RESIDUAL STRESS EVALUTION ON INDUSTRIAL HEAVY PLATES BY ACOUSTICAL BIREFRINGENCE

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Abstract: The manufacturing process of heavy steel plates generates some internal residual stresses. During machining process at the end users, shape defects may be created by these residual stresses. An industrial characterization method of residual stress state in heavy steel plates with a thickness of several hundreds of millimetres is described here. The measurement principle by acoustical birefringence and the used experimental equipment are presented.
The first tests were performed on standard plates representative of the various possible residual stress states. The analysis of ultrasonic signals allowed the definition of the most suitable measurement configuration and the attainment of satisfactory accuracy. Assessments of the acoustical birefringence coefficient across plate width permits to estimate residual stress profile of these plates and to identify heavy plates where the geometric stability during the machining process will be insufficient. The method is then validated on the heavy industrial plates at different manufacturing steps.

Introduction: The manufacturing process of heavy steel plates generates some internal residual stresses. These stresses are modified at every manufacturing step, for example during hot rolling or during cooling. At the final manufacturing step, heavy plates present residual stress profiles in the main directions. Further manufacturing operations at the end user's plant, as machining or splitting or cutting operations, will produce a relaxation of these stresses. A new stress balance will then established. If the residual stress profiles are not homogeneous, the new stress balance will be accompanied by geometric deformations of plates such as camber defect or flatness defect during manufacturing operations. After that, such shape defects are not acceptable to the end user. Therefore, one of the main quality criteria of heavy plates is to present a good geometric stability.
If we consider the longitudinal splitting operation, three possible plate deformations can be observed (fig. 1). These three mechanical behaviours depend on residual stress profile across the plate width. The notch width is constant for a naught stress profile. For an arbitrary profile, the notch width fluctuates during the splitting and the two plate pieces have a camber defect. It is also possible for the plate to burst before the cutting end.

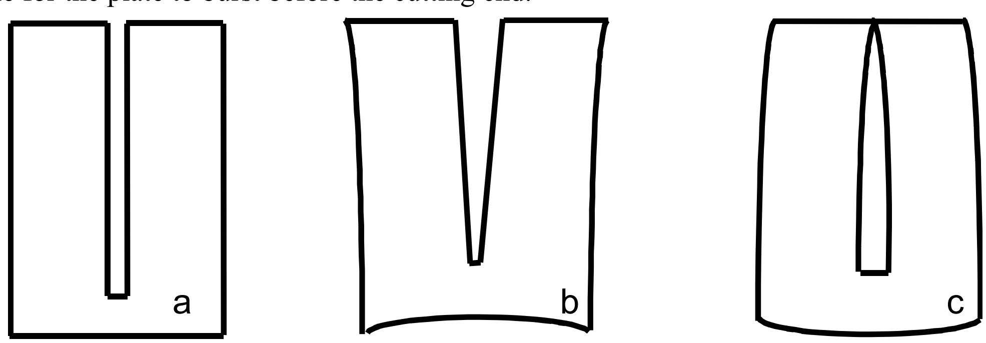

Fig. 1 - Different observable behaviours of heavy industrial plates during longitudinal splitting operation: a) the notch is linear without plate deformation, b) the notch opens up, c) the notch closes itself.

The aim of the study was to develop an industrial method to assess stress profiles on isotropic heavy plates with a thickness of several hundreds of millimeters (100 to 300 mm). In this paper, we will describe the method used for measurements and we will discuss its adequacy to respond to industrial needs.

Experiment: Considering these properties, the most suitable non-destructive technique to evaluate these profiles is the acoustical birefringence method.

Principle of the stress analysis:

The principle of this ultrasonic method of residual stress analysis is relatively simple. It is based on a measurement of the propagating velocities of different ultrasonic waves. Hughes and Kelly proposed the basis of this principle in 1953 [1]. They theoretically and experimentally examined the influence of a tensile stress on ultrasonic wave propagating velocities. This work was then extended to different ultrasonic waves and non-isotropic materials [2]. The first applications of the acoustical birefringence were made in the 1970's [3].

