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Statistical evaluation of the measurement of residual stresses in the surface layer of CP1000 steel sheets using the magnetic Barkhausen noise and X-ray methods

Janusz Kliś[1], Rafał Nawrat[1], Jakub Olbrych[1], Michał Węgrzyniak[1], Damian Szydło[1], Grzegorz Toczek[1], Liwia Sozańska-Jędrasik[2]*

[1] ArcelorMittal Distribution Solution Poland sp. z o.o., Poland.
[2] Łukasiewicz Research Network – Upper Silesian Institute of Technology, Poland.

Abstract

The paper presents an analysis of the possibility of measuring the residual stresses of metal sheets with the application of the so-called Barkhausen effect. The aim of the research was to compare the residual stress levels measured by two methods of multiphase steel sheets (ferritic-martensitic-bainitic) in grade HCT980C after flattening on a roller leveller in industrial conditions. The measurements were carried out using two methods: the Barkhausen effect method and the X-ray method. The paper describes in detail the methodology used for testing the measurement of residual stresses. The residual stress testing of sheets made of the CP1000 steel group was supplemented with tests of chemical composition, microstructure and mechanical properties (Re, Rm, A80, HRC hardness). In the analysis of the research results, elements of statistics were also used, in the form of ordinary correlation. The research results showed that in the case of sheets after flattening on a roller leveller in industrial conditions, it is possible to replace the commonly used and recognized, but labour-intensive X-ray method, with a simple, innovative and cheap to use method using the Barkhausen effect. Stress measurement using the Barkhausen effect has already been found to be applicable in the diagnostics of tracking changes in the stress value in the material in industrial pipelines, where access to the other measurement methods is difficult or even impossible. Currently, the measurement of stress in sheets by the magnetic method is introduced on the transverse cutting line when cutting the sheet metal from coils to metal sheets. The measurement of stresses in the production of steel sheets is important because the difference in stress between the top and bottom sides of the sheet has a significant effect on the flatness of manufactured metal sheets.

Keywords: state of stress, residual stress, surface layer, Barkhausen noise analysis method, cos(α) method, CP1000 steel

1. Introduction

Determination of the state of stress in steel products is a very important issue from a technical point of view. The value of stress occurring in steel products determines the possibility of their further use in production processes.

All types of stress can be divided into two groups:

1. stress occurring in materials, which comes from the action of external forces;
2. stress occurring in materials, which is not caused by external forces.

* Corresponding author: liwia.sozanska-jedrasik@git.lukasiewicz.gov.pl
ORCID ID: 0000-0001-8168-5045 (L. Sozańska-Jędrasik)

In the absence of external forces, we are talking about the so-called internal stresses or residual stresses.

The internal stress can be divided depending on the range of action into:

- type I stress, called macrostresses: these are interzone stresses arising between parts of the product or its cross-sectional zones;
- type II stress, called microstresses: which occur inside a grain or between neighbouring grains;
- type III stress, also classified as microstresses: which occurs within several cells of the crystal lattice of metals (Senczyk, 1996).

Macrostresses arise during practically all treatments: mechanical (turning, grinding, milling, cutting), thermal (hardening, tempering, welding), thermomechanical (plastic forming, heating or cooling), thermochemical (casting, solidification of metals and alloys, electrolytic coating) as well as the assembly and operation of steel structures.

Microstresses of the second type arise as a result of local structural changes caused, for example, by plastic deformation of polycrystalline materials, non-uniform heating or cooling, or during the application of a diffusion layer on the metal surface. Microstresses of the third type are associated with structural defects, such as dislocations, precipitates or grain boundaries.

Residual stresses, or rather their increase, in most cases have a very negative impact on the quality, durability and properties of products, components and the preservation of steel structures, especially if they are subjected to further processing, e.g. they can cause changes of shape and uncontrolled deformations. In some cases, their increase (if compressive) may have a positive effect on the properties of products or structures. This is used, for example, in the process of increasing mechanical properties by surface treatment with working rolls or balls (Senczyk, 1996).

The state of stress has a significant practical impact on the expected behaviour of products, components and structures in further production processes and operation of machines and devices. There are several methods of measuring residual stress, which can be divided into destructive and non-destructive methods. In this paper, two methods of stress measurement are described: using X-ray diffraction cos(α) and using the Barkhausen effect (BE). Practically used methods also include: the non-destructive method using ultrasonic waves and the partially destructive Mathar method, which is based on the measurement of strain gauge deformation caused by borehole drilling.

Measurement of stress by X-ray diffraction is based on Bragg's law (Equation (1)), which defines the diffraction conditions on crystal planes:

$$n\lambda = 2d\sin(\theta) \tag{1}$$

where:

n – order of X-ray diffraction,
λ – X-ray wavelength [Å],
d – interplanar distance [Å],
θ – diffraction angle [rad].

Stress measurement by X-ray diffraction is based on the relation between the position of the diffraction peak (in other words: diffraction line) (angle θ) and the interplane distance d. The change in the interplanar distance of the deformed crystal is directly related to the relative deformation, and the measure of this deformation is the change in the angle of the diffraction peak (for type I stresses) and the widening of this peak (for type II and III stresses). Type I stress testing consists in measuring the interplanar distance for different inclinations of the X-ray tube relative to the surface. The measure of this inclination is the angle between the axis of symmetry of the incident beam and the reflected beam and the normal axis of the surface to be tested (Guo et al., 2021; Kandil et al., 2001; Skrzypek, 2002; Sozańska-Jędrasik, 2021; Tanaka, 2019; Totten, 2005; Withers & Bhadeshia, 2001).

The direction of the X-ray incidence plane relative to the axis of the sample corresponds to the direction of the lattice constant deformation test. The stress level is determined from the slope of the strain dependence diagram on the value of the angular distribution of the strain and is possible by repeating the tests for different angles. This is a quantitative method that does not require calibration. However, it is necessary to know the lattice constants of the elementary cells in the unstressed state, as well as the elastic constants for a given phase of the material (Guo et al., 2021; Kandil et al., 2001; Skrzypek, 2002; Sozańska-Jędrasik, 2021; Tanaka, 2019; Totten, 2005; Withers & Bhadeshia, 2001).

The stress measurement is averaged from the volume of material into which the X-rays penetrate, and the effective depth of penetration of X-rays depends on the chemical composition of the material, the wavelength of the X-ray radiation used, the angle of the diffraction peak and ranges from a few to several tens of micrometres. For this reason, the X-ray diffraction method provides information about the state of internal stresses in the strictly near-surface layer. With the typical use of the X-ray method, it is assumed that the material is isotropic, and the grain size is much smaller than the cross-section of the X-ray beam (Skrzypek, 2002).

X-ray stress measurement is widely used and recognized, and the results can be considered as a reference to other methods.

On the other hand, the method of measuring stress using the Barkhausen effect is innovative and is just entering into use in many branches of industry. In particular, its application for stress measurement in CP1000 three-phase steel represents a notable innovation. The advantage of this method is primarily the simplicity of the measurement itself, as well as the very short time of this measurement (in the range of a few seconds).

The Barkhausen effect, also called the Barkhausen phenomenon, consists of step changes in the magnetization of a ferromagnetic material under the influence of changes in the strength of the external magnetic field. Such a step character of changes in magnetization is the result of the abrupt displacement of magnetic domain boundaries (so-called Bloch walls), resulting in the change of local magnetization of the magnetic domain in the direction of the external magnetizing field (Hosseinzadeh et al., 2009; Tiitto, 1985, 1989).

