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Comparison and Verification of Stress Measurement Results Using the Barkhausen Effect during Three-Point Bending

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Non-destructive stress measurement techniques are extremely important and are still being developed in engineering research and diagnostics of materials. They allow for a quick assessment of their condition without damaging the structure. Their development is crucial for the safety of structures and extending the life of materials. One of the new methods is the measurement of stress using the Barkhausen effect. The MagStress 5d device was used for the tests. In this work, stress measurements were performed using the MagStress 5D device during three-point bending of a steel flat bar. The results were verified using resistance strain gauges and numerical simulation was performed in the Abaqus program. The measurements indicate that the MagStress 5d device using the Barkhausen effect can serve as a complete alternative to traditional extensometers. The results provided by the introduced method showed very good agreement with the latter.

Keywords: Bending testing, Numerical modelling, Barkhausen effect, Stress analysis, S355 steel

1 Introduction

Understanding the stress state in industrial products is one of the key issues facing measurement technology. Despite advanced manufacturing techniques, the modern manufacturing industry still encounters challenges with the methodology for measuring stress state in machine and structural components. Due to the complex stress state prevailing in materials, measuring these values is very difficult. The most commonly used measurement methods include electrical resistance strain gauges and X-ray examinations. These methods focus on point-based stress measurement. The measurement process is quite difficult and labor-intensive. The most stressed points in the tested component must be selected and then the surface of the tested components must be properly prepared. Many researchers are focusing on finding a much simpler measurement method that would allow for measuring stress state anywhere in the structure without the need for surface preparation. One such solution is the Magstress 5D measuring system manufactured by NNT (Novel Nondestructive Testing). This measuring device is based on determining the angular stress distribution in the material using a bidirectional Barkhause effect probe [1,2]. The proposed measurement method allows for rapid measurement of the stress state in ferromagnetic materials. This non-destructive measurement method allows for effective use in industrial environments. The automated device is equipped with a magnetizing probe, which allows for measurements that take just a few seconds. The result provides information about the elastic deformation of the material in a direction parallel to the magnetization direction. Proper preparation of the measuring device is an essential element of the research. The intensity of the Barkhausen effect depends on various physical properties of the tested materials. A calibration procedure is necessary to determine the dependence of the Barkhausen effect intensity on the elastic strain level. According to the manufacturer's recommendations, the most suitable calibration samples should be homogeneous. From a practical perspective, this is difficult to achieve, therefore, the calibration procedure should be performed for a wide range of physical parameters [3-5]. The automatic calibration process significantly reduces preparation time. Based on the calibration measurements, two-dimensional distributions of magnetic field strength as a function of strain were obtained. In the next stage of the measurement, the determined stress values will be correlated with the calibration curves.

In this research, the focus was on measuring strain during a three-point bending test with the MagStress device after the device calibration process using a sample made of S355 structural steel [6,7]. The obtained results were compared with the strain readings measured using a resistance strain gauge and with the results of numerical simulation performed in the Abaqus program.

2 Measuring system

The MagStress 5D device with a calibration device (Fig. 1) was used for the tests. This advanced measuring instrument is used for non-destructive testing of deformations and residual stresses in steel, particularly in steel structures. Its operating principle is based on the Barkhausen effect, which is the phenomenon of electromagnetic pulse emission during the magnetization of ferromagnetic materials [8,9]. The device consists of a central unit (analyzer) and a probe. The measurement involves local magnetization and real-time signal analysis. A Zwick & Roell Z100 universal testing machine with a maximum load of 100 kN and an accuracy of 1 N of force/0.01 mm of displacement was used for the high-precision load test. The fixture for performing the three-point bending test was placed on the machine's stationary base. Furthermore, for comparison purposes, a resistance strain gauge was attached to the sample to measure micro-strains for the specified bending force values (Fig. 2).

