{dV_{11}}{V_{11}} = A_{11}\, d\varepsilon = \frac{A_{11}}{E} d\sigma \;\; with \;\; \varepsilon = \frac{\sigma}{E}$$

Where A_{11},ε, E and σ are respectively acoustoelastic constant corresponding to the longitudinal mode, deformation, Young modulus and stress or constraint.
Thus, according to (1), the relative velocity variation is proportional to the constraint. The constant of proportionality is a coefficient which depends on considered material and its metallurgical state.

This dependence is described by quasi-linear curves having different slopes (Fig. 1), according to propagating modes, as described by Egle and Bray [3].

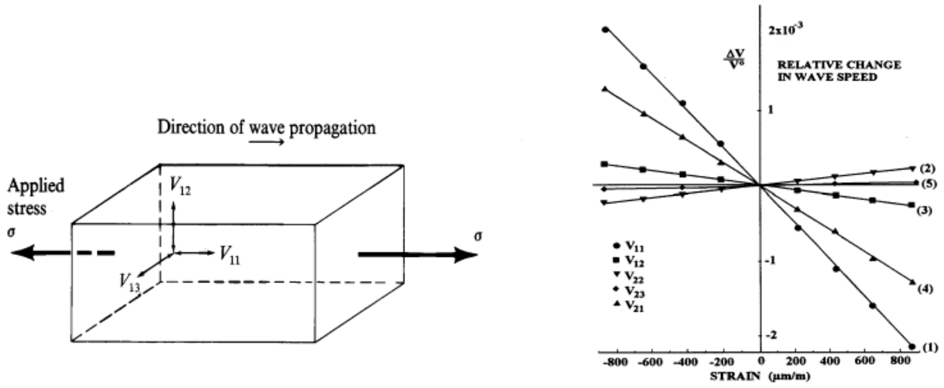

Fig 1: Propagation of acoustic waves in a solid against various modes and sensitivity of ultrasonic velocity versus stress, according to the propagating mode considered

Some laboratory trials and studies show the interest of ultrasonic technique for measuring the residual stresses [1] [2] [3] [5] [6] [7] [8]. We now will describe the application of the acoustoelastic effect on the determination of the stresses in the welded joints.

2. THE ULTRASONIC CONTROL OF RESIDUAL STRESSES

2.1 The need

The fatigue performance of the machine components is much related to their level of residual stress induced by the undergone treatments. Various techniques exist to measure these stresses, such as the diffraction of the x-rays, and the extensometric method of the hole. In addition, of the non-destructive methods can be applied to determine the constraints, such as the ultrasonic method and the ferromagnetic noise. The Barkhausen method applies to the ferromagnetic products and is the other publication object of CETIM. This article deals with ultrasonic method, which presents the potentiality of realization of fast measurements on site. The ultrasonic method described below is based on the exploitation of the wave of crawling compressions (longitudinal wave refracted with the first critical angle). This technique was described by many authors [4] [5] [6] [7]. Former publications [5] described a method which takes into account the effect of the microstructure, through the application of coefficients of corrections to the measurements carried out in the melted zone and the heat affected zone. These coefficients had been appreciated in experiments thanks to measurements on test-parts extracted the melted zone. In this article, we describe the realization of measurement with a methodology of correction of the effect of the microstructure, evolution of that which presented by us before (5). Thanks to developed methodology, we could successfully apply the method by correcting measurements of the effect of the microstructure.

2.2 Description of the component of test welds and calibration of measurement.

- The test parts consist in two welded sheets of following characteristics:
- All Rolled Sheet • Thickness 30 mm
- Sheet Nr1• steel P460 grade (high yield stress) manual welding with X chamfer
- Sheet Nr2 steel P265 grade automatic welding with X chamfer

Figure 2 presents the diagram of the parts of test and the sites of test sample selection of calibration.

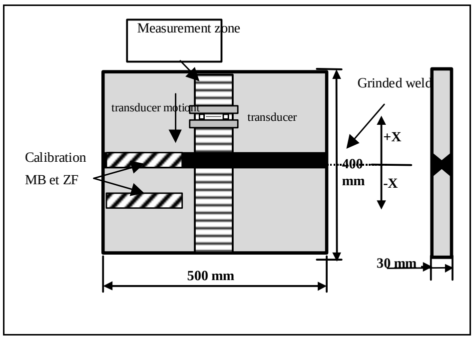

Fig 2: Welded sheets, positioning of the ultrasonic sensors and representation of the zones of test sample selection of calibration MB=base metal ZF = melted zone

2.2.1 The LCR technique for ultrasonic measurement of stress

The ultrasonic waves refracted longitudinally (LCR) sometimes called creeping waves, have various advantages, further clarified, compared to the other types of wave.
Wave LCR is generated with the critical angle, as indicated on the acoustic general diagram presented of figure 3.

