ISSN 0036-0295, Russian Metallurgy (Metally), Vol. 2016, No. 3, pp. 189–192. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © G.A. Vorob'eva, E.Yu. Remshev, 2016, published in Metally, 2016, No. 2, pp. 24–28.

Effect of the Parameters of Aerothermoacoustic Treatment of 40Kh Steel on the Acoustic Emission Parameters

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Received December 15, 2014

Abstract—The effect of aerothermoacoustic treatment on the mechanical properties of 40Kh steel and the acoustic emission parameters is experimentally studied. Aerothermoacoustic treatment is found to affect the mechanical properties of the steel and the acoustic emission parameters.

DOI: 10.1134/S0036029516030162

Acoustic emission (AE) is the phenomenon that appears in materials during the generation and propagation of elastic vibrations (acoustic waves) in them. The AE method is based on this phenomenon and is used to study the processes that accompany the deformation and fracture of materials. The advantages of the AE method are the possibilities of observation of local restructuring in materials subjected to external mechanical actions and obtaining information on various dynamic processes, such as the multiplication and motion of lattice defects, phase transformations, and microcrack nucleation and growth. AE appears in solids as a result of stress relaxation during restructuring in solids. The main macroscopic AE sources in practice are considered to be plastic deformation and crack growth.

Plastic deformation is accompanied by dislocation generation and motion, which results in stress relaxation via shear without the formation of discontinuities and cracks in solids. Continuous emission is provided by plastic deformation processes. The formation and development of cracks produce new surfaces, which is related to the appearance of high-amplitude elastic wave pulses, namely, emission stress waves. The AE method is used to estimate the behavior of materials under static and quasi-static loading conditions, where a load either increases slowly or is constant. The AE method can be applied to detect growing defects, and the results obtained can be used to estimate the state of an object from AE signal parameters in a wide loading range, including constant-load operation (real operating conditions), strength tests of commercial objects (hydro- and pneumotests), and standard static tensile tests of materials.

The interpretation of AE signals in estimating the behavior of material is related to the use of some AE parameters, including the AE signal amplitude and the number of AE signals. Experimental data and simple models served as the basis for creating a local dynamic criterion for estimating the state of object in the form of the parameter

$$n\Delta NP/N\Delta P, \quad (1)$$

where ΔN is the increment of the total counts when the loading parameters increase by ΔP at total counts N and loading parameter P. The loading parameters can be an increasing load (force, pressure, stress), time (at a retained load during operation), and so on. The AE method can be used to reveal material defects and the degree of their danger. According to [1], a situation is considered to be dangerous if n in Eq. (1) exceeds unity at least one time and to be catastrophic if n exceeds unity three or more times. This approach was used to classify AE sources. According to this classification, they are divided into the following four classes [2]: passive ($n < 1$), active ($n \approx 1$), critically active ($1 < n < 6$), and catastrophically active ($n > 6$) sources.

In this work, we studied the influence of aerothermoacoustic treatment (ATAT) on AE in structural 40Kh steel during standard static tensile tests. The tests were carried out on an MST-1 tensile-testing machine to record stress–strain curves. The number of AE signals N as a function of the strain and the test time was simultaneously determined with a Lokton-2004 device. A sensor was attached to a specimen. Specimens were made of 40Kh steel in the initial state (after normalizing), and some specimens were additionally subjected to martempering, i.e., quenching followed by tempering at 500°C (which is standard heat treatment (SHT)). ATAT used to process 40Kh steel consisted of a multicycle action of the acoustic field of a nonstationary low-speed air flow at a frequency of 0.4–2.0 kHz (sound pressure of 160–185 dB) and a temperature of 20°C according to the conditions given in Table 1. The mechanical proper-

Table 1. Heat-treatment conditions and the mechanical properties of 40Kh steel

No.	Initial treatment	σ_u	σ_y	δ, %	*HRC*/*HB*	ATAT***
		MPa				
1	Normalizing (N)	810	500*	11.7	–/190	–
2	″	822	510*	12.7	–/191	Along (ATAT-1)
3	″	832	640*	11.2	–/190	Along + across (ATAT-2)
4**	″	590	345*	18.0	–/>200	–
5	Quenching + tempering at 500°C (SHT)	1060	970*	13.0	30/–	–
6	The same	1039	970	16.0	30/–	ATAT-2
7	″	1050	980	17.0	31/–	ATAT-1
8**	″	1000	800*	10.0	–/–	–

* Values of $\sigma_{0.2}$.
** Reference data from [3].
*** Position of specimens in a treatment chamber with respect to an air flow.

ties of 40Kh steel are presented in Table 1 for specimens subjected to heat treatment and ATAT.

