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Results of the European collaborative project "Product Uniformity Control" to improve the inline sensing of mechanical properties and microstructure of automotive steels

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Abstract

From 2013 to 2017, a European consortium consisting of four major steel manufacturers and 10 academic technology institutes has conducted a research and development project, called "Product Uniformity Control" (PUC) [1], with the aim to enhance non-destructive (inline) measurement techniques to characterise the (uniformity of the) microstructure of steel strip products.

In this project, a multitude of strip steel samples from various stages of production have been collected from the four participating steel manufacturers. The samples have been characterised in various ways, namely on their (1) non-destructive measurement parameters using different non-destructive evaluation (NDE) techniques, (2) fundamental ultrasonic (US) and electromagnetic (EM) properties (wave speed, ultrasonic attenuation, magnetisation loops, coercive field), (3) tensile properties (stress-strain curves) and (4) microstructure. The analysis of these characterisations will be addressed.

Besides the experimental characterisation, a strong accent has been on modelling activities: during the project, fundamental models have been developed to describe, starting from 2D and 3D microstructures, the ultrasonic and magnetic properties, which are next used as input to sensor models that predict the output of the measurement equipment.

This contribution presents the recent results of experimental work, which underlines the importance of associated modelling studies for the interpretation of the measurement data for the benefit of inline characterisation of the mechanical properties complementary to traditional destructive tensile testing.

1. Introduction

In view of the ever increasing competitiveness in the production of steel structures and components, the yield of the entire manufacturing chain is of huge importance. Higher production yields imply lower waste, lower cost, higher throughput and hence a higher profit. Moreover, it contributes to the circular economy objectives.

Besides the focus on supply chain yield, there is an increasing demand for weight reduction and structural health of structures and components. These trends, which are mainly driven by the automotive and transport sectors, with the objective to reduce total life cycle emissions and increase passenger safety, have strongly stimulated the development and application of advanced high-strength steels (AHSS). The share of AHSS in personal cars' body-in-white has increased from ~5% in 2003 to ~25% in 2017.

AHSS owe their higher strength to the finer dispersed granular microstructure containing various metallurgical phases like martensite, bainite, ferrite and pearlite, whereas the traditional low carbon steel contain primarily ferrite with 5 – 20 times larger grains. The more complex microstructure of the AHSS, in combination with the increased focus on yield, has motivated four main European suppliers of automotive steel strip to collaborate on technological developments to monitor the uniformity of the microstructure of steel strip during production.

In a partnership with 10 academic institutes (see author affiliation list), the steel suppliers Tata Steel (coordinator), ArcelorMittal, thyssenkrupp Steel Europe and Salzgitter have run a common research and development project from July 2013 until December 2017, with subsidy from the Research Fund for Coal and Steel (RFCS). During this project, a significant amount (~200) of samples have been collected from production plants, some of which (~30) have been used to produce reference microstructures to evaluate various ultrasonic and electromagnetic non-destructive testing techniques. The samples have finally been characterised destructively on their fundamental physical and mechanical properties and on their microstructure. The microstructures have been mimicked in a specific microstructure descriptor language for forward modelling of their fundamental ultrasonic and electromagnetic properties. In their turn, the fundamental ultrasonic and electromagnetic properties have been used in instrument models to predict the output of the inline measurement techniques under various measurement conditions in dedicated parametric studies.

2. Background

The wide range of applications of steel is largely due to two factors: the abundance of iron ore, rendering it an economically attractive material, and the ability to tune its mechanical properties to meet a large variety of needs in terms of strength and forming possibilities. To obtain the desired mechanical properties, different microstructure parameters can be modified, e.g. the alloying content, dislocation density, precipitation size and number density, grain size and grain morphology, secondary phase fractions and crystallographic texture. The mechanism behind "strengthening" is to impede the motion of dislocations; forming properties can be further tailored by making use of the anisotropy in deformation behaviour of a textured grain structure and different grain morphologies.

