



**HAL**  
open science

## How the EU project "Online Microstructure Analytics" advances inline sensing of microstructure during steel manufacturing

Frenk van den Berg, M. Aarnts, H. Yang, S. Melzer, D. Fintelman, B. Ennis, L. Gillgren, Denis Jorge-Badiola, A. Martínez-De-Guerenu, Claire Davis, et al.

### ► To cite this version:

Frenk van den Berg, M. Aarnts, H. Yang, S. Melzer, D. Fintelman, et al.. How the EU project "Online Microstructure Analytics" advances inline sensing of microstructure during steel manufacturing. European Conference on Non-Destructive Testing (ECNDT), Jul 2023, Lisbonne, Portugal. hal-04195819

**HAL Id: hal-04195819**

**<https://hal.science/hal-04195819>**

Submitted on 6 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.



## How the EU project “Online Microstructure Analytics” advances inline sensing of microstructure during steel manufacturing

Van Den Berg F<sup>1</sup>, Aarnts M<sup>1</sup>, Yang H<sup>1</sup>, Melzer S<sup>1</sup>, Fintelman D<sup>1</sup>, Ennis B<sup>1</sup>, Gillgren L<sup>2</sup>, Jorge-Badiola D<sup>3</sup>, Martinez-de-Guerenu A<sup>3</sup>, Davis C<sup>4</sup>, West G<sup>4</sup>, Zhou L<sup>4</sup>, Jolfaei M<sup>4</sup>, Peyton A<sup>5</sup>, Wilson J<sup>5</sup>, Volker A<sup>6</sup>, Martina Q<sup>6</sup>, Duijster A<sup>6</sup>, Malmström M<sup>7</sup>, Jansson A<sup>7</sup>, Hutchinson B<sup>7</sup>, Mocci C<sup>8</sup>, Vannucci M<sup>8</sup>, Colla V<sup>8</sup>, Reboud C<sup>9</sup>, Skarlatos A<sup>9</sup>, Miorelli R<sup>9</sup>, Lombard P<sup>10</sup>, Hubert O<sup>11</sup>, Taurines J<sup>11</sup>, Lobanova I<sup>12</sup>, Despréaux S<sup>12</sup>, Labbé S<sup>13</sup>, Celada-Casero C<sup>14</sup>

<sup>1</sup> Tata Steel, IJmuiden, The Netherlands, [frenk.van-den-berg@tatasteeleurope.com](mailto:frenk.van-den-berg@tatasteeleurope.com)

<sup>2</sup> SSAB Europe, Borlänge, Sweden

<sup>3</sup> Asociación Centro Tecnológico Ceit-IK4, San Sebastian, Spain

<sup>4</sup> University of Warwick, Coventry, UK

<sup>5</sup> University of Manchester, Manchester, UK

<sup>6</sup> Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO), Den Haag, The Netherlands

<sup>7</sup> SWERIM, Kista, Sweden

<sup>8</sup> Scuola Superiore Sant'Anna (SSSA), Pisa, Italy

<sup>9</sup> Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA), Palaiseau, France

<sup>10</sup> ALTAIR, Meylan, France

<sup>11</sup> Ecole Nationale Supérieure Paris-Saclay (ENSPS), Gif-sur-Yvette, France

<sup>12</sup> Université Grenoble Alpes (UGA), Saint Martin d'Hères, France

<sup>13</sup> Sorbonne Université, Paris, France

<sup>14</sup> National Centre for Metallurgical Research (CENIM-CSIC), Madrid, Spain

### Abstract

Weight savings in mobility and transport are mandatory in order to reduce CO<sub>2</sub> emissions and energy consumption. The steel industry offers weight saving solutions by a growing portfolio of Advanced High Strength Steel (AHSS) products. AHSS owe their strength to their largely refined and complex microstructures, containing multiple metallurgical phases. Optimal control of the thermo-mechanical processing of AHSS requires inline sensors for real-time monitoring of evolution and consistency of microstructure and material properties.

To coordinate and accelerate European development activities in this domain, the project "Online Microstructure Analytics (OMA)" was established in 2019, constituting of a consortium of 14 specialised research organisations. The EU-funded OMA project,

with a total budget exceeding 6 MEU, focuses on inline sensing techniques to monitor the consistency and homogeneity of microstructure, texture and mechanical properties for automotive steels and in particular for AHSS.

