EFFECT OF STRENGTH LEVEL AND ORIGINAL AUSTENITE GRAIN SIZE ON THE CRACK RESISTANCE OF STEEL 38KhN3MFA

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In studying forgings of rotor shafts for electrical machines exhibiting stable strength and ductility properties through the cross section, it has been established that crack resistance may not be uniform throughout and a change in crack resistance is connected with the structure of the metal and the original austenite grain size.

The effect of original austenite grain size on static crack resistance, i.e., fracture toughness and the threshold value for stress intensity factor with cyclic loading (ΔK_{th}), has been studied in metal of the zone near the surface of rotor forgings made from ingots weighing 25 tons of acid open-hearth steel 38KhN3MFA melted by the technology of a complete silicon reduction duplex process. The chemical composition of the steel corresponded to GOST 4543-71. Specimen blanks cut in the longitudinal direction were hardened under conditions providing through martensitic hardenability and tempered to three levels of strength category corresponding to the total range for possible practical application of the rotor steel: KP 600, KP 800, KP 1200 (GOST 8479-70). At each strength level preparation of original austenite grain size at three levels was provided, i.e., fine, medium, and coarse, No. 10, No. 7, and No. 1 respectively (Table 1).

In order to obtain the original austenite grain size in specimens use was made of heat treatment corresponding to the standard heat treatment for rotor shafts of high-power two-pole generators.

A fine original austenite grain size was obtained by a special heat treatment (Table 1). Heating was carried out in an electric shaft furnace. After the first two heating cycles blanks were cooled in a stream of cold air, and after the third in oil. Temperature monitoring of blanks during thermal cycling was carried out with a thermocouple introduced into a deep hole drilled in the blank.

In order to obtain a coarse austenitic grain size blanks were heated for 25 min in molten barium chloride salt at 1200°C with prior warm-up; blank quenching was carried out from 1200°C in oil.

Blank tempering after quenching independent of austenite grain size was carried out in an electric muffle furnace by an identical schedule providing three strength levels (Table 1).

Standard mechanical properties were determined in smooth cylindrical specimens under axial tensile conditions according to GOST 1497-73 and specimens for impact bending tests type 11 according to GOST 9454-78.

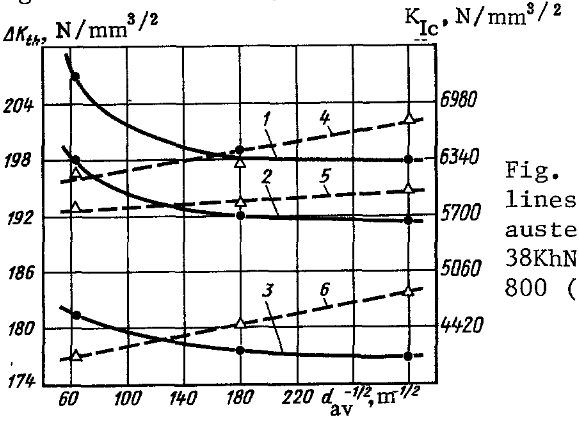

Fig. 1. Dependence of K_{Ic} (broken lines) and ΔK_{th} (solid lines) on austenite grain size d_{av} for steel 38KhN3MFA with KP 600 (1, 4), KP 800 (2, 5), and KP 1200 (5, 6).

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TABLE 1

Heat-treatment schedule	Heat treatment	d_{av}, mm	Design. of tempering schedules for obtaining strength		
			KP600	KP800	KP1200
1	Austen. at 900°C (60 min), furnace cooling + TCT (750-650°C) oil quenching from 820°C + tempering	11.2	M60	M80	M120
2	Austn. at 900°C (60 min), furnace cooling + oil quenching from 860°C + tempering	31.5	C60	C80	C120
3	Austen. at 900°C (60 min), furnace cooling + oil quenching from 1200°C + tempering	250	K60	K80	K120

Note. Schedules M60, C60, K60 are heating to 680°C, soaking for 20 h, furnace cooling; M80, C60, K80 are heating to 640°C, soaking for 10 h, furnace cooling; M120, C120, K120 are are heating at 580°C, soaking for 5 h, furnace cooling.