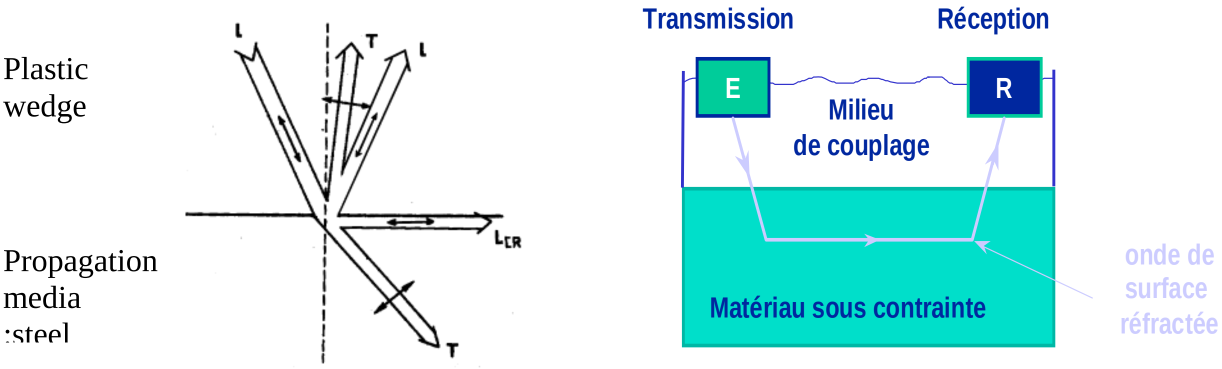

Fig 3: Generation of a LCR (longitudinal wave refracted with the critical angle) and general diagram of the ultrasonic sensor

In our case, we used as prism of refraction a shoe of the Plexiglas type. Wave LCR is propagated by shaving the surface of sheet material, on a thickness of a few millimetres. It will thus be influenced by the constraints sitting in this zone. This wave is more sensitive to the constraint than the other waves, and in particular the wave of Rayleigh. It is also less sensitive than the latter to the microstructure. However, although this influence of the microstructure is weaker than the other waves, it cannot be neglected for measurements. Thus, the influence of the microstructure will be taken into account thanks to the calibration.
The relation binding the variation of constraint according to the acoustic travel times is given by

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

With	$\Delta\sigma$	Stress variation
	E	Young's modulus
	A_{11}	Coefficient acoustoelastic for a wave which is propagated in the same direction as the constant applied

Et, Δt_T Influence variation in temperature to the measures of time

2.2.2 Knowledge of coefficient acoustoelastic in the base metal and the melted zone

The knowledge of the coefficients acoustoelastic of material is necessary to apply the ultrasonic measurement of constraint. These constants are obtained thanks to measurements of ultrasonic travel times carried out on a test-part installed on a tensile testing machine (figure 4).

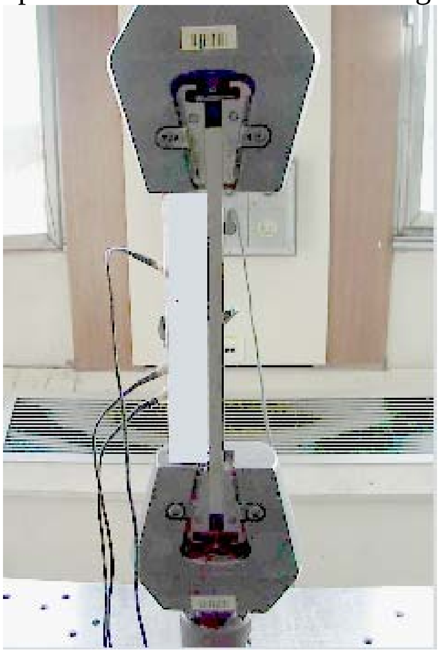

Fig. 4: Tensile test on test-tube taken in the base metal or the melted zone

The operation of welding is accompanied by an important heat flux localised in the welded zone. If one examines the welding while going from the base metal towards the line of fusion, one meets typical microstructures, function of the maximum of temperature reached. One distinguishes, of the base metal to the axis of the welding, a ferrito-perlitic evolution of structure (base metal) to a bainitic microstructure, in the ZAT and the melted zone [5] [6], as described of figure 5. These structures thus present different coefficients acoustoelastic [6]. In the case of welding, one determines the constant:

$$\kappa_{11} = \frac{A_{11}}{E}$$

in the base metal and the melted zone.

