



HAL
open science

Influence of biaxial stress on magnetic behavior of hot-rolled steels

Olivier Hubert, Julien Taurines, Zakariae Maazaz, Raphael Crepinge, Carola Celada-Casero, Frenk van den Berg

► **To cite this version:**

Olivier Hubert, Julien Taurines, Zakariae Maazaz, Raphael Crepinge, Carola Celada-Casero, et al.. Influence of biaxial stress on magnetic behavior of hot-rolled steels. European Conference on Non-Destructive Testing (ECNDT), Jul 2023, Lisbonne, Portugal. hal-04195831

HAL Id: hal-04195831

<https://hal.science/hal-04195831>

Submitted on 4 Sep 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Influence of biaxial stress on magnetic behavior of hot-rolled steels

Olivier Hubert¹, Julien Taurines¹, Zakariae Maazaz¹, Raphaël Crepinge¹, Carola Celada-Casero² and Frenk van den Berg³

1 LMPS (Univ. Paris Saclay, CentraleSupélec, ENS-Paris-Saclay, CNRS) France,
olivier.hubert@ens-paris-saclay.fr

2 MATERIALIA Research Group, Centro Nacional de Investigaciones Metalúrgicas
(CENIM-CSIC), Av. Gregorio del Amo 8, Madrid, 28040, Spain

3 Tata Steel, PO-Box 10.000, 1970CA IJmuiden, The Netherlands.

Abstract

On-line non-destructive magnetic monitoring (NDM) techniques are relevant to evaluate the quality of steels and their fluctuations during forming process. The on-line monitoring faces different issues. Due to magneto-mechanical coupling, stress that may be applied during NDM may have a strong effect on the magnetic behavior that may lead to erroneous estimations of the microstructure quality of the material. The multiaxial character of the stress state is another strong issue. In this communication, some new results showing the effect of a uniaxial and biaxial stress on the magnetic behavior of 3 grades of hot-rolled steels are presented (from low carbon steel to AHSS).

1. Introduction

In the last few years, a growing interest of the car industry for the use of Advanced High Strength Steel (AHSS) products has been observed, especially considering the weight saving solutions they lead to. Their excellent mechanical behavior comes from the very complex microstructure they exhibit, achieved thanks to precise thermomechanical treatments. The AHSS microstructure is highly sensitive to small variations in the manufacturing process, and it is the purpose of developments in online non-destructive evaluation to detect these minor variations. Such monitoring is made on laminations usually subjected to multiaxial mechanical stress (due to band tension or bending on cylinders) and known to have a strong effect on the magnetic behavior. Stresses can therefore modify the perception of the microstructure given by the sensors. Magnetomechanics must consequently be taken into account in the reverse identification process and requires developing multiaxial experiments and multiaxial magneto-mechanical models. Previous works have addressed magnetic behavior change due to multiaxial stress [1-4]. Some new results showing the effect of a uniaxial and biaxial stress on the magnetic behavior of 3 grades of hot-rolled steels are presented (from low carbon steel to AHSS). Experimental results are compared to the output of simplified modeling according to a previous definition of equivalent stress.

2. Materials and experimental protocol

2.1 Materials

Materials considered in this study are hot-rolled interstitial free (IF), low carbon (LC) and dual-phase (DP) steels provided by Tata Steel. Thicknesses are 3.4, 3.7 and 3.6 mm respectively.

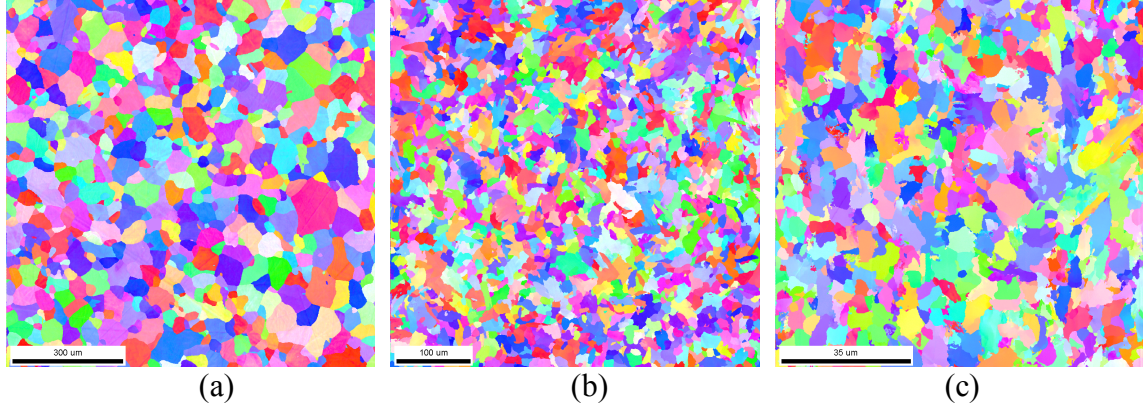


Figure 1. Inverse pole figures illustrating the microstructure of IF (a), LC (b) and DP (c) hot-rolled steels.

