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Robot measuring head for automated Barkhausen Noise testing

Abstract*. The paper presents the construction of a mechatronic measuring head of the magnetic Barkhausen noise for operating with the industrial robotic arm. It is designated to the automated multipoint investigations of residual stress state in the metal sheets and strips by the Barkhausen method. Thanks to used solutions of the shock-absorbing and fitting of the magnetization yoke, it can operate on non-flat surfaces with unknown profiles. All construction parts were manufactured using 3D printing*

Streszczenie. *W artykule przedstawiono konstrukcję głowicy pomiarowej szumu Barkhausena do współpracy z ramieniem robota. Przeznaczona jest do zautomatyzowanych badań stanu naprężeń własnych w blachach i taśmach metodą Barkhausena. Dzięki rozwiązaniom amortyzacji i dopasowania jarzma magnesującego może pracować na niepłaskich powierzchniach o nieznanych profilach. Wszystkie części konstrukcyjne zostały wyprodukowane przy użyciu druku 3D (**Głowica pomiarowa robota dla zautomatyzowanych pomiarów szumu Barkhausena**)*

Keywords: Barkhausen noise, non-destructive testing, measuring head, robotization, 3D printing
Słowa kluczowe: Szum Barkhausena, badania nieniszczące, głowica pomiarowa, robotyzacja, druk 3D

Introduction

Non-destructive methods of testing metallic materials and products are susceptible to automation [1]. In industrial practice, ultrasonic or eddy current inspection systems for repeatable measurements have been commonly used for many years. They are also robotized [2,3]. In the case of the group of magnetic studies relying on the magnetic Barkhausen noise (MBN) [4-8], not widespread in the industry as mentioned earlier NDT methods, also exists a limited number of commercial solutions. There are known systems for cylindrical metal pieces testing on grinding defects [9] or specialized cells equipped with robots operating standard MBN measuring heads [10].

In view of the growing importance of scientific research on flat and relaxation residual stress in metal sheets for further processing [11], such as laser cutting or press brake forming the MBN method offers a quick tool to evaluate the efficiency of applied technology of straightening and stress removal [12]. In this case, the general dependence of the Barkhausen noise intensity, generated during cyclical remagnetization of the ferromagnetic materials, with stress is utilized [13,14] (Fig. 1).

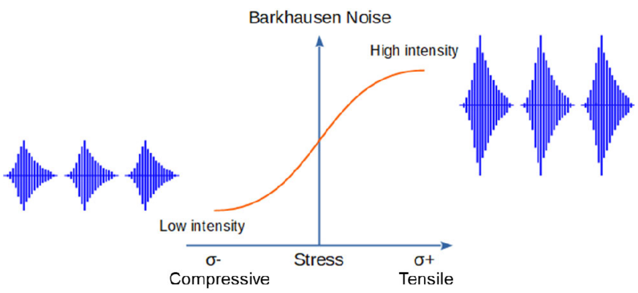


Fig.1.Dependence of the Barkhausen noise with stress

Hand-operating the MBN probe and multipoint measurements in industrial conditions has a lot of disadvantages and limitations. First, very often, in line with continuous production conditions, human presence is prohibited due to safety requirements and the downtimes result in financial losses. Besides, industry measurements need a two-person team, one for operating the probe and one for data saving. For the operator, a few hours of touching and angular positioning of the measuring head causes finger and wrist pain. It may result in problems with repeatable applying perpendicular to the tested surface and changing the magnetization conditions influencing Barkhausen noise reading [15]. Another time-consuming and tiring operation is applying the measurement point matrix with direction lines on the surface of the tested sheet.

The natural consequence in the realities of modern industry is to replace the human worker with a robot in these tedious operations. Initial tests with applications of the standard measuring head fixed to the robot showed the weak sides of such solutions.

First of all, the real metal sheet surface is not always flat. Each sheet even after straightening operations may be wavy. It is caused by unfavorable residual stress reveals distributions after uncoiling and leveling [16] So, the changes in relative height to the reference level are noticed, and moreover in the inclination of the tangential surface. If the measuring head is operated manually by the operator, there is no problem with delicate touching and leveling to the tested surface orientation.

