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DIAGNOSTIC EXAMINATION OF P265GH BOILER STEEL PLATE USING THE BARKHAUSEN METHOD

ABSTRACT

The article presents the results of diagnostic examination of P265GH boiler steel plate. During blanking, cutting and cold forming of elements from this plate, their spontaneous plastic deformation and warping took place, indicating an unfavourable internal stress state of a considerable magnitude occurring in the steel plate. In order to identify the causes of this situation, examinations were carried out, which included a microstructure assessment and a Vickers hardness test. In view of the absence of clear differentiation, in terms of both structure and hardness, in different steel plate areas, diagnostic examination was performed by the Barkhausen magnetic method, which included the determination of the principal direction of residual stresses and the determination of their anisotropy based on the measurement of the effective value of Barkhausen noise. As their result, a significant anisotropy of residual stresses was revealed on the steel plate surface. Moreover, the adverse phenomenon of perpendicularity of the principal directions of stresses was found to occur on the opposite plate surfaces, being the direct cause of warping of elements cut out from the plate

Key words: *Barkhausen effect, residual stress, anisotropy*

INTRODUCTION

The measures of usefulness of the signal carrying diagnostic information include the ease of detection and the speed at which a measurement can be taken with it. In respect of the examination of some properties of ferromagnetic materials and machine parts, equipment and constructions made from these materials, these conditions are satisfied by the measurement of so called Barkhausen noise (voltage signal). This voltage signal is induced in a detection coil placed in the vicinity of the surface of a ferromagnetic material during its remagnetization. The direct causes of it are fluctuations in magnetic induction within the material under examination, which result from the phenomenon of jumpy motion of magnetic domain wall (the Barkhausen effect) and the associated abrupt change in domain wall magnetization [1]. Indeed, in a microscopic scale, this effect is caused by the occurrence of structure defects such as phase precipitates, grain boundaries, or dislocations, which block the free motion of magnetic domain walls Clearing these barriers takes place in the form of a "jump" and requires an appropriate amount of energy to be supplied, which comes from the growing external magnetic field. This results also in a jumpy change in the magnetization of the particular domains, which causes single voltage pulses to be induced in the detection coil, which create with time a characteristic so called Barkhausen magnetic noise (BMN) which is

composed of "packets" of pulses of a different amplitude. The parameters of the generated noise are principally dependent on three main factors influencing the Barkhausen effect itself, namely the microstructure, the internal stress state, and the state of magnetization of the object being tested. By correlating selected noise parameters, such as the number of pulses, the rms (root mean square)value, or the shape and parameters of the rms envelope, with mechanical properties or microstructural characteristics, it is possible to determine and test, on a comparative basis, the microstructure properties and stress state of ferromagnetic materials.
Owing to the relatively simple structure of testing apparatus and the straightforward measurement concept, testing methods based on the Barkhausen effect have found application in many areas of science and technology [2], e.g. in the diagnostics of the pre-failure state of aircraft engine vanes [3], the wear of bearings, the quality assessment of welded joints [4], the examination of residual stress distributions in constructional shapes [5], the diagnostics of the degree of steel degradation in power installations, or the diagnostic examination of stress concentration in metallurgical rolls [6]. These methods were also successfully used in the examination of residual stresses in plates [7, 8].
This article presents the results of diagnostic examinations that were carried out to identify the residual stress state existing in steel plate used for the manufacture of boilers. An adverse state of these stresses, which had been suspected before the start of the examinations, resulted in the spontaneous deformation of elements being cut out from the steel plate.

TESTING METHODOLOGY

Subject of testing

The subject of testing was hot rolled P265GH steel plate manufactured by a Steel Mill in Slovakia. In its as-delivered state, sheet has the following dimensions 5×1500×3000 mm (Fig. 1).

