# ONLINE MATERIAL CHARACTERISATION OF STEEL SHEETS IN HOT-DIP GALVANIZING LINES BY MEANS OF HARMONIC ANALYSIS OF EDDY CURRENT SIGNALS

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**Abstract:** Cold rolled flat steel is still the classic material for the automotive industry and as quality demands ever increase it becomes necessary to characterize not only singular test samples at isolated positions of the steel strip but to provide immediate information on the produced steel sheet quality over the entire length of the steel strip. Since such a online testing of a product can for obvious reasons only be provided by nondestructive and non-contact testing methods, a measuring system was developed which uses the harmonic analysis of eddy current signals. It is based on the fact that the material condition, that is its arrangement of structure, grain size, alloy composition, dislocation density etc. define not only the mechanical-technological characteristic values like yield strength $R_{p0.2}$ and tensile strength $R_m$ but also the electrical and magnetical properties of a material. This indirect relationship is used to compute e.g. the $R_{p0.2}$- and $R_m$-values solely from harmonic measuring values using multi-dimensional regression analysis.
The online implementation of this system, the Harmonic-Analysis-Coil-Online-Measuring system HACOM, makes possible the monitoring of characteristic material values like the $R_{p0.2}$- and the $R_m$-values in order to maintain the highest possible product quality. The HACOM-system has been in operation in the two Salzgitter-Flachstahl GmbH SZFG´s hot-dip galvanizing lines for more than 3 years monitoring more than 55000 steel strips from a large variety of steel qualities over their entire length. It reliably provides highly accurate information on the named material characteristics as well as precise indication of changes of the material structure which may be caused by variations of furnace temperature, degree of skin-passing as well as degree of levelling.

**Introduction:** Cold rolled flat steel and galvanized steel sheets are classic materials for the automotive industry and one of the major products of steelmaking plants. To ensure the qualtity of the products it becomes necessary to characterize not only test samples of the beginning and the end of a produced steel strip but to provide information on the produced steel sheet quality over the entire length of the steel strip. Destructive testing systems are obviously not the appropriate means to this task of online quality checks. These systems are not only requiring too much time including a time-lag but are also destroying the test samples during the tests, i.e. in destructive quality checks the entire product is destroyed. Therefore, a nondestructive and non-contact measuring system was developed at the IW, which uses the harmonic analysis of eddy current signals to determine characteristics of the measured steel strip [5,6,7,8]. As shown in [3,4] the system is based on the fact that there is an indirect relationship between the mechanical-technological characteristic properties like yield strength $R_{p0.2}$ and tensile strength $R_m$ and the electrical and mechanical properties of the material because both properties are defined by the material condition, that is the arrangement of structure, grain size, alloy composition, dislocation density etc. and the manufacturing process. This relationship is used for an indirect determination of the desired characteristic material properties computing mechanical-technological properties solely from harmonic measuring values using multi-dimensional regression analysis [1,2].
The *H*armonic-*A*nalysis-*Coil*-*O*nline-*M*easuring System HACOM was implemented in two Salzgitter-Flachstahl GmbH SZFG's hot-dip galvanizing lines so that it was possible to maintain the characteristic material values like the $R_{p0.2}$- and the $R_m$ -values in order to maintain the highest possible quality of the steel strips. The system has been in operation for more than 3 years

monitoring more than 55000 steel strips from a large variety of steel qualities and thickness over their entire length.

**Results:**

**Determination of strength values:** To show the quality of the measured data the nondestructively determined strength values are compared with strength values of tensile test samples taken at the beginning of each steel strip. Due to different magnetic properties caused by different chemical composition and different manufacturing parameters, especially heat treatment, it is necessary to divide the measured data into groups of comparable steel qualities. After subdividing these data into groups of comparable sheet thickness to minimize the disturbing effect of different thickness regression analysis' computations were performed.

