Quality assurance of sheets rolling on the basis of modeling the destruction process, plastic restructuring the structure of the material of the slab and the acoustic emissions parameters

V V Nosov1,2,3, A M Shipachev1, A G Palaev1 and E V Grigorev1

1 Saint-Petersburg Mining University, 2, 21st Line, St. Petersburg, 199106, Russia
2 Peter the Great St.Petersburg Polytechnic University, 29, Polytechnicheskaya, St. Petersburg, 195251, Russia
3 Corresponding author, Е-mail: nosovvv@list.ru

Abstract The problems of modeling the fracture process under conditions of plastic restructuring of the material structure, the transformation of the strength state of the material of plastically deformable workpieces into the state of the product material, the acoustic emission assessment, which determines the defectiveness of the final product of the predisposition of the workpiece defects to development during the rolling process, are considered.

Introduction
Development of quality control methods that are aimed at plastic deformation of blanks is supposed to promote the optimization of the technologies of plastic metal working and facilitate the timely detection, identification, and elimination of flaws that reduce the quality of the final produce. However, most of the existing control techniques reveal flaws using signs that are not clearly related to the probability of the emergence of flaws or to the degree of their hazardousness in the final item. To solve this problem, a testing technique was suggested in [1–4] that is based on a relationship between the strength state of metallurgical slabs, the results of registering acoustic-emission (AE) signals from plastically deformed slabs that are interpreted from the viewpoint of the micromechanical model of temporal dependences of AE parameters (MMAE), and the faultiness of sheets produced from these slabs. The technique aroused a lot of interest among engineers and scientists, so let us explain what it is about.

Technique development and underlying physical principles
Increasing the efficiency of AE diagnostic tools is based on the principles of informative optimization that include sequential construction of logically connected and hierarchically subordinated informative models of the processes that govern the serviceability of test objects and the AE parameters related to these processes [5]. When applied to assessing the quality of plastically deformed blanks, this assumes construction of the structural models of the blanks, separation of the strength characteristics of the structural elements as the main quality indicator, necessity to model the process of damage to these structures under the conditions of plastic restructuring, and possibility of forecasting the time of accumulation of a critical value of damage concentration based on observing the damage using the AE
phenomenon under the conditions of significant interferences. This requires a refinement of an elementary act of this process in the form of appearance of a microcrack, a quantitative description of the process based on using kinetic regularities and universal physical constants, the formulation of process completion conditions, similarity criteria between the failure process and the AE phenomenon, the rules for conducting acoustic-emission testing, signal filtration, and the choice of informative AE parameters.

Plastic deformation is represented as movement of dislocations and is associated with a change in the structure of materials that leads to strength increase and reduction in the degree of their inhomogeneity [6, 7]. The processes of plastic deformation, microcrack formation, and elastic emission occur concurrently and are closely related to each other. The rupture of bonds between atoms in a crystalline lattice underlies both processes. The only distinction is that during plastic deformation, a broken bond is immediately restored. Both processes are thermally activated. A number of experimental facts evidence the effect of thermal fluctuations on the process of plastic deformation; these are dependence of the deformation resistance on the loading rate and temperature, the presence of a sluggish deformation under constant load and temperature, and delayed flow (the appearance of deformation some time after a load is applied) [8, 9]. As mentioned in [10], at the stage of dislocation hardening, when collective dislocation effects start to exhibit themselves, plastic deformation and failure turn out to be related to such a degree that they can be considered to be one process with the common activation energy.

**Experimental section.**

The micromechanical acoustic-emission model is most successful of the existing models that describe the dependence of the number of AE pulses on the load under plastic deformation conditions. This model has confirmed its efficiency for a wide range of materials. The use of MMAE allows one to use the acoustic-emission testing data not only to determine the current state of a test object but also to forecast its residual service life. The fact that this model has a physically sound basis in the form of the kinetic concept of strength makes it possible to extend its applicability domain to plastic deformation.

