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MATERIAL SCIENCE AND NANOTECHNOLOGY

Application of acoustic emission to the analysis of phase transformations in 27MnCrB5-2 steel tests during continuous cooling

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Abstract. The goal of the research was to analyze the acoustic emission signal recorded during heat treatment. On a special stand, samples prepared from 27MnCrB5-2 steel were tested. The steel samples were heated to 950°C and then cooled continuously in the air. Signals from phase changes occurring during cooling were recorded using the system for registering acoustic emission. As a result of the changes, Widmanstätten ferrite and bainite structures were observed under a scanning microscope. The recorded acoustic emission signal was analyzed and assigned to the appropriate phase transformation with the use of artificial neural networks.

Key words: microstructure; phase transformation; ultrasonics; acoustic emission; continuous cooling.

1. INTRODUCTION

Studies using the acoustic emission (AE) method are becoming increasingly popular, being used in new aspects of technology development. Acoustic emission is one of the interdisciplinary methods. It is used whenever the source of information about the change in the state of the tested material and the course of the technological process are structural vibrations [1–5]. The aim of the study was to apply acoustic emission in research of the heat treatment process. An artificial neural network was used to analyze the signals occurring during quenching. The combination of both techniques made it possible to control and analyze the processes performed. For the tests, 27MnCrB5–2 (1.7182) alloy steel was used for quenching. During thermal improvement operation, a very important aspect was to control the parameters of the process. The acoustic emission method can effectively be used to monitor the heat treatment process [6, 7]. During phase transformations, acoustic effects are generated as a result of dynamic triggering of cumulated energy. Due to the non-invasive method of measuring acoustic emission, it is possible to monitor transformation processes in steel [8–11]. As a result of changes in the tested object, elastic waves are propagated. In the acoustic emission method, signals occurring in a broad frequency band from kHz to MHz are recorded and used. Research using the acoustic emission method is gaining increasing popularity and finding application in more and more recent aspects of technology development. The results of experimental research related to the measurement of acoustic emission during heat treatment processes show that this method is the source of relevant information about the phenomena occurring in the processed material [6, 7, 11, 12]. Measurement of acoustic emission signals is performed using the passive method. The apparatus used has no influence on the tested object. Registered signals are related only to the acoustic effects occurring in the material under study [13]. Sources of acoustic emission in metals are [3, 5, 14–21]: dislocation motion due to plastic deformation, formation of twins, phase transitions of the displacive type, micro and macro cracks. Acoustic emission is a method of obtaining new information about phenomena occurring during phase changes. The applied research techniques may be used in the industry to test large samples in the future. Monitoring of heat treatment processes is vitally important for the utility values of finished industrial products. By tracking the breakdown kinetics of supercooled austenite, processes can be regulated and improved. New solutions and technologies in this aspect are still being searched for.

2. MATERIALS AND METHODS

2.1. Research material

The samples were prepared from 27MnCrB5-2 steel. Samples were taken and prepared from one steel rod. Cylindrical specimens with diameters of 22 mm and height of 25 mm were made. The chemical composition of 27MnCrB5-2 steel is presented in Table 1.

The steel subjected to the tests is used in the automotive industry for fasteners of machine parts. The fasteners are heat treated to improve the properties of the material from which they are made. During the tests, the continuous cooling process was performed on the samples.

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Table 1
27MnCrB5-2 steel cast analysis (%)

Cast	C	Si	Mn	P	S	Cr	Ni	Mo	V	Ti	Cu	Al	Nb	B	N
0	0.26	0.26	1.34	0.015	0.011	0.52	0.15	0.06	0.014	0.04	0.17	0.004	0.002	0.0029	0.0108