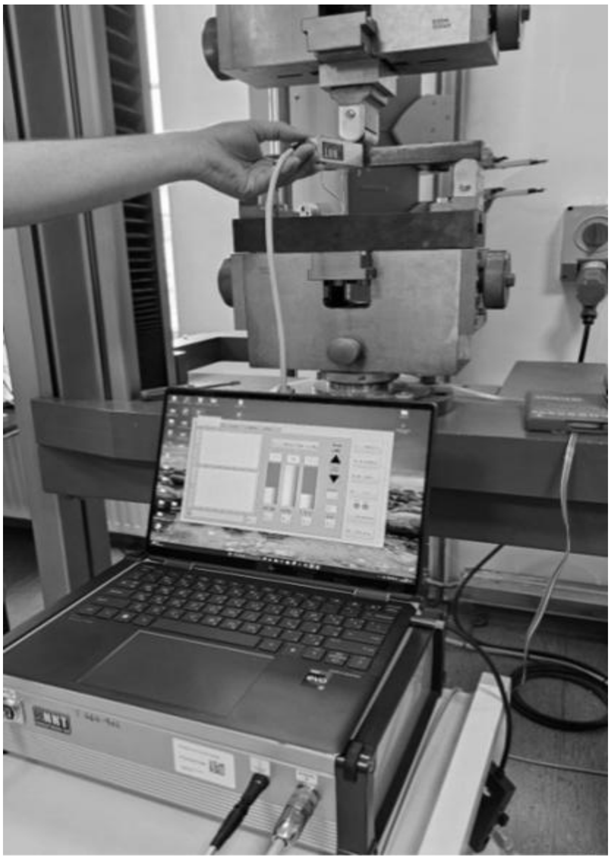

Fig. 1 *MagStressACS machine*

Fig. 2 *Sample with a resistance strain gauge attached*

2.1 Magstress system - calibration

The automatic calibration process of the Magstress 5D measuring device is carried out on the MagStressACS automatic calibration device [10]. It is an effective device enabling the quick generation of calibration curves of the dependence of the Barkhausen effect intensity on the strain state for a biaxial stress state. Calibration was performed once for the original material from which the test samples are made. A properly performed calibration must be loaded each time before measuring the test samples. Figure 3 shows the calibration device.

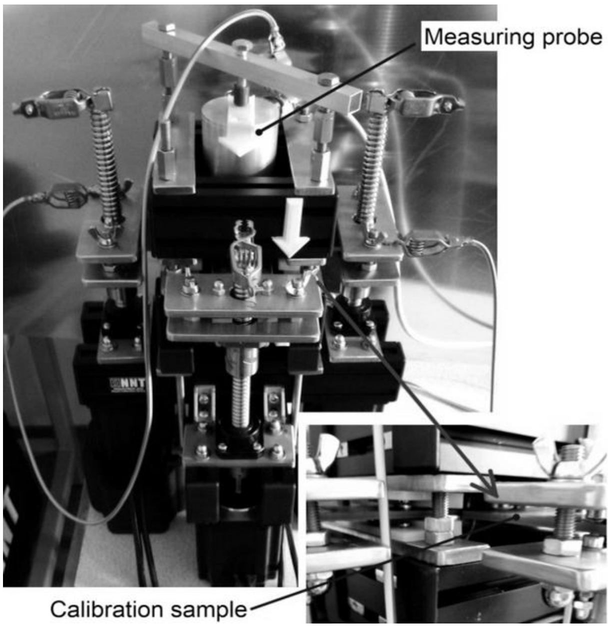

Fig. 3 *MagStressACS automatic calibration machine*

The device uses samples in the form of a cross (Fig. 4), on which a strain gauge sensor is placed (the device allows the use of bidirectional sensors or strain gauge rosettes).

As part of the calibration tests, three samples were made of 6mm thick S355 carbon steel. The samples were cut with the waterjet machine from one sheet of metal. The chemical composition of S355 steel is shown in Table 1 [1].

The thermal and mechanical properties of the steel under consideration are presented in Table 2.