Figures 1a-c provide microstructure observations of the three grades. All exhibit a low crystallographic texture and equiaxed grains structure. Average grain size varies from 26 μm for IF to 9 μm for LC and 3.2 μm for DP. All material are mainly single-phased (BCC, i.e. Body-Centred-Cubic, ferrite) with very few pearlite islands in LC and DP steels.

2.2 Experimental set-up for magnetic measurement in uniaxial condition

Specimens for tensile testing and magnetic measurements under uniaxial stress condition consist of 180 mm long, 12 mm wide strips cut along the rolling direction by electro-erosion machining. An MTS electro-hydraulic machine is used to get the stress/strain behavior and to apply constant stress during magnetic measurement. The magnetic set-up (not illustrated due to page number limitation) is composed of a primary magnetizing coil and a pick-up B-coil. Two high permeability ferrite yokes close the magnetic circuit allowing for a global decreasing of demagnetizing field. The magnetic field is estimated using Ampere's law from electric current. Magnetic induction is calculated from the electromotive force from B-coil. 0.1Hz magnetic field rate is used. Stress is applied in the elastic range from compression to tension depending on the yield stress of each material.

2.3 Experimental set-up for magnetic measurement in biaxial conditions

The experimental protocol used for biaxial experiments can be found in [5,6]. A cross-shaped specimen is used to promote homogeneous stress and magnetic field in the central area. The specimen is positioned inside the multiaxial machine ASTREE composed of 4 independent hydraulic jacks (two by two perpendicular to each other). An interaction matrix α_{ij} allows passing from the applied forces (F_1 , F_2) along each axis to the axial components of the stress tensor (σ_1 , σ_2):

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \end{pmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix} \begin{pmatrix} F_1 \\ F_2 \end{pmatrix} \quad (1)$$

with $\alpha_{11} = \alpha_{22} \approx 4.0$ MPa/kN and $\alpha_{12} = \alpha_{21} \approx -0.89$ MPa/kN. A previous finite element mechanical calculation also demonstrates that compression can be applied without risk of buckling. Due to stress concentration (maximal amplitude of 2.5) and considering the yield stress of the material only LC and DP have been tested. The central mechanical loading amplitude cannot exceed 100MPa.

For biaxial measurements, the experimental procedure consists to: i) clamp the specimen in the multiaxial machine and position the magnetic set-up; ii) apply the mechanical loading iii) demagnetize the material by applying a sinusoidal magnetic field of decreasing amplitude up to zero; iv) perform low frequency magnetic hysteresis (0.2Hz) and anhysteretic measurements [7,8].

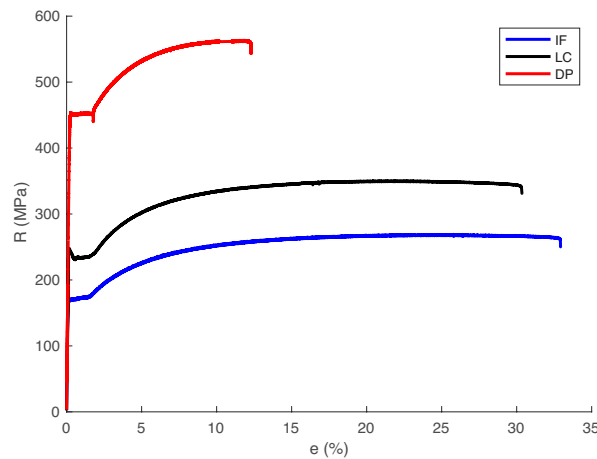


Figure 2. (conventional) stress-strain behavior of the three steels.

3. Experimental results

3.1 Reference mechanical and magnetic measurements

Some preliminary measurements have been conducted to evaluate the initial (without applied stress) behavior of the materials. Figure 2 show the stress-strain behavior of materials. IF exhibits a low yield stress (YS) and high ductility. DP is harder and breaks much sooner than IF. LC exhibits and intermediate behavior.