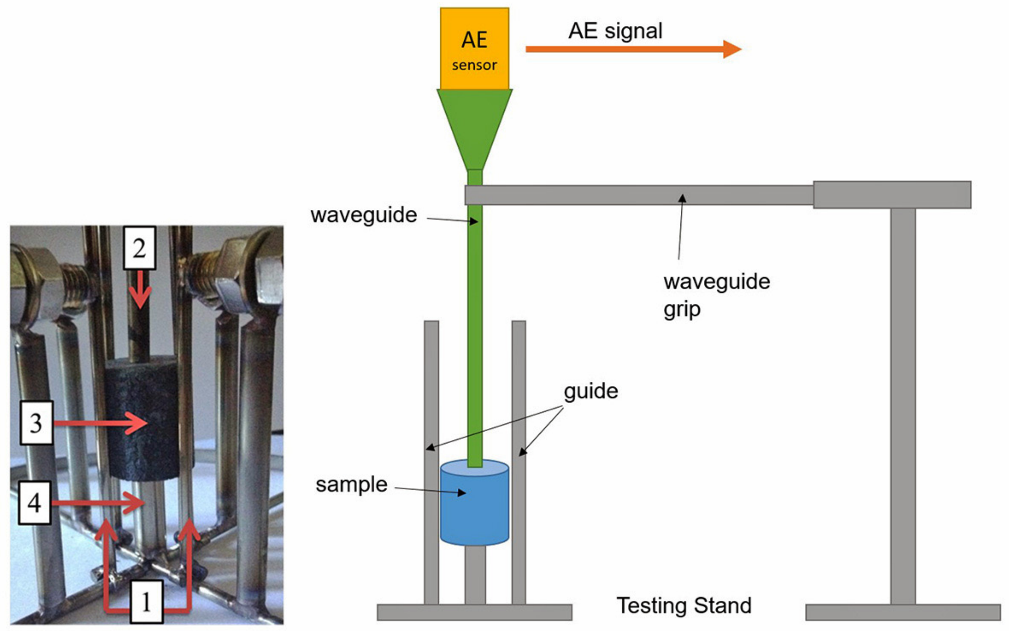


Fig. 1. Test stand for continuous cooling in the air

2.2. Research methodology

27MnCrB5–2 steel samples were heated to 950°C and kept at this temperature for 30 minutes. During the heating process, the samples were stored in a chamber furnace under argon atmosphere. The argon flow was set to 10 L/min. After heating to austenitizing temperature, samples were immediately transferred to the test bench and cooled continuously in the air.

The stand is shown in the photograph in Fig. 1. The sample (3) was placed in stabilizing guides (1) to prevent the sample from tipping over. The sample, after moving along the guides, rested on the support (4), ensuring minimal contact with the sample. The waveguide (2) used to transmit the AE signal from the sample to the sensor was placed in the upper part of the station, opposite the support. The force of the waveguide's pressure on the sample stabilized its position. To ensure uniform cooling of the sample with surrounding air, utmost care was taken to ensure minimal contact of the station surface with the surface of the sample.

Signals from phase changes occurring during sample cooling were recorded using the acoustic emission registration system. In the acoustic emission method, signals occurring in a broad frequency band from kHz to MHz are recorded and used. Figure 2a shows a block diagram and photographs of the AE signal measuring equipment.

The piezoelectric system of the ultrasonic transducer changes the crystal lattice caused by phase transformations into an electrical signal.