***Tab. 1** Chemical composition of S355 steel in [%]*

C	Mn	Si	Cr	Ni	Al	P	S
0.19	1.05	0.2	0.08	0.11	0.006	0.028	0.02

***Tab. 2** Thermal and mechanical properties of S355 steel [11,12]*

Thermal properties				Mechanical properties				
T [°C]	λ [W/m °C]	ϱ [kg/m^3]	c [J/kg°C]	T [°C]	E [GPa]	Re [MPa]	ν [-]	α^T [1/°C]
20	52	7800	650	20	190	320	0,3	2,3e-5
200	49	7800	650	400	160	310	0,3	1,8e-5
1000	26,5	7800	650	600	130	125	0,3	1,75e-5
1477	33,5	7800	650	700	110	60	0,3	1,7e-5
1502	34	7300	745	800	40	55	0,3	1,6e-5
1527	34	6800	840	900	10	50	0,3	1,48e-5
2500	194	6800	840					
T - temperature; *λ*- thermal conductivity; *ϱ*- density; *c* - specific heat; *E* - Young's modulus; R_e - yield point; *ν* - Poisson's ratio; a^T - coefficient of thermal expansion								

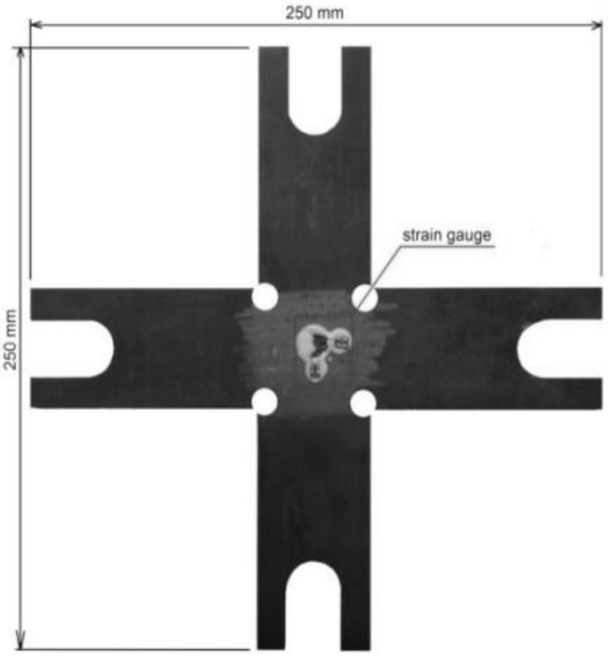

***Fig. 4** Calibration sample – S355 steel*

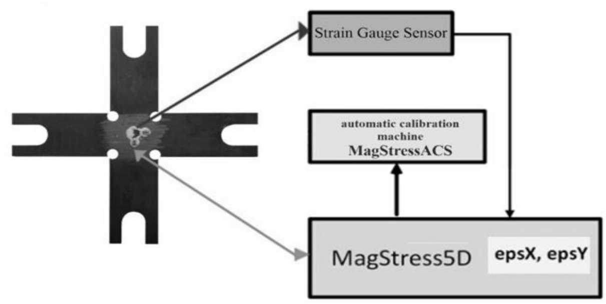

***Fig. 5** Measuring system operation scheme*

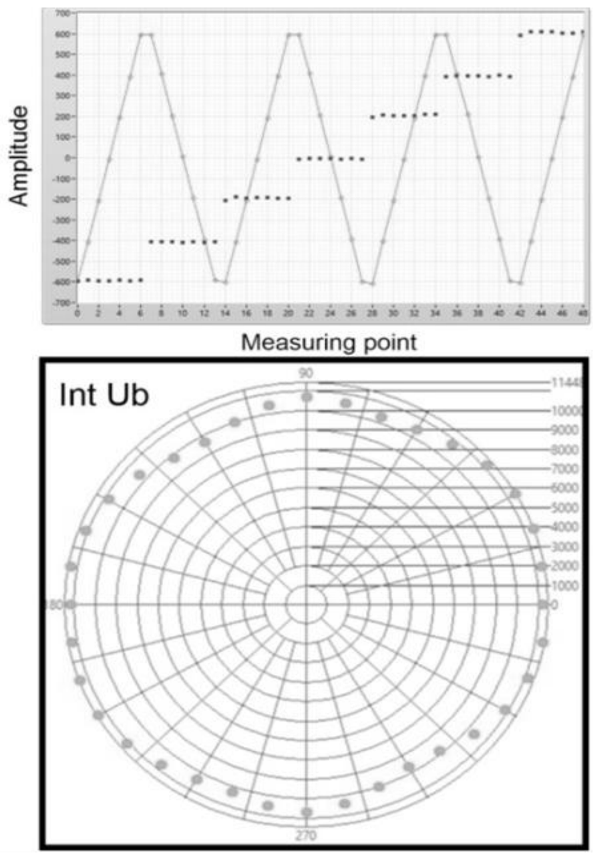

***Fig. 6** Calibration process*

The operational scheme of the calibration device is shown in Figure 5. During the test, the device cooperates with the Barkhausen effect intensity measuring head. The calibration process involves imposing a biaxial stress state by bending the sample in the shape of a cross. The four-point support of the two arms of the cross allows for the free generation of deformations in its central part. The deformation level is recorded using a strain gauge sensor [13,14].