Basic information about this effect, as well as its relation to the state of stress in ferromagnetic materials, is described in the referenced paper (Augustyniak, 2003). The essence of this phenomenon lies in the use of the fact that polycrystalline grain is divided into several magnetic domains. In the demagnetized state, the directions of magnetization of the domains are arranged homogeneously in volume, and thus, the total magnetization of the ferromagnet is zero. The external magnetic field forces the material to magnetize mainly through the displacement of the domain boundaries. The boundaries are anchored by microstructure defects. Boundaries unanchored from local defects move in a stepwise manner and this phenomenon is referred to as the Barkhausen effect (BE). A rapid change in local magnetization in the area of boundary stroke generates an electromagnetic wave that induces a voltage pulse in a material-like detection coil, creating a characteristic BE noise voltage signal. The magnetic structure of non-zero magnetostriction ferromagnets is also modified by stresses acting in an area larger than the grain dimension. This is due to the fact that for a material with positive magnetostriction, the atoms move away from one another in a direction consistent with the direction of the magnetic field and approach one another in a perpendicular direction. Thus, by changing the distance between atoms through stress, the spatial arrangement of magnetic moments of magnetization is influenced.

Tensile stresses occurring homogeneously inside the grain cause an increase in the volume of magnetized domains in a direction close to the direction of stress, equally for parallel and anti-parallel reversals. Accordingly, compressive stresses result in an increase in the volume of magnetized domains in a direction perpendicular to the axis of such stresses. Stresses occurring in grains therefore modify the magnetic structure in the unmagnetized state and thus change the magnetic properties of the ferromagnet. In particular, the material which is stretched magnetizes more easily than the compressed material, and consequently, its BE intensity is highest when the direction of magnetization is parallel to the direction of the tensile stress component and the lowest when the material is magnetized in the direction perpendicular to the previous one. The observed phenomenon of dependence of BE intensity on stresses can be described qualitatively using basic dependencies from the theory of magnetoelasticity. A quantitative description for a given steel is not possible due to the lack of information about the real magnetic structure of a given steel, nor about the microstructure, and also because an effective mathematical model describing the BE generation process under stress conditions is not yet developed, and this for the case of a flat state stresses. In practice, calibration tests are performed for a given steel grade, which provides information on the dependence of BE on the level of applied deformation in elastic range. It is optimal to perform calibration for a biaxial state of stress.

If the chemical composition, microstructure or stress state of a material changes, then the intensity of BE also changes (Tiitto, 1989). This can be easily determined by comparing the condition of the material or structural element under test in its changed state with that of a standard made of the same material. Therefore, the Barkhausen phenomenon can be successfully used in non-destructive testing of ferromagnetic materials (steel, cast steel, cast iron). Such tests consist of local magnetization of the surface layer of the tested material with C-core electromagnet and simultaneous measurement with a pick-up coil positioned between the C-core poles of BE voltage pulses. The RMS (root mean square) value of those pulses' amplitude was used, as the value of the so-called magnetoelastic parameter MP (Tiitto, 1985, 1989).

If the stress level is to be expressed in MPa, then a special calibration procedure should be carried out on a standard sample made of the same material and obtain a so-called "calibration curve" to allow the device to be scaled from MP to MPa. Transcription of BE intensity (represented, for example, by MP) to stress level (represented in units of MPa) is possible when well defined requirements are met. A prerequisite for such calibration to be effective and reliable is that the microstructure of the standard sample is as close as possible to that of the tested material. In addition, such a sample

should be free from internal defects such as discontinuities or pores, as these are natural notches and stress concentrators and may contribute to the falsification of the calibration results. An additional disadvantage of such a procedure is a requirement that the surface layer of the standard sample be prepared for measurements in the same way as the tested material (grinding, etching, polishing, etc.) (Kokosza & Pacyna, 2016).

The positive distinguishing feature of the BE method is that some descriptors of the effective value of the voltage change significantly under the influence of uniaxial stress. For typical steels, you can usually observe a nearly twofold increase in the intensity of BE for tensile stresses close to the yield point and a correspondingly nearly twofold decrease for analogous compressive stresses (Augustyniak, 2015).

To assess the microstructure of the tested material, characteristic hysteresis loops, which show the relationship between the effective voltage BE and the magnetic field strength are used. From the charts, you can get information, among others, about the size of the grain or the steel grade.

The key issue for the evaluation of the practical use of BE is to know the effectiveness and quality of determination of the stress state of the tested material when it has a complex multiphase crystallographic structure.

It should be emphasized that the query of the literature database shows the conclusion that the previously published studies concerned the study of the stress state in ferromagnetic materials with a relatively simple phase structure. The project implementation report (Augustyniak, 2015) describes the results of the stress state study in low-alloy steels (ferritic phase or ferritic-pearlitic and ferritic-bainitic structure) and martensitic steels. There are no reports from stress state studies using the BE signal measurement methodology in more than two-phase systems. You can also find messages about good compliance of the results of stress state measurements performed by BE and XRD methods and the Mathar method (Augustyniak, 2015) as well as the trepanation method (Augustyniak et al., 2019), but for the above-mentioned steel structures and for the cases of products/materials with a relatively large wall thickness (above 5 mm). Thus, the performance and comparison of the results of stress state measurement using the BE method and the XRD method for steel consisting of three components of the phase structure and a relatively thin sheet metal (thickness of few mm) is in the nature of cognitive and at the same time utilitarian research, because this type of steels in the form of sheets are introduced into many branches of industry (mainly automotive). For obvious reasons, it is therefore desirable to develop an effective, non-destructive method for diagnosing the stress state of such a specific material.

Regardless of calibration, the applied test method allows to determine and compare with high accuracy the level of stress in different areas of the same component or after different technological treatments, as long as there have been no significant changes in the microstructure of such a component during these procedures. Measurements made in a 0.20 mm thick surface layer can be considered particularly valuable, as they provide information about the state of stress in a layer about 10 times thicker than in the case of the commonly used X-ray method.

However, it is always necessary to check whether the results of the stress measurement using the Barkhausen effect coincide with the results obtained by the X-ray method and whether there is a correlation between them (Szymański et al., 2015).

It should be noted that the new generation of BE intensity meter is already available on the market, which automatically performs measurements of the angular distribution of BE intensity and, in a few seconds, determines the main components of the stress tensor. It was developed during a research project (Augustyniak et al., 2014).

Comparison of the results of stress level measurements performed using the BE technique and the XRD technique should take into account the fulfilment of measurement conditions that result from the technique-specific metrological properties. These conditions relate to the magneto-mechanical properties and microstructure of the tested material, as well as the spatial distribution in depth of the tested stress state. With regard to magneto-mechanical properties, testing by both techniques is possible only for ferromagnetic materials with non-zero magnetostriction. Such properties are possessed by polycrystalline structural steels with ferrite phase content. Grain morphology (grain size, shape and phase distribution) determines the presence or absence of anisotropy of magneto-mechanical properties. The spatial distribution of stress in the surface layer of the material under study is described assuming there is a plane state of stress. The state of this stress is determined by the values of the two principal components of stress, S1 and S2 (mutually perpendicular). Of particular importance – especially for the results of measurement by the BE technique – is the dynamics of change (gradient) of the values of these two components as a function of distance from the surface of the test object. It should also be mentioned that the two techniques provide information about the σ stress level in a methodologically significantly different way.