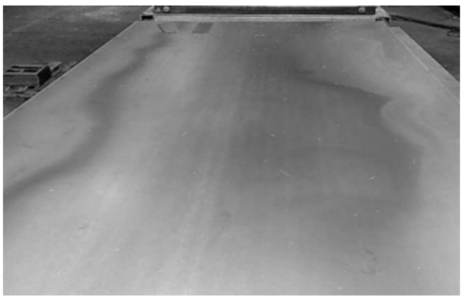

Fig.1. Macroscopic view of investigated steel sheet

The steel of which the plate was produced is designed for operation at elevated temperatures of up to 430 ˚C and in a water vapour atmosphere. This steel grade belongs to unalloyed ferritic steels. Its assayed chemical composition is given in Table 1. The chemical element contents are within the limits set out by the standard [9]. With respect to the contents of its specified elements, the steel under examination had considerably lower contents of copper, phosphorus and sulphur, all being regarded for this steel grade as impurities.

Two plate sections were provided for the tests. One section had the shape and dimensions as shown in Figure 2 (together with locations of HBN and microstructure measurements. The other section was in the form of 500 mm long and 50 mm wide strip.

***Table 1**. Chemical composition of P265GH steel, [%]*

C	Si	Mn	P	S	Al	Cr	Cu	Mo	Nb	Ni	Ti	V
0,13	0,18	0,73	0,011	0,010	0,045	0,02	0,03	0,004	0,002	0,01	0,001	0,002

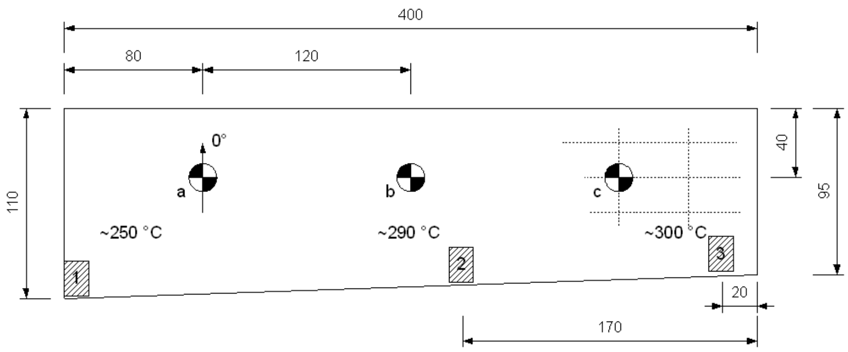

Fig.2. Dimensions of tested fragment (specimen 1) with location of HBN measurement points (a,b,c) and microstructure test areas(1,2,3)

Preliminary structural examinations and mechanical tests

On the plate section provided for testing, metallographic examination was performed. The locations from which samples were taken for preparing metallographic sections are indicated by oblique shading. The prepared sections were etched with Nital. In spite of the samples being taken from three different areas differing in tarnish colours, indicating uneven cooling, no distinct differences in microstructure were found. Each of the analyzed areas was characterized by a fine-grained ferritic-pearlitic structure. Microstructure photographs taken from Area 2, being representative for all sections, are shown in Figure 3. The average ferrite grain size, as estimated using standards, was ~14 μm.