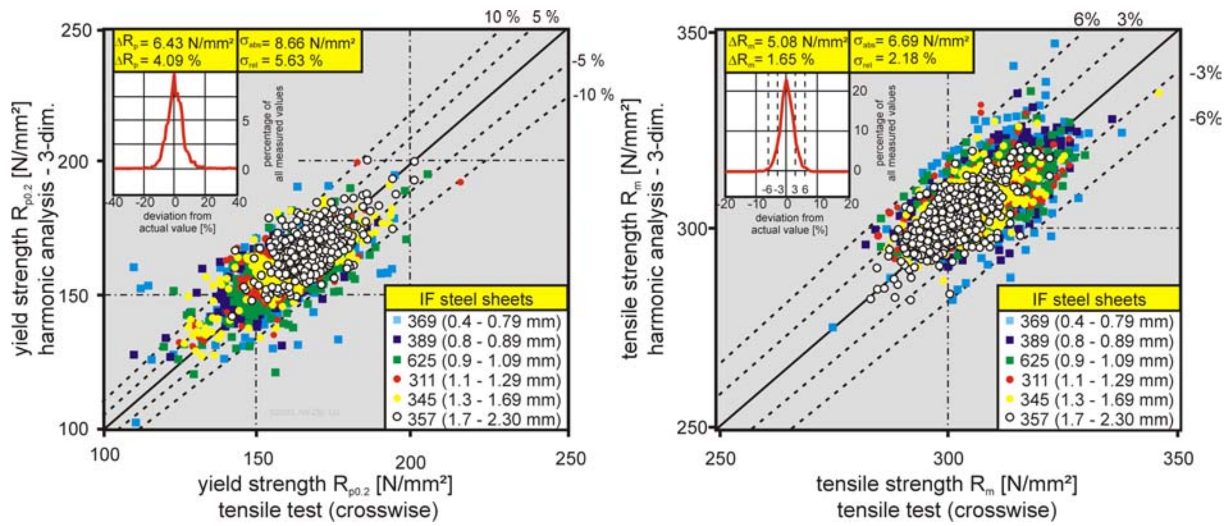



**Figure 1:** 3-dimensional regression results for IF-steels measured in HDG2

The example shown in figure 1 presents the results of a 3-dimensional regression for IF-steel qualities which are commonly used in the automotive industry. For these qualities there were roughly 2400 steel strips for which destructive data were available as reference values. The nondestructively determined strength values show a good accuracy compared with the destructively measured values. About 80% of the tensile strength values are located in a deviation interval of ±3% resp. nearly all strength values in a ±6%-deviation interval from the regression line with a relative deviation of □$R_{m,rel}$ = 1.65% and □$_{rel}$= 2.18%. The scattering of the yield strength values compared with the tensile strength is higher with relative deviations of □$R_{p,rel}$ = 4.09% resp. □$_{rel}$= 5.63%. These higher values are caused by the much lower values for the yield strength so that the absolute deviation values for the tensile strength with □$R_{m,abs}$ = 5.08 N/mm² and □$_{abs}$= 6.69 N/mm² and the yield strength with □$R_{p,abs}$ = 6.43 N/mm² and □$_{abs}$= 8.66 N/mm² are at the same level.

The 3-dimensional regression results of 1040 high-strength S-steel qualities are presented in figure 2. The results also show a good accuracy of the nondestructively determined strength values with deviations of □$R_{m,abs}$ = 12.26 N/mm² resp. □$R_{m,rel}$ = 2.67% and □$_{abs}$= 9.84 N/mm² resp. □$_{rel}$= 2.11% for the tensile strength and □$R_{p,abs}$ = 8.80 N/mm² resp. □$R_{p,rel}$ = 2.77% and □$_{abs}$= 6.87 N/mm² resp. □$_{rel}$= 2.15% for the yield strength. The distribution curves in figure 2 indicate that the majority of the measured steel strips deviate less than ±3% for the tensile strength $R_m$ and less than ±5% for the yield strength $R_p$.