During robotization of the MBN inspection, the first problem can be eliminated partially by the low robot speed and collision monitoring (especially while the measuring head is operated by the *cobots*). The second one is not simple, because the magnetization yoke always should be touching at the right angle to the surface's slope. In a harsh environment, laser scanning [17] and detailed contour mapping of the surface of each piece predicted for investigations are not effective.

Additionally, based on experience, a dangerous phenomenon of the spring back has been observed in the sheets, which may pose a risk of mechanical damage to the rigidly mounted measuring head.

Based on previous Author experience in MBN sensor development [18,19], in order to solve the above disadvantages, an original solution of the robotic MBN measuring head was developed. It is dedicated to automated Barkhausen noise testing in a large number of points. Thanks to the special construction, can operate on non-ideal flat surfaces of the tested material. Lots of the elements have been made with 3D printing [20]. This improved the process of prototyping and checking subsequent functionalities [21]. Due to embedded additional electronic modules for data displaying or internal motion control, it can be assumed as the mechatronic construction.

Characteristic of measuring head structure

In Figure 2, a general view of the system of the robot (KUKA KR15/2) with a mounted MBN measuring head is presented. This construction was built on the basis of a concept prototype shown in Figure 3

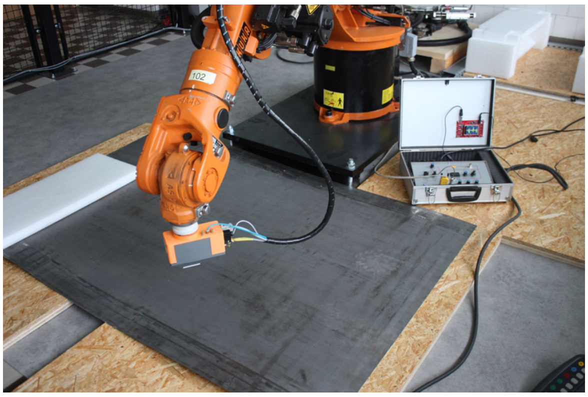


Fig.2. A view of the robot operating MBN measuring head

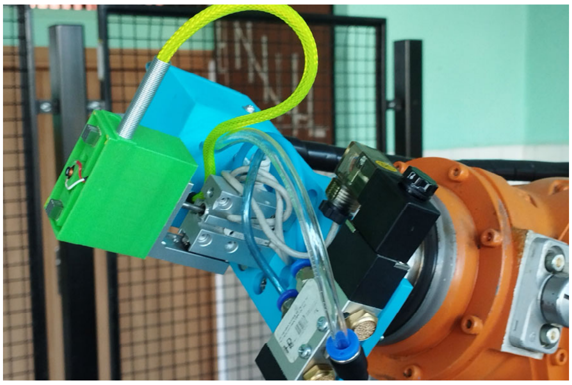


Fig.3 Details of the prototype's construction

Figure 4 shows a functional diagram of the complete measuring head. From the point of view of its purpose, the main essential part is the magnetization yoke with the coil. The C-shaped yoke pole cross-section is 36 mm^2 and the winding has 300 turns of 0.25mm laminated copper wire wounded on the 3D printed spool. The magnetization coil is fed up from external the bipolar current generator inside the MBN measuring apparatus [18].

Between the pole yokes, a detection coil (commercial SMD choke with ferrite) of Barkhausen jumps is placed. A special suspension system with a two-part spring and holder was used. In opposite to the known damper system with one vertical spring, this solution lets the pick-up coil move up-down, horizontally, and tilt too.

A similar system was used to clutch the yoke to the probe housing but with four springs working in a compression/tension regime. By selecting springs with appropriate characteristics, both appropriate stiffness and flexibility are achieved. In Figure 5, details of the operating fitting system on the slope of the surface are presented.

The casing is mounted to the end of the actuator, which lets move up and down the probe independently of the robot's movements. As the actuator, a rail-guided pneumatic cylinder MXH6-10Z type with a stroke of 10 mm was used.