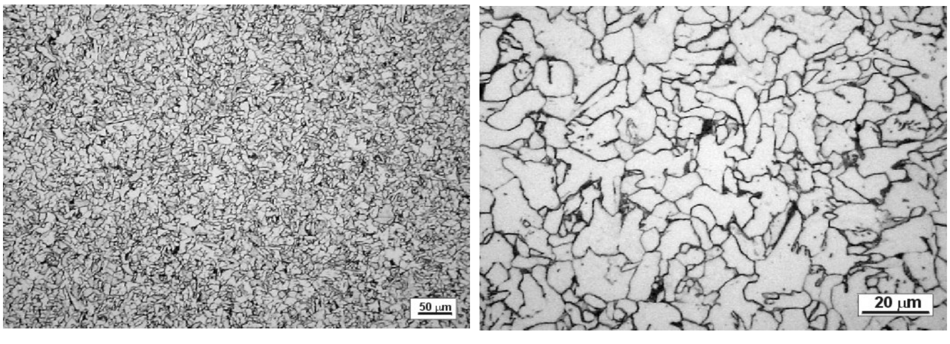

Fig.3. Microstructure of P265GH steel. Area no 2

The steel plate had the following mechanical properties: the ultimate tensile strength, R_m = 448 MPa; the upper yield point, R_{eH} = 342 MPa; the proof stress, $Rp_{0,2}^{300}$ = 219 MPa; and the permanent percentage elongation, A = 34%.
In three points in the areas selected for metallographic examinations, microhardness was also determined by the Vickers methods with a load of 30N. This averaged out at 127 HV_{30}, with the difference between particular areas being at a level of the standard deviation of 1.3 HV_{30}.

Examination using the Barkhausen method

The examinations and tests described above found that the metal plate fragment under examination exhibited homogeneity in terms of both microstructure and mechanical properties, as represented by hardness. This state suggested most probably the presence of internal stresses introduced by mechanical deformation during the plate production process. Therefore, further diagnostic examination of stress was carried out by a non-destructive method using the so called Barkhausen method. The purpose of this examination was to identify the presence of residual stresses in the sub-surface plate layer, to determine the principal directions, and to estimate their anisotropy. As the measured parameter being dependent on mechanical stresses, the root mean square value of BMN - RMS_{BMN} was used.
The first stage of examination included the determination of the characteristics of polar variations of the RMS_{BMN} while the second stage – the quantitative determination of the anisotropy of the effective value of Barkhausen noise, using a two-directional measuring head specially designed for this purpose.

Measuring apparatus

The examinations were carried out using measuring apparatus developed at Technical University of Czestochowa, in the Institute of the Modelling and Automation of Plastic Working Processes [10]. Its functional flow chart is shown in Figure 4. It is composed of three basic parts: a magnetization block, a measuring circuit, and a Barkhausen noise processing block. The integral part of the measuring apparatus is also a measuring head that integrates the function of magnetization of material being examined and the detection of Barkhausen jumps.
The magnetization block is constructed based on the circuit of a symmetric sawtooth step-controlled frequency voltage generator and a power amplifier with the characteristics of a current amplifier. It provides an infinitely variably regulated current I_m feeding the magnetizing winding of the measuring head.
The measuring circuit is built based on two amplifying stages. The first of them is accomplished based on a specialized low-noise integrated measuring amplifier enabling amplification of the order of 80 dB to be achieved. Additionally, the use of the measuring amplifier at the input stage allows the effective suppression of synphase disturbances. The other amplifier enables the step adjustment of amplification in the range from 0 to 40 dB. Through the combination of the amplifications of particular stages it is possible to adapt the best measuring circuit to the test conditions - the type of material to be tested, the measuring head used, or magnetizing current parameters.

