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INFLUENCE OF ALLOYING BY RARE-EARTH METALS ON THE MECHANICAL PROPERTIES OF 17G1S PIPE STEEL

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The positive influence of microadmixtures of rare-earth metals on the strength, plasticity, impact toughness, and cyclic crack-growth resistance of 17G1S pipe steel is discovered. The decomposition of the impact toughness into the work of crack initiation a_i and the work of crack propagation a_p made it possible to discover the following specific features in the temperature dependences of a_p: at elevated testing temperatures guaranteeing the ductile fracture of steel, the positive effect of alloying by REM is preserved. At the same time, at lowered temperatures of brittle fracture, this effect becomes negative and the work a_p decreases. Distilled water somewhat decreases the cyclic crack-growth resistance of steel and the positive effect caused by the REM admixtures manifests itself only in the increase in the cyclic fracture toughness of steel.

Keywords: pipe steel, alloying by microadmixtures of rare-earth metals, strength, plasticity, impact toughness, cyclic crack-growth resistance.

The practice of long-term operation of the main pipelines demonstrates that their serviceability strongly depends on the optimal combination of the characteristics of strength, brittle fracture resistance, and corrosion resistance of steels [1, 2]. As one of the methods used to improve the quality of the metal, its mechanical and corrosion properties, one can mention the microalloying of pipe steels and welds with modifying elements and, in particular, with rare-earth and alkaline-earth metals [3–7]. The efficiency of the influence of these microadmixtures is connected with the changes in the morphology, distribution, and the range of particle sizes of the structural components of the metal, the composition of the grain boundaries, and their state. It was shown that the high resistance to general and pitting corrosion and to sulfide stress-corrosion fracture of low-alloy steels and welded joints can be attained by the lean modification of these materials with microadmixtures responsible for deep structural and phase transformations decelerating the corrosion properties. The following optimal contents of modifiers (in %) were proposed and justified for low-carbon steel in [8]: 0.01–0.03 cerium, 0.01–0.025 yttrium, 0.007–0.015 barium, 0.001–0.0025 calcium, and 0.02–0.04 zirconium. For the welds, the corresponding contents are as follows: 0.01–0.02 cerium, 0.015–0.022 yttrium, 0.0014–0.0025 barium, 0.0012–0.002 calcium, and 0.031–0.044 zirconium.

However, this promising direction in the formation of a complex of mechanical properties of pipe steels requires subsequent investigation. In what follows, we study the influence of admixtures of rare-earth metals (REM) on the plasticity of 17G1S steel and its brittle-fracture resistance.

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Table 1. Contents of REM Microadmixtures after Alloying of 17G1S Steel (in %)

Composition	Ce	Y	Ba	Ca	Zr
1	0.013	0.017	0.0011	0.0012	0.0027
2	0.033	0.032	0.025	0.0027	0.052

Table 2. Chemical Compositions of Steels Alloyed with REM

Procedure of alloying	Heat	Composition, %					
		C	Si	Mn	Cr	S	P
Alloying with Composition 1	Experimental A	0.17	0.43	1.23	0.13	0.019	0.021
Without admixtures	Reference B	0.17	0.41	1.17	0.11	0.028	0.029
Alloying with Composition 2	Experimental C	0.17	0.55	1.33	0.10	0.042	0.017
Without admixtures	Reference D	0.17	0.52	1.28	0.07	0.076	0.030

The metal was alloyed under the laboratory conditions by the method of electroslag remelting. Two compositions of admixtures were used for this purpose (Table 1). Composition 1 corresponds to the optimal content of modifiers for 17G1S steel (base metal) proposed in [8] from the viewpoint of improvement of the corrosion resistance of this steel by microalloying. In Composition 2, the content of REM is about twice higher than in Composition 1. Two heats of steel were prepared, namely A, B and C, D (Table 2). Each heat was poured into two vessels. REM admixtures were introduced into one of these vessels for each heat (to get experimental and reference heats). Note that the compositions of steels alloyed with REM are characterized by lower contents of harmful impurities (sulfur and phosphorus) decreasing their brittle-fracture resistance, stress-corrosion fracture resistance, and the resistance to hydrogen-induced cracking [9].