In this project, the effect of these so-called "strengthening mechanisms" via microstructural changes on the EM and US properties has been systematically investigated. Previous collaborative projects [2-6] attempted primarily to obtain empirical relationships between mechanical strength parameters and EM and US properties. Such an approach is fine as long as the steel grade portfolio slowly develops; however, in recent years, new steel grades with more complex microstructures are being introduced to the market at an accelerating pace. For this reason, a more fundamental approach has been followed to develop and validate models that describe the relations between the microstructure (of automotive steels) and the EM and US base properties. In addition, models have been developed to relate the output data of NDE instruments to the basic EM and US properties. With the instrument models, also side-effects due to (variation in) lift-off, strip speed and other measurement conditions have been studied.

Literature already provides many data and models on e.g: the relation of magnetic properties as a function of grain size [7-12], dislocation density [10,13,14], precipitation density [15] and the degree of recovery and recrystallization [16-18]. Many studies on magnetic properties of steels concentrate on grades for magnetic applications (i.e. FeSi grades), having significantly different composition and microstructure than the structural steels for automotive applications, which are the interest of the steel manufacturers in the present research collaboration. With regard to ultrasonic properties, theoretical foundations by [19,20] have been experimentally tested by [21-24] (and, together with improvements in laser-based ultrasonic measurement technology, in [25,26]), demonstrating correlations with the average grain size and simultaneously showing the need to understand effects from different grain size distributions, grain morphology, precipitation and complicated microstructures containing multiple phases.

In the present and previous conferences, a number of papers have described the fundamental models and instrument models and their verification [27-34]. In this contribution, the focus will be on the results obtained from the analysis of steel strip sections that have been cut into samples to investigate the sensitivity of different (inline) measurement techniques to detect non-uniformities in the microstructure.

3. Experimental approach

Sections of the steel strip with suspected non-uniformity have been selected based on (relatively) strong variations in either process parameters like temperature, or EM data that has been measured inline on the product. A typical example of how the sample taking has been done is sketched in Figure 1. Here an overshoot in the temperature in the continuous anneal furnace has occurred, causing a part of the micro-alloyed (MA) strip (70 - 80 m) to be heated above 900 °C, i.e. above the austenitisation temperature.

To assess if EM and US techniques could discriminate between uniform and non-uniform parts, a total length of about 200 m of strip has been removed, also containing a long uniform section of about 100 m length prior to the temperature overshoot, as well as a short length of about 20 m where the temperature was back to normal. With a period of 5 - 7 m, the following samples have been cut out:

- 500 mm x 500 mm for EM measurements
- 500 mm x 500 mm for preparation of dogbone samples for tensile testing
- Narrow 100 mm wide samples for US measurements and microstructure characterisation.

Samples have been labelled consistently to bookmark their position and orientation.