The two-directional operation of it is controlled by the 5/2 type electric valve. By the adjustment of pressure throttling, the lowering of the sensor can be smoothed and additionally cushioned. Reaching the extreme positions is detected by two piston's position sensors. These signals as well as the steering signal (0V or 24V) to the valve are grouped together at the control interface connected to the PLC system cooperating with the robot's control system.

From the other side, the actuator is fixed to the base plate The base plate to the mounting ring is attached via sliding pins passing through holes in the sets of four cylindrical permanent magnets. The same set is placed in the ring creating a magnetic damper. By screwing the pins into the nuts, can be changed the level of shock absorption.

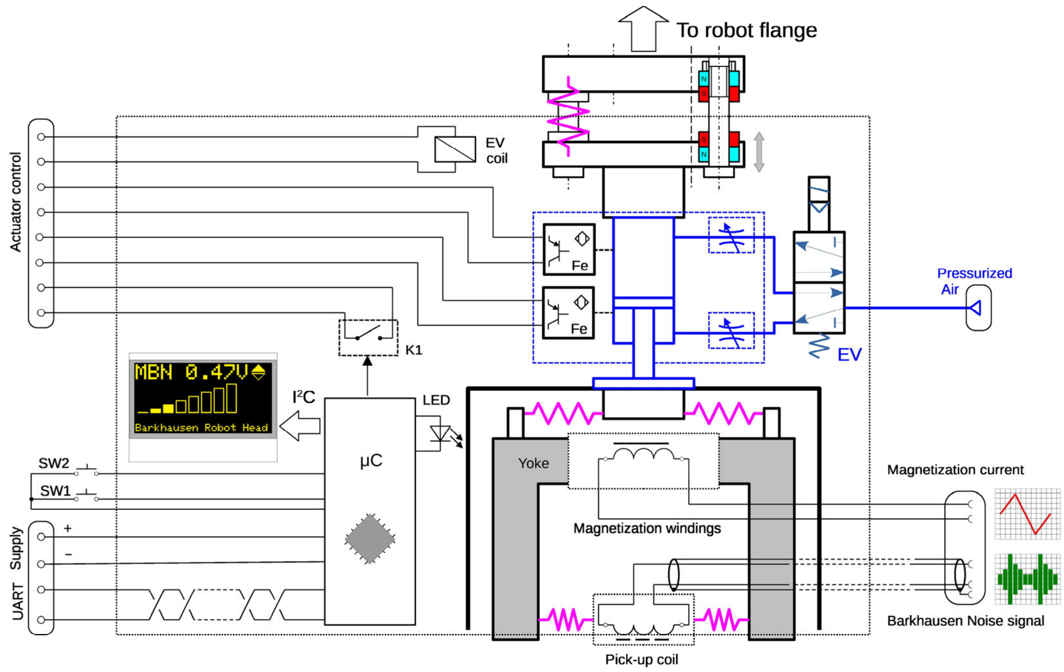


Fig.4. Functional scheme of the MBN measuring head

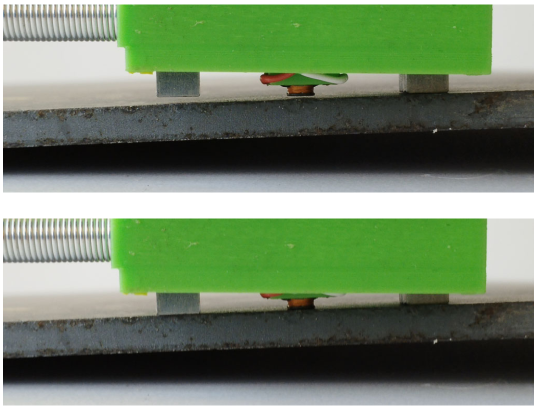


Fig.5. Details of the fitting of the yoke and detection coil to the slope of the curved surface, while the head is moved vertically.