We determined the following mechanical characteristics:

— the strength (σ_u and $\sigma_{0.2}$) and plasticity (δ, ψ) characteristics of smooth specimens with a diameter of the working part of 4 mm in tension;

— the impact toughness was found for standard specimens with U- (KCU, the radius of the notch ρ = 1 mm) and V-shaped (KCV, $\rho = 0.25$ mm) stress concentrators by plotting the serial curves of cold brittleness and specimens with V-notches containing fatigue cracks (KCT; for the total length of the concentrator and the crack equal to 5 mm);

— the cyclic crack-growth resistance in laboratory air and in distilled water was found by constructing the kinetic diagrams of fatigue fracture (KDFF), i.e., the dependences of the fatigue crack-growth rate dl/dN on the range of the stress intensity factor ΔK under a cyclic loading by bending with a frequency of 1 Hz and a load ratio $R = 0.8$, for beam specimens $8 \times 10 \times 160$ mm in sizes containing lateral stress concentrators.

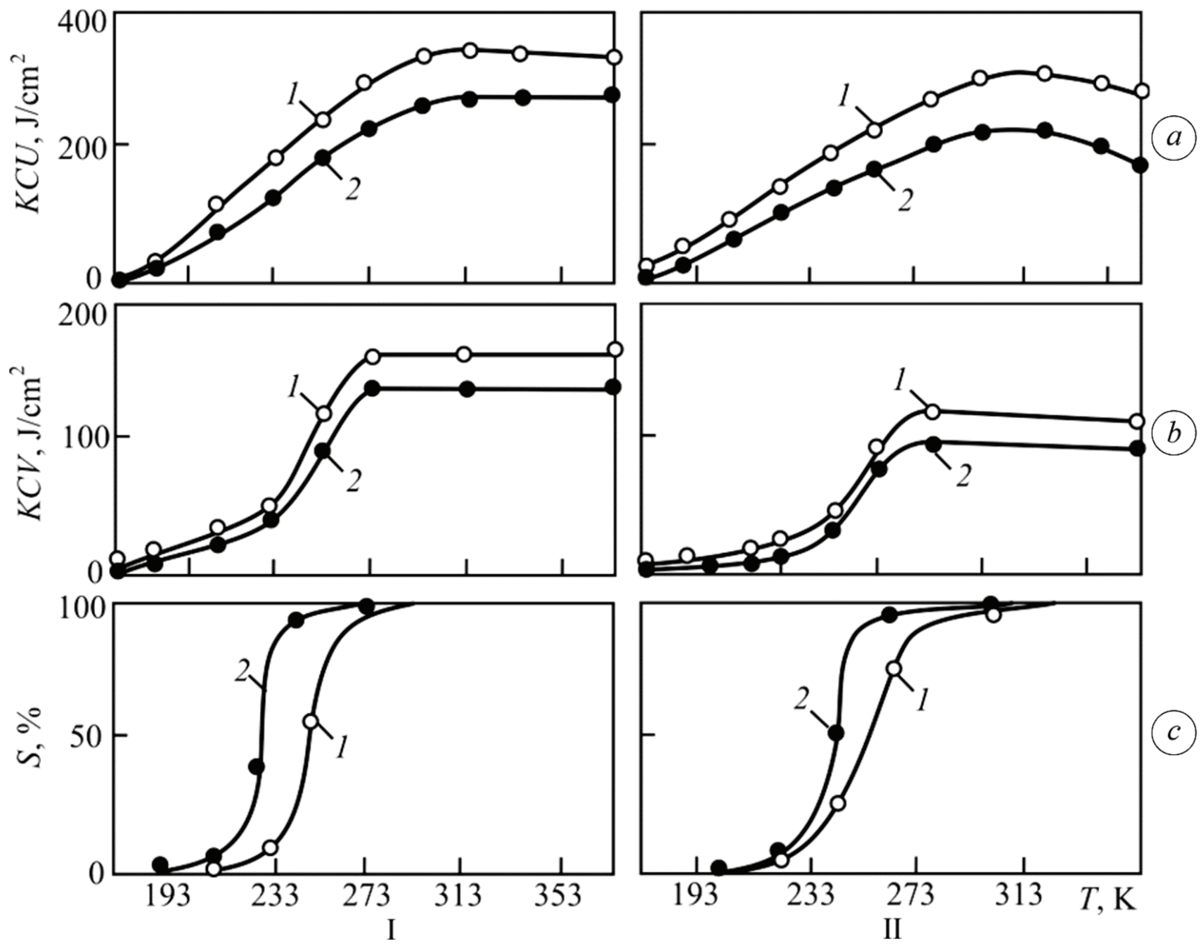

Fig. 1. Influence of testing temperature T on the impact strength KCU for $\rho = 1$ mm (a) and KCV for $\rho = 0.25$ mm (b) and the fractions of ductile component S in the fracture surfaces of 17G1S steel alloyed with REM (1) and without REM (2): (I) Composition 1; (II) Composition 2.

Table 3. **Strength and Plasticity of Steels Alloyed with REM**

Melting method	Heat	σ_u	$\sigma_{0.2}$	δ	ψ
		MPa		%	
Alloying with Composition 1	Experimental *A*	545	433	27	65
Without admixtures	Reference *B*	534	427	26	61
Alloying with Composition 2	Experimental *C*	578	495	28	67
Without admixtures	Reference *D*	557	476	26	60

As a result of the treatment of steels with REM, we observe a clear trend to increase in their characteristics of strength and plasticity (Table 3). In this case, the increase in relative narrowing ψ is more pronounced than the increase in relative elongation δ.