In the case of the XRD technique, using the sin2(ψ) method, the level of the σ stress component in the adopted test direction can be determined unambiguously. In the case of the BE technique using a standard probe (one yoke electromagnet), the measured BE signal intensity value for a given magnetization direction is converted into a selected descriptor of this intensity (the INT magnitude in the MEB2Cx meter). This descriptor is used to calculate the *eps* strain level using the *FO*(*X*) calibration function. The *eps* strain value is converted formally by the MEB2Cx meter to the σ level using a linear function of the form $\sigma = E \cdot eps$, where E is Young's modulus. Determining the case of plane stress state, the stress value in any direction using the BE technique is possible, but it requires measuring INT in at least three directions, differing by an angle of 45°. The three *eps* values thus determined are used to calculate the values and directions of the two principal components of stress (S1 and S2) as well as the σ level in any direction of measurement.

It should also be noted that the FO calibration functions used in the MEB2Cx meter are determined under the conditions of generation when calibrating a quasi-homogeneous deformation state deep into the specimen. The properties of the MEB2Cx meter described here result in the σ value given by this meter being optimally close to the σ value given by the XRD technique if the test by both techniques is performed in the direction of the stress principal axis and there is no stress gradient in the direction perpendicular to the surface of the test object. We have grounds for assuming that the direction of the principal axis of stress in the test sheets is parallel to the rolling direction, and thus, BE measurements in this direction alone can be considered sufficient to obtain stress level indications made by both techniques that are comparable to each other.

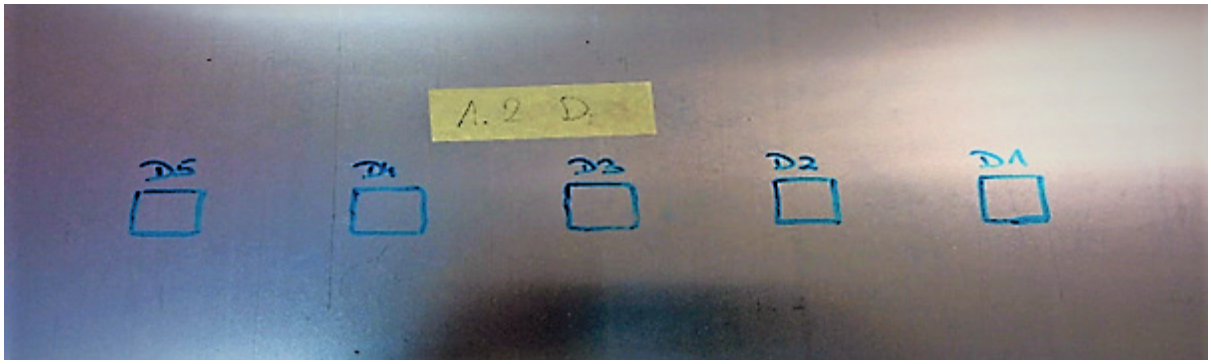
2. Material and methodology of research

The test material was steel sheets of HCT980C (CP1000). A 550 mm × 1,000 mm specimen was cut from a 1.6 mm thick strip levelled on a roll flattener, with the rolling direction being consistent with the longer edge of the sample.

On both sides of the sample (top and bottom), five measuring points 50 mm apart were drawn along the axial line of symmetry (Fig. 1).

It should be noted that the condition of the surface of the tested material is very important. The sheet metal used for the tests was cold-rolled, its surface was free of scale and impurities. In addition, it has been cleaned and degreased.

a)



b)

Fig. 1. Stress measuring points: a) bottom side; b) top side

At each point, stress measurements were made: five times by means of the X-ray method and five times by means of the BE method.

In both measurements, the volume tested was large enough for stress measurements using the X-ray method and with the application of the Barkhausen effect (Fig. 2).

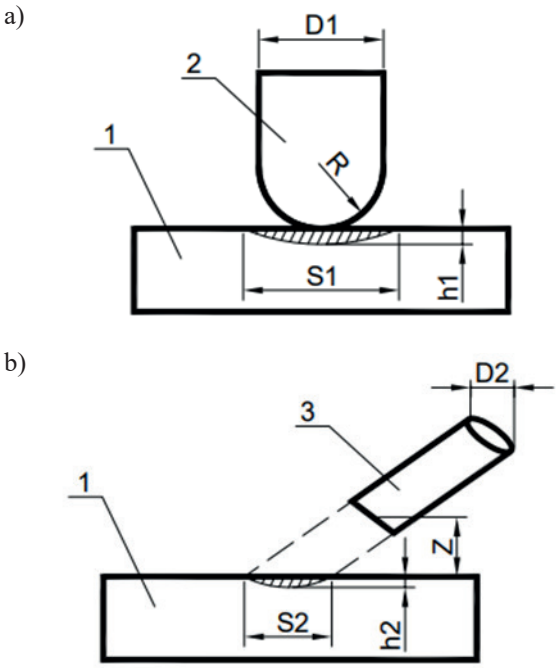


Fig. 2. Diagram of the stress measurement area: a) using the method based on the Barkhausen effect; b) using the cos(α) method

Stress measurement using the method based on the Barkhausen effect was carried out with the MEB2Cx device, manufactured by NNT Innowacyjne Techniki Badań Nieniszczących (NNT Innovative Non-Destructive Testing Techniques), a company based in Gdańsk, Poland (Augustyniak et al., 2014; NNT, 2019).

The experiment to determine the internal stress using BE (non-destructive method) was performed using a detection electromagnetic probe with a ferritic core (2) with a diameter of 4 mm (D_1). The end of the core has the shape of a bowl with a radius of curvature of 2 mm (R). During measurement, the ferritic core is in direct contact with the tested object (1).

The place of measurement of stress on the cross-section is shown schematically in Figure 2a. Electromagnetic pulses are emitted from that area and recorded by the detection coil wound on the ferritic core. The base dimensions of the measuring area, i.e. diameter (S_1) and depth (h_1), can be specified for given magnetization parameters and detection path. The meter used in the device magnetizes the object with a frequency of f = 10 Hz, and electromagnetic voltage signals are recorded in the frequency band from 1 kHz to 100 kHz.

It is assumed in the experiment that for such parameters the diameter (S_1) has a dimension comparable to the diameter of the core (D_1) and the depth (h_1) has a value of 0.5 mm. It should be emphasized that the effectiveness of magnetic signal detection decreases exponentially with depth and the pulses generated in the near-surface layer, i.e. 50–100 μm, have the largest share in the intensity of the electromagnetic signal. It follows that the magnetic method reveals a volume-averaged stress state with a higher weight for the near-surface layer of the tensile stress state.

In the case of CP1000 steel, the stress state was determined using the MEB2Cx meter (former version of the MagStress5c meter) (NNT, 2019), which is used to determine the stress state according to the guidelines of the PB01 procedure (Augustyniak, 2017). This procedure has been recognised by PRS (Polish Register of Shipping, 2017) and UDT (Office of Technical Inspection, 2020). The MEB2Cx meter measures BE intensity with a standard probe (with one magnetizing core). The direction of magnetization thus determines the direction of the BE intensity test. The BE voltage signal induced in the probe detection coil is converted into the BE intensity descriptor, which is the INT parameter. This is the integral of the instantaneous voltage of the effective voltage signal BE for one period of magnetisation. The INT value is converted in the meter to the equivalent deformation *eps* according to the *eps* = *FO*(*X*) type calibration curve, where *X* is the quotient of the measured INT intensity and the INTref value stored in the meter's memory, which reference value is assumed to be representative of the undeformed state (*eps* = 0). Four points were determined on the test sample, two on the upper side and two on the lower side of the sheet, selected at random. Subsequently, INT values were measured at these points.