Acoustical birefringence method requires measurements of velocities of orthogonally polarised shear waves propagating through the material thickness [4,5]. The normalised difference between transverse sound velocities is the acoustic birefringence coefficient B.

$$B = (V_1 - V_2)\ V_{ave}$$

where V_1 and V_2 are the velocities of shear waves along a given path, with V_1 polarised at 90 degrees to V_2, and V_1 being the larger velocity. V_{ave} is the average velocity.

It is often easier to measure acoustical birefringence than velocity if it is possible to propagate both polarisation waves along the same path. This is the case for a sample with parallel faces such as a plate. Then measuring the ultrasonic waves' times of flight and their difference readily provides the coefficient of birefringence, independent of part thickness. The difference between minimum and maximum velocities is usually less than 1 percent; independence from part thickness is very advantageous [5].

$$B = 2\ (t_2 - t_1) / (t_2 + t_1)$$

where t_1 and t_2 are the times of flight relative to both velocities of shear waves.

If the measurements are performed on the principal directions of the material, it is easy to link the birefringence coefficient to principal stresses in the case of isotropic materials [6,7]. The birefringence coefficient then depends linearly on principal stress through the intermediary of Murnaghan's constants.

The residual stresses evaluated by this method reflect the average stress level in the thickness of the material.

Experimental stress analysis:

The measurements were performed with a KarlDeutsch device used in broadband mode (fig. 2). It was connected to a piezoelectric emitter - receiver transducer whose reference is Panametrics VM154. Its frequency was 2.25 MHz and it allowed to generate some transverse waves to normal impact (fig. 2). Ultrasonic signals are digital to the frequency of 400 MHz and stored on a PC.

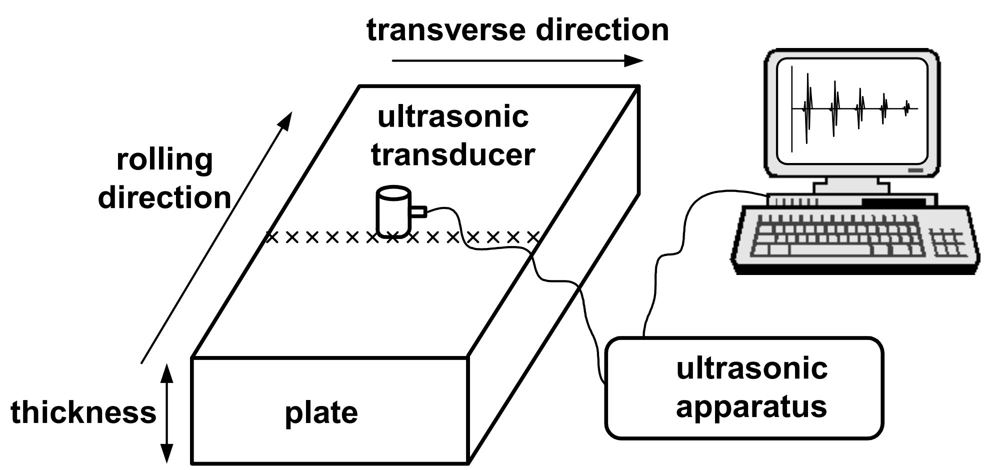

Fig. 2 - Schematic diagram of experimental apparatus used for birefringence coefficient determination. Crosses indicate the different measurement locations on heavy plates.