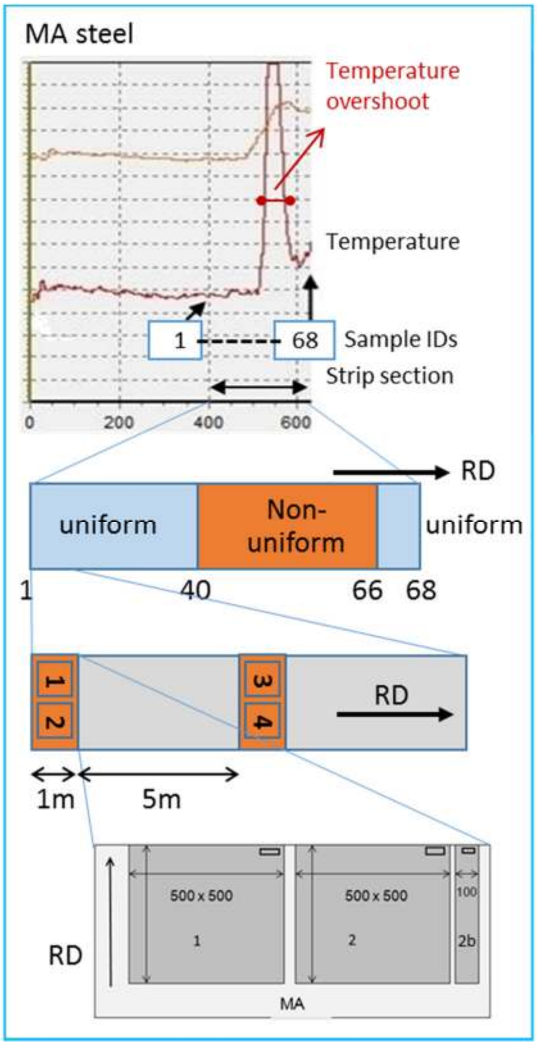

Figure 1. Strip section selection based on temperature profile and sample definition. The acronym RD signifies Rolling Direction.

Figure 2 shows an example where the sample taking has been based on an inline magnetic measurement method (IMPOC system), which makes a measurement at an interval rate of 2 m strip length. In Figure 2, one can observe a significant increase of the IMPOC signal in the first 60 metres of a Dual Phase (DP) steel strip. Here, samples have been collected at length positions of 10, 20, 30, 40 and 50 m; at each length position, 2 samples have been cut.

4. Microstructure investigation

For three samples from the MA grade strip (see Figure 1) the microstructures were determined with light microscopy (Figure 3 a-c), as well as their texture by X-ray diffraction (Figure 3 d-f); Two samples are from the non-uniform region with the temperature overshoot (samples 51 and 53) and one from the regular section (sample 65). Samples 51 and 53 show a microstructure that is typical for a transformed material after phase transition to austenite. The textural plots represent the orientation distribution

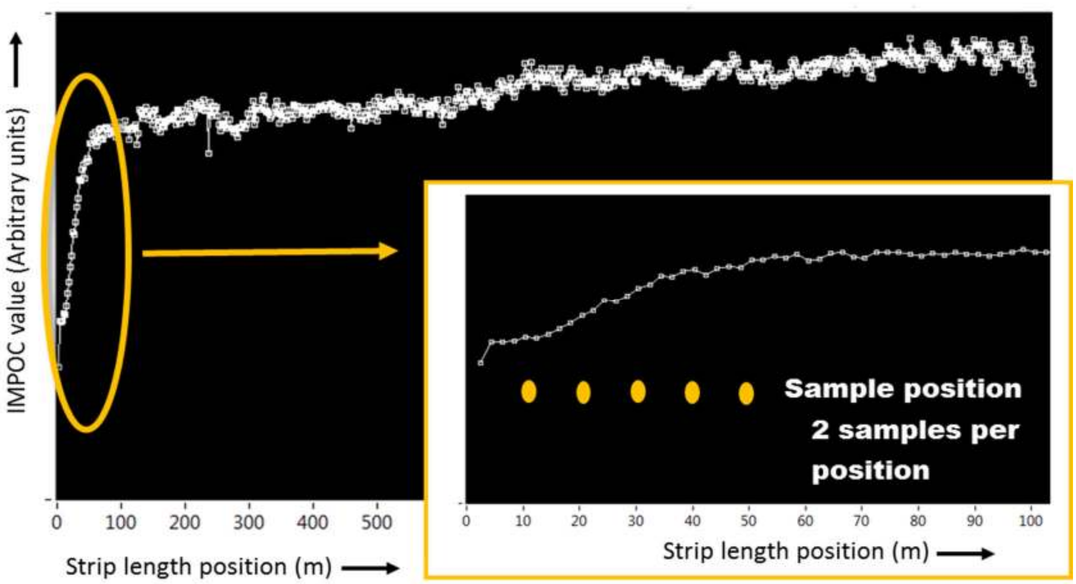

Figure 2. Illustration of selection of non-uniform dual phase steel strip section based on inline electromagnetic measurement (IMPOC); inset: indication of the positions where samples have been cut for laboratory characterisations.

functions (ODF) at cross section plane $\phi 2 = 45°$. The ODFs of sample 51 and 53 show a weak gamma fibre texture, i.e. a crystallographic {111} plane parallel to the rolling plane, with nearly uniform intensity along the fibre. The ODF of sample 65 from the regularly processed region shows significantly stronger intensity near the alpha fibre.