These values were reference values for the performed stress measurements. The meter formally converts the value of *eps* into the equivalent σ stress level according to the principle $\sigma = E \cdot eps$, where E is Young's modulus of stiffness (E = 210 GPa). The *FO*(*X*) calibration function stored in the memory of the MagStress5C meter was used in the tests. This function was determined for this steel grade using the method of four-point load of the reference (standard) sample while the condition of the sample was after levelling on a roll flattener. It should be noted that the reference sample had a difference in the level of residual stress on both sides of it at the level of about 20 MPa and the determined calibration function is a relation-

ship taking into account this difference. The anisotropy at the level of the BE signal (intensity difference for rolling direction and perpendicular direction) for the reference sample did not exceed 5% on both sides. Thus, it is legitimate to conclude that the sample used was formally isotropic, and the determined calibration function *FO* can be used to determine the residual deformation level *eps* for any direction of magnetization on the tested surface.

The functionality of the meter used in relation to its indication of the σ stress level should be treated as a very useful way in the diagnostics of the construction to quickly estimate the value of the σ stress component in the direction of magnetization. However, it is also possible to determine with this meter the values of the main components σ1 and σ2 of the stress tensor for the usually occurring flat stress state. For this purpose, it is necessary to measure the BE intensity in the directions of the largest and smallest BE or by performing three measurements of BE intensity in directions differing by 45° – calculate these two stress components using the relations known for the flat stress state between the three so measured deformations of *eps*1, *eps*2 and *eps*3 and these components. These calculations are made using an appropriate spreadsheet (using the INT values recorded by the meter for these three directions and the FO calibration function appropriate for a given steel). The graph of the FO function used in the research is shown in Figure 3.

This function describes the inverse relationship between the level of deformation *eps* (cause) and the relative change in intensity BE (effect) determined by the quantity *X*. Significant dynamics of changes in BE intensity (several dozens of percent) can be observed in relation to the change in deformation in the elastic range. This property results in a high resolution of the stress state measurement method using the BE phenomenon.

The experiment of determining the residual stresses by X-ray diffraction (non-destructive method) was performed using the cos(α) method with the application of a portable X-ray stress analyser μ-X360s from Pulstec with a chrome anode lamp (λ = 2.291 Å) (Pulstec Industrial, 2022). The internal stress measurement by X-ray cos(α) method is carried out using a collimator (3) shown in Figure 2b with a diameter of 2 mm (D_2). Since the collimator is inclined at an angle of 35° and the distance from the object (1) is 51 mm (*Z*), the measuring surface is an ellipse with diagonals of 4.7 mm and 3.9 mm (S_2) – the measurement scheme is shown in Figure 2b. During operation, the device is set to the ferrite phase. Since the tested steel is multiphase (ferritic-martensitic-bainitic structure), a stress measurement program covering all components present in the material structure was used. The depth of penetration of X-rays allows to effectively measure stress to a depth of 10 μm (h_2) (Augustyniak, 2016; Guo et al., 2021; Kandil et al., 2001; Skrzypek, 2002; Sozańska-Jędrasik, 2021; Tanaka, 2019; Totten, 2005; Withers & Bhadeshia, 2001).

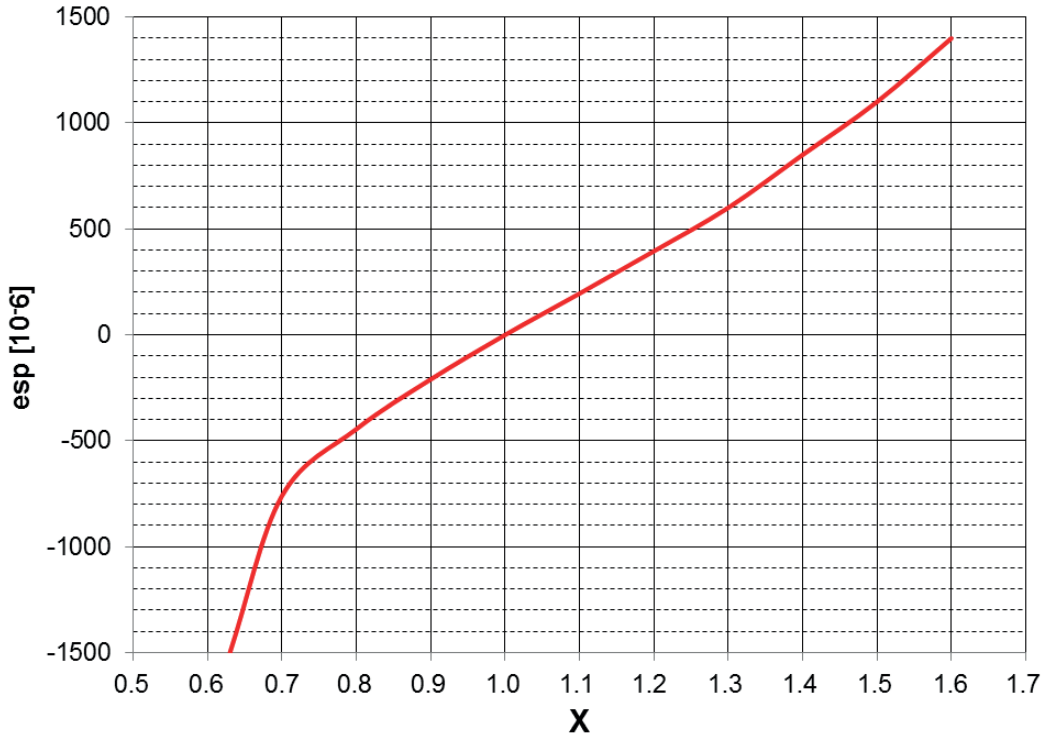


Fig. 3. *FO*(*X*) calibration function used in the BE stress meter

The analysis of the chemical composition was performed by optical spectrometry with inductively coupled plasma using a Spectromaxx Lmm05 spectrometer.

Tensile tests were carried out on flat samples taken longitudinally to the rolling direction, using a universal testing machine GmbH 114.300 kN. Samples with dimensions L = 80 mm were used.

Hardness measurements were made using the Rockwell method with the application of an Ergotest DIGI 25 R hardness tester.

Microstructure testing was performed using the Inspect F scanning electron microscope on a cross-section of a sample taken from the sheet after levelling.

3. Research results

Results of tests on the chemical composition and mechanical properties of the tested CP1000 sheets are presented in Tables 1–3.

The analysis of the results of the chemical composition of the tested sheet metal sample showed compliance with the chemical composition of the metallurgical certificate and corresponded to the applicable standard (PN-EN 10338:2015-10).

The mechanical properties of the tested sample were consistent with the mechanical properties of the metallurgical certificate and corresponded to the applicable standard (PN-EN 10338:2015-10).

Table 1. Chemical composition of HCT980C steel

Steel name	Designation of steel	Chemical composition [% mas.]									
		C_{max}*	Si_{max}*	Mn_{max}*	P_{max}*	S_{max}*	Al	$Cr + Mo_{max}$*	$Nb + Ti_{max}$*	V_{max}*	B_{max}*
HCT980C	as per PN-EN 10338:2015-10	0.230	1.000	2.70	0.080	0.015	0.015–2.000	1.000	0.150	0.220	0.005
	according to manufacturer's certificate	0.092	0.338	2.27	0.010	0.000	0.056	0.136	0.029	0.005	0.002
	according to laboratory certificate	0.111	0.289	2.28	0.015	0.001	0.051	0.119	0.027	0.005	–

* "max" refers only to the norm.