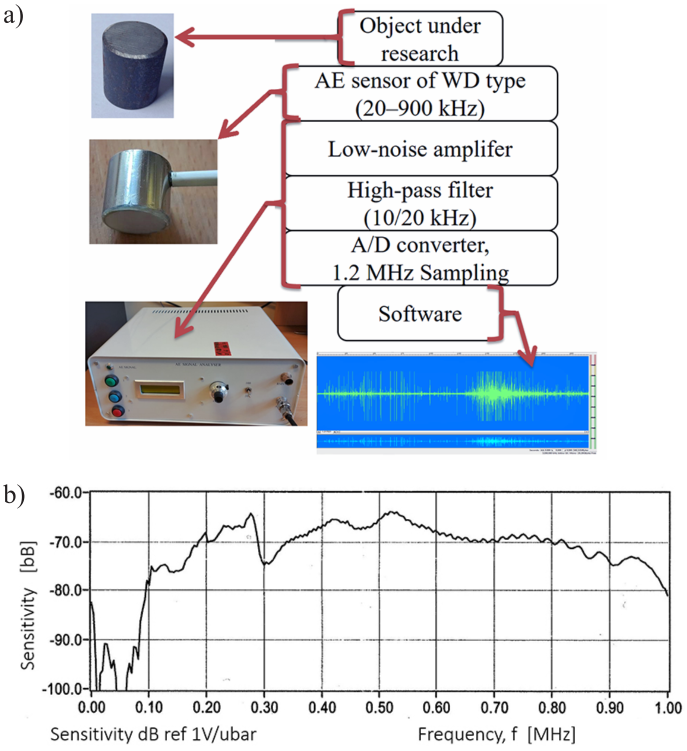


Fig. 2. Specialist workstation for testing AE signals: a) block diagram of specialist workstation for testing AE signals, b) characteristic of WD sensor to measure AE signals

The test bench used a piezoelectric broadband sensor to measure WD type acoustic emission (20–900 kHz, Fig. 2b). Signal registration was performed using the AE SIGNAL ANALYZER. The acoustic emission signal received by the sensor was initially filtered by the recorder. The recorder was equipped with a filter through which signals from the background were eliminated. The signals coming from the phase transformation processes were subjected to further processing. The AE signal was sent from the AE recorder and saved on the computer disk via the ADLINK 9812 card. The card allowed to register an AE signal at 1200 kHz. The time of the recorded signal with 1.2 MHz sampling was 240 s. Due to the use of modern measuring equipment equipped with very sensitive sensors and specialized software for measuring AE signals coming from the tested sample, detailed analysis of the obtained test results is possible. Correctness of the measuring system operation was checked prior to commencement and following completion of the tests. In order to check the system, the Hsu-Nielsen source – a method of AE standard sourcing by means of pencil-lead break [22, 23] was used, as presented in Fig. 3.

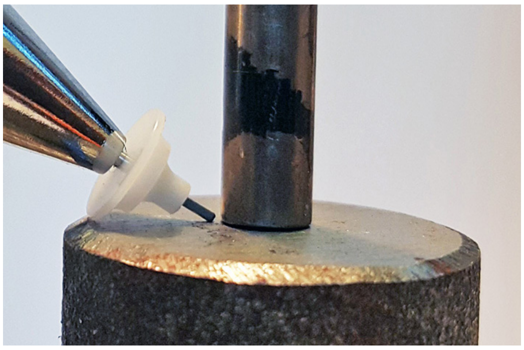


Fig. 3. Hsu-Nielsen source – AE standard sourcing by means of pencil-lead break

For the tests, we used software that consists of three programs that enable us to track changes in AE signal parameters from different processes [24]. An artificial neural network (ANN) was used to analyze the acoustic emission signals occurring during the hardening of the steel. A large number of AE events were recorded during the measurements. These events are characterized by different energies and have different spectral characteristics. Software consisting of three programs was used to identify AE events. In the first stage, the signal was divided into segments with duration of 7.35 ms. AE events have been identified in these segments. Based on the detected events, the average energy of AE events was determined for each segment. Then the spectral characteristics were plotted. The spectral characteristics are presented in the frequency domain, and they represent the power spectral density function. Spectral characteristics allow to determine the power spectrum of the acoustic emission signal in a selected frequency range. The spectral characteristics consisting of 80 spectral coefficients of the signal power density intervals were processed by the binary coding method, with the use of a logarithmic function, into appropriate sets of ones and zeros. The processed characteristics are pattern feature vectors recognized by the artificial neural network. This was followed by "network training", a process of autonomously modifying the network organization. An artificial neural network made of two layers was used (Fig. 4). The input layer enables the input into the network of 4000 zero-one data elements of signal feature vectors. The first of the weighting factor tables contains 200 000 coefficients representing the connection between the units of an input layer and 50 units of the next layer. The second of the weighting factor tables contains 3000 factors representing the connections between the units of the second layer and the six units of the output layer.