As follows from these results, ATAT influences the mechanical properties of the steel (strength, plasticity). The degree of this influence depends on preliminary heat treatment of the steel: the mechanical properties changes most significantly after ATAT if preliminary treatment consisted of quenching followed by high tempering. The mechanical properties depend on the treatment parameters and the location of specimens in a treatment chamber with respect to an air flow. As compared to SHT, the plasticity of the specimens located along the flow increases at a retained strength in the case of ATAT. After normalizing (N), the strength of the specimens located along + across the air flow in the chamber increases slightly as compared to the initial state at a retained plasticity. For this location of specimens during SHT, the yield strength does not change and the plasticity increases to a smaller extent as compared to treatment according to the ATAT-1 schedule. Structural materials are characterized by anisotropy of the mechanical properties, which is caused by the specific features of structure formation (including structure formation during production).

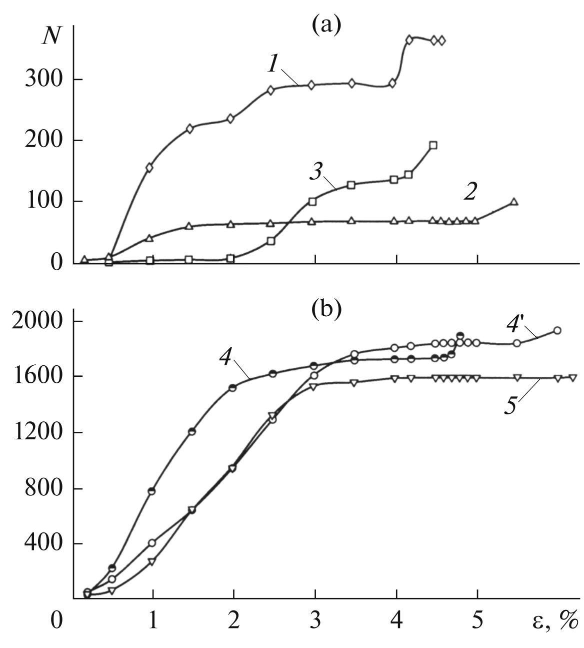

Fig. 1. Total number of AE signals *N* vs. strain ε for specimens subjected to the following preliminary treatment. (a): (*1*) normalizing, (*2*) normalizing + ATAT-1, and (*3*) normalizing + ATAT-2; (b): (*4*, *4*′) SHT and (*5*) SHT + ATAT-2.

The structural heterogeneity (dendritic segregation) appearing at the stage of solidification depends on the chemical composition, the method of deoxidizing and modification, and the rate of cooling of an ingot. As the impurity content increases, the coarse-grained as-cast structure changes during deformation: grains become elongated, and nonmetallic inclusions are distributed as stitches along an applied force and increase the rolling-induced anisotropy. The anisotropy of plastically deformed alloys is related to the following three types of texture: mechanical, dislocation, and crystallographic texture [2]. Crystallographic texture affects all types of anisotropy in solids. Anisotropy is estimated using the ratios of strength, plasticity, and impact toughness. Impact toughness is most sensitive to anisotropy: the values of *KCV* of transverse and vertical specimens differ threefold.

The anisotropy of the mechanical properties is known to be related to anomalous changes in the velocity of elastic waves, the trajectories of their propagation, and their scattering coefficient (damping). Therefore, we were able to use this anisotropy to develop optimum treatment conditions, including ATAT conditions. The number of AE signals detected during static tests is given in Table 2. Figure 1 shows the total number of AE pulses *N* versus strain ε during static tensile tests of standard specimens. The following three stages of deformation can be traced in these curves: the first stage corresponds to local plastic deformation; the second stage, to decelerated plastic

Table 2. Total number of AE pulses *N* as a function of strain ε of 40Kh steel specimens in various states*

ε, %	N	N + ATAT-2		N + ATAT-1	SHT		SHT + ATAT-2		
		1	2		1	2	1	2	3
0.2	–	–	–	5	22	40	18	35	4
0.5	3	1	30	9	216	136	56	147	21
1.0	156	5	210	41	771	400	266	375	67
1.5	220	7	347	60	1193	639	639	581	127
2.0	237	9	370	65	1505	936	948	948	213
2.5	283	38	384	67	1609	1281	1310	1310	292
3.0	293	103	392	70	1666	1595	1520	1520	336
3.5	296	130	415	72	1708	1750	1550	1550	356
4.0	297	139	415	72	1716	1798	1580	1580	367
4.2	368	148	415	73	1718	1812	1583	1583	374
4.5	368	196	415	73	1724	1829	1583	1583	382
4.6	368	–	415	73	1730	1832	1584	1584	384
4.7	–	–	470	73	1752	1836	1584	1584	385
4.8	–	–	470	73	1887	1837	1584	1584	388
4.9	–	–	490	74	–	1837	1584	1584	390
5.0	–	–	–	74	–	1837	1584	1584	392
5.5	–	–	–	105	–	1838	1584	1584	397
6.0	–	–	–	–	–	1930	1586	1586	464
6.2	–	–	–	–	–	–	1586	1586	–
6.8	–	–	–	–	–	–	–	1714	–

* Preliminary treatment conditions (N, N + ATAT, SHT) are given in Table 1.