3.2 Influence of uniaxial stress

Figure 3a-c illustrates hysteresis loops of the material at different stress levels (in accordance with [9,10]): compression decreases magnetic properties (increasing coercive field and decreasing remanent induction); uniaxial tension leads on the contrary to an increase of the magnetic properties of the material for a stress range up to 200MPa (for LC and DP). This increasing gradually saturates and gives way to a global decreasing. This non-monotony has recently been interpreted as the result of a second-order phenomenon (morphic effect) [11]. Two crossing zones are highlighted for magnetic field levels close to the coercive field. This crossing is related to the well-known Villari effect [9,12]. Coercive field plotted in figure 3d for the three grades highlights differences between materials (the harder exhibits a higher coercive field), non monotony for stress higher than 200MPa an apparently similar sensitivity to stress.

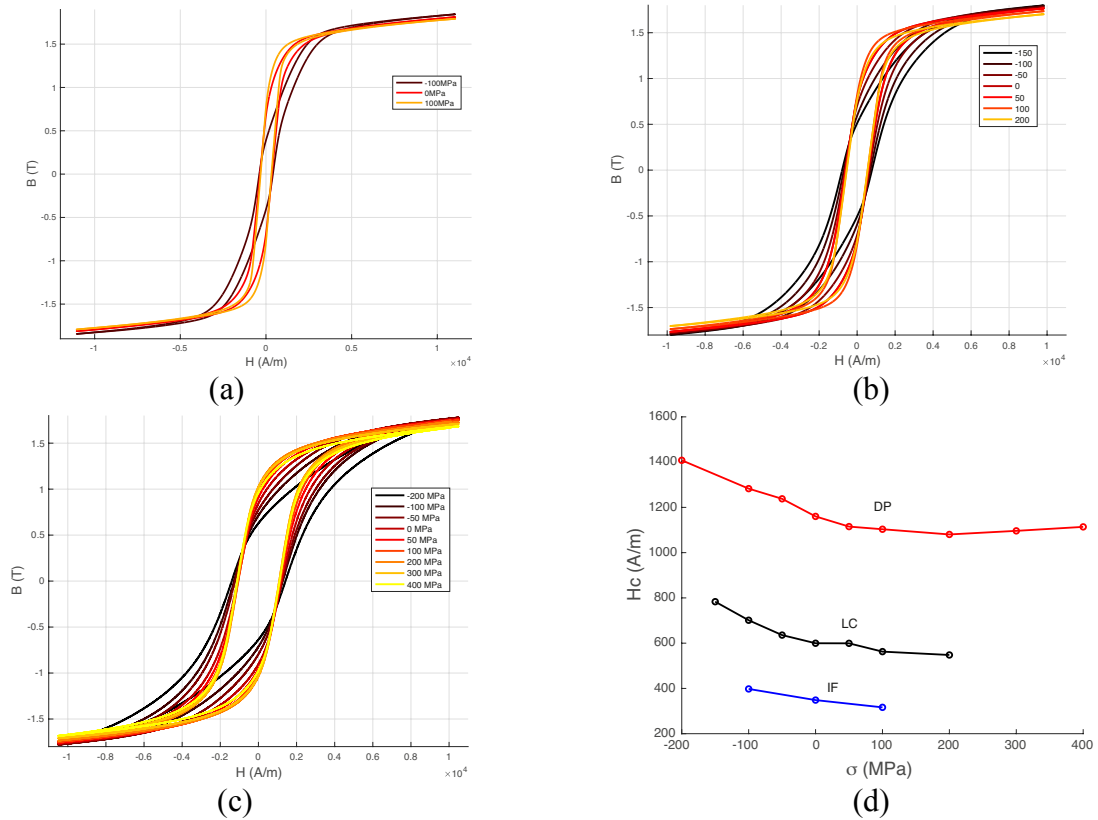


Figure 3. Magnetic behavior of the three steels ((a) IF (b) LC (c) DP) subjected to uniaxial stress. (d) variation of coercive field with stress for three grades.

3.3 Influence of biaxial stress

Results presented in this communication are limited to anhysteretic behaviors carried out along the rolling direction of the sheet (magnetic field applied along axis 1). 25 biaxial stress states have been tested, for stress level varying between -100MPa and +100MPa. Some particular mechanical situations are highlighted in figure 4 (results given for DP steel): *Longitudinal* tests correspond to situations where $\sigma_1 \neq 0$ and $\sigma_2 = 0$; *Transversal* tests correspond to $\sigma_1 = 0$ and $\sigma_2 \neq 0$; *Equibiaxial* tests mean $\sigma_1 = \sigma_2$; and *Shear* tests verify $\sigma_1 = -\sigma_2$.