For the test samples, calibration was performed in the deformation range from ε = −600÷600 10−6 in steps of 200 10−6. The same magnetization parameters were used for all samples. For the assumed deformation parameters, 49 measurement points were obtained, as shown in Figure 6.

Based on the measured angular distributions of the Barkhausen effect intensity, the signal intensity-strain relationships are determined. For the analyzed samples, Figure 7 shows an example of the dependence of the Barkhausen effect intensity as a function of strain. The obtained results are two-dimensional maps for two perpendicular directions.

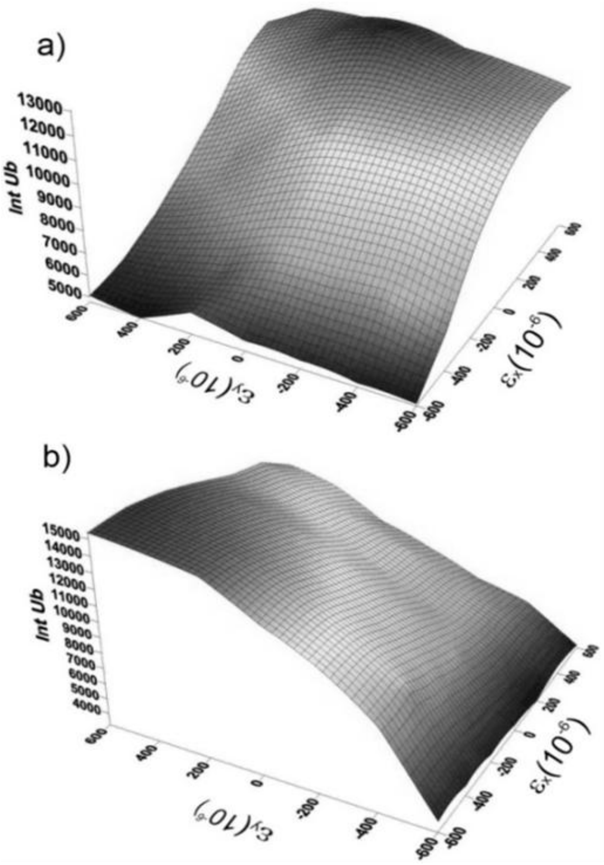

Fig. 7 *Two-dimensional state of the Barkhausen effect signal intensity values: a) along the measuring probe axis b) transversely to the measuring probe axis*

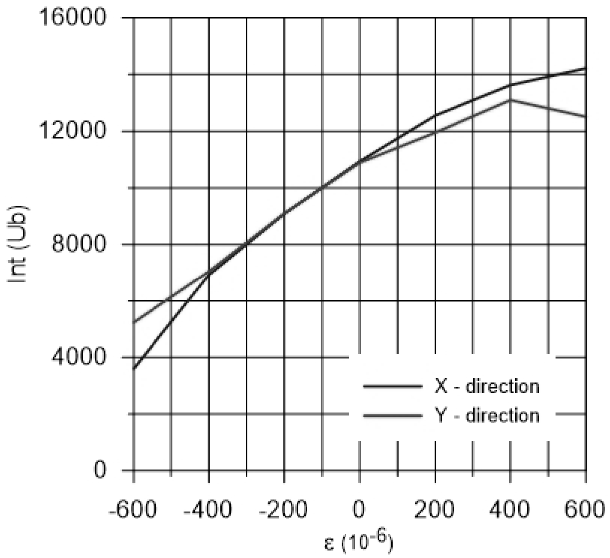

Fig. 8 *Calibration curves of the Barkhausen effect intensity as a function of strain*

The obtained two-dimensional distributions provide full information about the influence of strains on the intensity of the Barkhausen effect. In the case of using the obtained calibration results in stress measurements, it is more convenient to use one-dimensional curves (Figure 8).