The control method [1-3], based on the correlation of the strength state of metallurgical wells, the results of recording acoustic emission signals (AE) during their elastic deformation, interpretation from the standpoint of a multilevel model of time dependences of AE parameters (MMAE) and defectiveness of sheets produced from them is proposed.

The values of AE counterparts of material damageability $\xi(t)$ (the primary informative AE parameters that include the number of pulses, the total AE, the total amplitude, the energy of AE signals, etc.) are proportional to the microcrack concentration $C(t)$:

$$\xi(t) = k_{AE} C(t),$$

where $t$ is the current time and $k_{AE}$ is an acoustic emission similarity coefficient (AEC). The strength state of a particular object is described by the distribution $\Psi(\omega)$ of a strength-state parameter $\omega$ over the structural elements, the parameter being expressed by the formula:

$$\omega = \gamma \sigma / RT$$

where $\gamma$ is a structure-sensitive coefficient in the Zhurkov formula; $\sigma$ are stresses in a structural element; $R$ is the universal gas constant; and $T$ is the absolute temperature. The parameters of the distribution $\Psi(\omega)$ characterize the inhomogeneity of both structural ($\gamma$) and strength ($\sigma$) states of a material. It is obvious that plastic deformation should affect the form and parameters of this distribution, as shown in figure 1.

In figure 1 you may see a model of the transformation of the strength state of a slab material during plastic deformation (1a), in figure 2 a diagram of loading a slab by lifting it with a mechanical gripper (2a), a graph of the time dependences of the logarithm of the total number of signals for a steel slab (1) and an increase in stress values (2) at (2b). The rectangle marks the portion used to determine the diagnostic parameter $W_{AE}$, to show a uniform failure before the occurrence of local fluidity. Prior to the start of the plastic processing process, there is a material of a technological cast billet with increased heterogeneity of the strength state of structural elements associated with both the uneven
size of these structural elements and the difference in their location, stress state, and critical values of perceived stresses. During the action of the rolls of the rolling mill, part of the distribution elements $\psi_0(\omega)$ with values $\omega > \omega_{cr}$ corresponding to the most defective structural elements worsen their strength state, which manifests itself either in their destruction or in an increase in the parameter $\omega$. Structural elements with values of $\omega < \omega_{cr}$ are in a “living” state and therefore are hardened as a result of plastic rearrangement of the workpiece material structure, which is modeled by a decrease in the state parameter $\omega$ of structural elements. Thus, plastic restructuring of the structure leads to hardening of the material and a decrease in the values of $\omega$. A part of the structural elements of a defective billet during plastic impact on it by rolls will have time to collapse during the time $\Theta_T$ of the technological impact, these elements in the future are the concentrators of the defective zones at the rental and places of the most likely occurrence of defects.

Figure 1. Model of transformation of the strength state of the material of a flawed (a) and quality (b) blank under plastic deformation. Curves 1–4 are the graphs of the density function $\Psi(\omega)$ of the distribution of the values of the strength-state parameters of structural elements for a flawed blank (1), a flawed sheet (2), a quality blank (3), and a quality sheet (4). Curve 5 is the tested segment of the distribution of strength parameters of uniformly destroyed structural elements of a blank. Curve 6 is the domain of the distribution $\Psi(\omega)$ that corresponds to the structural elements of a blank that are destroyed at the stage of nonuniform destruction. Legend: $\omega_{0\text{sh}}, \omega_{1\text{sh}}$ are the parameters of two-rectangle versions of the distributions $\Psi(\omega)$ for a flawed and quality blank, respectively; $\omega_{cr}$ is the value of the strength parameter of a structural element that corresponds to its critical durability, equal to the processing time period during rolling; and $\omega_{0\text{sh}}$ are the parameters of the two-rectangle version of the distribution $\Psi(\omega)$ for a blank after rolling.
Figure 2. The results of full-scale AE testing of a metallurgical slab: a - slab loading diagram; 1-graph of the distribution density function of the parameter of the strength state of structural elements of a defective slab, 2-defective sheet, 3-quality slab, 4-quality sheet; b - graphs of time dependences of the logarithm of the total number of AE signals (1) for a steel slab and an increase in stress values (2).