The acoustical birefringence coefficient is determined from the analysis of two shear waves propagating through the thickness of the product, respectively polarised along and perpendicular to the rolling direction. This determination requires an accurate measurement of the wave's time of flight. This measurement is made between two back wall echoes according to the following methodology:

- The birefringence coefficient measurement is achieved while positioning the wave polarisation successively at 0° and 90° in relation to the principal directions.
- The position of the n^{th} back wall echo is determined on the first negative alternation of significant signal amplitude. A fourth degree polynomial is adjusted to the least linear square sense on the digital points of this negative alternation (fig. 3). The minimum of polynomial t_n is calculated from the polynomial expression. This minimum is assimilated to the position of the back wall echo.
- The determined time of flight between the n^{th} and the m^{th} back wall echo is given by next equation. The incertitude of time of flight is therefore linked to the incertitude on the position t_n calculation. This incertitude is relatively constant; it depends very little on the back wall echo choice, but it is related to the digitalisation frequency.

$$t_1 = t_{m1} - t_{n1}$$

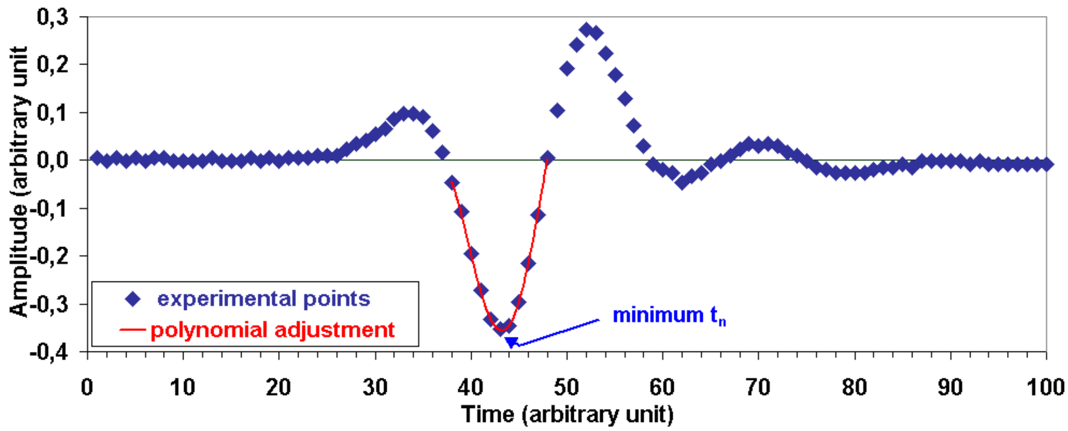

Fig. 3 - Determination of the back wall echo position by adjustment of a 4^{th} degree polynomial on the first negative alternation of back wall echo and calculation of polynomial minimum t_n.

Repeatability measurements were carried out on 50 mm thick plates. The standard deviation on the birefringence coefficient decreases by $0.1 \cdot 10^{-4}$ when waves cover a distance, which is twice the thickness of plate. It is therefore preferable to use two back wall echoes, which are clearly separated. The first and the fourth back wall echo are generally used. In these conditions the measurement accuracy is about $0.6 \cdot 10^{-4}$ and it is compatible with industrial needs. These results validate the choice of the method used to evaluate the residual stress in heavy plates.
This approach allows to determine the birefringence coefficient at one point of the plate, as indicated by a cross on figure 1. The birefringence coefficient was calculated at different points on the plate width in order to get the transverse evolution of the coefficient: the transverse profile. This evolution is characteristic of the present residual stress state in heavy plates. It provides an evaluation of the residual stress gradient across the width and averaged over the thickness of sample.

Results: Three standard heavy plates of 1000 mm long, 450 mm wide and 50 mm thick were used to validate the method. Particular cooling conditions were applied to these standard plates to describe the three configurations likely to be observed during an industrial splitting (fig. 1). These different behaviours are directly linked to residual stress gradients.
The birefringence coefficient was evaluated at half-length in the width of standard plates every 25 mm as described in figure 2. Evolutions of the birefringence coefficient are different for the three standard plates (fig. 4). Values obtained for plate (a) are small and relatively constant in the

width. This evolution indicates that the residual stress level is small and homogeneous. This plate warps very little or not at all during the longitudinal splitting (fig. 1a).