5. Measurement results on MA: EM, US and Mechanical Properties

Figure 4 shows the results of the analysis of the MA samples on their tensile properties (yield (Rp02) and tensile strength (Rm)) and a selection of EM and US measurements. Some measurements have been done in both rolling (RD) and transverse directions (TD).

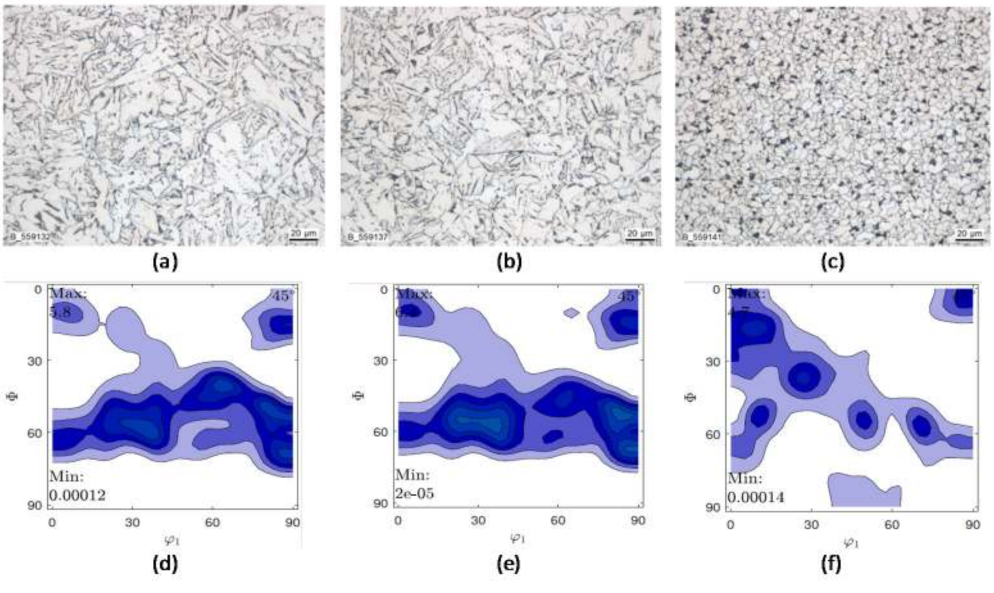

Figure 3. Micrographs (top) and texture ODFs (bottom) of samples 51 (a + d); 53 (b + e) and 65 (c + f). Samples 51 and 53 were heat affected, sample 65 is from the uniform region.