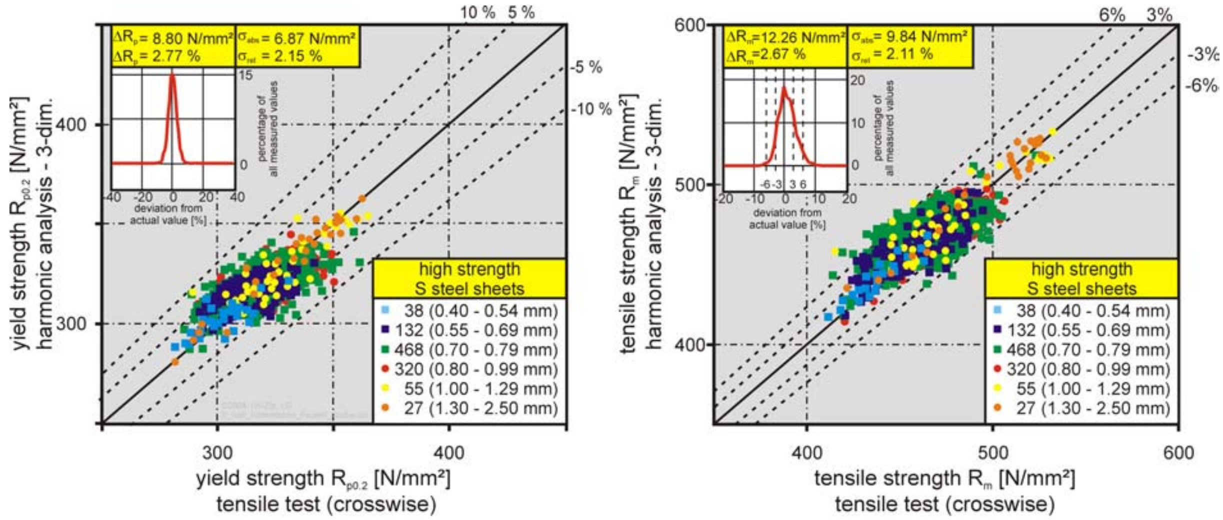



**Figure 2:** 3-dimensional regression results for high strength S-steels measured in HDG2

**Influence of disturbing values:** In the examined case of a hot-dip galvanizing line the production line includes amoung others a furnace for deoxidation and recrystallization of the steel sheet as well as a temper mill and a leveller. These are integrated into an online process control system and may therefore exert varying influences on the steel sheet during its passing through the production line. Their influences on the harmonic measuring values are shown below.

**Degree of levelling:** A means to adjust the mechanical characteristics of steel is cold straining. In the case of the SZFG's hot-dip galvanizing line a leveller is integrated into the production line towards this end.
The usual range of the degree of levelling is from 0% to 2%. Figure 3 presents an example concerning the degree of levelling, an IF-steel of 0.8 mm sheet thickness. In the upper part the degree of levelling as well as the computed yield strength values are shown. At the beginning of the second quarter of the steel sheet there is a peak of the degree of levelling followed by a longer passage of approximately 0.7% degree of levelling before it is reduced to roughly 0.35% at the end of the second quarter. The computed yield strength values clearly indicate this development of the degree of levelling. In the lower section of figure 3 those Harmonic Measuring values are presented which are used to compute the yield strength values. Obviously the real part of $11^{th}$ harmonic of the $2^{nd}$ frequency is insensitive to changes of the degree of levelling whereas the imaginary part of the $1^{st}$ harmonic of the $2^{nd}$ frequency and especially the imaginary part of the $5^{th}$ harmonic of the $4^{th}$ frequency show linear dependencies to the degree of levelling. However, since the latter do have a significantly higher valence within the correlation equation of up to 40 compared to the $11^{th}$ harmonic the insensitivity of the $11^{th}$ harmonic is of no significance.