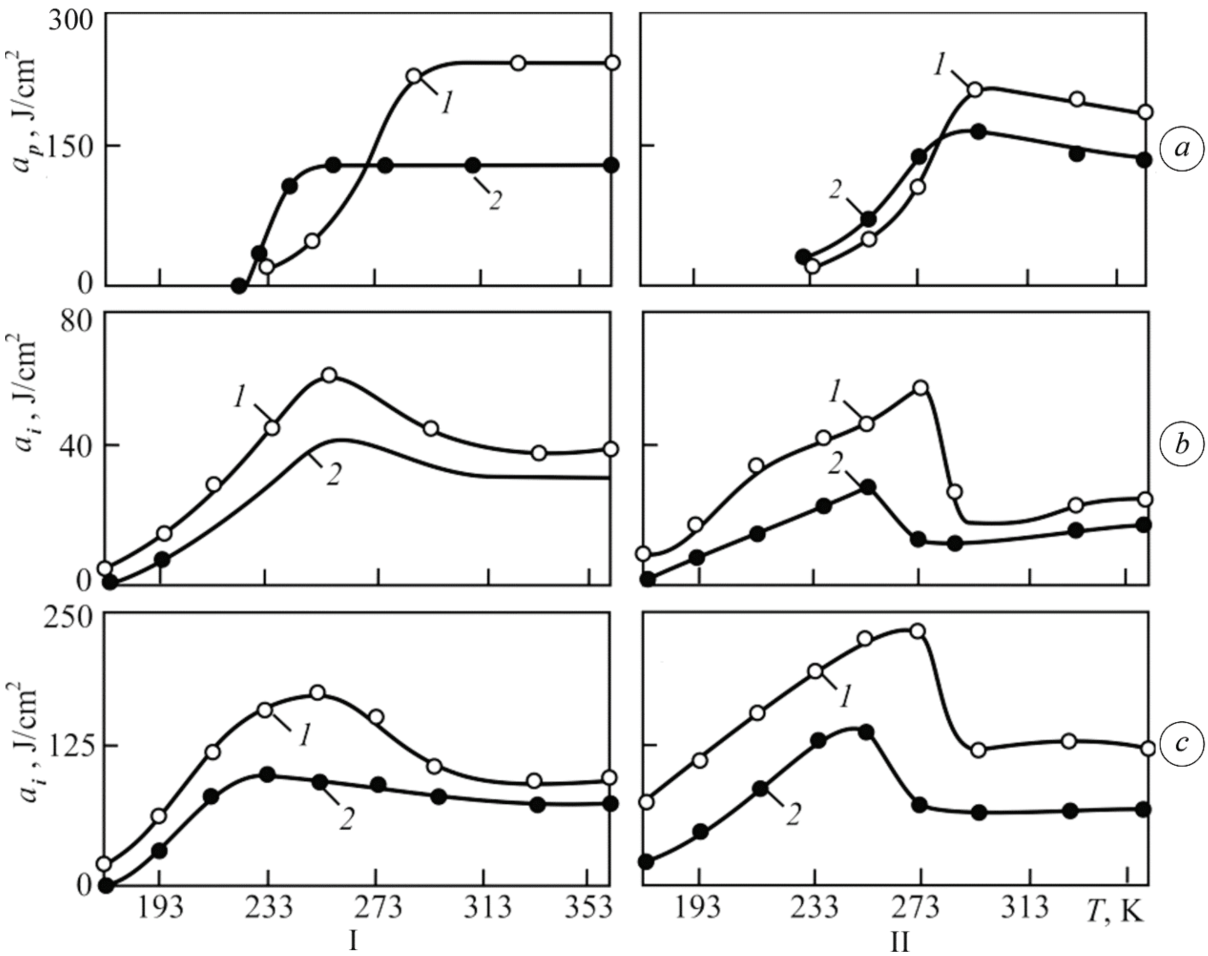

Fig. 2. Serial curves of the work of crack propagation a_p (a) and the work of crack initiation a_i [(b) ρ = 0.25 mm, (c) ρ = 1 mm] for 17G1S steel alloyed with REM (1) and without REM (2): (I) Composition 1, (II) Composition 2.

Thus, we can increase the plasticity of steel by its alloying with REM, even together with a certain increase in the characteristics of strength.

The REM admixtures also have a positive effect on the impact toughness of steel (Fig. 1). Note that this effect is stronger for specimens with U-shaped stress concentrators of larger radius (Fig. 1a). For specimens with V-shaped concentrators (Fig. 1b), the difference between the values of *KCV* for the reference metal and the metal alloyed with REM disappears as temperature decreases in a broad range of testing temperatures.

The estimates of the fraction of ductile (noncrystalline) component *S* in the fracture surfaces of specimens after impact tests were found to be unusual (Fig. 1c). For the reference steel (without REM), the curve of transition from ductile to brittle fracture is somewhat (by 10–15°C) shifted in the direction of lower temperatures as compared with the experimental (alloyed) steel. This means that the alloyed steel embrittles at higher temperatures than the ordinary steel, although according to the estimates of impact toughness, the curves of cold brittleness reveal the opposite effect.

