DRAWABILITY ASSESSMENT OF STEEL SHEETS BY AN ULTRASONIC METHOD

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INTRODUCTION

The "on-line" characterization of parameters linked with the microstructure and the metallurgy of products is needed by the development of continuous annealing on steel thin sheets production lines. The determination of the texture of products is of great importance in this context, in order to ensure an efficient operation of annealing furnaces. Firstly, the texture determination can be used to control the recrystallization process. Secondly, a more detailed determination could provide an evaluation of sheets properties regarding their drawability. This is particularly interesting for materials used in automotive body, can production, house-hold appliances.

At the present time several works are conducted in order to perform the "on-line" characterization of the texture using ultrasonic techniques [1-5] or X-ray methods [6] applied to aluminium products or steel products. The aim of this paper is to show that ultrasonic techniques associated with mechanical models of plastic strain behaviour of materials, can be used to predict the strain ratio (or Lankford coefficient), usually determined by tensile testing. The first laboratory results obtained on several samples from different grades of steel thin sheets are presented.

RELATIONSHIPS BETWEEN ULTRASONIC VELOCITIES AND TEXTURE COEFFICIENTS

Several authors have shown that the evaluation of fourth-order coefficients of the Orientation Distribution Function (O.D.F.) can be derived from the determination of ultrasonic velocities [7,8]. Basically, the plane wave propagation in an anisotropic medium is given by the eigenvalues of the Christoffel matrix

$$\mathrm{Det}(\Gamma_{il} - \rho V^2 \delta_{il}) = 0 \qquad (1)$$

where Γ_{il} is a function of C'_{ij}, the elastic constants of the sample. In fact, these constants are the average of the constants C_{ij} of the single crystal overall crystallites as a function of their orientation (assuming the approach of Voigt i.e the uniformity of elastic strain across grain boundaries). Consequently, the elastic constants C'_{ij} of the polycristal are only expressed in terms of changing coordinate system, referred to that of the single crystal constants C_{ij} , using the three Euler angles ψ, θ , φ . This orientation function may be developed on a spherical harmonic basis as

$$< r > = \sum_{l=0}^{\infty} \sum_{m=-l}^{+l} \sum_{n=-l}^{+l} r_{lmn} \, w_{lmn} \tag{2}$$

Thus the plane wave velocity may be expressed as a function of the coefficients of the ODF. Let Oxyz be an orthogonal set of reference axes fixed in the sample with Ox parallel to the rolling direction and Oz parallel to the normal direction. Following Sayers [7]

$$\rho V_{zz}^2 = C_{11} - 2C \; (1/5 - 16/35 \sqrt{2} \Pi^2 W_{400}) \tag{3}$$

$$\rho V_{zx}^2 = C_{44} + C \left[1/5 - 16/35 \sqrt{2} \Pi^2 (W_{400} - \sqrt{5/2} W_{420}) \right] \tag{4}$$

$$\rho V_{zy}^2 = C_{44} + C \left[1/5 - 16/35 \sqrt{2} \Pi^2 (W_{400} + \sqrt{5/2} W_{420}) \right] \tag{5}$$

where the first subcript denotes the direction of propagation and the second the direction of polarisation. In other words, the texture coefficients W_{lmn} can be determined by using wave velocities measurements. This involves that the same characteristic values obtained with several methods, can be compared. For example, the ultrasonic values are often compared with those measured with the neutron-diffraction method [2] .

Recently, several developments were proposed in order to predict the plastic behaviour of anisotropic materials, incorporating the ODF. In particular, such models are interesting tools for calculating the strain ratio r (or Lankford coefficient) and its variations as a function of the angle with the rolling direction. In this work, ultrasonic texture coefficients are used as input data in the models.

MECHANICAL MODELS

Two classical models among several existing are retained in the present work. These are the Hill model and the Taylor model. These approaches are well adapted to predict the plastic anisotropy of materials as a function of texture.