In this paper, we will highlight the uncommonly harsh measurement conditions in the steel industry, in particular in the hot strip mill and the continuous annealing process where these sensing techniques are most required. Next, we will present characterisation and modelling results of AHSS' microstructures, magnetic properties and ultrasonic properties and demonstrate how these contribute to better interpretation of the inline measured data in relation to microstructure and mechanical properties.

The European project "Online Microstructure Analytics" paves the way for improved quality monitoring and enhanced process control of novel high-strength steel grades which favour a more sustainable society.

**KEYWORDS:** Steel; Microstructure; Material Characterisation; Mechanical properties; Ultrasonics, Electromagnetics.

## 1. Introduction

In the automotive and transport industries, there is a continuous drive to construct light-weight vehicles to reduce energy consumption and CO<sub>2</sub> emissions. The steel community has responded by the development of advanced high strength steels (AHSS). AHSS owe their higher strength to their largely refined and complex microstructures, containing multiple metallurgical phases. The usage of AHSS in today's vehicles body structure has drastically increased from about 10% in 2010 to about 40% (and for some models up to 60%) in recent years [1].

The favourable strength properties of AHSS are obtained from well-engineered combinations of thermal and mechanical treatments of selected chemical compositions of the steel. For strip steel, which is targeted for the automotive sector, the production stages comprise sequentially hot-rolling, pickling, cold-rolling, continuous annealing, zinc coating and levelling / skin-passing. Amongst them, hot rolling and continuous annealing play primordial roles in the formation of the microstructure, since during the cooling steps in these processes, the steel transforms into ferrite, pearlite, bainite and martensite phases in ratios that critically depend on the temperature-time path. Depending on the capabilities of a production line, different paths can be selected through the so-called TTT (Time-Temperature-Transformation) diagram.

In addition to the metallurgical phase ratios, also other microstructural parameters like grain size, crystallographic texture, stress, dislocations, precipitates are well-known to influence the mechanical properties of the steel product. With the steel microstructure being more dispersed in AHSS, combined with the tightening of the mechanical property windows imposed by demanding applications, inline monitoring of the microstructure parameter distributions becomes particularly important for world-class process control.

## 2. Approach

### 2.1 Measurement of grain size

As stated in the previous section, the temperature and the cooling rate govern the phase transformation process for a given chemical composition of the steel. Another important factor impacting the phase transformation evolution is the (average) size of the austenite grains, because their grain boundaries act as nucleation centres where the transformation is initiated. Smaller prior austenite grain size corresponds to a larger nuclei density, promoting the onset of ferrite formation and lowering the martensite start temperature  $M_s$  [2].

For evaluation of the prior austenite over the length of the coil, partners SSAB and SWERIM have developed a laser ultrasonic (LUS) measurement system which has been installed in the zone just after the finishing mill in the hot strip mill of SSAB Borlänge. Measurement conditions at this location are particularly harsh, as the steel strip target is hot (temperature around 900 °C) and is surrounded by dust and steam, as exemplified by the picture in Figure 1. The LUS system, and results of measurement campaigns, are discussed in a separate contribution to this conference [3] and in [4].



**Figure 1: Illustration of measurement conditions in the vicinity of the finishing mill.**

### 2.2 Measurement of volume ratio of metallurgical phases

As pointed out in the introduction, modern AHSS inherit their strength from the high volume fraction of the hard phases pearlite, bainite and martensite. To measure the phase fractions during the cooling process on the run out table (ROT) of the Hot Strip Mill, Tata Steel has implemented the EMSpec<sup>®</sup> (ElectroMagnetic Spectroscopy) sensor technology, which is the result of a long-standing collaboration between the university of Manchester, University of Warwick, Primetals and Tata Steel. The technology and results from inline measurements are presented in a separate paper at this conference [5]. In addition to the hostile conditions described in section 2.1, the ROT cooling uses high amounts of water for strip cooling, projected from both top and bottom onto the strip, as depicted in Figure 2, which the measurement device has to be resistant and operate robustly against.