Table 2. Mechanical properties of HCT980C steel

Steel name	Designation of steel	Mechanical properties		
		$R_{e\,0,2}$ [MPa]	$R_{m\ min}$* [MPa]	$A_{80\ min}$* [%]
HCT980C	as per standard PN-EN 10338:2015-10	780–950	980	6.0
	according to the manufacturer's certificate	900	994	8.3
	according to the laboratory certificate	919	1,012	9.7

* "min" refers only to the norm.

Table 3. HRC hardness measurements

Place of measurement	Measurement number					Average [HRC]
	1	2	3	4	5	
Bottom surface of sheet metal						
1	30.9	32.8	34.3	32.7	32.1	32.56
2	33.0	32.9	34.2	33.2	32.0	33.06
3	34.5	31.9	34.6	34.3	34.2	33.90
4	32.1	34.2	32.5	33.7	34.2	33.34
5	32.7	33.3	33.6	33.1	34.7	33.48
Top surface of sheet metal						
1	31.4	34.7	34.9	32.8	34.2	33.60
2	31.8	32.7	32.9	33.1	34.5	33.00
3	31.5	32.4	33.4	34.4	34.8	33.30
4	30.4	34.1	33.2	33.7	34.0	33.08
5	33.5	33.0	34.7	34.6	34.8	34.12

Table 4 presents the results of residual stress tests performed by both methods. Based on the analysis of the results it was found that the stresses determined by the X-ray method were higher on the top surface of the sheet in comparison to the ones determined by the Barkhausen method. On the bottom surface of the sheet, however, comparable stress values determined by both methods were obtained.

Microstructure testing results of a sample after levelling are shown in Figure 4. The sheet has a bainitic microstructure with martensite. A small amount of ferrite was also identified. No microstructure diversity was found between the areas at the upper and lower surfaces and the centre of cross-section of the sheet metal.

Table 4. Internal stresses in MPa

Measuring field number	X-ray method						Barkhausen method					
	measurement number					average (y)	measurement number					average (x)
	1	2	3	4	5		1	2	3	4	5	
Top of sheet metal												
1	70	67	68	70	76	70.2	11	8	8	9	5	8.2
2	50	58	51	50	52	52.2	7	10	7	8	13	9.0
3	18	16	16	13	19	16.4	−43	−45	−47	−49	−45	−45.8
4	58	57	56	58	55	56.8	8	4	5	3	5	5.0
5	46	50	44	43	43	45.2	1	10	5	4	3	4.6
Bottom of sheet metal												
1	11	9	2	6	8	7.2	16	13	15	13	14	14.2
2	8	0	8	2	7	5.0	16	15	12	12	8	12.6
3	9	7	6	8	8	7.6	13	11	12	14	12	12.4
4	11	13	15	17	15	14.2	16	17	19	16	18	17.2
5	17	19	15	14	18	16.6	16	16	19	15	19	17.0

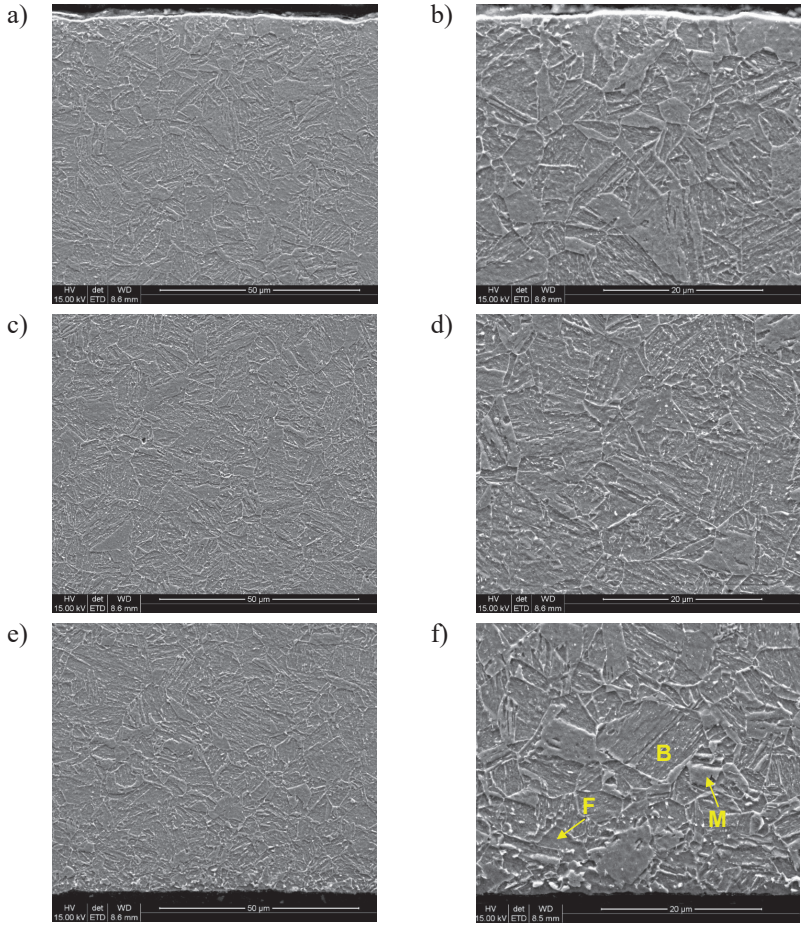


Fig 4. Microstructure of the sample after flattening: a, b) upper surface of the sheet; c, d) central cross-section of the sheet; e, f) lower surface of the sheet; F – ferrite, B – bainite, M – martensite

4. Discussion of results

The purpose of the study was to answer the following question: is it acceptable to replace the internal stress measurements made with the X-ray method with a much simpler and cheaper method using BE? Such a replacement, however, is subject to the fulfilment of an essential condition. Both methods should lead to insignificantly different observations (desired case) or significantly linearly (positively) correlated (sufficient case from a practical point of view). In this respect, a preliminary qualitative analysis was carried out first and then a statistical analysis of the results (Maliński, 2010).

As part of the statistical analysis of the results, an attempt was made to assess the significance of the correlation between the results of stress measurement obtained by X-ray and BE methods, as well as the correlation between the level of stress and hardness.

In the first stage of the analysis, the value of the Pearson correlation coefficient r was calculated according to the formula:

$$r = \frac{\sum_{i=1}^{n} x_i y_i - n\overline{xy}}{\sqrt{\left(\sum_{i=1}^{n} x_i^2 - n\overline{x}^2\right)\left(\sum_{i=1}^{n} y_i^2 - ny^2\right)}} \tag{2}$$

where:

n – number of measurement locations ($n = 5$),

x_i – stress values determined by the Barkhausen method [MPa],

$\overline{x}$ – average stress determined by the Barkhausen method [MPa],

y_i – stress values determined by the X-ray method [MPa],

$\overline{y}$ – average stress determined by the X-ray method [MPa].