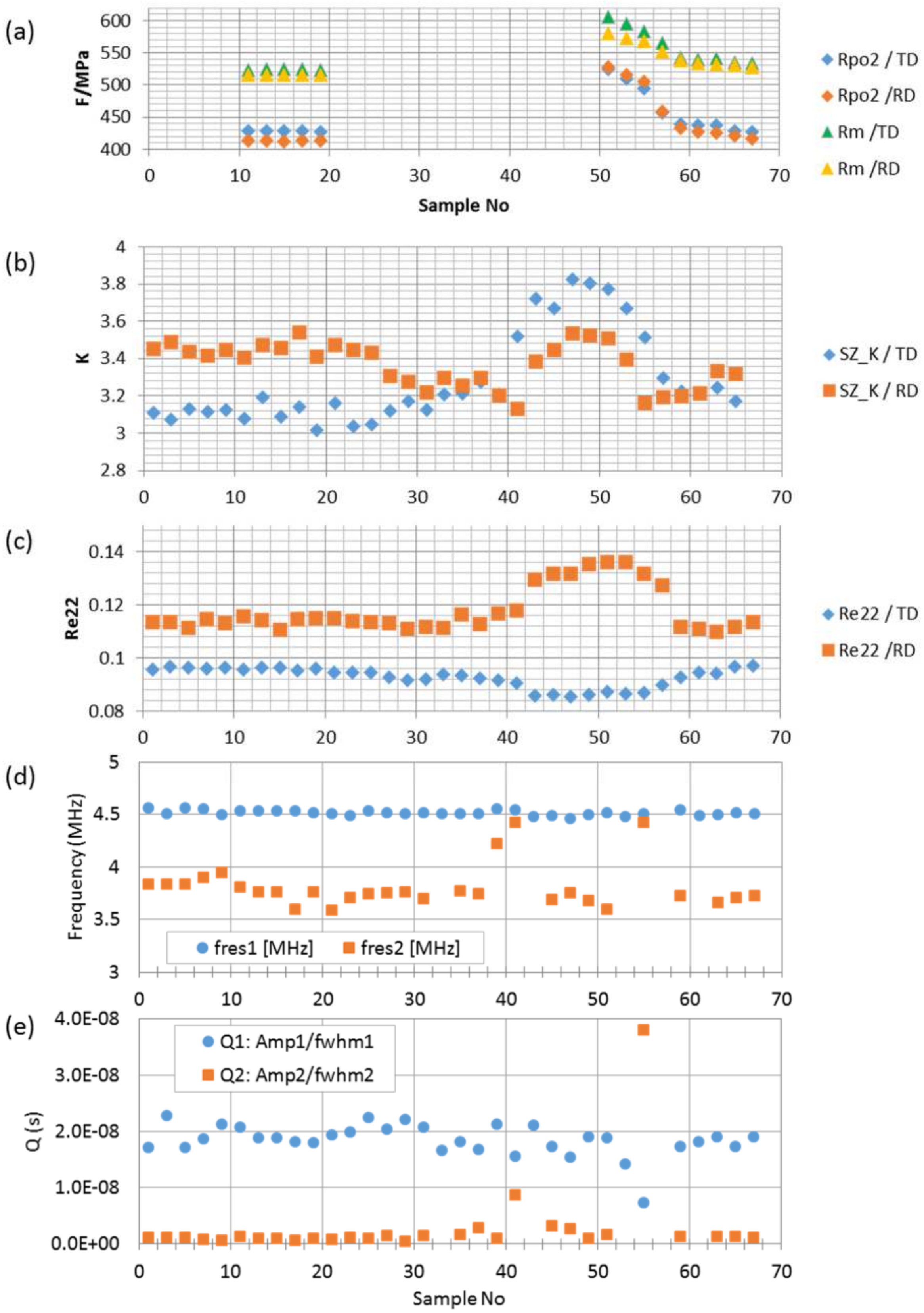

Figure 4. Results obtained on the MA samples, of (a) Tensile testing; (b) EM distortion factor K; (c) EM Harmonic analysis parameter Re22; (d) US resonance frequencies; (e) US attenuation. See text for details.

Figure 4a clearly demonstrates the strength increase in the region with the temperature overshoot. Note also that the small anisotropy in the tensile properties in the regular region (samples 10-20 and > 64) switches oppositely in the affected process regime, which is connected to the change in texture observed in figure 3. Additional data (not plotted) from the tensile tests like E-modulus and anisotropy (r-value) showed nearly no influence, the elongation before fracture (A80) decreased strongly in the heat affected region.

Figure 4b shows the magnetic distortion factor K, measured by the 3MA system [35] and figure 4c presents the Re 22 parameter from a harmonic analysis measurement by the HACOM system [3]. Both K and Re22 have been determined in the RD and TD directions. The heat affected section of the strip can be clearly distinguished in all these measurements. In addition, the change in texture in the non-uniform region modifies the anisotropy in K and Re22.