Table 3. AE parameter *n* for 40Kh steel specimens treated according to the SHT and SHT + ATAT-2 conditions

ε, %	SHT			SHT + ATAT-2		
	σ/Δσ	Δ*N*/*N*	*n*	σ/Δσ	Δ*N*/*N*	*n*
0.1–0.5	2.0	136/136 = 1.00	2.00	2	46/56 = 0.80	1.60
0.5–1.0	2.1	264/400 = 0.66	1.40	2	210/266 = 0.74	1.50
1.5–2.0	2.4	239/639 = 0.37	1.00	2	375/639 = 0.55	1.10
2.0–2.5	4.5	300/936 = 0.32	1.35	2.1	300/948 = 0.32	0.64
2.5–3.0	12.0	314/1585 = 0.20	2.40	3.2	210/1520 = 0.13	0.40
3.0–3.5	52.0	155/1750 = 0.08	4.00	51	30/1550 = 0.02	1.00
3.5–4.0	17.0	48/798 = 0.03	0.51	51	30/1580 = 0.01	0.51
4.0–5.0	16.0	39/1837 = 0.02	0.32	2.00	4/1584 = 0.002	0.004
5.0–6.0	4.0	93/1930 = 0.05	0.20	7.00	2/1586 = 0.001	0.007
6.0–6.8	–	–	–	4.00	–	–

deformation; and the third, crack development. Here, intense plastic deformation proceeds and new surfaces form. The type of heat treatment and the ATAT conditions do not affect the strain dependence of the number of AE pulses: these three stages are present in all curves. However, as compared to steel in the normalized state, the total number of AE signals in the specimens subjected to SHT is larger. However, this AE parameter after normalizing and SHT during deformation is slightly smaller when ATAT is additionally used.

Table 3 presents the values of parameter *n* determined by Eq. (1) at strain ε = 0.5–7% for 40Kh steel after SHT and SHT + ATAT-2. Figure 2 shows parameter *n* versus strain ε for 40Kh steel in the states after these treatments.

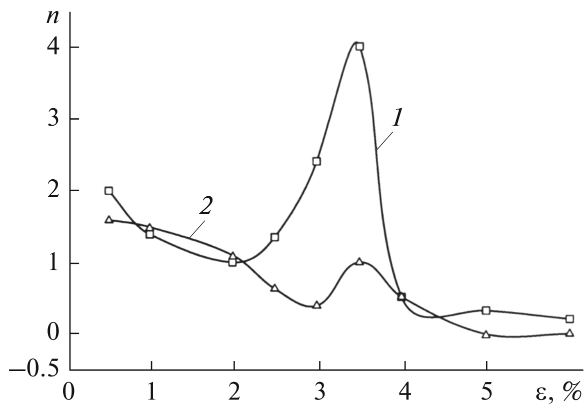

Fig. 2. AE parameter *n* vs. strain for 40Kh steel subjected to treatment according to regime (*1*) SHT and (*2*) SHT + ATAT-2.

The strain dependences of parameter *n* for steel in the states after SHT and SHT + ATAT are similar. At a strain up to $\varepsilon = 2\%$, parameter *n* in both cases is near unity; that is, AE sources are active at this stage. This segment in the curves corresponds to a significant increase in the number of AE signals. As the strain increases, parameter *n* for the steel after SHT increases to 2.4 and then 4, which corresponds to the presence of critically active AE sources. When ATAT is additionally used, parameter *n* does not exceed unity, and the values of *n* decrease when the strain increases further for all types of treatment.

To find the danger of defects from the AE parameters, it is important to reveal their relation to the parameters of the mechanical processes that occur near a defect in a material. Products made of viscoelastic materials fail because of plastic deformation and crack growth. The energy consumed for the formation of unit crack surface area for ductile materials is higher than for brittle materials. However, the coherence of stress relaxation decreases and the number of AE signals decreases or does not increase despite higher released energy (Fig. 1b, curve *5*). The development of fracture of brittle materials is related to larger number of signals and a higher rate of increase of signals before fracture, which is observed during tests of the 40Kh steel specimens subjected to SHT (Fig. 1b). The number of AE signals in the specimens subjected to ATAT decreases, which characterizes a high plasticity of the material. This behavior is supported by the results of mechanical tests (see Table 2).

CONCLUSIONS

(1) The criteria of estimating the state of material can be the time of detecting AE signals, which indicates the beginning of plastic deformation in a stress concentration zone, and the total number of AE signals corresponding to the accelerated development of plastic deformation.

(2) Local dynamic criterion *n* for estimating the state of object can be used to characterize the behavior of a material in loading. This is supported by the following experimental results: when specimens are placed in a chamber along an air flow (ATAT-1 regime), the 40Kh steel subjected to additional ATAT has a higher margin of plasticity than this steel after SHT (quenching followed by tempering at 500°C) and is characterized by a lower value of parameter *n* (maximum value of this parameter is twice as high).

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Translated by K. Shakhlevich