**Figure 2: Strip cooling in the ROT using water jets.**

To enhance the interpretation of the EMSpec signals for the wide variety of steel microstructures, the universities of Manchester and Warwick have designed and constructed equipment for laboratory characterisation of the high temperature magnetic

behaviour of steel. Results of these studies are discussed in another ECNDT conference paper [6]. Tata Steel has carried out dedicated plant trials to produce materials with a variation in martensite and bainite volume ratios; more extended phase ranges (0-100% martensite and 18 – 80% bainite) have been obtained in laboratory anneal cycles at partner CEIT, followed by microstructure and magnetic characterisation, on which is reported in [7].

### 2.3 Measurement of strength

For the assessment of the mechanical strength, the steel world relies on tensile testing on specimens sampled from the head or tail of steel strip. The key mechanical parameters are derived from these tensile tests according to international standards and provide the basis for the quality specifications between steel strip manufacturers and their customers. However, due to the partly batch-wise processing as well as grade transitions, non-uniformities in properties occasionally occur at the coil extremities. The microstructure (non-)uniformity over coil length has been the subject of a predecessor European Steel Research project [8].

Magnetic sensing is an accepted measurement tool to investigate microstructural and strength variations over coil length of the final strip product. Two such products are the IMPOC [9][10] and PropertyMon [11] devices, which can typically be installed at the exit of the hot-dip galvanising (HDG) line, at relatively friendly operating conditions, viz Figure 3. Both IMPOC and PropertyMon are non-contact and robust inductive measurements, operating from both sides of the strip. IMPOC, for instance, measures the material's response to an intense magnetic pulse, at an interval of every 2 m strip length.

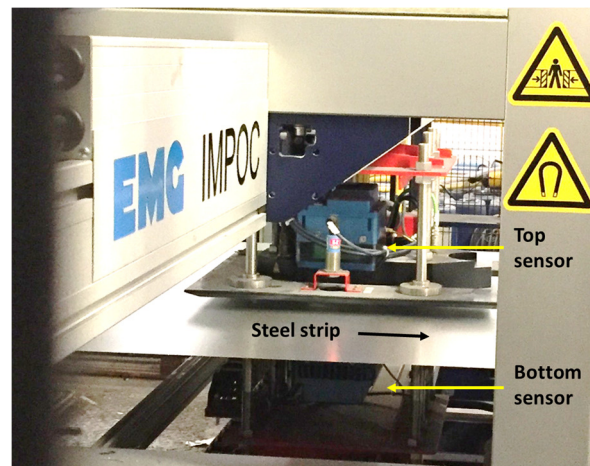


Figure 3: IMPOC measurement installed in HDG line.

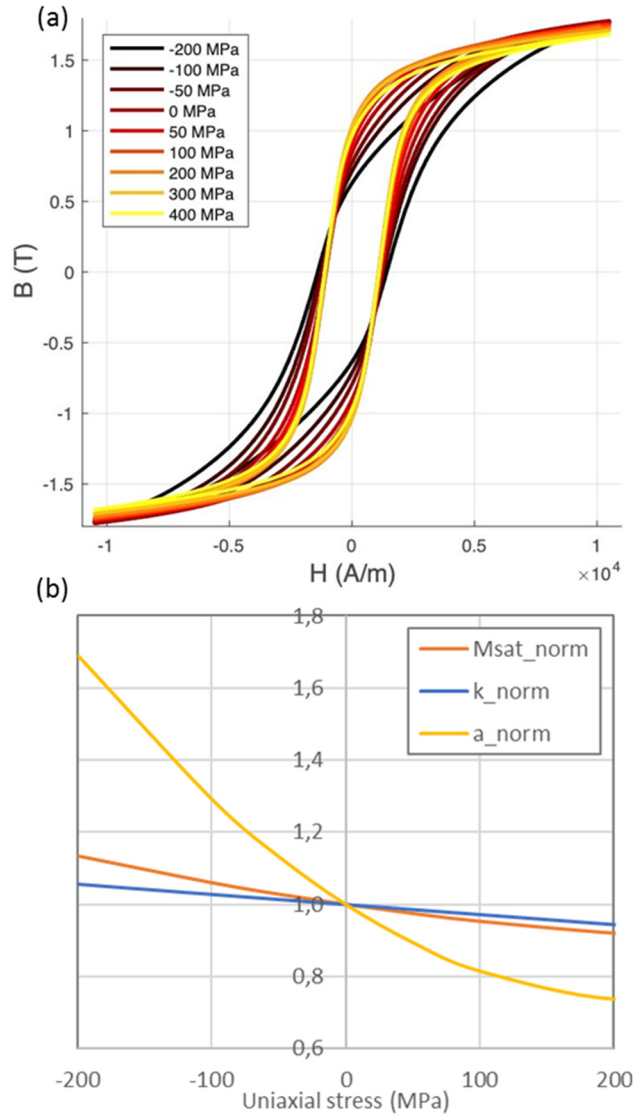
Within the OMA project, partner CEA has developed sensing models to predict IMPOC values for steels with given magnetisation loops measured by CEIT. Effects from stress fields on the magnetic properties have been investigated experimentally by ENSPSay [12], see Figure 4, and incorporated as parametrisation into the Jiles-Atherton (JA) description [14] of the magnetisation curve by partner ALTAIR [13] as alternative for the Jiles-Atherton-Sablik model [15]. These phenomenological descriptions are supported by fundamental ab initio modelling of the magnetoelastic effect pursued at the universities Grenoble Alpes and Sorbonne [16]. Figure 5 shows how the stress-dependency of the BH curve propagates into stress-dependency of the IMPOC value. From these results it can be concluded that stresses arising from strip tension, which are in the order of 20 – 30 MPa, will have a negligible (1%) effect on the IMPOC.