The samples also have been characterised on their US properties by Fast Fourier Transformation (FFT) analysis of the resonance signals from longitudinal ultrasound waves in normal direction using a 4 MHz conventional transducer. The FFT spectra were analysed by fitting to Lorentzian functions, from which amplitude, frequency position and full width at half maximum (FWHM) were derived. Figure 4d shows the first two resonance frequencies and figure 4e shows the amplitude divided by the FWHM which can be regarded as a measure for the attenuation. In the US parameters, some data points deviate, but no systematic behaviour can be observed. The fluctuations are believed to be mainly due to variations in sample thickness.

6. Measurement results on DP: EM, US and Mechanical Properties

Figure 5a depicts the tensile test results from the Dual Phase steel samples that have been sampled based on the non-uniformity indication of the inline IMPOC signal, as displayed by Figure 2. The 'statistics' of 2 samples per length position allow an impression of the scatter in these properties to be obtained, being as small as about 2 MPa. There is a consistent increase in strength at the head of this strip, of the order of 5 and 10 MPa for Rp02 and Rm respectively, representing a relative change of less than 2%. Even though this is a small increase, the magnetic measurements appear to be strongly sensitive to the underlying change in microstructure. Figure 5b shows that the upward trend in the inline IMPOC signal can be reproduced in the lab, although the lab values at length position = 50 m slightly drop again. The harmonic analysis Re22 parameter correlates very well with this trend, and has even a little higher sensitivity, but also more scatter. Also the distortion factor K, displayed in figure 5c, correlates very well with the other EM signals. The various US parameters deduced from resonance ultrasonics (figure 5c only shows the difference between the first two resonance frequencies) did not exhibit any correlation either with the tensile or with the EM measurements.

7. Discussion

The results in this paper demonstrate that process measurements and inline measurements can be used to select strip sections with microstructure variations. The example for the MA steel grade concerns a relatively strong microstructure variation, which was clearly