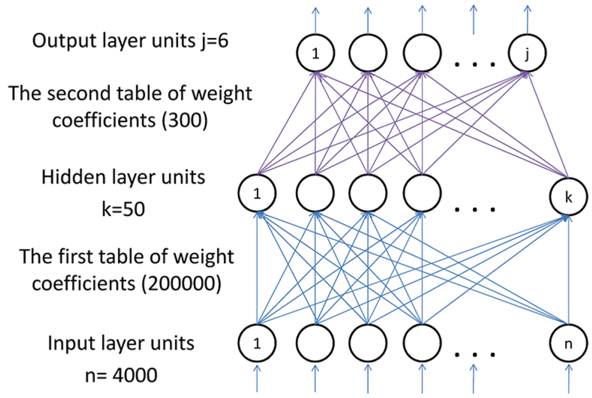


Fig. 4. Process of neural network learning by the method of the reverse propagation of error

The algorithm of "backward error propagation" was used to remember the pattern features vector.

$$\Delta w_{ij}^{(k)} = \eta_1\left(d\theta(E_i)/dE\right)x_j\delta_i^{(k)} + \eta_2 m_{ij}^{(k+1)}, \tag{1}$$

where: θ – activation function, $\Delta w_{ij}^{(k)}$ – weighting coefficient between neuron labelled i in the k and neuron j in the layer $(k-1)$, η_1 – parameter called the learning rate, in the described work experimental set to 0.01, η_2 – momentum, parameter optimizing the learning process, in the described work set to 0.008, E_i – total excitation of *j-th* neuron in layer k, equal to $\Sigma_j w_{ij}^{(k)} x_j$, z_i – described signal at *i-th* output of the network, y_i – temporary signal at *i-th* output of the network, m_{ij} – weight change used in the previous iteration, $\delta_i^{(k)} - z_i - y_i$ for the output layer or $\Sigma_1 \mathrm{w}_{1\mathrm{i}}^{(\mathrm{k})} \delta_1^{(\mathrm{k}+1)}$ for the other layers.

The process of training the network consisted in carrying out a series of repetitions of the algorithm sequentially for all patterns. A signal dependent on the feature vector set at the input was obtained at the output of the network. In the last stage, the reaction of the network outputs to the set patterns was examined. If the output signal from the neural network (ANN) exceeds the threshold value, i.e. the value of 0.9, an event is registered in the file with the results of the procedure – a signal with spectral characteristics similar to the defined pattern was found. The dependence of the frequency of acoustic emission events as a function of time was plotted.

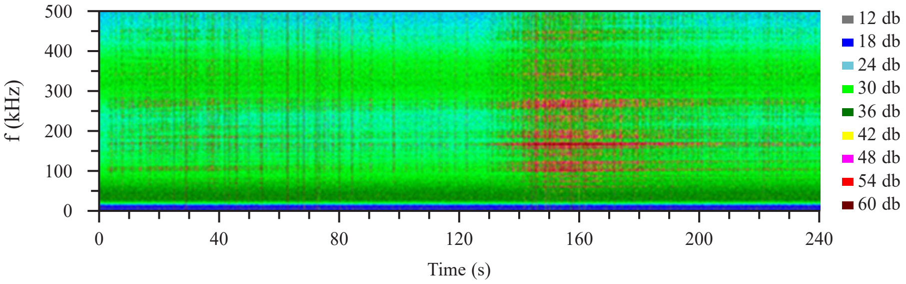


Fig. 5. AE signal spectrograms for 27MnCrB5-2 steel during continuous cooling in the air. Colors encode the square root value of signal power spectral density

3. RESULTS

As a result of the tests, an acoustic emission signal related to phase changes occurring during continuous cooling in a 27MnCrB5–2 steel specimen was recorded. The main parameters of the emission signals are signal amplitude, duration of the event and acoustic activity. The recorded signal was further processed and spectral characteristics were made in the form of an acustogram. The acustogram in Fig. 5 shows the visualization of maximum values of the recorded signal depending on the frequency and time. The dominant spectral range of signals from phase transitions is in the range of 100–300 kHz. The most intense signal is observed around the frequency of 183 kHz.