In addition to physics-based modelling of the IMPOC instrument for enhanced understanding of the sensitivities, also data-driven studies have been conducted by partners SSSA and CEA to identify (combinations of) process parameters most influencing the material properties. These studies have been presented in [17].

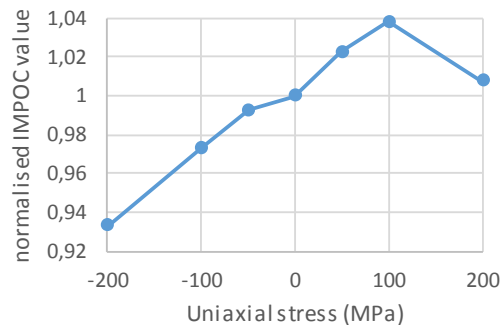
## 2.4 Evaluation of texture

Forming steels, in particular those which are subjected to deep drawing processes, are designed to exhibit anisotropic deformation behaviour. The deep drawability is expressed in the plastic strain ratio  $r_\alpha$ , which describes the material resistance to thinning when strained in direction  $\alpha$  with respect to the rolling direction. The r-value is strongly related to crystallographic texture, i.e. a preferred orientation of the crystals in the microstructure. Texture also manifests itself in anisotropy of the magnetic and ultrasonic properties.