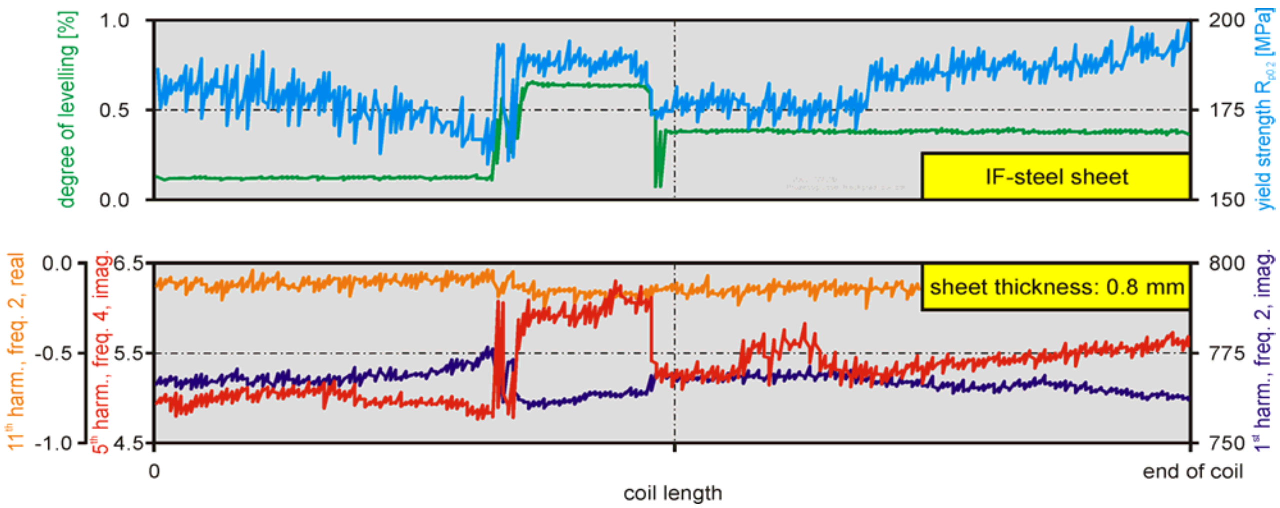



**Figure 3:** Influence of the degree of levelling

**Degree of skin-passing:** Among others a hot-dip galvanizing line integrates a temper mill to apply a specified degree of skin-passing in order to create dislocations in a small layer below the steel sheet surface and thus to eliminate a distinct yield strength without influencing grain size or texture.