It is possible to extract events of varying intensity from the recorded signal. These events differ in both spectral characteristics and energy. Recorded events can be divided into high energy events – above 10 000 pJ, medium energy events in the range of 1000–10 000 pJ, and low energy events – below 1000 pJ.

In the process of learning the network, three pairs of patterns were used: A1, B1, C1, A2, B2, C2. The learning scheme for the 3 patterns was as follows: (16×A, 8×B, 4×C). The learning sequence was repeated 8 times in an alternating cycle. In further considerations, we will discuss signals from high and medium energy events, as per Fig. 6.

In order to extract individual components from the uniform signal, neural networks were used. The software (neural network) identifies AE events with different energy values, based on the spectral characteristics (patterns) assigned to a given event. The spectral characteristics for high energy and medium energy events are shown in Fig. 7. Spectral characteristics that are patterns for training neural networks were generated on the basis of selected signal samples corresponding to the high and medium energy of the event.

From the whole recorded signal, the software using neural networks separates individual signals from different events, placing them in separate collections. As a result of this activity, two separate graphs are created, showing the intensity of events presented in Fig. 8.

Due to the use of neural networks, the recorded signal of the acoustic emission was analyzed and the signal was assigned to the appropriate phase transformation. As a result of the changes occurring during heat treatment, the Widmanstätten ferrite and bainite [25] structures were observed under the scanning microscope, as shown in Fig. 9.