The fixing ring is designed to be screwed to a robot flange with a standard diameter of 63 mm. Thanks to the independent possibility of vertical movement of the MBN sensor, the kinematic structure of the robot can remain immovable If the directional diagrams of MBN [^]are prepared. Only the last sixth rotary axis is used for the angular orientation of the head.

Inside the presented measuring head were placed also electronics circuits for measured signal displaying. Barkhausen noise after detection is transferred and processed inside the measuring equipment. After high amplifying (above 80 dB) and high-pass filtering (f_c =1 kHz), first of all, the root mean square (RMS) value is determined [18] as the most correlated parameter with stress. After digitalization, this value is transferred back by UART to the microcontroller (Atmega328P on Arduino Nano development kit) which is steering user display via I^2C protocol.

a)

b)

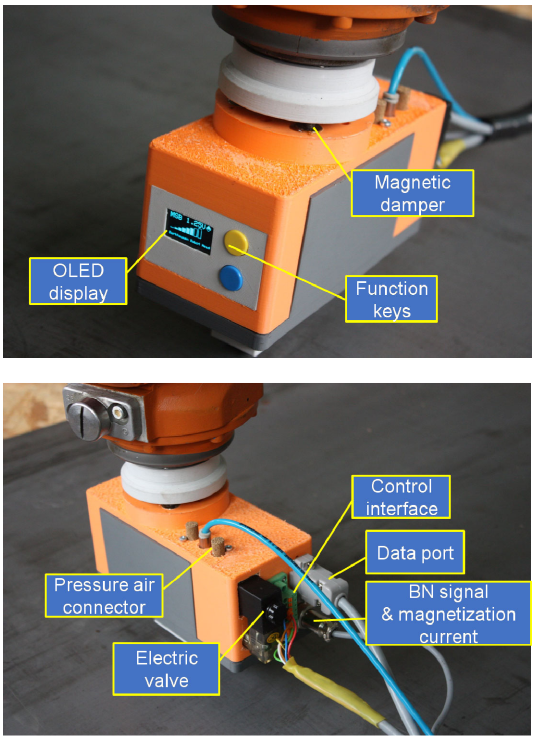


Fig. 6. Details of the measuring head: a) front view, b) rear view with interfaces.

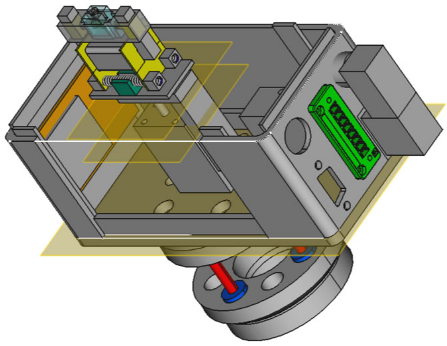
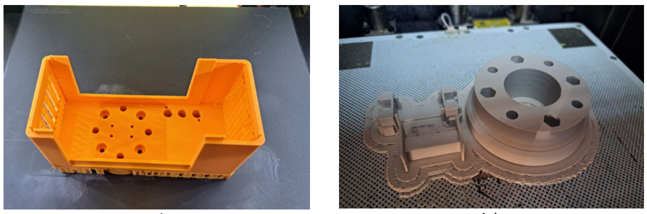


Fig. 7. A view of the process of modeling the construction of the measuring head using FreeCAD software

At the 0,96" OLED display, the MBN value in numeric format and with graphical representation is presented. This µC is also an interface for free-function two programmable buttons and an internal contact (or photocoupler) connected to the input of the PLC control system. In the future, it is planned to add a laser distance sensor for the measurement of the real base distance for each measurement point on the investigated sheet.

In Figure 6 a detailed view of the measuring head with placement of the main elements is shown. The different kinds of outgoing and incoming signals were grouped and output on connectors located on the rear part of the head. On the front, the display and function keys were placed.