Fracture toughness was determined using force and energy (according to the J_{Ic}-integral) approaches in specimens according to GOST 25.506-85; ΔK_{th} was determined with an asymmetry factor R = 0 and loading frequency 25 Hz. Crack advance was recorded with a cathetometer. Compact specimens 6 mm thick were tested by the procedure in [1].

All of the tests were carried out in air at normal temperature.

Results of the studies are given in Table 2 and in Fig. 1.

Yield strength and ultimate breaking strength for specimens with a coarse-grained structure after tempering by an identical schedule are higher than for specimens with a smaller grain size, whereas according to the well-known Hall—Petch relationship the reverse might be expected. Ductility and impact strength decrease with an increase in grain size.

From data provided in Table 2 and in Fig. 1 it also follows that with an increase in yield strength independent of grain size for steel 38KhN3MFA both static and cyclic crack resistance decrease.

An increase in grain size with the same strength levels has a different effect on crack resistance: K_{Ic} decreases, but ΔK_{th} increases. Whereas with an increase in grain size K_{Ic} decreases almost by a linear rule, the increase in ΔK_{th} occurs by a complex relationship: in the fine and medium grain size regions ΔK_{th} increases a little, but with a change over into the coarse grain size zone its increase becomes quite marked.

Mathematical treatment of the results obtained using the least squares method made it possible to approximate experimental data by empirical equations.

Graphical representation of the dependence of fracture toughness on original austenite grain size (see Fig. 1, curves 4, 5, and 6) corresponds to an analytical relationship of the Hall—Petch type:

$$K_{Ic}=A+Bd_{av}^{-1/2}.$$

TABLE 2

Av. grain diam., mm	Strength category	$\sigma_{0,2}$	σ_B	δ	ψ	$a_{0,25}$	K_{Ic}	ΔK_{th}
		N/mm²		%		J/cm²	N/mm$^{3/2}$	
11,2	KP 600	550	780	22,5	63,0	181	6810	199,7
	KP 800	780	900	20,0	57,5	149	6020	192,5
	KP 1200	1110	1200	15,0	55,0	59	4840	177,0
31,5	KP 600	570	768	22,0	64,0	165	6290	199,7
	KP 800	810	915	17,0	51,3	146	5820	193,0
	KP 1200	1120	1230	14,0	47,7	55	4460	178,0
250,0	KP 600	620	810	21,0	61,5	121	6170	209,0
	KP 800	860	1000	15,5	45,5	83	5800	199,7
	KP 1200	1190	1270	13,5	42,0	36	4120	182,0

With KP 600 A = 188, B = 0.0850; with KP 800 A = 180; B = 0.0298; with KP 1200 A = 124, B = 0.0975. Correlation coefficient r with KP 600, 800 and 1200 is 0.95; 0.93 and 1.0 respectively.

Graphical interpretation of the dependence of cyclic crack resistance on original austenite grain size (see Fig. 1, curves 1, 2, and 3) is described by a power relationship

$$\Delta K_{th}=L\,[d_{\text{av}}^{-1/2}]^{m},$$

where L and m are coefficients. With KP 600 L = 7.52, m = —0.0321; with KP 800 L = 6.95, m = —0.0242; with KP 1200 L = 6.19, m = —0.0178. Correlation coefficients r for KP 600, KP 800, and KP1200 are 0.96, 0.97, and 0.98 respectively.

In order to explain the dependence of mechanical properties and crack resistance on strength level and grain size, metallographic analysis of the structure, carbide analysis, and fractographic evaluation of specimen fractures were carried out.

Metallographic and carbide analyses were carried out on specimens of steel 38KhN3MFA heat treated for fine and coarse grains with three strength levels.

The structure of steel 38KhN3MFA with a reduction in strength from KP 1200 to KP 600 of troostite—sorbite with clear martensitic orientation and nonequilibrium decomposition of supersaturated α-phase transforms into a sorbitic structure with less clearly defined martensitic orientation; the nonequilibrium nature of phase decomposition disappears.

Carbide phase* with strength KP 1200 is mixed (globular and elongated forms), and with an increase in tempering temperature it becomes entirely globular. Steel grain size has a considerable effect on carbide placement: in fine-grained steel it is distributed quite uniformly, but in coarse-grained steel it is located along the boundaries of martensite platelets and the original austenite grains [1].