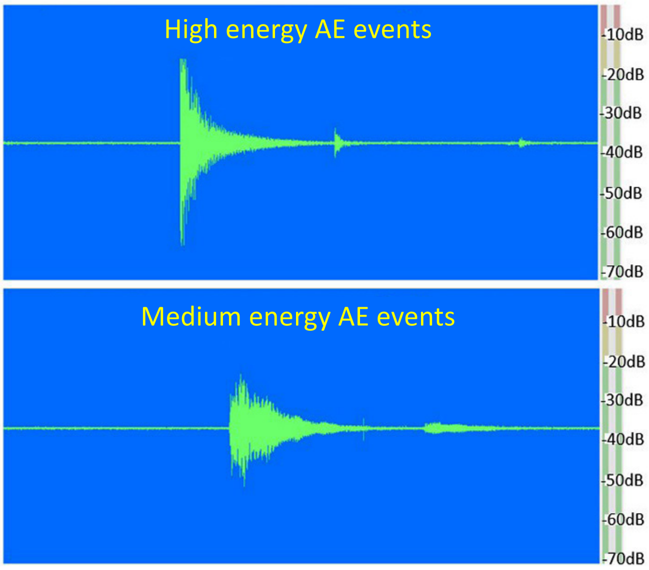


Fig. 6. Examples of signals from high and medium energy events

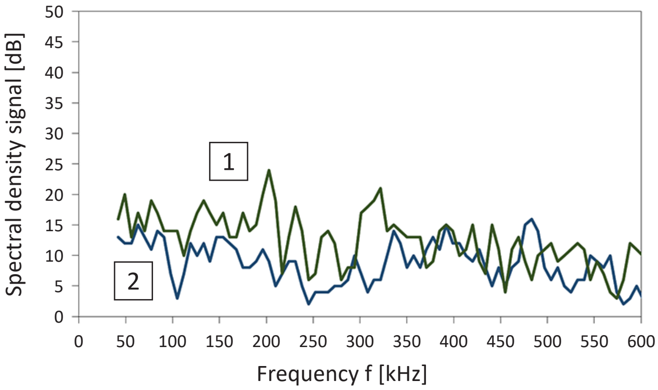
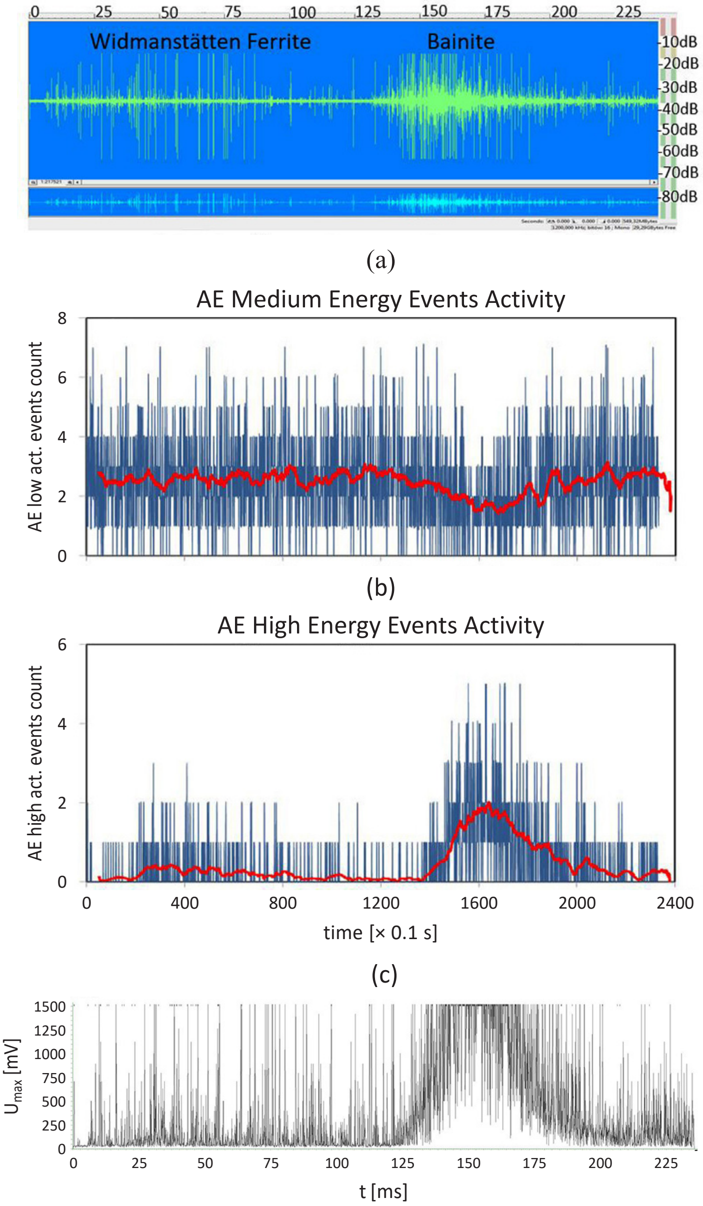


Fig. 7. Spectral characteristics for 27MnCrB5-2 steel indicating energies of event patterns used in artificial neural networks (ANN), 1 – high energy AE events, 2 – medium energy AE events

The medium energy event signals are related to the Widmanstätten ferrite transformation and occur at the beginning of the cooling process. The high energy signals of events are associated with the bainitic transformation and appear from 130 s of the recorded signal, as shown in Fig. 8.



(a)

(b)

(c)

Fig. 8. Relationship of detected AE events correlated with patterns: a) for medium energy AE events, b) for high energy AE events, c) graph of the intensity of RMS signals for the frequency of 183 kHz

