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Railway Rail Residual Stress Evaluation by Acoustic Birefringence Technique

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Abstract

Flash butt welding and aluminothermic are the most of the worldwide heavy haul railway steel coupling. Both produces microstructural and residual stress variations that can increase the weld failure chance when the rail chance is under service conditions. Regarding the analysis of residual stresses, many works available in the literature are about superficial or sub-superficial stresses. Nonetheless, this work sought to do an experimental study of residual stresses analysis in rails, by using a non-destructive technique based on the acoustoelastic and birefringence effect of the material. The measured residual stress is like works using others techniques, about 150 MPa tensile stress. Was found out that there is not any detectable influence in the residual stress by the surface cooling or by the welding.
Keywords: nondestructive evaluation, birefringence, residual stress, heavy-haul rail, ultrasonic, acoustoelastic effect.

1 Introduction

Since the manufacturing process, the rail is tested to verify its microstructural aspects, mechanical behavior, and residual stresses. The latter may increase the crack and fail as a function of its nature and magnitude, decreasing the rail life cycle.

Nowadays, rail welding occurs by two main processes, the aluminothermic and the flash butt welding (FBW). FBW is highly used due to automation, good welding quality, and a stable welding process. Its process parameters affect the rail mechanical performance, heat affected zone (HAZ) width, hardness, and residual stresses. The literature shows that the rail residual stresses are tensile in the head and in the foot and compressive in the web [1] after the straightening. Nonetheless, after the welding, the residual stresses pattern near the coupling is inverted. The rail head and foot stresses became compressive and tensile in the web [2]. This can be beneficial as there is inhibition of the crack nucleation and propagation through fatigue.

The rail residual stress appears and changes over three manufacture stages, the first is the cooling after the rolling, the second is the straightening and the last is the welding. The residual stresses appear after welding because of heterogeneous energy application and localized melting, of phase transformation and the contraction and non-homogeneous plastic strains during cooling.

For this reason, the rail residual stress studies have great significance, because they imply a failure prediction and proactive maintenance. Many rail residual stress works discuss mainly about superficial or sub-superficial stresses by using blind hole [2], neutron and x-ray diffraction [3], or simulations [1, 2]. The residual stress measurement by acoustic birefringence is a non-destructive technique with low cost and easy-to-use, which the physical principle is based on acoustoelastic effect, that is the wave velocity change associated with stress in the metal [4]. Works like Schramm [5] and Hirao [6] show a high correlation between the ultrasonic wave velocity and stress in rail.

Thus, in this work, is evaluated the residual stresses by acoustic birefringence technique in railway FBW joints. To that end, two constants must be evaluated, the initial acoustic birefringence B_0, and the birefringence acoustoelastic constant C_A.

2 Methods

The equation that is used to measure the stress with ultrasonic is

$$B = B_0 + C_A(\sigma_1 - \sigma_2) \tag{1}$$

Here,

$$B = 2\frac{t_1 - t_2}{t_1 + t_2} \tag{2}$$

Where B the birefringence, B_0 the initial birefringence, measured in a stress-free material, C_A the acoustoelastic constant, t_1 and t_2 the time of flight of shear wave polarized parallel and perpendicular with rolling, and $\sigma_{1,2}$ the principal stresses.

2.1 Materials

Were made two groups of samples. The first, Figure 1, are for constant measurements (B_0 and C_A). These samples were machined with electrical discharge machining, to avoid increasing residual stress, with dimensions 27,3 x 7,4 x 250 mm^3, followed by heat treatment for stress relief with 450°C for 1 hour and cooling in furnace.

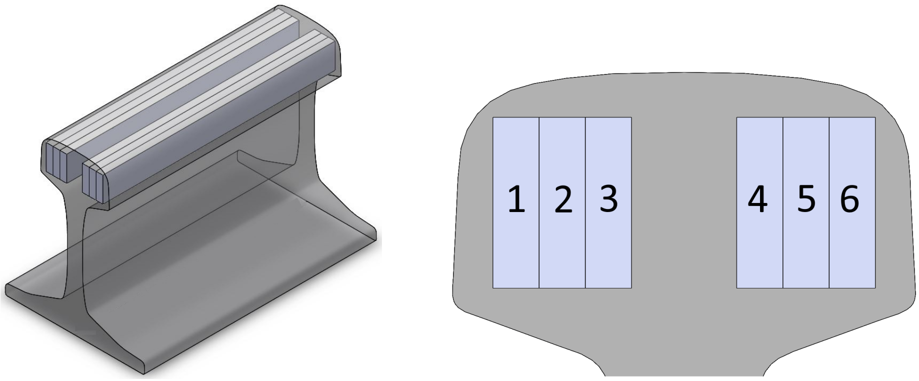

Figure 1: Rail head test specimens and numbering from 1 to 6.