Independent of quenching temperature, in the structure of steel after tempering by the schedules adopted cementite carbide $(Fe, M)_3C$ forms; with an increase in tempering temperature and a reduction in strength properties the amount of carbide phase decreases (Table 3). However, whereas in fine-grained steel the amount of carbide phase decreases after tempering at 640 and 680°C, in coarse-grained steel it only decreases with an increase in tempering temperature to 680°C. Carbon content in the carbide phase increases with an increase in temperature [2]. The degree of carbide alloying changes ambiguously. The total content of Mn, Cr, Ni, Mo and V in carbide phase is at a minimum after tempering at 580°C (KP 1200), and with an increase in tempering temperature to 640°C (KP 800) it increases to 22.24% (with a coarse grain size) and 23.65% (with a fine grain size); with a further increase in tempering temperature to 680°C (KP 600) the degree of carbide phase alloying corresponds to 19.75% (with a coarse grain size) and 22.48% (with a fine grain size).

Thus, with tempering of alloyed steel with different grain size the kinetics of the diffusion redistribution processes for alloying between α-phase and carbides are different. In coarse-grained steel α-phase is more alloyed than in fine-grained steel in spite of an identical tempering schedule. This may explain the increase in level of strength properties for steel 38KhN3MFA with a coarse-grained structure.

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*Estimation of carbide phase was carried out in the Central Laboratory of the Izhorsk factory under the leadership of A. I. Farutinaya.

TABLE 3

Tempering schedule	Carbide phase content,* %	Carbon and alloying element content in carbide phase,† %					
		C	Mn	Cr	Ni	Mo	V
K 60	4,00	8,75	2,75	10,00	1,00	3,00	3,00
M 60	3,78	9,26	3,44	11,90	1,32	3,17	2,65
K 80	4,63	7,56	3,24	12,96	0,86	2,59	2,59
M 80	4,06	8,62	4,19	12,56	0,99	3,45	2,46
K 120	4,52	7,74	3,00	6,68	1,38	3,46	2,30
M 120	4,34	8,06	3,10	7,52	1,70	3,52	2,43

*Carbide type (Fe, **M**)$_3$C.
†Balance iron.

As a result of these studies it has been established that α-phase decomposition and formation of carbides during tempering does not proceed simultaneously, which leads to the occurrence of a nonuniform composition for ferrite and a heterophase structure, and consequently also to a reduction in K_{Ic} and impact strength of specimens with a coarse-grained structure, which is most marked with KP 1200. This appeared in the structure of specimen fractures. Fractographic analysis showed that failure of coarse-grained steel with KP 1200 proceeds with a predominantly brittle mechanism of the 'trans-shear—intershear' type in contrast to ductile intergranular pitted failure for fine-grained steel with KP 600 [3].

An increase in ΔK_{th} with an increase in grain size for steel 38KhN3MFA may be explained by the fact that retardation of a slowly growing (quasistatic) crack may occur as a result of its reaction with interblock boundaries which are well-formed and developed with a brittle grain, and under these conditions a crack changes direction and it is often stopped [4].

In fine-grained steel crack growth is governed by the reaction with stress fields due to nonmetallic inclusions, for example carbides. With uniform distribution of carbides in the matrix in the path of a fatigue crack a continuous front of stress fields forms facilitating its development. Fractographic studies of the fatigue zone for the majority of steel 39KhN3MFA conditions revealed a typical lined fracture. An increase in ΔK_{th} as a result of coarsening of the original austenite grains is accompanied by an increase in the proportion of more energy-consuming intragranular failure, which is revealed in fractograms of fractures as an increase in fragments of lined failure.

CONCLUSIONS

1. Static fracture toughness and threshold values of the spread in stress intensity factor for rotor steel 38KhN3MFA heat treated under conditions providing through hardenability depend on yield strength and the original austenite grain size.

2. The inversely proportional empirical relationship of fracture toughness with original austenite grain size for steel 38KhN3MFA corresponds to an analytical relationship of the Hall—Petch type.

3. An increase in threshold values for the spread of stress intensity factor correlates with an increase in austenite grain size for the steel according to a power function.

4. A reduction in the strength level for rotor steel leads to an increase in fracture toughness and the threshold stress intensity factor.

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