The first model has been developped by Arminjon [10] who derived linear relationships between the Orientation Distribution Function coefficients and the coefficients of the Hill criterion of plastic strain. In the case of steel, the Pencil-Glide hypothesis is assumed [11] .

The second model is the Taylor model based on a pure-cristallographic approach [11, 12]. For these two models, it has been shown that the eighth order of the development of the Orientation Distribution Function is sufficient to have a good description of the plastic strain behaviour. This order is retained for measurements performed with the X-ray diffraction method. The first step of this work was to verify that the truncation of the development at the 4th order is still possible in the case of steels that generally have rather weak textures.

ULTRASONIC MEASUREMENTS

The laboratory method used for the ultrasonic velocity measurements is, at the present time, a manual technique using longitudinal and shear waves with horizontal polarization. The longitudinal waves as well as the horizontally polarized shear waves with propagation along Oz are produced by high frequency piezo-electric transducers. The horizontally polarized shear waves in the sheet plane are produced by electro-magneto-acoustic transducers using a meander-coil configuration. The method retained for ultrasonic velocity measurements is the pulse-echo-overlap method.

ACCURACY OF MEASUREMENTS

The major problem encountered in the determination of texture coefficients with ultrasonic velocities measurements arises from the accuracy of this determination. This problem has been mentionned by some authors 2 , particularly concerning the first coefficient W_{400} . This last coefficient is calculated from the absolute values of velocities, while the W_{420} and W_{440} coefficients are determined from variations of velocities. In order to solve this problem, a statistical technique based on redundant measurements was used. Relationships given by C.M. Sayers and R.B. Thompson 7,8 between ultrasonic velocities and ODF coefficients, may give new relationships between velocities as follows

$$V_{zz}^2 + V_{zx}^2 + V_{zy}^2 = K_1 \qquad (6)$$

$$- 1/4 V_{zz}^2 + V_{SHO}^2(0°) + V_{SHO}^2(45°) = K_2 \qquad (7)$$

where K_1 and K_2 are independent of the ODF. The as measured values must verify these relationships. The equations (6) and (7) being verified, the algorithm used allows to minimize the errors with a least-square method.

SAMPLES

The results shown below have been obtained on several steel samples cut in industrial cold-rolled, and annealed thin sheets. The grades are low-carbon steels in one hand (Samples 1 - 4) and ferritic stainless steels in the other (Samples 5 and 6). Several characterization methods have been tested on these samples : Ultrasonic velocities measurements, texture measurements with X-ray diffraction in the reflexion mode, and finally, tensile tests in order to determine the standard mechanical anisotropy coefficients r_m and r.

RESULTS AND DISCUSSION

The ODF coefficients values obtained with the ultrasonic method and with the X-ray diffraction method are shown in Table 1. It is worth mentioning, here, that the values given in this table are those calculated using the Bunge formalism. It is quite easy to obtain the ODF coefficients of Bunge from the Roe coefficients using reference [13]. A satisfactory agreement is obtained on most of the samples, except for the sample number 4. The first coefficient calculated from absolute values of velocities does not present significatively larger discrepancies than the other coefficients for samples 1, 2, 3 and 6. Larger discrepancies are noted on the lowest values of the ODC. The differences between X-ray and US values observed on the samples number 4 and 5 will be discussed below.

The evolution of the anisotropy coefficients in the sheet plane are shown in figure 1. Results obtained with different methods (ultrasounds, X-ray, tensile tests) are given on the same curves. These curves display the part taken by the mechanical model on the results. Obviously, the choice of the model of plastic strain is of great importance in the result. In our case, the Hill-model underestimates the variations of the Lankford coefficient as a function of the angle with the rolling direction. This is true for both methods i.e ultrasound and X-ray diffraction. On the opposite, the Taylor-model overestimates these variations, particularly in the transverse direction i.e 90° with the rolling direction.

Table 1 : ODC obtained with ultrasonic and X-ray measurements.