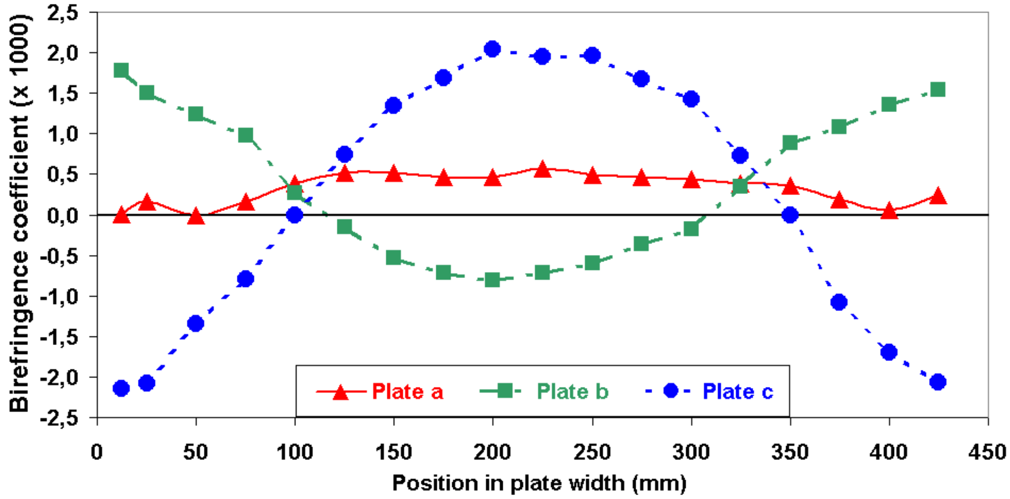

Fig. 4 - Different birefringence coefficient evolutions across the width of the three standard heavy plates, reflecting different residual stress states.

Birefringence coefficient values vary strongly across the width for the two other standard plates (fig. 4). These evolutions reveal the occurrence of a residual stress gradient. Standard plates are therefore going to warp during the splitting. The reversed evolutions between the two curves indicate a reversed stress distribution, which leads to an opposed mechanical behaviour during the splitting. The notch will open up for plate (b) (fig. 1b). It will shut for plate (c) (fig. 1c). The mechanical behaviour of these three standard heavy plates was confirmed during the cut operations of the twin plates, which were obtained at the same time under the same manufacturing conditions.

The birefringence coefficient sign seems to correspond to the macroscopic residual stress sign. A positive coefficient would correspond to tensile stress and a negative coefficient would correspond to compressive stress.

Discussion: The previous approach was applied to heavy industrial plates. Three heavy plates were controlled. These plate measurements were very large: the length varied between 3.5 to 3.7 m, the width varied between 1.5 to 1.8 m and the thickness was about 180 mm. The birefringence coefficient was calculated in the plate width every 50 mm at the edges and every 200 mm at the centre.

The first measurement series was made after a standardisation treatment. Birefringence coefficient evolutions across the width are identical for the three heavy plates (fig. 5). They are relatively regular. A decrease in the area of the edges over a distance of 400 mm can be observed: coefficient values range from $15 \cdot 10^{-4}$ to $-5 \cdot 10^{-4}$. The central part is constant and its value is $-5 \cdot 10^{-4}$ on average. These evolutions are close to the one obtained for standard plate (b).

These three plates have a heterogeneous residual stress state across the width. The stress level increases at the edges (tensile stress). It is smaller in the middle but its sign is opposite (compressive stress). The longitudinal splitting operations of these plates should lead to an opening of the notch under these conditions.