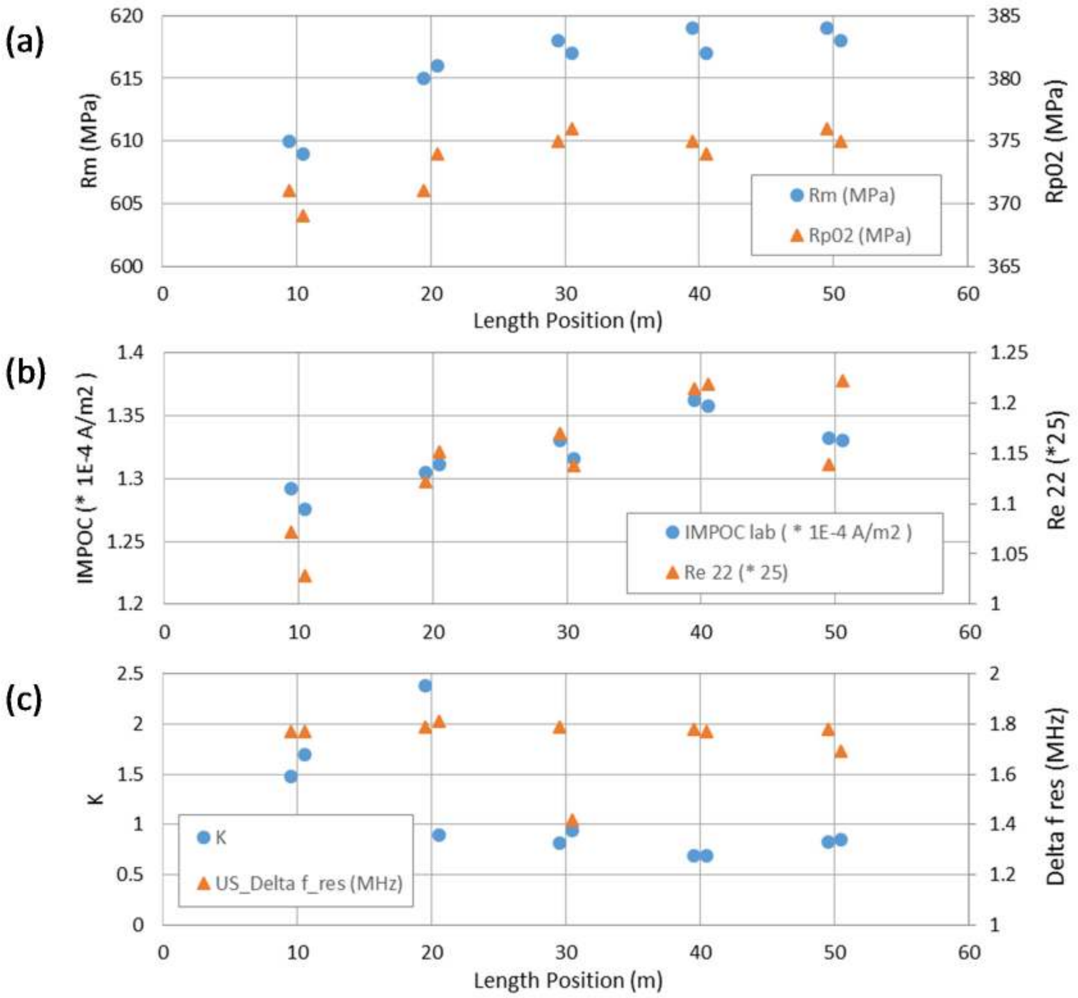

Figure 5. Results of laboratory characterisations of the DP steel samples. (a) Tensile testing; (b) EM IMPOC and harmonic analysis parameter Re22; (c) EM distortion factor K and US different frequency between resonance peaks. To improve visibility, an offset length position of - 0.5 m and + 0.5 m has been given to the real sample position.

observable in micrographs and textural analysis and in the tensile properties. In the daily practice, variations in mechanical properties within a given steel grade are small, in the order of 1 – 2 %. The associated fluctuations in the microstructure are very subtle and hardly quantifiable with the current microstructure and texture characterisation tools (e.g. microscopy, electron backscatter diffraction and X-ray diffraction) unless exceptionally large surfaces or volumes are analysed at high resolution. The case of the DP grade described in section 6 is an example where the microstructure differences are too small to be detected with conventional microstructural analysis, but still gave differences in mechanical properties. Still, various magnetic characterisation techniques appeared capable of consistently detecting these small variations with remarkably high sensitivity.

The way in which these magnetic techniques react to changes in the microstructure is also influenced by the texture, as demonstrated by the different response trends of the bi-directional measurements for the MA samples. This result underlines the importance of gaining insight in the anisotropic response in relation to texture and microstructural morphology. The latter aspect has been partly studied in [29].

8. Conclusions

In mass scale manufacturing, it is essential to produce material with consistent product quality. In particular for the newest AHSS generations, the microstructure is much more critical to the exact processing history. To guarantee quality and yield for these and future steel grades, the traditional approach of set-point driven process-control is being replaced by more dynamic ways of process control, like (model-based) predictive and adaptive control, based on inline measurements of the microstructure state of the material. Because of the complexity of the AHSS microstructures, the interpretation of EM and US-based inline measurement data requires important research efforts.

The approach in this study has been to use inline measurement technology to identify non-uniform strip sections, which have then been cut into samples for laboratory characterisation of the electromagnetic, ultrasonic, mechanical and microstructure properties. The microstructure of the investigated MA and DP structural steels appears to be too finely dispersed to detect variations with high-frequency conventional ultrasonic transducers. Electromagnetic measurements were shown to be strongly sensitive to these variations. In a relative sense, their sensitivity is even more than a factor 4 higher than the effect of the same microstructure variations on the mechanical strength properties. Since the microstructure variations in regular production steels are generally small, and often too small to be pinpointed by common destructive microstructure characterisation methods, it can be difficult to attribute the variation in EM properties to a given microstructure parameter. Hence, knowledge of the metallurgy and the material's process history is a prerequisite to interpret the (inline) EM measurement data in terms of the uniformity of microstructure and mechanical properties.

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