Sample		C_1^{mnu} US	C_1^{mnu} X-Ray
1	C_4^{10}	- 1.98816	- 1.91522
	C_4^{12}	- 0.10806	- 0.09178
	C_4^{14}	0.47403	0.34939
2	C_4^{10}	- 2.32009	- 2.25506
	C_4^{12}	- 0.39866	- 0.34702
	C_4^{14}	0.28377	0.11715
3	C_4^{10}	- 2.79249	- 2.59152
	C_4^{12}	- 0.36531	- 0.36918
	C_4^{14}	0.05765	0.03250
4	C_4^{10}	- 0.31322	0.47882
	C_4^{12}	- 0.29416	- 1.18519
	C_4^{14}	0.06917	- 0.22299
5	C_4^{10}	- 0.53455	- 0.17168
	C_4^{12}	- 1.12479	- 1.21842
	C_4^{14}	0.74879	0.90670
6	C_4^{10}	0.66897	0.59732
	C_4^{12}	- 1.24307	- 1.37036
	C_4^{14}	- 0.77192	- 0.80381

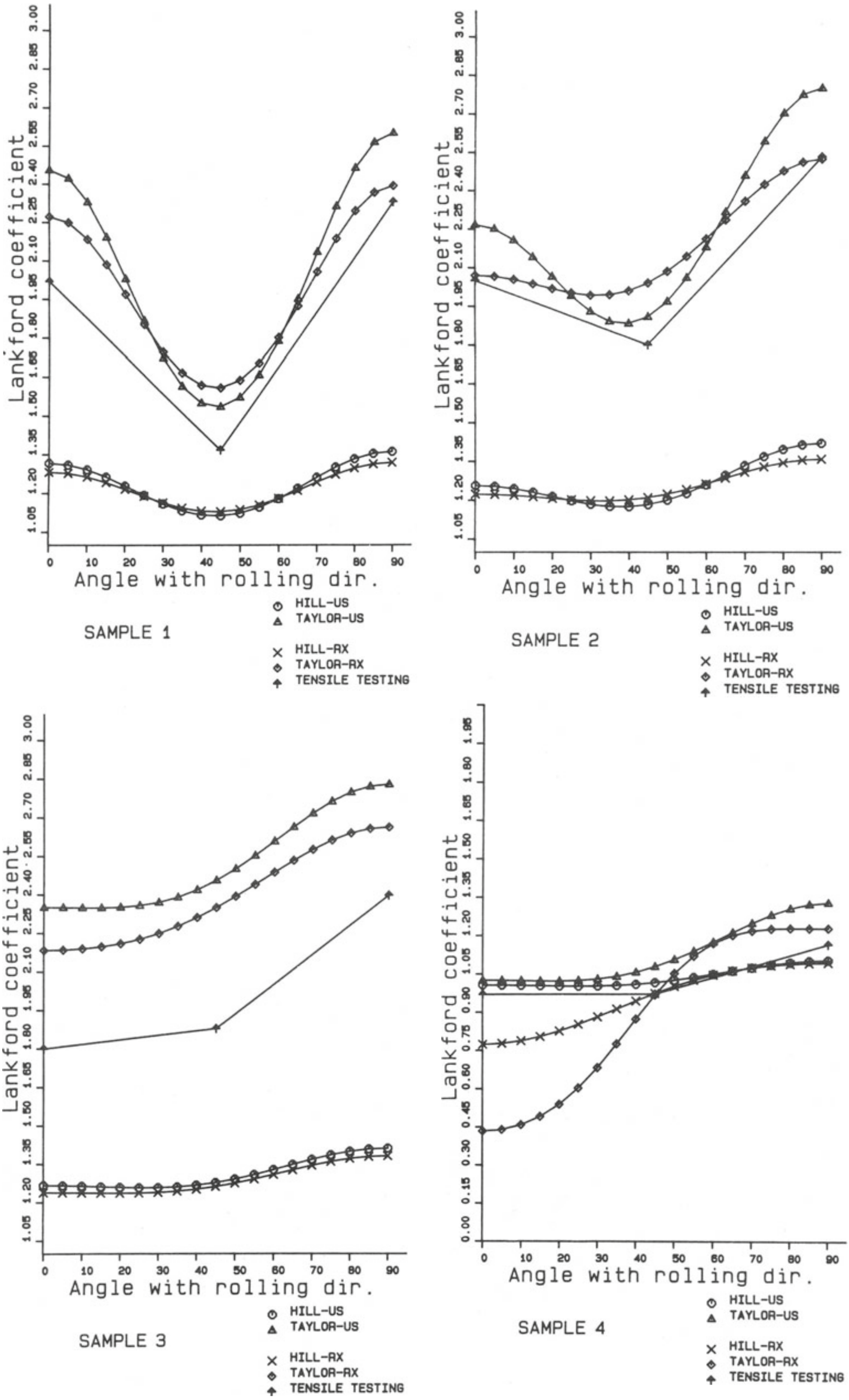

Fig. 1 : Evolutions of the Lankford coefficient determined by ultrasonic, X-ray, tensile testing (Samples 1 - 4).

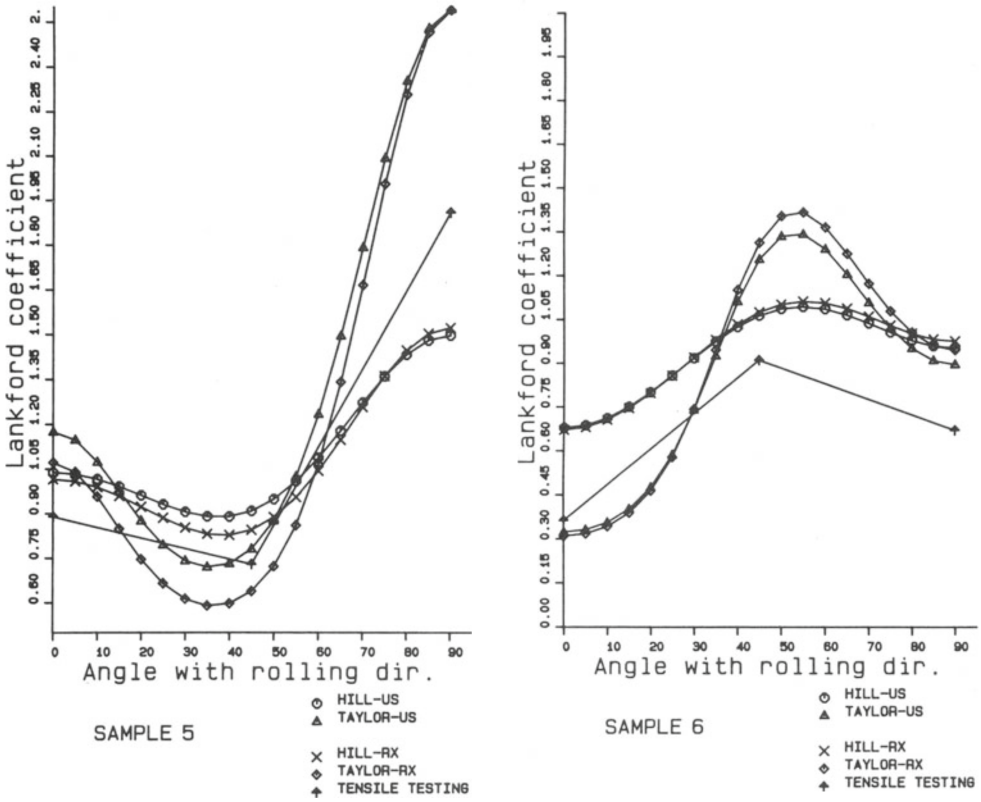

Fig. 1 : Evolutions of the Lankford coefficient determined by ultrasonic, X-ray, tensile testing. (Samples 5 and 6)