Subsequently, the correlation coefficient was statistically verified by means of a test for the correlation coefficient with a one-sided critical area. For this purpose, the value of the statistic t was calculated according to the formula:

$$t = r\sqrt{\frac{(n-2)}{(1-r^2)}} \tag{3}$$

and then, using the Student's t-distribution at $n-2$ degrees of freedom, the value p was determined, which, when compared with the classical value of the significance level $\alpha = 0.05$, is the basis for drawing a conclusion about the statistical significance of the correlation coefficient. A correlation is considered statistically significant when $p < \alpha$.

If statistical significance for the correlation coefficient is obtained, the further part of the analysis should consist in performing calculations as part of the regression analysis, the purpose of which is to determine the parameters of the trend line equation $y = b_1 x + b_0$ according to the formulas:

$$b_1 = \frac{\sum_{i=1}^{n} x_i y_i - n\overline{xy}}{\sum_{i=1}^{n} x_i^2 - n\overline{x}^2} \tag{4}$$

$$b_0 = \overline{y} - b_1\overline{x} \tag{5}$$

where n, x_i, $\overline{x}$, y_i, $\overline{y}$ denote the same quantities as those discussed for the correlation coefficient.

According to the presented algorithm, appropriate calculations were carried out using a Microsoft Excel spreadsheet. Their course is presented in Table 5 and Table 6, and a graphical interpretation of the results is in Figure 5.

Table 5. X-ray average stress correlation determined by X-ray method for the top of sheet metal

Measuring field number	X-ray method						Barkhausen method					
	measurement number					average (y)	measurement number					average (x)
	1	2	3	4	5		1	2	3	4	5	
1	70	67	68	70	76	70.2	11	8	8	9	5	8.2
2	50	58	51	50	52	52.2	7	10	7	8	13	9.0
3	18	16	16	13	19	16.4	−43	−45	−47	−49	−45	−45.8
4	58	57	56	58	55	56.8	8	4	5	3	5	5.0
5	46	50	44	43	43	45.2	1	10	5	4	3	4.6
					Formula (1)	$r = 0.904$						
					Formula (2)	$t = 3.671$						
					From Student's t-distribution	$\mathbf{p = 0.035}$						
					Formula (4)	$b_0 = 51.072$						
					Formula (3)	$b_1 = 0.766$						

Table 6. X-ray average stress correlation determined by X-ray method for the bottom of sheet metal

Measuring field number	X-ray method						Barkhausen method					
	measurement number					average (y)	measurement number					average (x)
	1	2	3	4	5		1	2	3	4	5	
1	11	9	2	6	8	7.2	16	13	15	13	14	14.2
2	8	0	8	2	7	5.0	16	15	12	12	8	12.6
3	9	7	6	8	8	7.6	13	11	12	14	12	12.4
4	11	13	15	17	15	14.2	16	17	19	16	18	17.2
5	17	19	15	14	18	16.6	16	16	19	15	19	17.0
						Formula (1) $r = 0.931$						
						Formula (2) $t = 4.429$						
						From Student's t-distribution $\boldsymbol{p = 0.021}$						
						Formula (4) $b_0 = -19.333$						
						Formula (3) $b_1 = 2.006$						

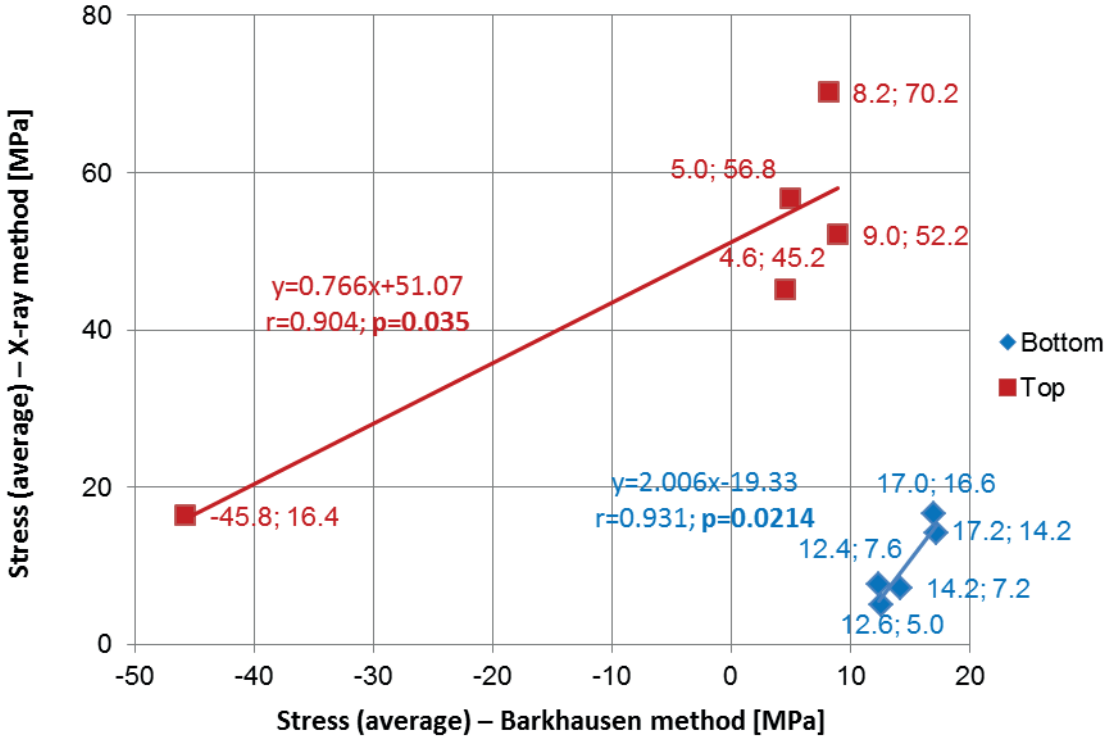


Fig. 5. Correlation graph of average stress determined by X-ray method and Barkhausen methods

Statistically significant, positive correlations were demonstrated for both the bottom (r = 0.931; p = 0.0214) and top (r = 0.904; p = 0.0350) sheet metal surface. Both correlations make it possible to assess the amount of stress using a simpler and definitely cheaper Barkhausen method. It should be emphasized that the results obtained for the top surface of the sheet are clearly biased by the location of the point corresponding to the measuring field no. 3, which deviates from the expected trend. Both values are questionable, the ones measured by the X-ray and the Barkhausen method. It is very likely that at this point of measurement, the upper surface of the sheet metal was mechanically damaged. In this situation, an attempt to obtain an equation by means of which it would be possible to convert the values of stress obtained by the Barkhausen method into values approximately consistent with the values corresponding to the X-ray method is essentially doomed to failure. Obtaining such an equation involves the fulfilment of two conditions. It is necessary to have parallelism of both regression lines and a small difference of free terms b_0 of the order of a few MPa. The first of these conditions can be verified by testing the parallelism of the regression line.

In the trendline parallelism test, the value of the statistic t is calculated according to the formula (Maliński, 2004):

$$t = \frac{b_{1(D)} - b_{1(G)}}{\sqrt{\frac{s^2_{(D)}(n_D - 2) + s^2_{(G)}(n_G - 2)}{n_D + n_G - 4}} \cdot \frac{1}{\sqrt{\left[\frac{1}{\sum_{i=1}^{n_D}\left(x_{i(D)} - \bar{x}_D\right)} + \frac{1}{\sum_{i=1}^{n_G}\left(x_{i(G)} - \bar{x}_G\right)}\right]}} \quad (6)$$

where:

D, G – the bottom and top surface of the sheets, respectively,

b_1 – directional coefficient of the regression line (trend line) calculated according to the formula:

$$b_1 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (7)$$

where:

x_i – stress according to the Barkhausen method [MPa],

y_i – stress according to the X-ray method [MPa],

s^2 – residual variance calculated as per the formula:

$$s^2 = \frac{\sum_{i=1}^{n}(y_i - b_1 x_i - \bar{y} + b_1\bar{x})^2}{n-2} \quad (8)$$

n – number of measurements.