It can be observed that tension increases the permeability whereas compression decreases it for case (a) in accordance with uniaxial tests; an opposite effect is observed for case (b); the equibiaxial situation (c) leads to a significant insensitivity of the magnetic behavior in the range of experiments; the most significant changes are observed for shear (d). These results are in accordance with previous results [3,5,7,8] for various materials and for LC material (not presented).

Figures 5a and 5b give a map representation of biaxial stress influence on initial anhysteretic permeability recorded for the 25 loading states and interpolated for LC and DP steels respectively. Iso-values behave similarly between LC and DP. Results are in accordance with uniaxial test in the measurement range (along axis 1).

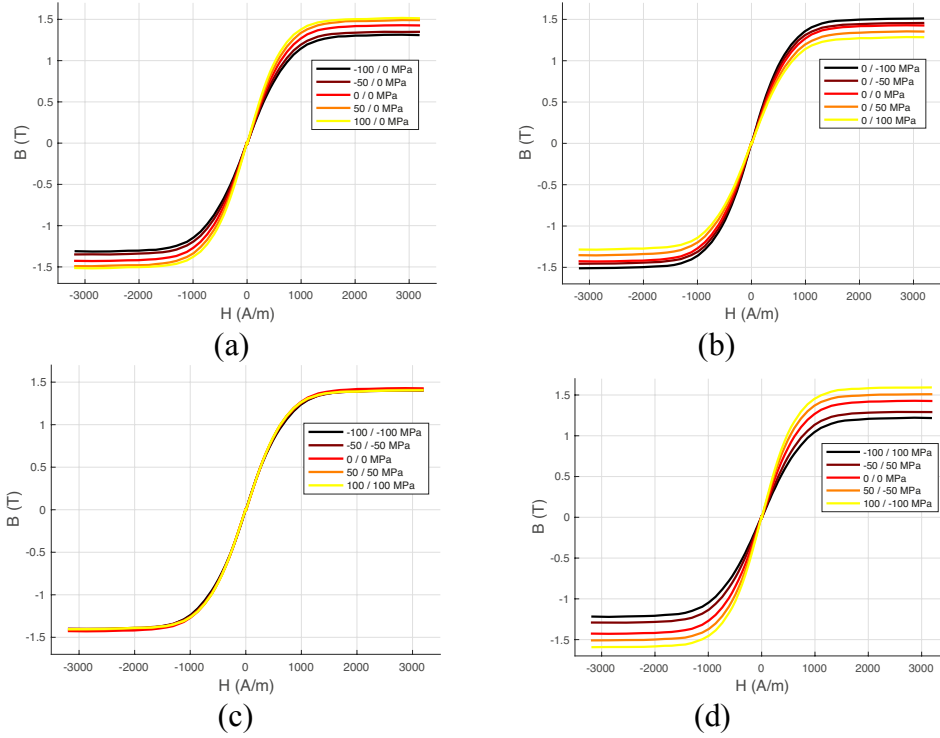


Figure 4. Anhyseretic magnetic behavior of the DP steel: (a) longitudinal, (b) transversal, (c) equibiaxial, (d) shear.

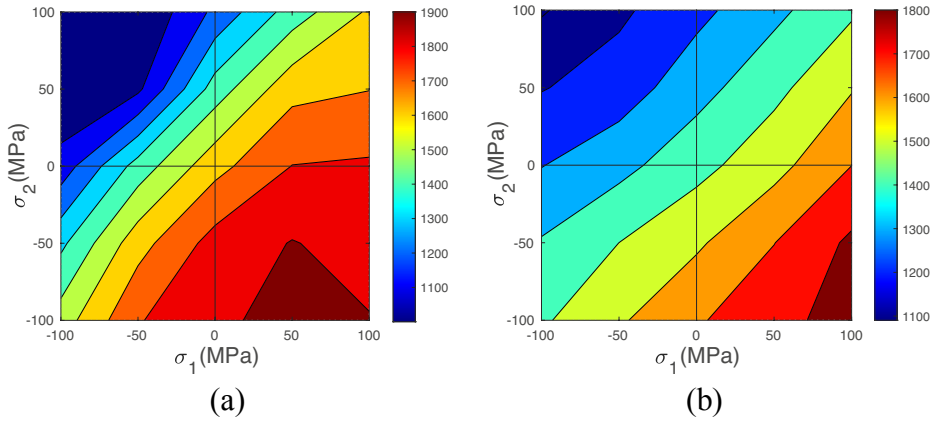


Figure 5. Anhyseretic initial susceptibility variation in stress plane: (a) LC, (b) DP.