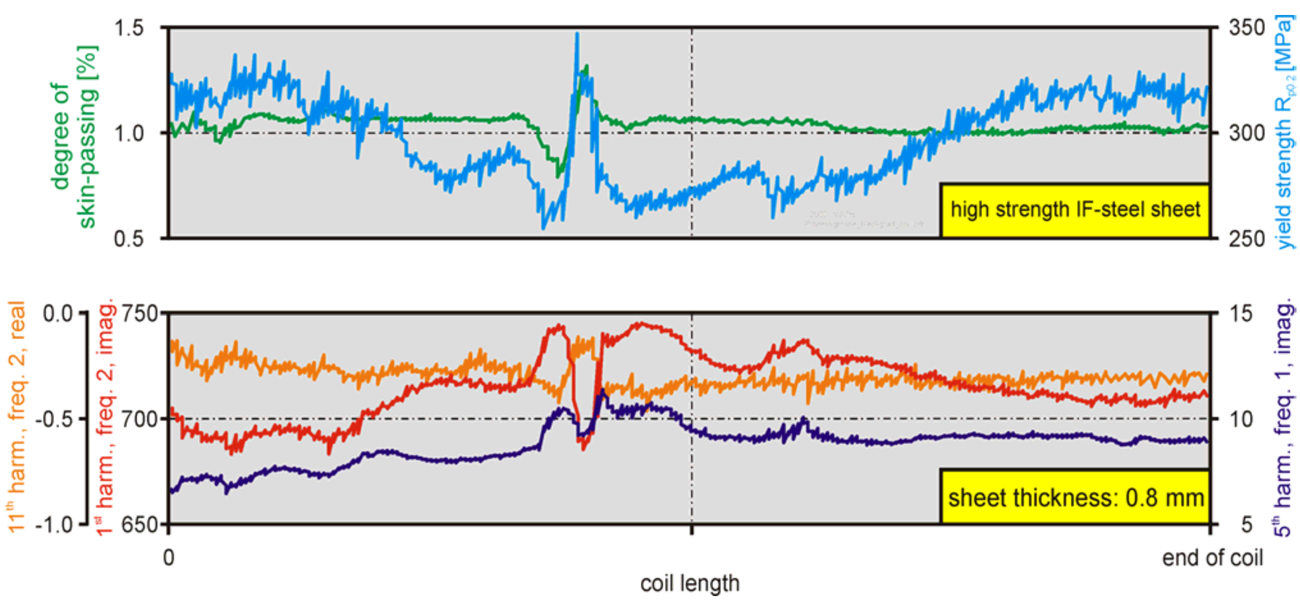



**Figure 4:** Influence of the degree of skin-passing

The example (fig. 4) shows a short yet pronounced irregularity of the degree of skin-passing during the production of a high strength IF-steel sheet of 0.8 mm sheet thickness. After a brief incursion to roughly two thirds of the apparent nominal value the degree of skin-passing increases momentarily from 0.8% to 1.3% before returning to its former level. This irregularity is reflected correctly, for example in the computed yield strength values increasing from 260 MPa to 320 MPa and returning to its former level. The harmonic measuring values which are used for these computations show counter-current curves compared to that of the degree of skin-passing, correlating precisely. Only the real part of the 11$^{th}$ harmonic value of the 2$^{nd}$ frequency does not show this behaviour as obviously as the other used Harmonic Measuring values.

**Changes of furnace temperature:** The *Harmonic Analysis Coil Online Measuring* system HACOM is sensitive to external influencing factors which induce changes within the material. Since these dependencies are especially important for those Harmonic Measuring values on which the correlations regarding yield strength $R_{p0.2}$ and tensile strength $R_m$ are based these are primarily examined. Considering the fact that carefully selected Harmonic Measuring values are linearly correlated to mechanical characteristic values it is easily demonstrated that thus the computed values for yield strength $R_{p0.2}$ and tensile strength $R_m$ also reflect the behaviour of process variables like the furnace temperatures.
Additionally, it was possible to extract steel sheets from the production line which had been especially released for this purpose. From these test sheets tensile test samples as well as metallographic test specimen were taken and analysed. The results prove conclusively the reliable dependencies of the Harmonic Measuring values on process variables which induce changes in the material corresponding with the knowledge of the material science.

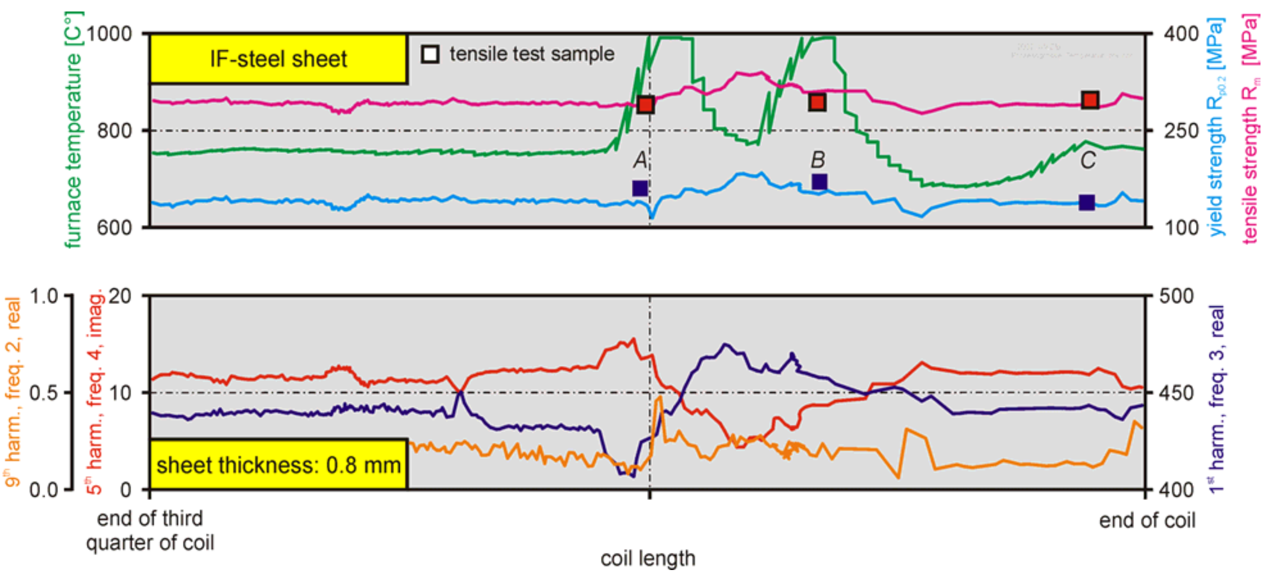
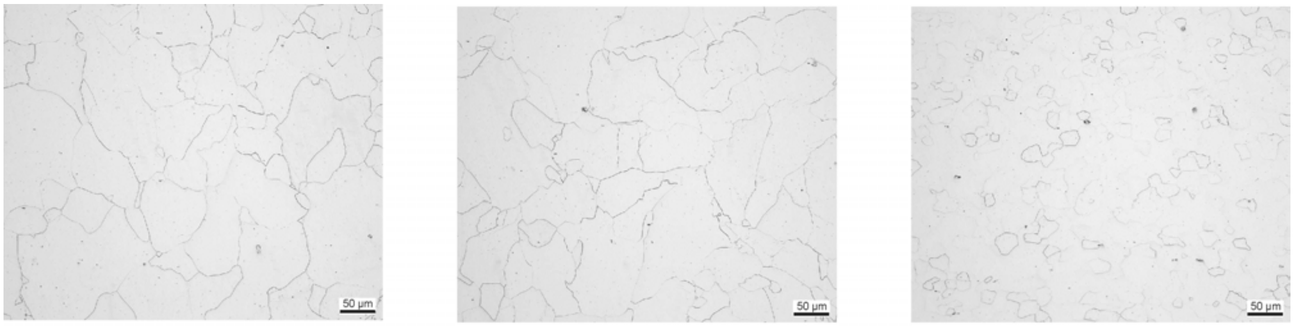