The t-statistic has a Student's t-distribution with a number of degrees of freedom equal to $n_D + n_G - 4$. From this distribution, the value of p is determined and compared to the significance level $\alpha = 0.05$. If $p < \alpha$ the hypothesis of parallelism of simple regressions is rejected, in the opposite case there are no grounds for rejecting it. After calculations, the following was obtained: $t = 0.804$ (Formula (5)) and $p = 0.452$. Analysing this result, it should be stated that the parallelism of both trend lines cannot be rejected, however, a visual assessment of the course of these regression lines (Fig. 5) suggests that this parallelism would be unambiguous if the measurements at the third point were not biased, as already mentioned. The lack of evidence for rejecting the hypothesis of the parallelism of regression lines is largely due to a small number of points (5). It is obvious that if the slopes of both trend lines had the same values, but the number of points on the correlation chart was clearly greater, the rejection of the mentioned hypothesis would almost be certain. The discussed doubts about the regression equation for the upper surface of the sheet metal can be dispelled by omitting the ill-fated, third place of measurement in the calculations.

With this approach, the result shown in Figure 6 would be obtained. This time, the parallelism is clearly visible, which would be confirmed by the result of the parallelism test ($t = -0.112$; $p = 0.915$). Difference in the values of free terms $b_{0(G)} - b_{0(D)} = 60.1$ MPa. It should be noted that for the upper surface, the correlation is not statistically significant. This is undoubtedly due to the fact that obtaining significance for correlation at 4 points is extremely difficult.

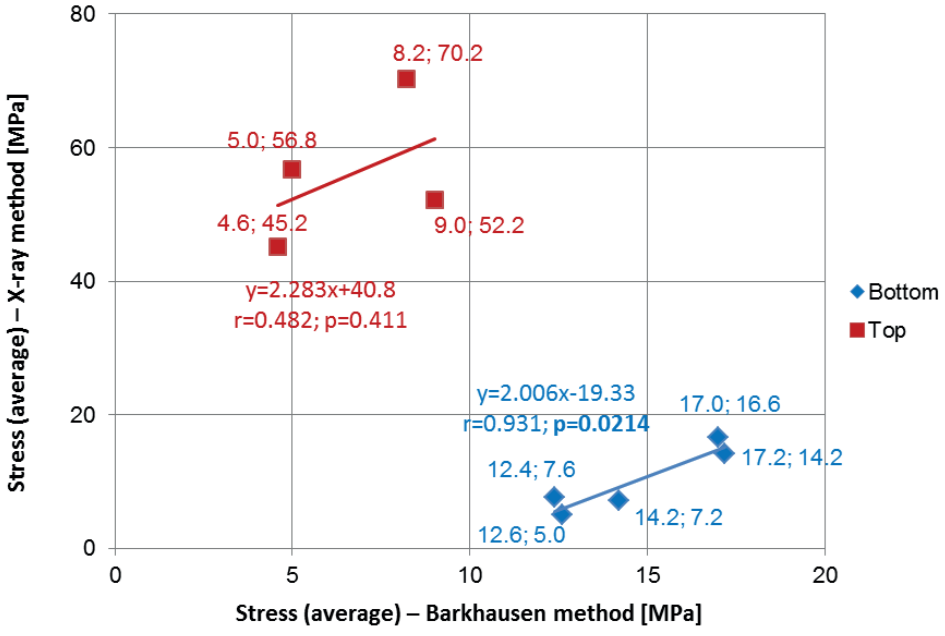


Fig. 6. Correlation graph of the average stress determined by X-ray method and Barkhausen method after removal of measurements from the third location of the upper surface of the sheet metal

Summing up the above considerations, it is worth taking into account the profile of average values obtained for subsequent measurement locations. The profiles for both methods of stress measurement, including the top and bottom surface of the sheet, are shown in Figure 7. The visual evaluation of these profiles indicates their clear parallelism for the bottom surface of the sheet metal and surprisingly good (despite the dubious values in point 3) for the top surface. It can also be noticed that for the bottom surface, the offset of profiles representing both measurement methods is of the order of a few to over a dozen MPa, while for the top surface, it is about 60 MPa. This is largely in line with the observations made earlier, in the analysis carried out without the values measured at the third point. In the discussed Figure 7, the values of standard deviations in the form of so-called "whiskers" are marked. They show that these deviations are small, not exceeding the value of 3 MPa. This proves the good repeatability of the measurements carried out, similar to the accuracy of the measurement itself.

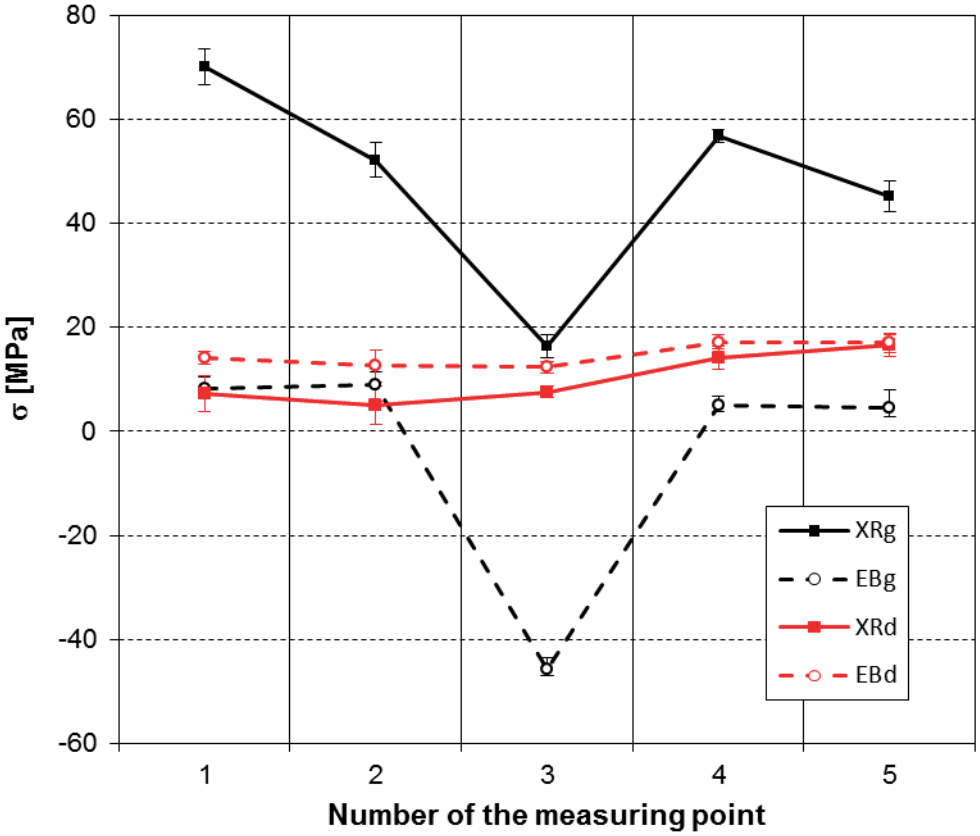


Fig. 7. Average stress profiles along the test sample determined by XR and BE

Another element of the statistical processing of the results was an attempt to assess the significance of the correlation between stress – determined by both methods and hardness determined using the Rockwell method (Tab. 3).