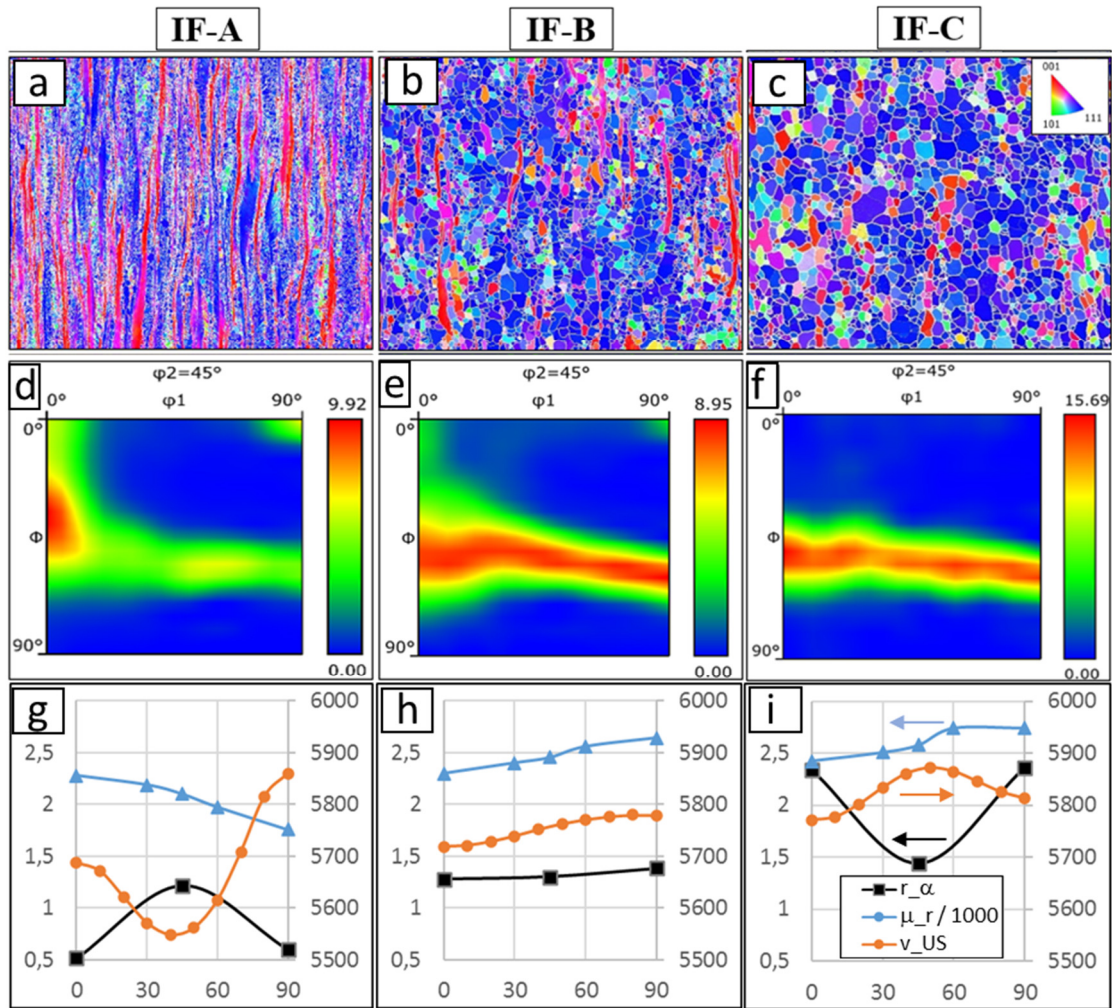
To study the interrelation between the different anisotropies, an annealing trial in a production plant has been arranged to produce steel strip with a gradual transition from alpha-fibre texture to gamma-fibre texture. Samples have been taken at different length positions to cover a wide range of texture states, and analysed in the laboratory on their microstructure, texture and (ultrasonic, magnetic, mechanical) anisotropies.



**Figure 4: (a) Influence of uniaxial stress on the major BH loop for a dual phase steel grade; (b) Stress-dependence of the (normalised) Jiles-Atherton parameters fitted to these curves.**



**Figure 5: Simulated IMPOC response for different stress levels, based on the results in Figure 4. Values are normalised to the stress-free situation (0 MPa).**



**Figure 6: (a-c): IPF figures showing the grain structure; (d-f): ODF plots showing the texture; (g-i): anisotropy plots of: r-value ( $r_\alpha$ ), magnetic permeability at  $H = 350A/m$  ( $\mu_r$ ) and ultrasonic wave speed ( $v_{US}$ ) versus planar angle (x-axis) with respect to rolling direction.**

Figure 6 shows the results from EBSD analysis (details provided in [18]) on 3 samples, the first (IF-A) being halfway recrystallisation, next IF-B being further, but not fully, recrystallised and finally IF-C which is fully recrystallised. Sample IF-A still has a deformed microstructure from cold-rolling (Figure 6a), whereas IF-C (Figure 6c) shows a clear granular structure. The middle row of Figure 6 shows the orientation distribution function (ODF) plots obtained from the EBSD analysis, demonstrating the alpha-fibre texture in sample IF-A, which develops towards a pronounced gamma-fibre texture in sample IF-C. The bottom row plots in Figure 6 show the r-values obtained from tensile testing. In particular  $r_0$  and  $r_{90}$  are low (around 0.5) for IF-A, and drastically increase during recrystallisation to ultimately arrive at about 2.4 in case of IF-C. On the contrary, the  $r_{45}$  is already above 1 for IF-A and rises only marginally to 1.5 for IF-C. Figure 6 (g-i) also show the magnetic and ultrasonic anisotropies. The magnetic data have been measured by a magnetic strip tester at Warwick University using steel strips cut in different directions, and is presented here as the relative permeability at an applied field strength  $H = 350A/m$ . The ultrasonic S0 wave speed anisotropy has been measured by an EMAT system (at partner TNO) operating at 200 kHz frequency, which rotates over

plate samples. Interestingly, along the rolling direction (angle = 0°) the magnetic permeability (and also the ultrasound speed) is approximately equal for all three samples, while the anisotropy of these properties swaps during the texture transition: note the changes in ultrasonic speed at 45° and in magnetic permeability at 90°. The ultrasonic experimental results could be quantitatively reproduced in numerical simulations employing finite difference modelling taking as input 3D microstructure geometry representations having the textures shown in figure 6 (d-f), as reported in [19].