The second are for stress measurements. All the rails have 2 meters long with the shape TR68, according to NBR 7590:2012 and were welded with FBW. The chemical composition is shown on table 1. This table shows the composition given by the manufacturer and measured in laboratory.

	TR1*	Sample TR1
C	0.80 - 0.85	0.80
Mn	0.50 - 0.60	0.55
Si	0.50 - 0.59	0.49
P (Max)	0.020	0.0122
S (Max)	0.005	0.0039
Cr	Add.	0.70
Ni	Add.	0.01

*Chemical composition from manufacturer.

Table 1: Rail material chemical composition.

2.2 Initial birefringence B_0 evaluation

The TOF of shear wave were measured at parallel and orthogonal to the rolling direction. The equation 2 is used to calculate the birefringence. The measurement points is shown in Figure 2.

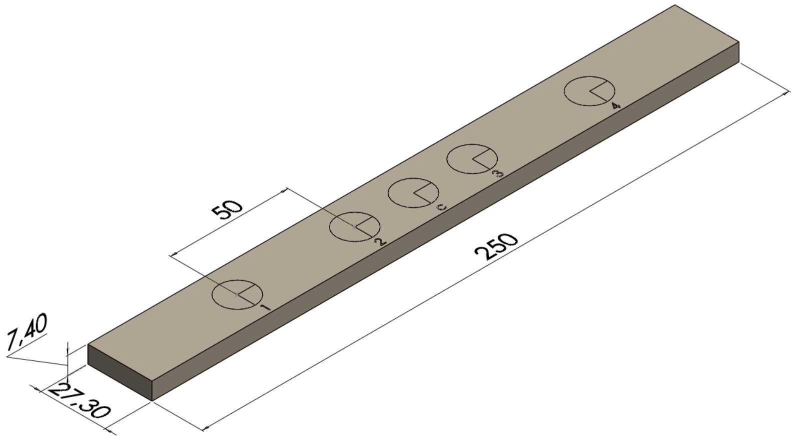

Figure 2: Measurement spots on the specimens.

2.3 Birefringence acoustoelastic constant C_A evaluation

The C_A evaluation is made through birefringence measurements while uniaxial stress over the sample increases. This creates a $birefringence$ x $stress$ linear relation, being the C_A it angular coefficient.

2.4 Residual stress evaluation

In total, 28 stress measurements were made in rail head of the second group of samples, outside the HAZ and welded region, 14 on each side of the weld, as shown on Figure 3.

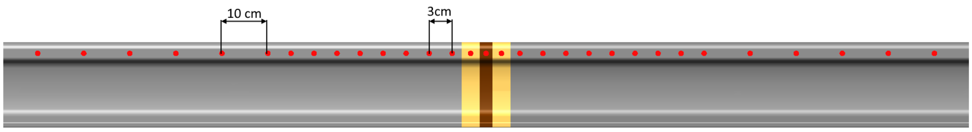

Figure 3: Stress measurements points in the second group of samples.

3 Results

3.1 Initial acoustic birefringence

In Figure 4, the mean TOF of each specimen is shown. It is possible to see that the wave has a preferential propagation direction because the TOF is lower in the **z** direction than the **y** direction, as the texture favors the propagation to the rolling direction. The birefringence was measured in each specimen, as the Figure 4 shows. The variation of these values is related to the variation of the texture throughout the rail, as Schramm [5] has already shown. Thus, the B_0 is the mean value of all measurements, that is $1,476 \times 10^{-3} \pm 2,75 \times 10^{-4}$, which was used as the reference to the stress evaluation.

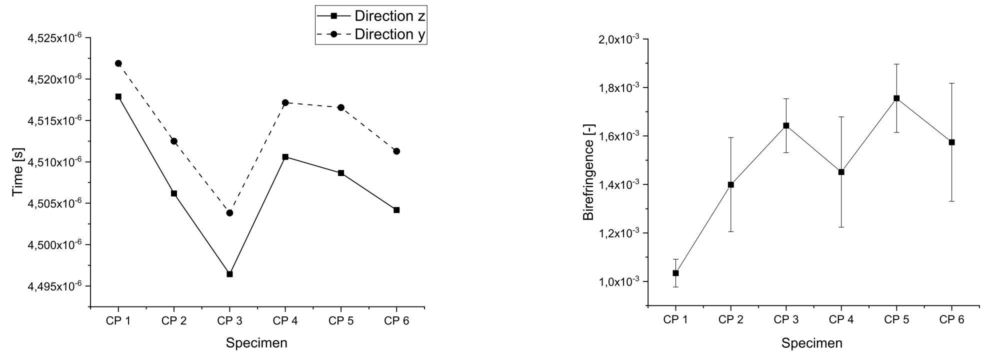
a)Mean TOF to each specimen. b)Mean birefringence to each specimen.