The obtained curves will be used for further stress measurements using the Magstress 5D measuring system.

3 Results and discussion

For the tests, a sample of S355 steel was prepared from a 25mm square bar. The sample was loaded successively with the following elastic force values: 7500 N, 10000 N, and 12500 N. After applying the appropriate force, the strain values were read in the X and Y directions using a resistance strain gauge and the MagSteress system measuring head. Figure 9 shows a diagram of the measurement system.

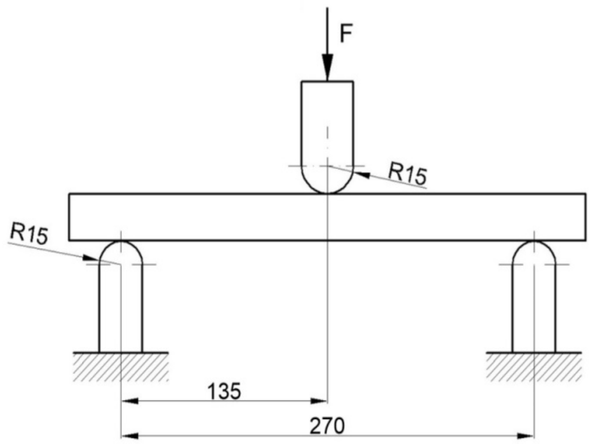

Fig. 9 *Diagram of the considered measurement system*

3.1 Results from numerical simulation Abaqus

Numerical model used in the work consists of 25350 deformable linear cuboids elements and analitical discrete rigid supports at both ends as well as pin in the middle of the beam. The force is applied to the pin within time period for three load cases used in the experiment. A frictional contact condition is established between the deformable beam and the pin with friction coefficient equal to 0.3. Young's modulus used in calculations equals E=200000 N/mm2, whereas Poisson's ratio equals ν=0.3. Numerical model with finite element mesh are presented in Fig. 10.

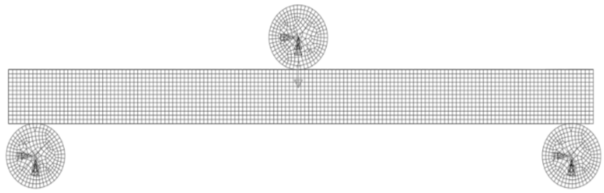

Fig. 10 *Numerical discrete model*

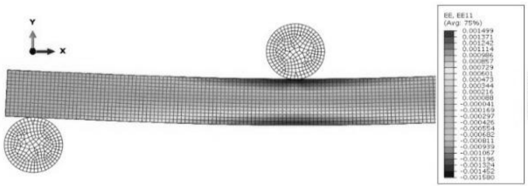

Fig. 11 *Calculated strain in lateral direction (x), force 7500 N*

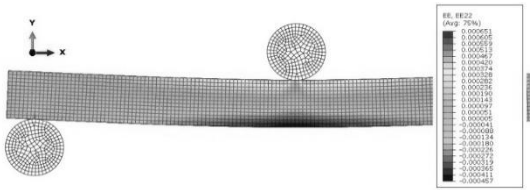

Fig. 12 *Calculated strain in lateral direction (y), force 7500 N*

Figure 11-12 shows the axial strain values determined from the numerical model calculated in Abaqus. The strain values for the 7500 N load are slightly lower than those measured by the strain gauge, amounting to 26 microstrain values, representing approximately 15% error.

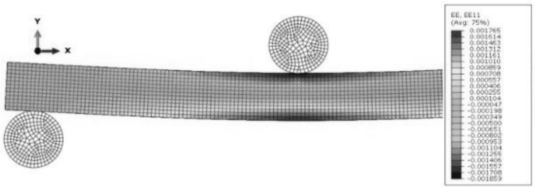

Fig. 13 *Calculated strain in lateral direction (x), force 10000 N*

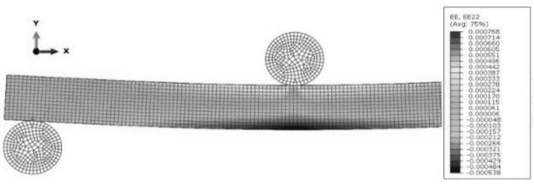

Fig. 14 *Calculated strain in lateral direction (y), force 10000 N*

Figures 13–14 show the numerically calculated axial strain fields for a load of 10000 N. For the axial strains, the x-axis differs from the values measured using a resistance strain gauge. For a load of 10000 N, the strain is 63 microdeformations (25% error).