The important result, however, is that the curves obtained with the same model, but with the two measurements methods of ODC, are very similar. This is true for all samples though the textures are very different. The sample number 4 which presents the most important differences on ODC measurements is, in fact, a quasi-isotropic steel. One can note in this case, that the ultrasonic r values are in better agreement with those of tensile tests than the X-ray values. There is no clear explanation of this result. One may suppose that the volume averaging provided by the ultrasonic method is more favorable to a good description of the texture than the X-ray diffraction in reflection mode. It can be stated that in its principle, the ultrasonic method averages the values on the whole volume of the tested material, not only on the surface such as X-ray diffraction does. For a real comparison between measurements, we should have measured texture of samples by neutron diffraction. But, the aim of this study was essentially to show the ability of the ultrasonic method for industrial applications, so the differences between X-ray and neutron diffraction were not taken into account. For the sample number 5, the difference noted on the C_4^{10} coefficient does not affect considerably the shape of the r(α) curve. In contrast, in the case of sample number 3, although a small difference is obtained between the X-ray and US ODC's, the corresponding r(α) curves calculated by the Taylor model are parallel but significatively separated. In fact, this sample presents a high value of the first ODC i.e a high anisotropy. Consequently, a small error on this coefficient may affect the result. However, the range of errors obtained with tensile testing on these very anisotropic samples are of the same order of magnitude i.e + 0.2 on the Lankford coefficient.

The good agreement obtained between ultrasonic and X-ray values on the ODF coefficients as well as the accordance between the resulting $r(\alpha)$ curves enable computing also the r_m and Δr coefficients and comparing now directly the US values with those measured by tensile tests. These calculated values are given in table 2. One may observe a satisfactory agreement between both measurement methods. However, one can appreciate the great importance of the mechanical model. One clearly observes that the Taylor-model overestimates variations (Δr values) when the Hill-model underestimates these variations.

In the context of on-line control, the determination of "absolute" values of the standard r_m and Δr parameters is not absolutely necessary. Nevertheless, it is very easy to perform correlations between the predicted values and the values determined by mechanical tests. Such as procedure should give corrected on-line values of $r(\alpha)$, r_m and Δr that would be directly in the good order of magnitude.

SUMMARY

The purpose of the study presented here was rather to evaluate the potential of the ultrasonic technique to control quantitatively the plastic anisotropy of steel sheets on production lines. The study was not aimed at solving the accuracy problems of the ultrasonic determination of ODC's. In this context, it appears that a simple statistical algorithm gives an acceptable estimate of ODC's on steel samples. This estimate is sufficient to calculate the Lankford coefficient by an adapted mechanical model of plastic behaviour. The Taylor model easily exhibits the variations of anisotropy coefficient. Generally, the errors on the computed values are of the same order of magnitude as those of the tensile tests. Thus, these results appears quite promising for the texture monitoring in a steel plant.

Now, this laboratory procedure has to be extended to the process control in industrial environment. In this case, any coupling medium must be avoided. Consequently EMATS wave generation is tested in laboratory, and an industrial device using SO and SHO modes in being developed and will be tested on line before long.

Table 2 : r_m and Δr results for ultrasonic and tensile tests.

Sample	Tensile Test		Hill + US		Taylor + US	
	r_m	Δr	r_m	Δr	r_m	Δr
1	1.77	0.81	1.23	0.23	2.03	0.99
2	2.05	0.49	1.26	0.16	2.22	0.62
3	1.99	0.22	1.31	0.06	2.53	0.13
4	1.02	0.10	1.03	0.04	1.13	0.10
5	1.07	0.67	1.09	0.36	1.33	1.10
6	0.71	-0.39	0.94	-0.25	0.93	-0.65

AKNOWLEDGEMENTS

This research is partly supported by the European Community of Steel under project n° 7210/GB/304.

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