Figure 4: Data obtained from the first group of samples.

3.2 Birefringence acoustoelastic constant

The results is shown in Figure 5. The red line is the linear regression from the results. The result of C_A is $-7,96 \times 10^{-6} \pm 0,126 \times 10^{-6}$.

3.3 Residual stress

As seen in equation 1, the birefringence technique only measures the stress difference. Hence, the Figure 6 show the stress differences between **z** and **y** direction on the side of the head. The head measurements vary around 100 MPa and 200 MPa. It was not seen any big changes by the weld.

Through rail simulations made by Carvalho [1], and works like Tawfik's [2, 7], the vertical residual stresses in parent metal tend to be 0 when it is distant 50 mm or 75 mm from the weld. With that the results of measurements made by acoustic birefringence can be no longer a stress difference, but stress in the z direction. Many works show that, after the manufacturing process, the longitudinal stress has a "C" pattern throughout the **y** direction. In head, the stress varies between

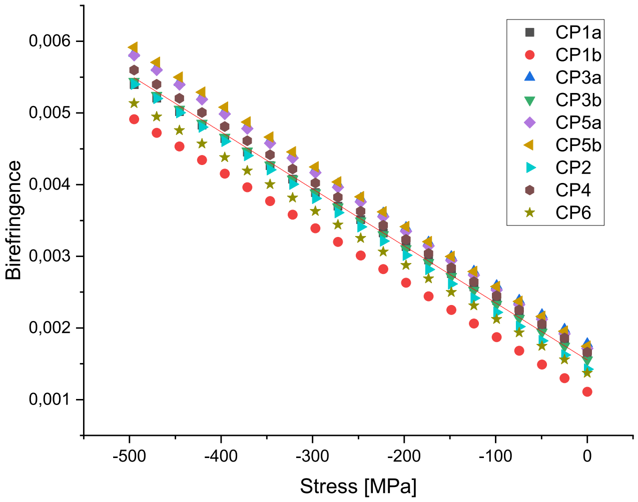

Figure 5: Birefringence in function of stress.

50 MPa and 200 MPa [1, 2, 7, 8]. This range includes what was obtained from the acoustic birefringence.

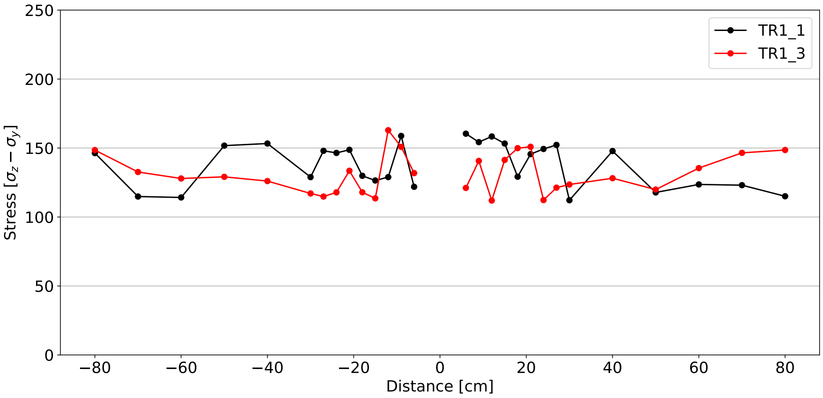

Figure 6: Rail head stress difference.

4 Conclusion & contribution

The shear wave ultrasound was used with acoustic birefringence technique to measure the residual stress distribution in heavy haul rail steel welded by FBW, concluding:

1. The standard deviation of both B_0 and C_A are less than 5% of the rail yield strength. Thus, the random variation of B_0 and C_A will not create a major error in residual stress measurements.

2. The residual stress measured by acoustic birefringence keeps the values around 100 MPa and 150 MPa in the head. Whereas the transversal stress is low, this value can be seen as the longitudinal stress, which is near the results from others methods.

3. This technique was not sensitive enough to measure the residual stress caused by the FBW.

4. The residual stress measurement by acoustic birefringence proved to be promising in rail head.

The continuous development of this work aims to predict future fails in railway rails just after the manufacturing, quality control when received and under service, measuring residual, thermal and load stresses. With the second conclusion, the theory is that any major variation may indicate a possible near future fail. Thus, monitoring the residual stress may prevent fails in the railway. This theory has to be proven in future works.

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