The opportunity to know the $\Theta_T$ value of the time of the technological impact on the workpiece during the rolling process allows us to determine the critical value of the strength parameter of the workpiece $\omega_{cr}$ and the scatter boundary of the value of the state parameter $\psi(\omega)$ of the sheet by the Zhurkov formula.

The processing time period $\Theta_T$ is taken from the data on rolling technology or can be calculated using formula:

$$\Theta_T \approx \frac{L}{V}$$  \hspace{1cm} (3)

where $L$ is the length of a slab section that is being acted upon by the mill rolls; $V$ is the velocity of the working roll surface, which can be calculated from the parameters of the equipment and rolling conditions.

$$L = \frac{D \cdot \sin[\arccos\left(1-\frac{H-h}{D}\right)]}{2}$$  \hspace{1cm} (4)

where $D$ is the diameter of the working roll surface; $H$ is the pre-processing slab thickness; $h$ is the slab thickness after rolling.

$$V = \frac{n \cdot D \cdot \pi}{i \cdot 60 \cdot 1000}$$  \hspace{1cm} (5)

where $n$ is the motor rotation speed, $i$ is gear ratio.

The values of the parameter $\omega$ are determined using an informative concentration-kinetic indicator

$$W_{AE} = \frac{d \ln \xi}{d K_N} = \omega,$$  \hspace{1cm} (6)

where $K_N$ is the load factor equal to the ratio of the diagnostic load to the working one.

The diagnostic sign of the state of a blank suitable for further processing looks as follows:

$$W_{AE} < [W_{AE}]$$  \hspace{1cm} (7)

An example of using the technique

The technique was practically tested in inspecting a fit slab under industrial conditions. The cold slab
was loaded with its own weight using cranage; this led to the emergence of the maximum tensile stresses at the surface that comprised a value of 40–60% of the yield limit and ensured the high probability of detecting acoustic-emission signals. A two-channel acoustic-emission measurement system was used to register acoustic-emission pulses. Acoustic-emission sensors were mounted in the middle part of the cold slab at a distance of 2 m from each other (figure 2a).

When processing the results of registering AE signals, the value of the diagnostic parameter \( W_{AE} \) was determined. The information was acquired under the conditions of heightened industrial interferences that included AE signals due to destruction of iron-oxide elements (scale) or other structural elements (“bars”) that did not affect the slab strength or rolled-metal quality, based on the kinetic informative signs that follow from the MMAE and on the time selection of AE signals [12, 15]. The destruction of the “bars” is kinetically nonuniform and manifests itself by an acoustic activity that is high at the beginning of loading and then gradually fades; this makes it possible to register informative AE signals due to uniform destruction that gain momentum at the same time. The total pulse count was used as the primary informative acoustic-emission parameter \( \xi(t) \).

The value of the diagnostic parameter was determined from the formula:

\[
W_{AE} = \frac{\ln \xi_2 - \ln \xi_1}{K_{H2} - K_{H1}}
\]

(8)

where \( \ln \xi_1 = 2.08 \), \( \ln \xi_2 = 3.43 \) are the values of the informative acoustic-emission parameter for the maximum stresses in the cross-sections \( \sigma_{max1} = 180 \) and \( \sigma_{max2} = 240 \) MPa in the sample at different time moments; \( K_{H1} \) and \( K_{H2} \) are loading coefficients determined by the formula:

\[
K_{H1} = \frac{\sigma_{max1}}{\sigma_T} \quad \text{and} \quad K_{H2} = \frac{\sigma_{max2}}{\sigma_T}
\]

(9)

where \( \sigma_T = 500 \) MPa is the yield limit of the slab material. The maximum stresses \( \sigma_{max1}, \sigma_{max2} \) in figure 2b are stresses that correspond to the maximum and minimum stresses of the set-off segment:

\[
K_{H1} = \frac{180}{500} = 0.36 \quad \text{and} \quad K_{H2} = \frac{240}{500} = 0.48 \quad W_{AE} = \frac{3.43 - 2.08}{0.48 - 0.36} = 11.25
\]

(10)

The admissible value of the diagnostic parameter was determined using the Zhurkov formula as:

\[
[W_{AE}] = \ln\left(\frac{\tau_0}{\Theta_T}\right) + \frac{U_0}{KT}
\]

(11)

where the processing time period \( \Theta_T \) was determined from the particular conditions of Novolipetsk iron & steel works (NISW) to be 0.19 s.