**Figure 5:** IF-steel sheet with a furnace temperature inconsistency

An example is shown in figure 5 which presents this dependency of the material, an IF-steel sheet with a sheet thickness of 0.8 mm, and thus the Harmonic Measuring values on the furnace temperature. In this special case it was possible to take tensile test samples at the indicated positions A, B and C. Their results are marked in the figure as well, clarifying once more the high quality of the correlations which are used in the HACOM-system. As in the figures above, the upper part shows the furnace temperature as well as the computed yield strength values together with the results of the tensile tests. As in the example above one Harmonic Measuring value, the $9^{th}$ harmonic of the $2^{nd}$ frequency, is evidently less sensitive to the changes in the material caused by the furnace temperature inconsistencies but its term in the correlation equation is negligible being only a $12^{th}$ respectively a $40^{th}$ of the other terms.




A B C

**Figure 6:** Metallographic specimen of the prior IF-steel sheet

However, in addition to the tensile test samples it was possible to take metallographic specimen at the same positions. The results of the metallographic inspections are depicted in figure 6. It is evident that the grain structure was changed significantly in the areas of the high furnace temperature of roughly 1000 °C because of coarsening (part A and B of fig. 6) respectively computed and measured yield strength values complying with the material scientific facts. In contrast to the first two micrographs the third (C) shows the expected fine grain indicating that the furnace temperature amounted to approximately 700 °C as required.

**Online detection of temperature-induced material changes:** In addition to the online computation of characteristic material values the HACOM-systems are able to real-time-analyse the Harmonic Measuring values with regard to temperature-induced material changes. The online-implementation of this approach is primarily the fast comparison of the complex harmonic measuring values to preselected trigger values.
Figure 7 shows exemplarily the effects of a test steel strip consciously overheated in selected parts: in the uppermost subframe the temperature of an IF-steel strip is shown over the length of the steel strip. Below that three of those harmonic measuring values which are used for the structure-analysis are exemplarily presented over the strip-length obviously indicating areas of material which was heated to temperatures above austenizing temperature. The concerned areas suffered from a transformation into a coarse grain structure (see micrographs at the bottom of figure 7) and also an entire loss of the material characteristics of cold rolled steel sheets such as texture. These temperature-induced material changes are correctly signaled (fig. 7, third graph from top) by means of a set of equations and restriction of the signaling event to another threshold. A threshold of $n_{Trig}/2$, i.e. 50% of the possible trigger events $n_{Trig}$ have to be triggered before an outward signal is given, preventing signals in areas of marginal material changes or due to other influences (e.g. the incursion of the degree of skin-passing in the first half of the strip).