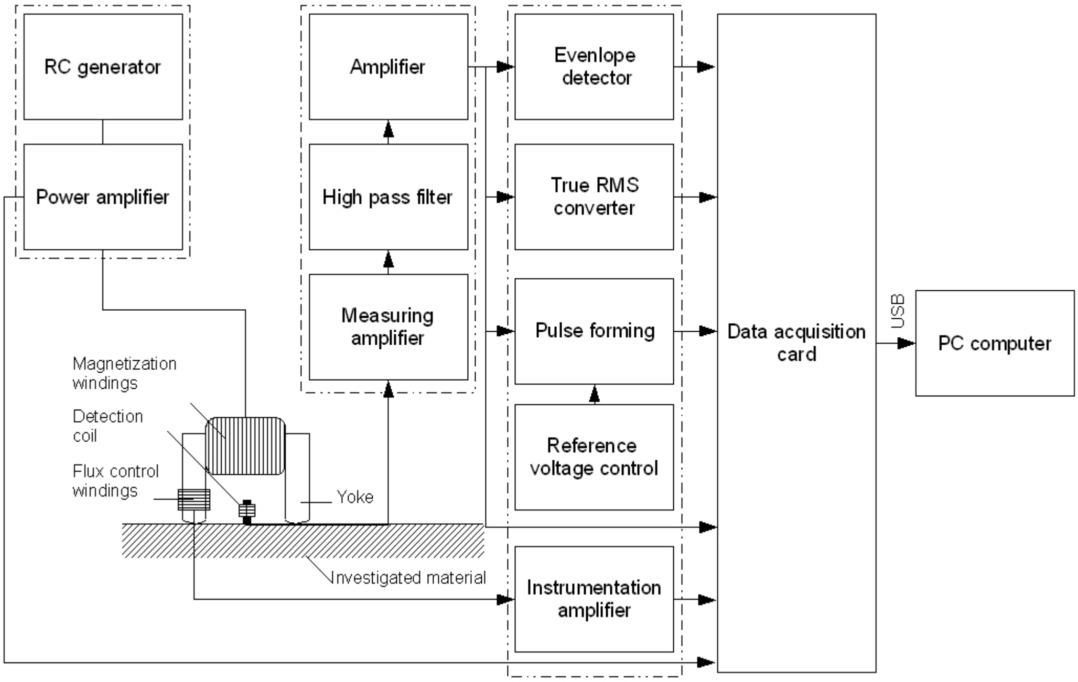

Fig. 4. Block diagram of measuring apparatus

Between the amplifiers there is a 1 kHz high-pass filter circuit. Its purpose is to eliminate any line interference and to filter out the strong magnetization current component and its harmonics, which are also generated in the measuring coil.
The Barkhausen voltage signal, filtered and amplified to a useful level, is fed to the processing block, where, using a *TrueRMS* integrated converter, its effective value is determined as well as an envelope voltage signal. Moreover, TTL standard pulses are shaped in this block, which correspond to the Barkhausen jumps voltage pulse of an amplitude above the specific reference voltage.

The determined Barkhausen noise parameters and the magnetization parameters in the form of voltage signals are acquisitioned by a measuring card and sent to a computer for subsequent processing, recording and visualization. Thanks to the hardware realization of the majority of measuring functions, the apparatus is practically independent on measuring & control software and data acquisition hardware used.
Two types of measuring head were used during the tests under discussion. The first of them, of a conventional construction, had a magnetization winding consisting of 300 turns, and a detection winding of 200 turns wound onto a ferrite core. It was used in preliminary tests and during the determination of the polar relationship of Barkhausen noise. For the measurement of stress anisotropy, the second measuring head was used. This head, specially constructed for this purpose, was composed of two pairs of pole shoes (yokes) with split magnetization windings. Its view and construction details are shown in Figure 5. The selection of the magnetization direction is done using a switch changing over the winding pairs, mounted on the housing body.

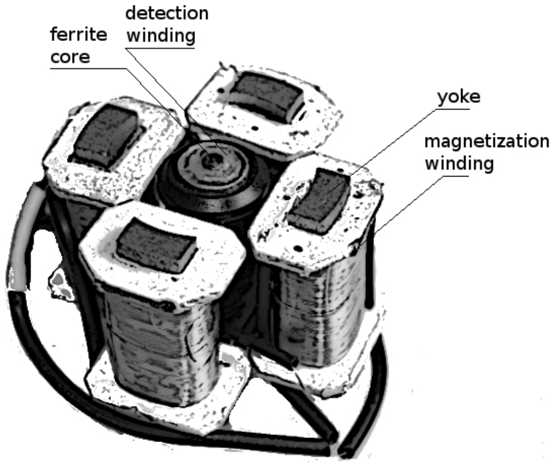

Fig. 5. Construction details of measuring head designed for stress anisotropy evaluation

Testing conditions

The measurements of Barkhausen noise were carried out for the following settings of the testing apparatus:

- measuring circuit amplification: 100 dB
- magnetization current frequency: 6 Hz
- magnetization current I_m intensity: 500 mA. This intensity was selected according to the procedure described in work [11] so as to achieve the greatest possible dynamics of RMS_{BMN} variations as a function of stress.