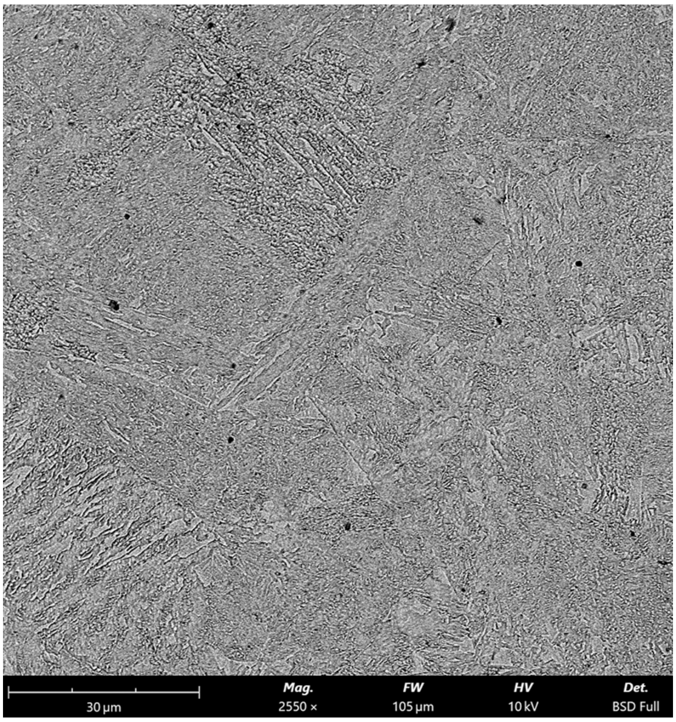


Fig. 9. Micrographs showing white-etching (nital) acicular ferrite and wedge-shaped Widmanstätten ferrite plates in a matrix of bainite

4. DISCUSSION AND CONCLUSIONS

During phase transformations of steel, such as the bainitic, martensitic and ferritic (Widmanstätten ferrite) one [25], you can register signals of acoustic emission. The sources of acoustic emission in metals are [3, 5, 14–18, 21]: dislocation motions due to plastic deformation, formation of twins, phase transitions of the displacive type, and the generated cracks and their propagation. Acoustic emission signals are generated by the emerging dislocations, blunting their accumulation and releasing the energy of these accumulations and the collective dislocation motion, as well as during the annihilation of dislocations [6, 7, 11–16, 26].

According to A. Pawełek, acoustic waves in metals are generated in the sources of the Frank-Read type. They are considered to be sources of acoustic emission, which are generated by the process of annihilation of dislocation segments at the moment of closing the loop generated from the source [27, 28]. Annihilation of dislocations occurs when closing and generating new dislocation loops from Frank-Read sources. According to A. Pawełek, the number of acoustic emission events is proportional to the number and length of dislocation sections that are annihilated. In the case of 27MnCrB5-2 steel continuously cooled in air, acoustic emission signals were also recorded. Formation of the Widmanstätten ferrite and bainite in steels is accompanied by acoustic emission. Due to the use of neural networks, it was possible to separate the signal into individual components. Then, based on the information about the phase transformations taking place in the tested material, the AE signals were assigned to specific phase transformations. Acoustic emission offers us new opportunities to track changes in the material during thermal processes [10, 29–32]. This method also creates the possibility of obtaining the correlation of recorded EA signals with the microstructure [30].

5. CONCLUSIONS

1. Based on the obtained results in the form of acoustic emission signals and microstructure pictures, it is concluded that as a result of conducted tests in the form of continuous cooling in air, the product of the transformation was Widmanstätten ferrite and bainite.
2. The source of the recorded AE signal were phase changes occurring in the tested sample made of 27MnCrB5-2 steel. Due to the software used, it was possible to analyze AE signals and extract signals from individual phase transformations.

3. On the basis of the recorded AE signal, an acustogram was generated, on the basis of which it can be indicated that the most dominant spectral range of signals from phase transformations is in the range of 100–300 kHz, and the highest values of the signal were located for frequencies around 183kHz. An RMS chart has also been generated for this frequency.
4. High and medium energy signal samples were selected from the recorded AE signal. They were used to generate spectral characteristics, which were then used as patterns for training neural networks. Neural networks were used to count high and medium energy events in the registered AE signal, related to phase transformation.
5. The analysis of AE measurement results recorded during continuous cooling in the air shows that the first less intensive signal up to 125 s originates from the Widmanstätten ferrite transformation, while the stronger signal from 130 s is responsible for the bainite transformation. AE signals were recorded during cooling from 950°C to ambient temperature. The AE signals analyzed were recorded above 400°C, while below the AE events, no AE events were recorded.

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