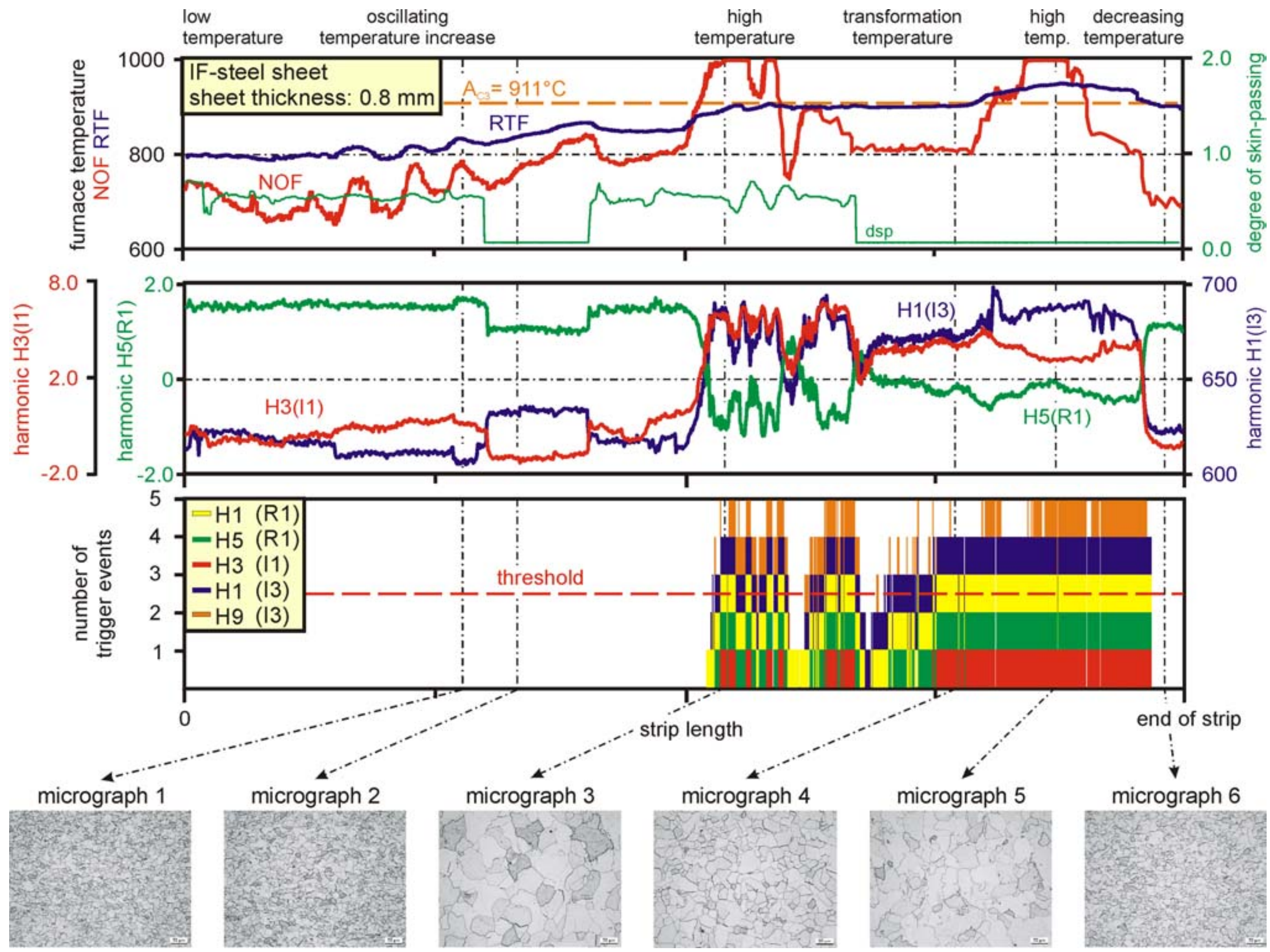


**Figure 7:** Online detection of temperature-induced material changes for test-steel strip which was consciously overheated in selected parts

**Conclusions:** The presented work shows conclusively the ability and quality of the implemented *Harmonic Analysis Coil Online Measuring*-systems for online-measuring of mechanical-technological characteristic values reflecting changes within the material reliably. It is also possible to detect and signal changes of the material structure caused by unwanted overheating of the material within the furnace of the hot-dip galvanizing line.

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