The preliminary tests, including the measurement of the root mean square value of BMN in two directions, were performed in the nodes of a 10×20 mm grid (Fig. 2) on either side of the plate fragment tested. As the obtained results were close to each other, three points, a, b, c, spaced 120 mm apart, were selected for further tests. The selection of the locations of the points was dictated by the need for maintaining a safe distance of the measuring head from the edge during tests, so as to eliminate the influence of boundary effects on the distribution of the magnetic field in the measurement zone [12]. Moreover, the influence of any deformations, which might have appeared during cutting out the sample, and associated stress relaxation were thus limited.

The direction parallel to the shorter edges of the tested segment, coinciding with the longer side of the steel plate, was taken as the reference direction (0˚). For each of the chosen points, polar measurements of the effective value of BMN were taken by changing the angular position of the head magnetization axis relative to the selected reference direction. The head position angle was varied in the range from 0 to 180˚ with a step of 22.5˚.

The second stage of tests, including only the measuring of the RMS value of BMN in two directions, was carried out on the second of the samples using a dedicated measuring head. The measurement point spacing was 40 mm, and the head yokes were oriented so that the directions of the magnetization axes were parallel to the sample edges. As the reference direction, the direction parallel to the longer edge, coinciding with the rolling direction, was applied.

RESULTS AND DISCUSSION

Examples of Barkhausen noise voltage signal oscillograms, as recorded in the perpendicular magnetization directions at one of the measurement points, are shown in Figure 6. The shape of the obtained plots is typical of unalloyed ferritic steels. Their preliminary observation alone allows one to find that strong difference of internal stresses occur in the material tested, as indicated by the very small BMN amplitude for one of the magnetization direction (Fig. 6b). Whereas, in the perpendicular direction (Fig. 6a), for the same magnetization conditions, this amplitude is much larger.

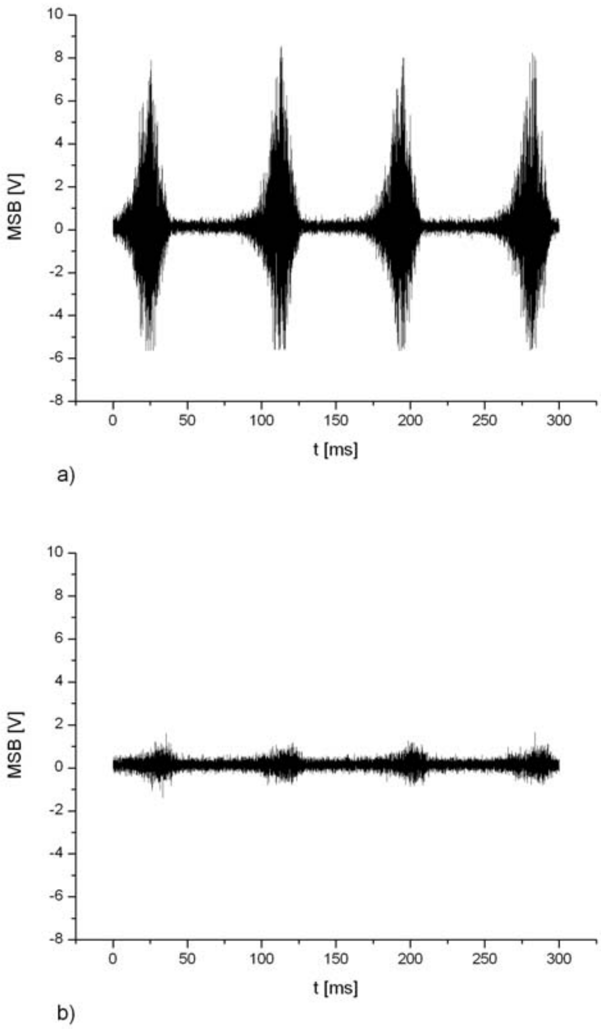

Fig. 6. Oscillograms of the Barkhausen noise voltage (MSB) for perpendicular magnetization directions