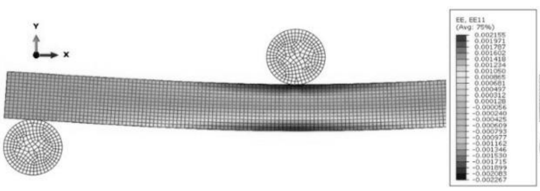

Fig. 15 *Calculated strain in lateral direction (x), force 12500 N*

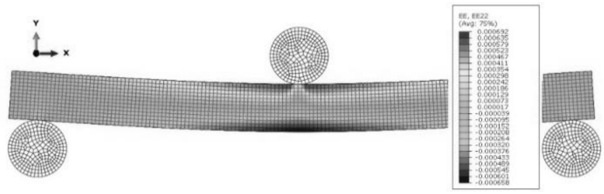

Fig. 16 *Calculated strain in lateral direction (y), force 12500 N*

Figures 15–16 show the calculated axial strain field for a load of 12500 N. The strain difference reaches 53 microdeformations (19% error). The total error for axial strain does not exceed 20%.

3.2 Results from Magstress system

Figures 17-19 show the measured directional strain values and magnetic field intensity curves, which indicate significant anisotropy. The largest directional differences were observed for a load of 12500 N.

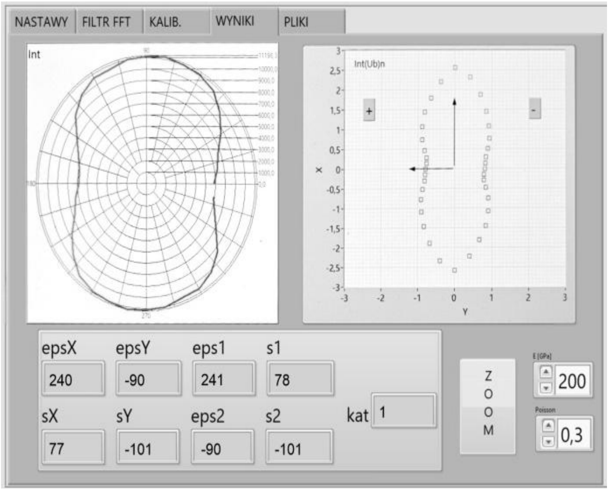

Fig. 17 *Angular distributions of BE radiation intensity and variances of directional strains (X and Y axes) measured at a point on the bar surface, force 7500 N*

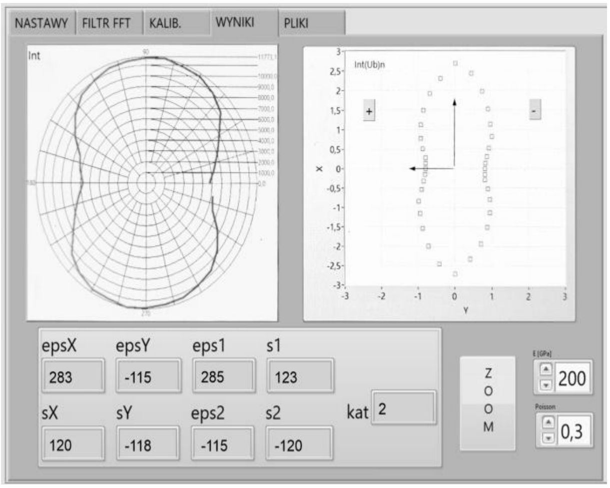

Fig. 18 *Angular distributions of BE radiation intensity and variances of directional strains (X and Y axes) measured at a point on the bar surface, force 10000 N*