To clarify the cause of this contradiction, we plotted serial curves according to the parameters of the work of crack initiation a_i and the work of crack propagation a_p in the steels alloyed with REM and without REM (Fig. 2). We use the well-known Drozdovskii's method who decomposed the specific work of fracture into the components a_i and a_p and, in addition, used specimens with preliminarily induced cracks [10]. In this case, the impact toughness of specimens with cracks KCT is regarded as the work a_p and the difference between the impact toughness KCU (or KCV) and KCT is regarded as a_i. To find KCT, we use the specimens with V-shaped concentrators.

It was established that, in the entire range of testing temperatures, the values of a_i for the steel with REM are higher than for the reference steel (Figs. 2b, c). In the stage of crack propagation, the positive effect of alloying with REM is preserved only within the temperature range corresponding to ductile fracture, i.e., the parameter a_p is higher for the experimental steel (Fig. 2a). At the same time, the drop of testing temperature leads to changes in the relative positions of the curves of the work of crack propagation. As follows from the dependences $S = f(T)$ (Fig. 1c), this is connected with the formation of crystalline regions in the fracture surfaces of the experimental steel.

The higher sensitivity of the parameter KCU to the presence of REM admixtures as compared with the parameter KCV also becomes clear because the work of crack initiation for the specimens with U-shaped concentrators of larger radius is higher than for the specimens with V-shaped concentrators.