The values of RMS_{BMN} as a function of the angle α between the adopted reference direction and the magnetization axis direction, as measured at points a, b and c on either side of the steel plate section, are represented in the form of polar graphs (Figs. 7a - 7b). Additionally, the polar graph of the mean and normalized RMS_{BMN} value calculated based on the data from three measurement points is shown in Figure 7d. Analysis of the shape of the graphs indicates that there is a strong dependence of the RMS value of BMN on the magnetization, implying the existence of a biaxial residual stress state.

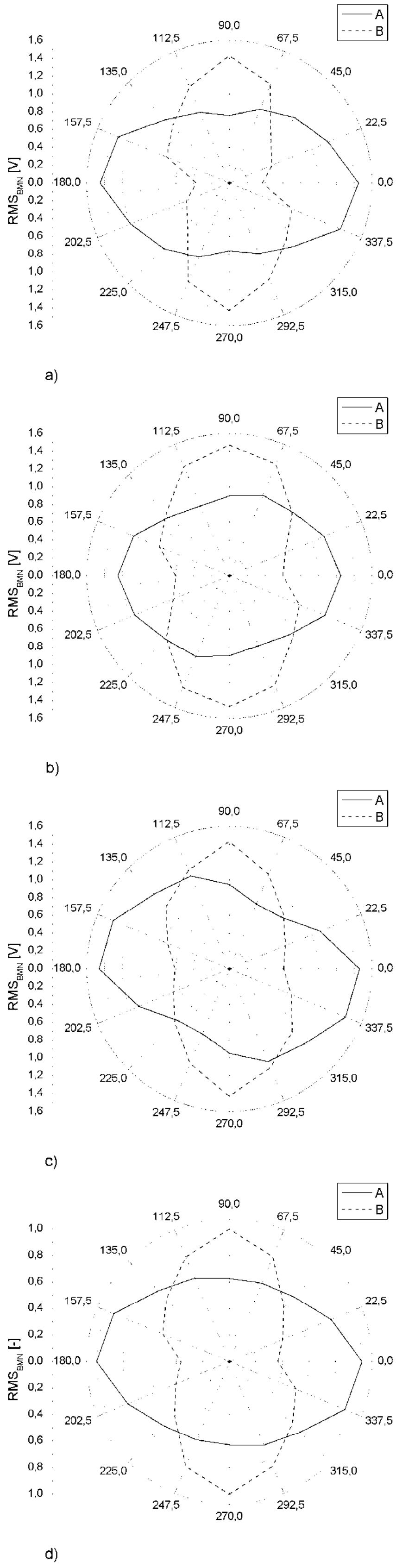

Fig. 7. Polar plots of Barkhausen noise intensity: a) – in point a, b) – in point b), c) – in point c), d) – relative average value from a, b and c points; A – top, B – bottom side of the plate

On the plate side labelled as A, conventionally assumed to be the top side, the orientation of the polar graph axis of symmetry indicates the direction of maximal stresses, which is practically coincident with the applied reference axis direction, showing a small deviation of a few degrees. Conversely, on the bottom side of the plate (labelled as B), the principal stress direction is oriented at the right angle toward the reference direction.
The RMS_{BMN} value anisotropy coefficients, k_A, as calculated for the adopted reference direction based on work by Rułka [13] (Table 2), may be equated with the value of residual stress anisotropy.