Table 7 summarises the values of correlation coefficients and *p*-values, on the basis of which the significance assessment was made.

A graphical presentation of the results obtained at this stage of the analysis is presented in Figures 8 and 9.

Table 7. Coefficients of stress correlation measured by X-ray and Barkhausen methods [MPa] and hardness [HRC]

	Surface	
	bottom	top
X-ray method		
r	0.322	0.029
p	0.597	0.962
Barkhausen method		
r	0.001	0.110
p	0.999	0.860

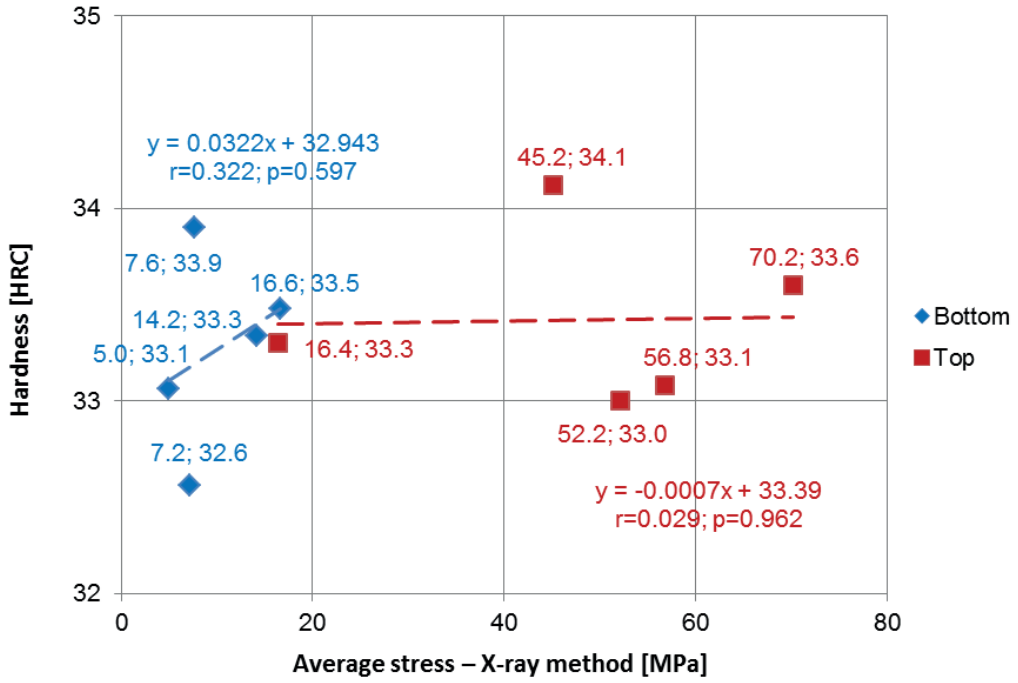


Fig. 8. Correlation graph of average stress determined by X-ray method and hardness [HRC]

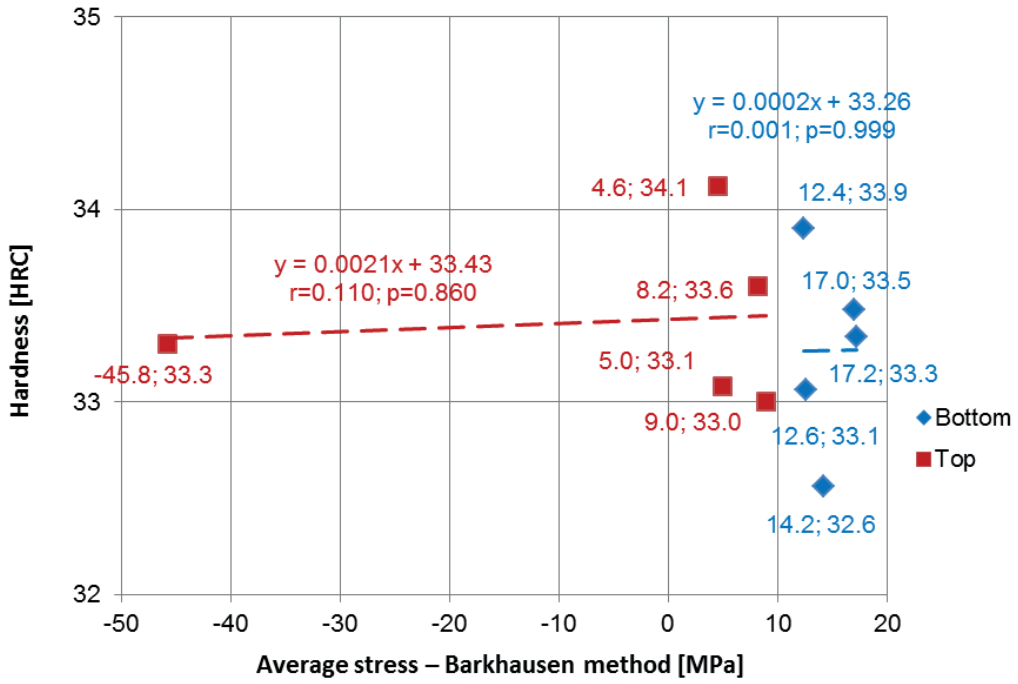


Fig. 9. Correlation graph of average stress determined by the Barkhausen method and hardness [HRC]

Based on the analysis of the results presented in Figures 8 and 9, it was concluded that no statistically significant correlations were obtained. This means that the stress values measured by both methods and hardness measured by the Rockwell method on both the bottom and top surfaces of the sheets are not related.

When looking for the reason for the differences in the indications of both methods for the bottom layer, one should take into account the specific differences between these methods with regard to, for example, the depth and thickness of a layer of material tested by means of a given method. In particular, the occurrence of different changes in the stress state in the near-surface

layer on both sides of the sample with a depth of several tens of μm must result in different results of the measurement of the stress level performed with both techniques. Such differences in stress state within the depth range in the near-surface layer cannot be confirmed by the results of the hardness measurement by the HRC method. This was confirmed by the results contained in Table 3.

5. Conclusions

1. For steel grade HCT980C, the X-ray residual stress measurement can be replaced with the Barkhausen method, but separately for both sheet metal surfaces, primarily due to the significant difference in the free terms of the trend line $b_{0(G)}$ and $b_{0(D)}$ obtained for 5 points data set.
2. A statistically significant correlation (coefficient $r = 0.904$) was found between the results of residual stress measurements using the X-ray method and the Barkhausen effect method on the top surface of the sheet metal.
3. A statistically significant correlation (coefficient $r = 0.931$) was found between the results of residual stress measurements using the X-ray method and the Barkhausen effect method on the bottom surface of the sheet metal.
4. There were no statistically significant correlations between stress measurement results and hardness, regardless of the method of determining the stress and the surface of the sheet metal as regards the residual stress range.
5. It is not possible to find a correlation between the results of residual stress measurements and the mechanical properties of the sheet metal due to the specificity of their determination (destructive tests), which makes it impossible to pair the stress values and mechanical properties.
6. Analysis of the results of residual stress tests obtained by the X-ray method and the Barkhausen effect method indicates that both methods can be used to assess the residual stresses for a homogeneous stress state within the depth range of the material.

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