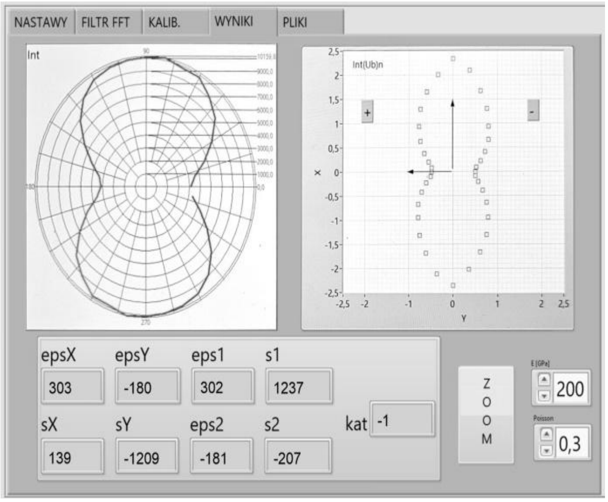

Fig. 19 Angular distributions of BE radiation intensity and variances of directional strains (X and Y axes) measured at a point on the bar surface, force 12500 N

3.3 Results from results of resistance strain gauge measurement

To confirm the results, measurements were taken using a two-channel resistance strain gauge with a nominal resistance of 120Ω. A directional foil strain gauge TF-5-2x/120 was glued to the inner surface of the sample, centrally below the contact point. The strain gauge was glued according to the manufacturer's recommendations. The measurement system consisted of a strain gauge amplifier, a bridge, and a data acquisition system. The measured values were read along the X axis (EPS1) and Y axis (EPS2). Figure 20 presents the results of the measurements for the specified force values.

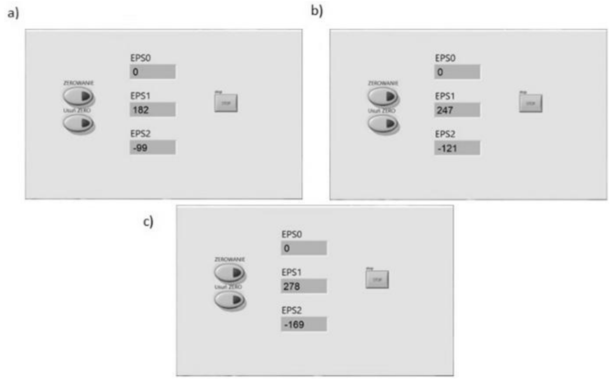

Fig. 20 Strain in lateral direction x and y, a) force 7500 N, b) force 10000 N, c) force 12500 N

Table 3 presents the summary results obtained from strain measurements using various methods. Strain values obtained using resistance strain gaging reach 24%. The measurement accuracy may be due to averaging non-uniform strain fields. The Magstress method, which utilizes magnetic phenomena to measure strain in three-point bending experiments, is quite accurate. The largest deviation was approximately 20%. It is important to note that in the example of measurements using this method, it is crucial to perform correct calibration on samples prepared from the same material as the one being tested.

Tab. 3 Comparison of strain values obtained for different measurement methods

Measurement method	Force [N]	Strain (x)	Strain (y)
Magstress 5D	7500	240	-90
	10000	283	-115
	12500	303	-180
Abaqus	7500	156	-109
	10000	184	-128
	12500	225	-155
Resistance strain gauge	7500	182	-99
	10000	247	-121
	12500	278	-169

4 Conclusion

The purpose of this paper was to conduct experimental measurements using the resistance strain gauge method to verify the accuracy of the Magstress device. A three-point bending test was used to compare the two approaches. The variable considered in the evaluation of both approaches was the directional strain, which was monitored at the center point of the specimen. Numerical simulations were also performed in Abaqus to assess this quantity. The Barkhausen effect is used to measure residual stresses. This paper presents the results of strain measurements in S355 steel during a classic bending test. The bending process introduces elastic stresses, which are very obvious and suitable for comparative analysis of measurements performed using different methods. Analysis of the Barkhausen signals allows for the assessment of these strains and stresses. This method is non-invasive and allows for quick and accurate measurements, which is particularly useful in industry, where monitoring the condition of materials subjected to stress is crucial to ensuring safety and efficiency. The most time-consuming step in performing measurements is preparing calibration samples and performing the actual calibration, which significantly impacts measurement quality.

The short measurement time allows for serial measurements, even on real objects. Comparative analysis of the results showed that the magnetization method can be an effective measurement tool.

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