Thus, the relative value of the parameter \( \tau_0 = 10^{-13} \pm 10^{-15} \), \( U_0/KT = 50.59 \), \( \omega_r = [W_{AE}] = \ln(\tau_0/\Theta_T) + U_0/KT \approx 20 \pm 30 \)

The calculated value of the diagnostic parameter \( W_{AE} \) does not exceed the admissible one \([W_{AE}]\); in accordance with the proposed diagnostic sign, this allowed us to treat the tested slab as one of satisfactory quality, a conclusion that corresponded to the reality.

Conclusion

Thus, a model has been described for the process of destruction of blanks under conditions of their plastic deformation. We have also proposed a model for developing processes of structure transformation in the course of plastic deformation of a metal, a testing procedure, a diagnostic sign and a criterion of the quality of a blank that have been confirmed by theoretical and experimental research as well as a technique for controlling the faultiness of a slab and, hence, the quality of a hot-rolled strip. The information required for testing has been obtained based on the micromechanical model of destruction, the kinetic signs of destruction stages, and the time selection of AE signals. The technique makes it possible to increase the operational efficiency of testing, to classify flaws using such characteristics as the prospects for a flaw to develop in local areas and the effect of changes in the acting technological stresses on the intensity of changes in the slab structure instead of indirect geometrical signs of the effect on the quality of the end rolled-metal produce (dimensions, disposition, flaw shape). A distinctive feature of the technique is the use of only mechanical loading as employing other types of loading may lead to the emergence of acoustic interferences that carry false information about the slab quality.
References

[1] Nosov V V 2016 *Diagnostics of Machines and Equipment 3rd Ed* (Saint-Petersburg: Lan’)
[2] Nosov V V 2013 *Mechanics of Composite Materials. Laboratory Works and Practice 2nd Ed* (Saint-Petersburg: Lan’)
[3] Nosov V V, Lavrin V G 2012 *Russian Journal of Nondestructive Testing* 48(3) pp 159–165
[4] Nosov V V, Sinchugov I S 2012 *RF Patent 2525584*
[5] Nosov V V 2016 *Russian Journal of Nondestructive Testing* 52(7) pp 386–99
[6] Oding I A, Ivanova V S, Burdukski V V, Geminov V N 1959 *Theory of Creep and Long-Term Strength of Metals* (Moscow: Metallurgizdat)
[7] Chechulin B B 1955 *Studying micro-inhomogeneities in plastic deformation of steel* (Moscow: Metallized)
[8] Olemskoi A I, Katsnel’son A A 2003 *Synergy of Condensed Matter* (Moscow: URSS)
[9] Stepanov V A, Peschanskaya N N, Shpeizman V V 1984 *Strength and Relaxation Phenomena in Solids* (Leningrad: Nauka)
[10] Betekhtin V I, Vladimirov V I, Kodontsev A G, Petrov A I 1979 *Deformation and development of microcracks* 7 pp 38–44
[11] Nosov V V 2013 *Bulletin of the belarusian-russian university* 2 pp 149–155
[12] Nosov V V 2014 *Russian Journal of Nondestructive Testing* 50(12) pp 719–29
[13] Chernov D V, Barat V A, Elizarov S V 2014 *Assessing the state of a material with indicator tenzocoating based on the micromechanical model of acoustic emission* (Proc. 5th Int. Sci. Tech. Conf.)
[14] Chernov D V 2016 *Bulletin of MPEI* 3 pp 97–103
[15] Nosov V V 2017 *Russian Journal of Nondestructive Testing* 53(5) pp 368–77