All parts of the presented measuring head were designed and modeled using FreeCAD v. 0.21 software (Figure 7). Next, exported from the program (in *stl* format) models of the particularly functional parts, were printed on two 3D printers [22]. The large elements with the spatial structure were made at Raise 3D Pro2 (Fig. 8a), and massive, carrying loads with full 100 % density as flange or magnetization coil carcas were printed on Zoltrax M200 (Fig. 8b)



a) b)

Fig.8 A view of raw printed elements of the measuring head, a) base plate, b) coil spool and mounting flange

Results

After assembling the head and mounting to the industrial robot KUKA KR15/2, the functional tests and regulation were performed. Air pressure settings and magnetic damper tension were adjusted, to obtain ±10 mm of safety operational margin. Next, the initial investigation of the MBN in the sheet of structural steel was carried out. In Figure 9, the results of the four MBN measurements' at different angles in relation to the rolling direction are presented. Obtained test results are typical for the directional residual stress distribution after straightening processes [23], indicating the correct operation of the head.

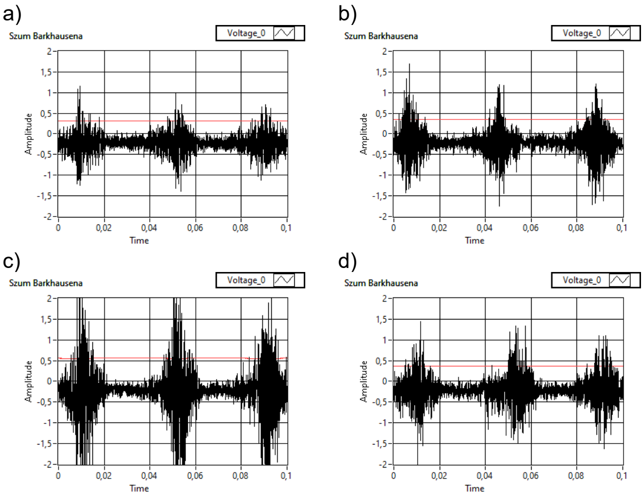


Fig.9 Example waveforms of the MBN measured at the different directions of magnetization: a) 0°, b) 45°, c) 90°, d)135°

Summary

The presented measuring head for Barkhausen noise testing by the robot, states a new comprehensive approach to such construction, which currently has no equivalent or similar solution. Thanks to the use of new technologies related to 3D printing or the use of easily programmable microcontroller systems, this head can be adapted in many aspects to individual research needs.

Some of the particular technical solutions used in this construction are pending under the patent protection procedures within applications P.446390 and P.446392.