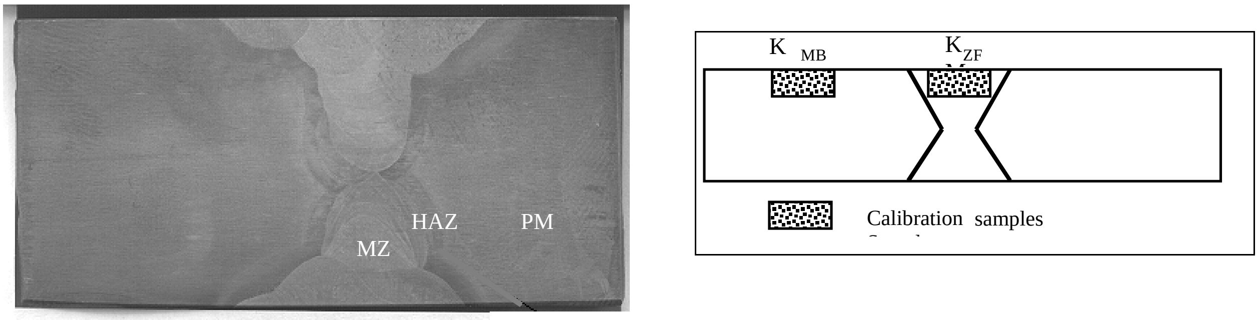

Fig. 5: Zones of extraction of the tensile specimens used for the determination of the coefficients acoustoelastic in the base metal and the melted zone

Table 1 gives the acoustoelastic values of the coefficients in two zones of different microstructure, namely the base metal (MB) and the melted zone (ZF). This constant represents the slope of the curve of the relative variation speed according to the constraint (figure 6). The following paragraph describes how one determines the origin of the curve which is also influenced by the microstructure.

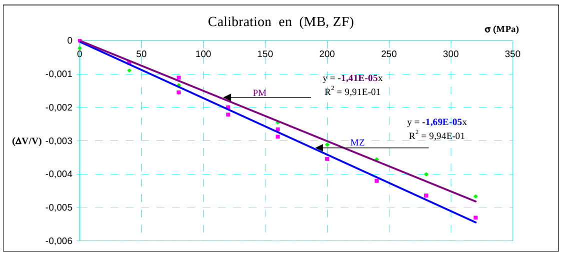

Fig.6: Curve of relative variation speed according to the constraint in the base metal (MB) and the melted zone (ZF)

	K_{11PM} (MPa^{-1})	K_{11MZ} (MPa^{-1})
P460 HLE	$-1.41\ .10^{-05}$	$-1.69\ .10^{-05}$
P265	$-1.33\ .10^{-05}$	$-1.48\ .10^{-05}$

Table (1): Acoustoelastic determination of the coefficients

2.3 Determination of ultrasonic propagation velocities on stressless test-part and machining of the test-parts of reference

We will determine here the propagation velocity ultrasonic on not forced test-parts, extracted the base metal and melted zone. The operation consists in fact to measure, for a distance known, the ultrasonic travel time on these two test-parts, beforehand relaxation. To measure the ultrasonic travel time, one uses ultrasonic transducers with normal wave of compression, who insonificate the side of the test-parts Fig.(7). Indeed, the nature of the wave refracted on surface (LCR) is the same one as that of the wave of volume that is propagated. The travel time of the echoe is measured, on approximately a 24 mm thickness, which represents the order of length traversed by the ultrasounds when we use LCR transducers. The curve representing the variation of the propagation velocity (or the reverse of the ultrasonic travel time) is given in Fig.(7) for the base metal and the melted zone.

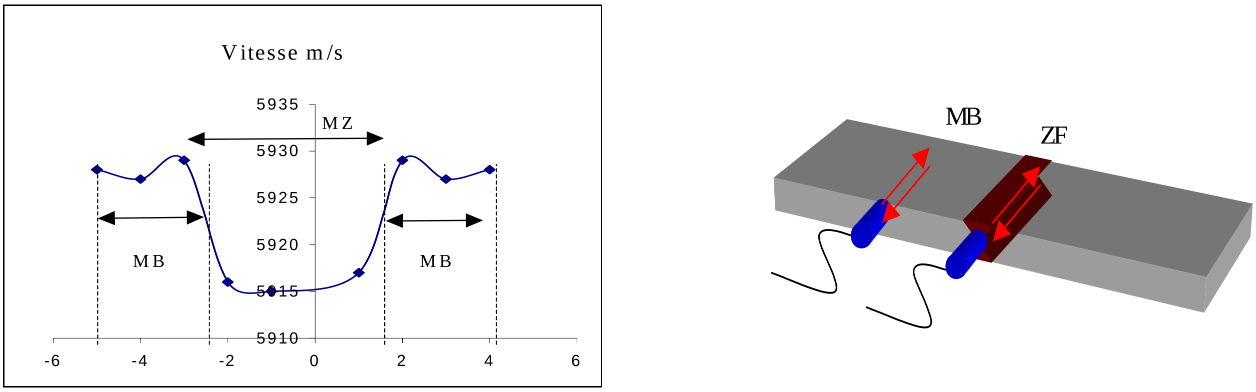

Fig. 7: Velocity measurement of longitudinal wave propagation on test-parts after stress-relief (sheet welded out of P460 steel)

