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Review

# Comparison of residual stresses on long rolled profiles measured by X-ray diffraction, ring core and the sectioning methods and simulated by FE method

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ABSTRACT

Sheet piles are produced by hot rolling, a cooling step and, if required, by a straightening operation. Numerical simulations indicate that the stress field is almost homogeneous through the thickness, justifying the comparison of X-ray diffraction, ring core and the sectioning methods applied after the cooling step and after the straightening process. The equipment, the steps of the experimental procedures and the results are detailed, showing the limits, the specificities and the advantages of each method. Moreover, the amplitude and the distribution of the stresses along the width of the sections present good agreement with results of numerical simulations.

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## 1. Introduction

The sheet piles studied in this research are produced by ArcelorMittal, by hot rolling. The following cooling step, at ambient temperature, generates residual stresses and deformations. As the sheet piles have to be perfectly straight to easily fasten them to the others, an additional straightening process is applied to meet the standards. This straightening operation is performed by a series of identical rollers which lead the pieces by friction. The rollers are placed alternately above and below the pieces with shifts creating a succession of bendings (Fig. 1) and modifying the residual stress field generated by the cooling procedure.

The residual stress fields, inherent to any manufacturing process, are important data to know and to control as they can have a destructive or beneficial effect. They can modify the stiffness, the toughness and have an impact on the piece service life. Numerous methods are developed to measure these stresses, each with specifications and limits, depending on the geometry of the pieces, the accessibility of the different parts, the measurement depth, the stress distribution … These different methods are largely described in literature, for instance by Rossini et al. [1] with a comparison of numerous techniques classified into three categories: non destructive [2], semi destructive and destructive. Withers et al. tested and compared some of these techniques on a thick section in [3] (magnetic, synchrotron and contour methods). Moreover, these manufacturing processes are also often studied by finite elements models. In this study, the numerical and experimental methods are coupled: first, the numerical distribution of the stresses helps to chose three methods to measure the residual stresses and, secondly, the experimental measurements, among which the residual stress fields, are used to validate the numerical model. The final goal is to create an efficient numerical tool for a better understanding of the procedures, making possible to study the sensitivity to the forming parameters, to optimize the industrial settings and, finally, to reduce both the final deformation and the level of the residual stress field.

The Finite Element method is often used to analyse the stress field. Quach et al. [4] used a numerical model to study the residual stresses in press-braked thin-walled steel section where the maximum levels occurred in the corner region and away from the surfaces, making difficult to use conventional measuring methods assuming a linear variation across the thickness. Jandera et al. [5] explored the effect of the residual stresses in cold-rolled stainless steel box sections using the X-ray diffraction measurements for a numerical model verification. These measures showed the influence of the through-thickness residual stresses on the structural behaviour of the sections.

The Finite Element code Metafor used in the current research, dedicated to process modelling, has already been applied on problems similar to straightening with difficult contact conditions, complicated boundary conditions and friction, highly nonlinear material behaviour… [6]. The applied models (the boundary conditions, the industrial setting, the thermo-physical properties, the material laws, the material parameter data) and the simulations results related to the cooling and straightening processes of sheet piles are described in Bouffioux et al. [7]. The simulation results, validated by the measurements of the deformations and the rollers forces, indicate that the stress field is almost constant throughout the thickness and that the longitudinal stresses are dominant in the central part of the web and the flanges. This information is precious as it helps to choose the appropriate methods to measure the residual stress fields.

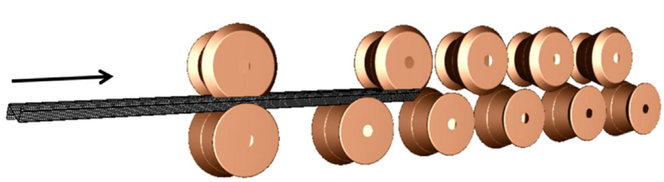

**Fig. 1.** Sheet pile and rollers during the straightening process.

The present article is focused on the residual stress measurements. Three methods are applied: first, a non-destructive one, i.e. the X-ray Diffraction (XRD) method, with measures near the surface, then another one, semi-destructive, i.e. the ring core method (with strain gauge rosettes) and finally, a destructive procedure, i.e. the sectioning technique. These procedures are selected in function of the material, the stress state, the geometry and the size of the pieces. ENSAM-Arts et Métiers ParisTech, laboratory LEM3, performed the XRD measurements and the MSM laboratory was in charge of the tests with the ring core and the sectioning methods.

XRD is mainly used for the determination of intergranular strains and residual stresses in crystalline materials. It is based on the measurement of the crystal lattice strains, through the variation of the interplanar spacing $d_{hkl}$ for some {hkl} diffraction planes. The current spacing $d_{hkl}$ measured is compared to that of a stress free state in order to get the average residual stress using the $\sin^2\psi$ method fully described in Macherauch et al. [8] and Inal et al. [9]. This technique is very efficient and enables to get the residual stress value in a few minutes provided there is no interference between the X-ray beam and the analyzed part. Some limitations exist; some errors can arise in particular for some materials containing coarse grains or severe textures.

For the ring core method, special strain gauge rosettes, with three strain gauges oriented in radial directions, are stuck on the surface. From the other side of the piece, rings are drilled around them. The stresses of the extracted small cylinders are released. The deformations appearing during the drilling are measured in the radial directions by the strain-gauges. The residual stresses are computed from these deformations with an elastic law. The method can be accurate since the stress field is homogeneous throughout the thickness. Usually, only an annular grove is drilled, on the surface around the strain gauge, leaving the upper part isolated from the surrounding material and causing the stress release [10]. In the present case, the complete extraction of the core, which is possible because the thickness is not too high, ensures the complete relaxation through the whole thickness. This method, not often documented in literature, is described by Masláková et al. [11]. As explained by Šarga and Menda [12], the method is less common than the hole-drilling method but is also less sensitive to the position of the cutting tool.

For the sectioning method, small tongue-shaped samples are cut. There are oriented in the length direction of the sheet pile. The stresses, which must be constant along this direction, are computed from the membrane and bending strains released by the cutting, in one direction only, neglecting deformations in the other directions. This implies to limit the measurements to the direction where the stresses are clearly dominant. The method can be accurate when the stress variation through the thickness is small or linear which is consistent with the results of the numerical model. This procedure, classically used in case of long profiles, is described by Spoorenberg et al. [13] for roller bent wide flange sections and by Cruise and Gardner [14] for the structural steel sections. Moreover, Yuan et al. [15] used this method to study the residual stress distributions in welded steel sections, proposed and validated distribution patterns for several geometries.

## 2. Experimental data

The geometry of the sheet piles studied is shown in Fig. 2a, with a length of 6000 mm. The curvilinear coordinates ($X_c$), shown

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