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REFERENCES

[1] Tabin J., Automatyzacja badań ultradźwiękowych, *Hutnik*, R.36, Nr 10, 1969
[2] Foster, E.A.; Bolton, G.; Bernard, R.; McInnes, M.; McKnight, S.; Nicolson, E.; Loukas, C.; Vasilev, M.; Lines, D.; Mohseni, E.; et al. Automated Real-Time Eddy Current Array Inspection of Nuclear Assets. *Sensors* 2022, 22, 6036. https://doi.org/10.3390/s22166036
[3] Fereshteh-Saniee, N.; Reynolds, N.; Norman, D.; Qian, C.; Armstrong, D.J.; Smith, P.; Kupke, R.; Williams, M.A.; Kendall, K. Quality Analysis of Weld-Line Defects in Carbon Fibre Reinforced Sheet Moulding Compounds by Automated Eddy Current Scanning. *J. Manuf. Mater. Process*. 2022, 6, 151. https://doi.org/10.3390/jmmp6060151
[4] Tu Le Manh, José Alberto Pérez Benitez, José Hiram Espina Hernández, José Manuel Hallen López: Barkhausen Noise for Nondestructive Testing and Materials Characterization in Low-Carbon Steels, Woodhead Publishing, (2020), DOI:10.1016/C2018-0-00863-4
[5] Jiles D. C.,Kiarie W.: An integrated model of magnetic hysteresis the magnetomechanical effect and the Barkhausen effect", *IEEE Trans. Magn*.,(2021), vol. 57
[6] Anthony Moses , Stanisław Zurek , Sławomir Tumański , Philip Marketos , Harshad Patel: Korelacja między powierzchniowym polem magnetycznym a szumami Barkhausena w blachach o ziarnie zorientowanym, , *Przegląd Elektrotechniczny*, (2009), No 1, 111-114
[7] Costa L .F. T, Gerhardt G. J. L, Missell F. P., De Campos M. F: Interpretation of magnetic Barkhausen noise bursts in low frequency measurements, *Acta Physica Polonica A*, (2019)Vol. 136, No.5
[8] Santa-Aho S.et al.: Barkhausen Noise Probes and Modelling: A Review, *Journal of Nondestructive Evaluation*, (2019), No. 94, 1-11
[9] https://www.stresstech.com/products/barkhausen-noise-equipment/inline-robot-systems/
[10] Karpuschewski B., Bleicher O., Beutner M.: Surface Integrity inspection on gears using Barkhausen noise analysis, Procedia Engineering 19 (2001), 162-171
[11] Moen C.D., Igusa T., Schafer B.W.: Prediction of residual stresses and strains in cold-formed steel members, *Thin-Walled Structures*, Vol. 46, Iss. 11, 2008, 1274-1289,
[12] Sebastian Mróz, Piotr Szota, Tomasz Garstka, Grzegorz Stradomski, Jakub Gróbarczyk, Radosław Gryczkowski, Selection of parameters of the preliminary roller straightener using FEM simulation, Conference materials, XIII Scientific Conference PLASTMET 2023, Rzeszów, 7-10 November 2023
[13] Gauthier J., Krause T., Atherton D.: Measurement of residual stress in steel using, magnetic Barkhausen noise method, *NDT&E International*, (1998), Vol. 31, No. 1, 23-31
[14] Ferreira da Silva S., Rodrigues Mansur T. R., Cruz J. R., Neto M. M.: The use of magnetic Barkhausen noise analysis for nondestructive determination of stresses in structural elements, (2007) International Nuclear Atlantic Conference, INAC 2007, Santos, SP, Brazil, September 30 to October 5, 2007
[15] Jančárik V., Pal'a J.: Influence of lift off on Barkhausen noise parameters of construction stee, *Journal of Electrical Engineering* (2018), 69. 474-476. 10.2478/jee-2018-0079
[16] Hidveghy J., Michel J., Bursak M., Residual Stress in Microalloyed Steel Sheet, Metalurgija, 42 (2) 103 (2003)
[17] Zhang, H.; Wang, J.; Guo, C. Tool Frame Calibration for Robot-Assisted Ultrasonic Testing. Sensors (2023), 23, 8820.
[18] Garstka T.: System pomiarowy do badań właściwości wyrobów stalowych z wykorzystaniem zjawiska Barkhausena, *Pomiary Automatyka Robotyka*, 12, (2008), nr 6, 58-61
[19] Garstka T.: Comparison of the Results of the Barkhausen Noise Investigations Conducted with Using Various Designs of 7Sensor, Przegląd Elektrotechniczny, 93, (2017), nr 7, 27-30,
[20] Kwapisz M.: Charakterystyka metod druku 3D, Inżynieria zarządzania. Cyfryzacja produkcji. Aktualności badawcze 1 (red.) KNOSALA Ryszard, Polskie Wydawnictwo Ekonomiczne, Warszawa, (2019), 67-74
[21] Garstka T., Krakowiak M., Kwapisz M., Integrated measuring head for Barkhausen testing, Przegląd Elektrotechniczny, R. 98, Nr 11, 2022, 151-154
[22] Kwapisz M., Bajor T., Krakowiak M.: Analysis of Strength Changes of PLA Samples Made in 3D Printing Technology, 28th International Conference on Metallurgy and Materials METAL 2019, Brno, Czechy 22 - 24 May (2019), TANGER Ltd.,1583-1588, DOI: 10.37904/metal.2019.963
[23] Garstka T, Koczurkiewicz B, Golański G.: Diagnostic examination of P265GH boiler steel plate using the Barkhausen method, *Advances in Material Sciences*, (2010), nr 10, 81-92