***Table 2**. Values of anisotropy coefficients k_A*

	a	B	c	
Top „A"	0,62	0,33	0,42	0,46
Bottom „B"	-1,18	-0,84	-0,8	-0,93

The characteristic necking of the polar plots on the bottom plate side seems to be the effect and, at the same time, indication of the plastic deformation [14, 15]. This situation might be caused by e.g. the deformation effected during straightening operations.
Releasing the internal stresses accumulated as a result of deformation effected in the manufacturing process is the cause of the appearance of spontaneous deformations of elements cut out from the steel plate under examination. For the identified stress state, this may result in an arcuation or saddle-like bend of cut out elements. This situation was observed in the second of the samples examined, having the form of a narrow strip. The partial release of residual stresses existing in the sample as a result of cutting caused a noticeable bend of the sample with a deflection of 6 mm, and a noticeable twist along the longer axis by approx. 10° (Fig. 8).

***Fig. 8.** Deflection of sample 2*

The distribution of the anisotropy k_A over the sample length was determined in this specimen from relationship (1), being a modification of the equation provided in the work by Rułka [13] quoted above. In the present work, instead of the average of two measurements, the average of all measurement was taken as the reference value.

$$k_A = \frac{RMS_{BMN\,x} - RMS_{BMN\,y}}{\overline{RMS_{BMN}}} \tag{1}$$

where:
$RMS_{BMN\,x}$ – RMS value of BMN in direction *x*, parallel to reference direction,
$RMS_{BMN\,y}$ – RMS value of BMN in direction *y*, perpendicular to reference direction,
$\overline{RMS_{BMN}}$ - average RMS value of BMN from all measurements

Thus obtained results are represented in the diagrams in Figure 9. Despite the occurring differences in absolute values, they confirm the stress state demonstrated previously and the intersection of the principal stress directions on the opposite plate sides.
Additionally, the application of two-directional head in these tests made it possible to retain the same magnetization conditions at a given measurement point and to maintain the invariability of its position.

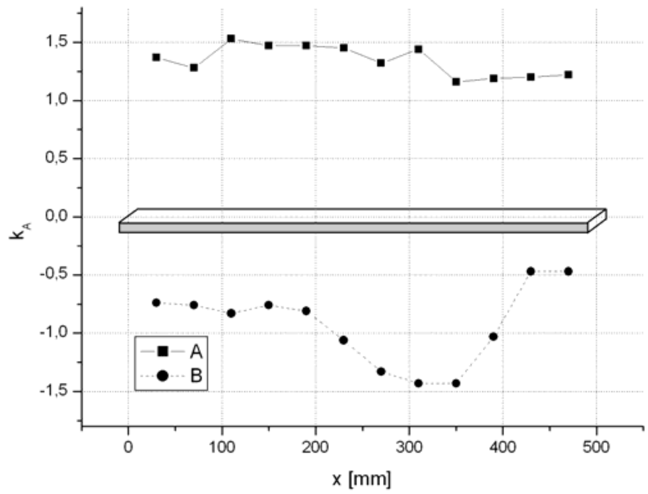

Fig. 9. Distribution of anisotropy coefficient k_A in sample 2

CONCLUSIONS

The results of the examinations carried out have demonstrated the existence of residual stresses of a large magnitude in the sub-surface layer the object examined, and their considerable anisotropy. Above all, it has been found, however, that the axes of the principal directions of stresses on the top and the bottom side of the steel plate are mutually perpendicular. This may be the result of the after-straightening operation, causing tensile stresses to appear on one side, and compressive stresses on the other. At the same time, the observation of the diagrams indicates that the material yield strength was probably exceeded on the bottom plate side, and a permanent deformation resulted.

The obtained examination results can be useful at the stage of designing the manufacture of products from this steel plate, considering the actual internal stress state and their impact on the cutting, shaping and welding processes, as well as for improving the existing production technology of this plate, or developing a technology for additional heat treatment operations with the aim of removing the unfavourable internal stress state. Moreover, the examination results enable one to conclude that the Barkhausen stress measurement method itself can provide a fast a reliable diagnostic tool for the quality assessment of boiler steel plates and their suitability for further working.

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