	V_{0MB} (m/s)	V_{0ZF} (m/s)	V_{0ZF} / V_{0MB}
P460 HLE	5928.5	5916	0.9979
P265	5932	5923	0.9984

Table 2: Determination of the propagation velocity in the no constrained case in two zones MB and ZF, for a longitudinal wave of volume in normal incidence

The values of constraint will be calculated by using the acoustoelastic constraints and the corrections of error of travel time at adequate rest, according to the zones of measurement, at a constant temperature.

$$\sigma_{MB} == -\frac{1}{K_{MB}} * \frac{(t - t_{0MB})}{t_{0MB}}$$

and

$$\sigma_{ZF} == -\frac{1}{K_{ZF}} * \frac{(t - t_{0ZF})}{t_{0ZF}}$$

2.4 Experimental result and discussion

The ultrasonic transducer used to measure the time of course of wave LCR works in transmission mode, as shown of figure 3. In fact, measurement is carried out in differential mode between two receivers, which decreases the influence of the coupling. One records measurements of time by moving the translator on both sides axis of the welding, with the axis of propagation ultrasonic wave parallel with this axis. One deduces the values from them from constraint, before and after correction of the effect of the microstructure, as explained previously. The profiles obtained are given in figure 8 (P460 steel) and figure 9 (P265). The results obtained were cross with the measurements obtained by the method of the hole.

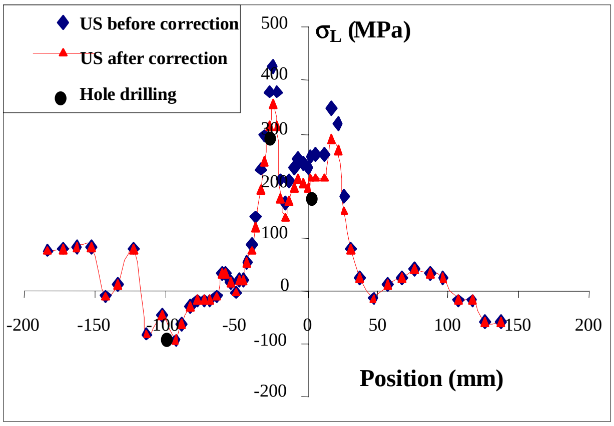

Figure 8: longitudinal constraint in sheets welded before and after correction of the microstructure - validation by the method of the hole (P460 steel)

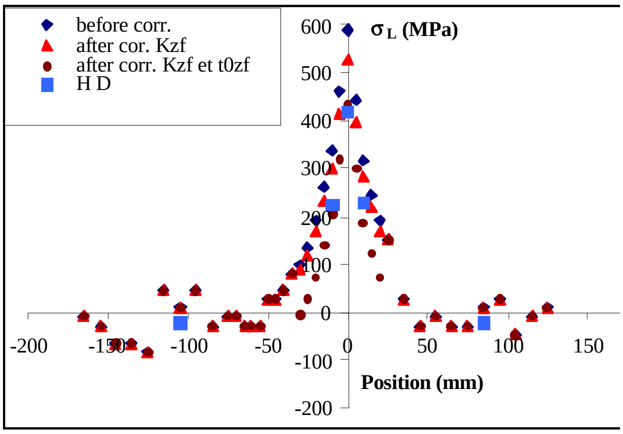

Figure 9: longitudinal constraint in sheets welded before and after correction of the microstructure - validation by the method of the incremental hole (P265 steel)

The results presented in figures 8 and 9 were obtained on sheets thickness 30 mm welded in X and nuance P460 HLE and P265. Measurements were reproduced 4 times to check their reproducibility. The correction of microstructure brought by the developed method is, for the melted zone, of 70 MPa for the P460 nuance and of 150 MPa for the P265 nuance.

3. Conclusion

Ultrasound enables the knowledge of surface stresses as on welded joints, provided the part to be inspected is compatible with ultrasonic coupling.

Work presented shows the possibility of evaluating the welding stresses by ultrasonic method. The method of the hole made it possible to check the results obtained. We thus have a methodology of reduction of the effect of the microstructure to the ultrasonic measure. Moreover, the speed of measurement enables us to carry out cartography with many points of measurement. An axis of important progress is the adaptation of measurement on curved surface.

Progress already observed constitutes a step moreover towards future industrialization of the method.

Current studies are lead by Cetim on ultrasonic stress measurement to improve these methodologies and develop industrial application.

4. References

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