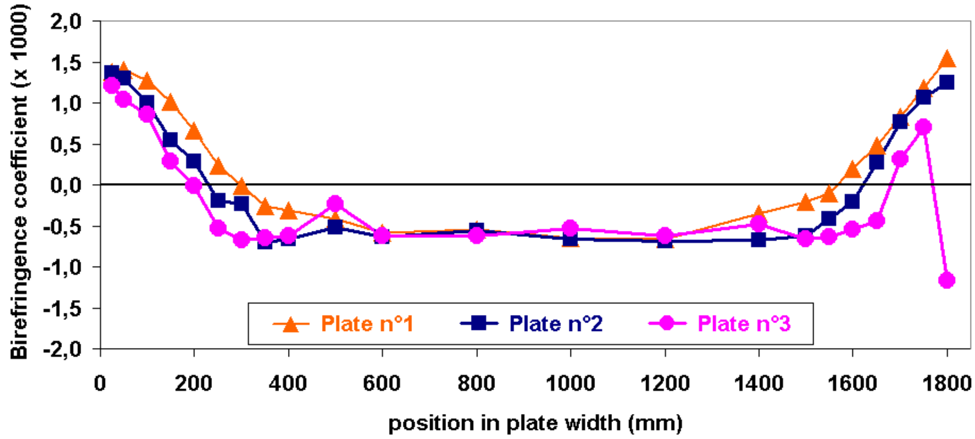

Fig. 5 - Birefringence coefficient evolutions measured across the width of three heavy industrial plates after a standardisation treatment. It displays a residual stress state across the width.

These plates did not conform to customers' specifications because of stress profile occurrence. A stress relieving heat treatment was then applied to minimise these stresses. After this treatment a second measurement series was made at the same points. Birefringence coefficient values obtained in the width are relatively constant and near to zero (fig. 6). They indicate that the stress profile is homogeneous across the plate width and that the stress level is nearly non-existent. The stress relieving heat treatment allowed the minimisation of the residual stresses. Measurements carried out at other locations of these heavy plates confirm the absence of residual stress. Therefore heavy industrial plates satisfy end users needs.

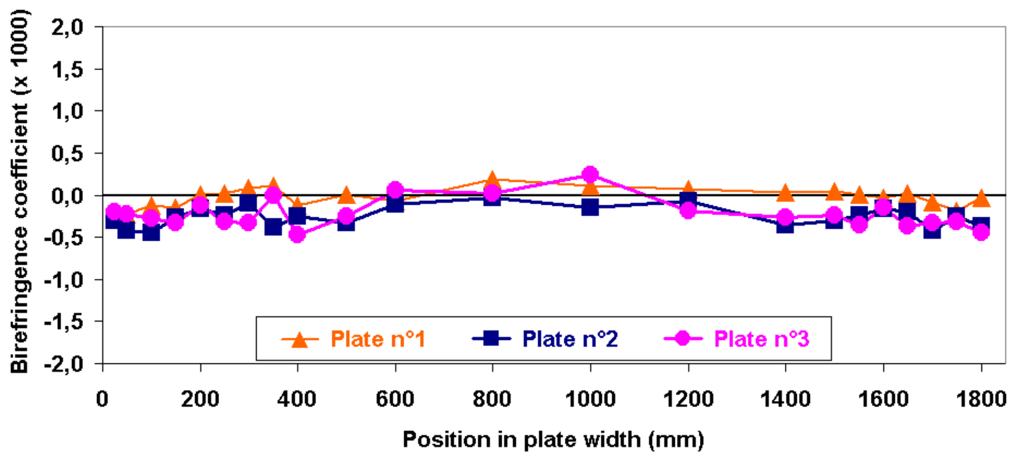

Fig. 6 - Birefringence coefficient evolutions measured across the width of same three heavy industrial plates, after a stress relieving heat treatment that minimised the residual stress gradients across the width.

Other heavy industrial plates were successfully controlled at different manufacturing steps. These results show that the developed method permits to evaluate the residual stress state of heavy plates whatever their thickness. This method will also permit the delivery of plates with regard to low residual stress levels to avoid any risk of plate distortion during the machining and cutting operations of the end user.

Conclusions: The method proposed to evaluate the residual stress state of heavy plates perfectly answers the industrial problem that was posed. It makes it is possible to check the low stress level in heavy plates that meet the end users requirements. This method is also reliable, robust and very easy to use. It was developed with a manual application (use of piezoelectric transducers), but its automation would not present any difficulty with the use of electro-magneto-acoustic transducers. Tests performed with such a transducer yield results that are identical to those obtained with piezoelectric transducers. This technique has been perfected and it provides a powerful control tool of heavy plates. It offers an opportunity to further improve the plate making process and to guarantee even better product quality.

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