The decrease in the values of a_p detected at low temperatures is compensated by the increase in the parameter a_i as a result of which the impact toughness of steel with REM additives is higher for all testing temperatures, although the positive effect becomes weaker as temperature decreases. The increase in the work a_i after treatment with REM is connected with a certain decrease in the content of nonmetallic inclusions and with the changes in the range of their dimensions and shape. Under these conditions, the relaxation of stresses is facilitated as a result of plastic deformation, the possibility of crack initiation decreases, and therefore, the work a_i increases.

At the same time, the effect of nonmetallic inclusions in the stage of crack growth can be different depending on the mechanism of fracture. Thus, in the case of ductile fracture, it is negative for the same reasons as in the stage of crack initiation, whereas within the temperature range of brittle fracture, the difference in the number of inclusions almost does not affect the development of plastic deformation in the fracture surface and, hence, the work of crack propagation a_p. It is possible to assume that this work somewhat decreases at these temperatures due to the fact that the number of efficient barriers in the path of the crack propagating according to the brittle mechanism decreases as the concentration of nonmetallic inclusions after treatment with REM becomes lower. In this case, we can speak about the positive effect of inclusions in the process of crack propagation when the plastic strains formed near the crack tip do not determine the crack-growth resistance.

Note that the mechanical properties of steels with REM admixtures in Compositions 1 and 2 undergo almost identical variations (see Figs. 1 and 2). Thus, the contents of REM admixtures proposed for the improvement of the corrosion-resistant properties of 17G1S pipe steel in [8] can also be regarded optimal for getting the required complex of the characteristics of strength, plasticity, and impact toughness.

Hence, we estimated the influence of REM on the cyclic crack-growth resistance of steel only for the heats A and B. The changes in the fatigue-fracture resistance of the material were evaluated according to the threshold values of the stress intensity factor K_{th}, cyclic fracture toughness K_{fc}, and the fatigue crack-growth rate in the middle section of the KDFF. The differences between the fatigue crack-growth rates and the threshold values of K_{th} for the ordinary steels and steels with REM admixtures were not discovered in the tests carried out in air and in distilled water. However, this does not mean that the corrosive medium does not affect the values of the parameter K_{th} (Table 4) decreasing for both states of the metal by ~ 24%.

Note that we revealed certain differences in the influence of REM on the parameter K_{fc}.

Table 4. Characteristics K_{th} and K_{fc} (MPa) for the Ordinary 17G1S Steel and the Same Steel Alloyed with REM (Composition 1) Tested in Laboratory Air and Distilled Water

Procedure of Melting	Laboratory air		Distilled water	
	K_{th}	K_{fc}	K_{th}	K_{fc}
Alloying with REM (Composition 1)	5.48	93.1	4.78	81.3
Without admixtures	5.41	84.1	4.72	70.5

Indeed, this parameter increases in air by 10% and in distilled water by ~ 15%, i.e., the positive effect of alloying is stronger under the action of the corrosive medium, although this medium decreases, in general, the cyclic fracture toughness of the metal. Judging from the character of the positive influence of REM admixtures on the process of fatigue crack growth, we can predict that the increase in the service life of pipes can be attained only as a result of the increase in the level of K_{fc} .

CONCLUSIONS

The procedure of alloying of 17G1S pipe steel with microadmixtures of rare-earth metals increases its strength and plasticity and the brittle-fracture resistance of the metal in terms of its impact toughness and cyclic crack-growth resistance. As the deformability of steel increases as a result of its treatment with REM, the impact toughness of the material becomes higher only for specimens with rounded notches. For the ordinary steel, the brittle–ductile transition corresponding to the change in the mechanism of fracture is somewhat shifted to the region of lower temperatures as compared with the experimental steel. At the same time, in terms of the impact toughness, it is shifted to the region of elevated temperatures. The values of impact toughness for the steel with REM admixtures are higher at all testing temperatures due to the increase in the work of crack initiation. It is not reasonable to increase the amount of REM admixtures over the optimal content with an aim to get higher corrosion resistance of steel because its mechanical properties remain almost unchanged. The aggressive influence of the corrosive medium (distilled water) on the growth of fatigue cracks in 17G1S steel manifests itself in the decrease in cyclic fracture toughness. The service life of the pipes of 17G1S steel with REM admixtures increases in the stage of growth of the fatigue cracks due to the increase in the cyclic fracture toughness of steel.

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