### 3. Conclusions

The EU-funded project "Online Microstructure Analytics (OMA)" has progressed the developments in inline sensing of microstructure and material properties in the harsh conditions encountered in manufacturing of steel strip. Characterisation of microstructural parameters like grain size and metallurgical phase composition in real time at short interval length (in the order of 1 – 2 metres) offers unrivalled opportunities for process improvements and quality control in the supply chain. The various scientific and technological advances are presented in depth in more than 10 contributions to the present ECNDT conference.

### Acknowledgements

This project has received funding from the Research Fund for Coal and Steel under grant agreement No 847296.

### References

- [1] <https://worldsteel.org/steel-topics/steel-markets/automotive/> (retrieved 5 Feb 2023)
- [2] T. Hanamura et al: "Effect of austenite grain size on transformation behaviour, microstructure and mechanical properties of 0.1C-5Mn martensitic steel", ISIJ Int. Vol. 53, No 12, pp. 2218-2225, 2013
- [3] M. Malmström et al: "Laser ultrasonics for online monitoring of microstructures in the hot strip mill", paper no. 190 ECNDT conf. Lisbon, July 2023.
- [4] M. Malmström et al: "Laser-Ultrasound-Based Grain Size Gauge for the Hot Strip Mill", Appl. Sci. 2022, 12(19), 10048;
- [5] H. Yang et al: "On the use of inline phase transformation sensors in a hot strip mill: case studies", paper no. 1, ECNDT conf. Lisbon, July 2023.
- [6] J. Wilson et al: "High temperature magnetic properties of selected steel grades", paper no. 3, ECNDT conf. Lisbon, July 2023.
- [7] A. Martinez-de-Guerenu et al: "Non-destructive magnetic evaluation of microstructure and mechanical properties of advanced high-strength steels", paper no. 105, ECNDT conf. Lisbon, July 2023.
- [8] F. van den Berg et al.: "Results of the European collaborative project "Product Uniformity Control" to improve the inline sensing of mechanical properties and microstructure of automotive steels.", paper no. 265, ECNDT Conf. Gothenburg, 2018.
- [9] V.F. Matyuk et al: "The plant for pulse magnetic on-line testing of mechanical properties of rolled products", paper Th.3.7.5, ECNDT conference 2006
- [10] The IMPOC system is commercialised by EMG Automation, Wenden, Germany



- [11] The PropertyMon system is commercially available from Primetals Linz, Austria.
- [12] O. Hubert et al.: "Influence of biaxial stress on magnetic behavior of hot-rolled steels", paper no. 37, ECNDT conf. Lisbon, July 2023.
- [13] P. Lombard et al.: "Formulation of a Mechanical Stress Dependent Macroscopic Magnetic Model for Incremental Permeability Simulation", paper no. 34 ECNDT conf. Lisbon, July 2023.
- [14] D.C. Jiles and D.L. Atherton: "Theory of ferromagnetic hysteresis", J. Applied Physics. 55, pp 2115- 2120, 1984.
- [15] M.J. Sablik and D.C. Jiles: "Coupled magnetoelastic theory of magnetic and magnetostrictive hysteresis", IEEE Trans. Magn. 29, pp 2113–2123, 1993.
- [16] I.I. Lobanova et al.: "Micromagnetic modelling of magnetostriction under uniaxial stress", J. Magnetism and Magnetic Materials 564 (2022) 170028.
- [17] R. Miorelli et al.: "Development of AI based analysis tools for online monitoring of steel-making process", paper no. 44, ECNDT conf. Lisbon, July 2023.
- [18] M. Jolfaei et al: "Non-destructive evaluation of magnetic anisotropy associated with crystallographic texture of interstitial free steels", Journal of Magnetism and Magnetic Materials, Volume 568, 2023, 170374
- [19] A. Duijster et al.: "Estimation of the stiffness tensor from Lamb wave velocity profiles measured on steel with different texture", paper no. 75 ECNDT conf. Lisbon, July 2023.