Figure 6a-b gives a model representation of anhyseretic initial susceptibility from a simplified formulation based on free energy minimization and multiscale modeling [8,11]. Please refer to reference to obtain information concerning the model. Parameters are gathered in table 2. Significance are defined in reference [8].

Table 2. Parameters used for multiscale modeling

Ms	K_1	λ_{100}	λ_{111}	χ_0
1.71×10^6	48×10^3	21	-21	1200
A/m	J/m ³	ppm	ppm	-

Figure 6a models the LC steel. Figure 6b models the DP steel. The only difference is a residual stress of (+100MPa, +100MPa) considered for the DP modeling. Results are in agreement with experiments.

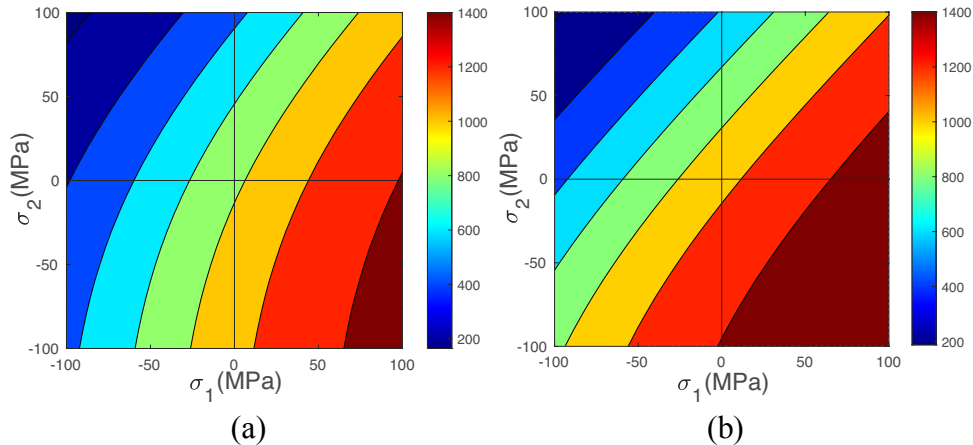


Figure 6. Simplified modeling of anhysteretic initial susceptibility in stress plane: (a) LC, (b) DP.

4. Conclusions

In this paper, magnetic measurements obtained under uniaxial and biaxial stress of low carbon steels were presented. The experimental results show a significant magneto-elastic coupling for all materials. Experimental results are in accordance with literature and with the output of a simplified multiscale model. A residual stress field must be considered for an appropriate modeling of DP behavior in biaxial stress condition.

Acknowledgements

The work has been developed within the project "Online Microstructure Analytics": Ref. OMA, Grant Agreement No. 847296, Research Fund for Coal and Steel of the European Union.

References and footnotes

1. J. Pearson, P.T. Squire, M.G. Maylin, and J.G. Gore. *IEEE Transactions on Magnetics*, 2000.
2. O.Hubert. *Przedglad Elektrotechniczny*, 83(4):70–77,2007.
3. O.Hubert, F.S.Mballa-Mballa, S.He, and S.Depeyre, *IEEE Transactions on Magnetics*, 52(5):1–4, 2016.
4. U. Aydin et al. *Journal of Magnetism and Magnetic Materials*, 469:19– 27, 2019.
5. O.Hubert, et al., *Journal of Magnetism and Magnetic Materials*, 565, (2023)
6. O.Hubert et al. *Przedglad Elektrotechniczny*,R81(5):19–23,2005.
7. M. Rekik, O. Hubert, and L. Daniel. *International Journal of Applied Electromagnetics and Mechanics*, 44(3-4):301–315, 2014.
8. O.Hubert and L.Daniel *Journal of Magnetism and Magnetic Materials*, 323(13):1766–1781, 2011.
9. R. Bozorth, *Ferromagnetism*, D. Van Norstrand, 1951
10. Z.Maazaz, O. Hubert, A. Zemmouri, *Non-Destructing & Evaluation International*, 134, (2023), 102782
11. O. Hubert. *Journal of Magnetism and Magnetic Materials*, 491, (2019), 1-16, 165564. DOI:10.1016/j.jmmm.2019.165564
12. O. Perevertov, *Journal of Magnetism and Magnetic Materials* 428 (2017) 223–228.