

POSSIBILITY OF PREDICTION OF PROPERTIES OF HIGH-TOUGHNESS MATERIALS BY COMPLEX ANALYSIS OF THE SIZE OF ZONES OF PLASTIC STRAIN AND OTHER PARAMETERS OF STEEL 09G2S

M. Yu. Simonov,¹ G. S. Shaimanov,¹ Yu. N. Simonov,¹ and A. M. Khanov¹

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Relations between the parameters of dynamic crack resistance, impact toughness, sizes of zones of plastic strain in the start region, hardness of the unstrained material, strength characteristics, and tempering temperature of steel 09G2S are determined. The linear regression equations are used to construct mathematical and graphical models for predicting the level of properties in quenched and tempered steel 09G2S. The method is used to predict the properties of a tubular billet from steel 09G2S with composition somewhat different from the rated one after quenching and high tempering at 570°C.

Key words: dynamic crack resistance, plastic strain zone, systematic variation of microhardness, prediction of properties.

INTRODUCTION

Raising of mechanical and operating characteristics of materials and analysis and installation of advanced methods of evaluation and prediction of the properties of materials has been a priority direction of the machine building industry for many years.

One of the criteria of dynamic crack resistance (DCR) is the specific energy of crack propagation KCT determined by testing in an impact machine by the method of B. A. Drozdovsky (GOST 9454–78, specimens of standard sizes 15 – 20). The fact that the side surfaces of the specimens are pulled down quite frequently, and virtually always in specimens from high-toughness materials, which takes considerable energy, has been ignored. A group of authors [1, 2] has developed and tested a method eliminating the contribution of side pulling down into the energy of crack propagation. It is important that in this method fracture always occurs in a macroscopically plane strain condition (PSC). On the other hand, the presence of a crack in KCT tests causes localization of stresses at its front [3]. Growth in the stresses to the level of the yield strength of the material inevitably gives rise to a plane strain zone (PSZ) [4]. In [5] we have developed and tested a method for estimating the shape and the size of PSZ by systematic measurement of microhardness. The volume

of data obtained by this method and the information it gives are not inferior to those obtained by the laborious method of estimation of PSZ with the help of x-ray analysis [6, 7] or EBSD [8, 9].

It is obvious that a very important direction of today's science of materials is prediction of their properties without resorting to complex techniques and expensive tests. The correlation dependences between hardness and strength are well known [10 – 13]. We also know of complex parametric relations permitting prediction of a set of properties of materials [14 – 16]. Such relations make it possible to evaluate the parameter of interest in terms of some known parameter with this or that degree of accuracy.

The aim of the present work was to develop approaches to prediction of the dynamic crack resistance and other properties of steel 09G2S by a complex analysis of its properties and to determine the correlation relations.

METHODS OF STUDY

We studied steel 09G2S melted at the “Kamastal” Company (Perm) and having the following chemical composition (in wt.%): 0.10 C, 1.38 Mn, 0.59 Si, 0.08 Cr, 0.12 Ni, 0.019 Ti, 0.011 Al, 0.01 P, 0.01 S, 0.01 As. Individual specimens were quenched from 925°C in water and tempered for 2 h at 200, 400, 500 and 650°C. The heat treatment was performed in SNOL 7.5/12 laboratory furnaces.

¹ Perm National Research Polytechnic University, Perm, Russia (e-mail: mto@pstu.ru).

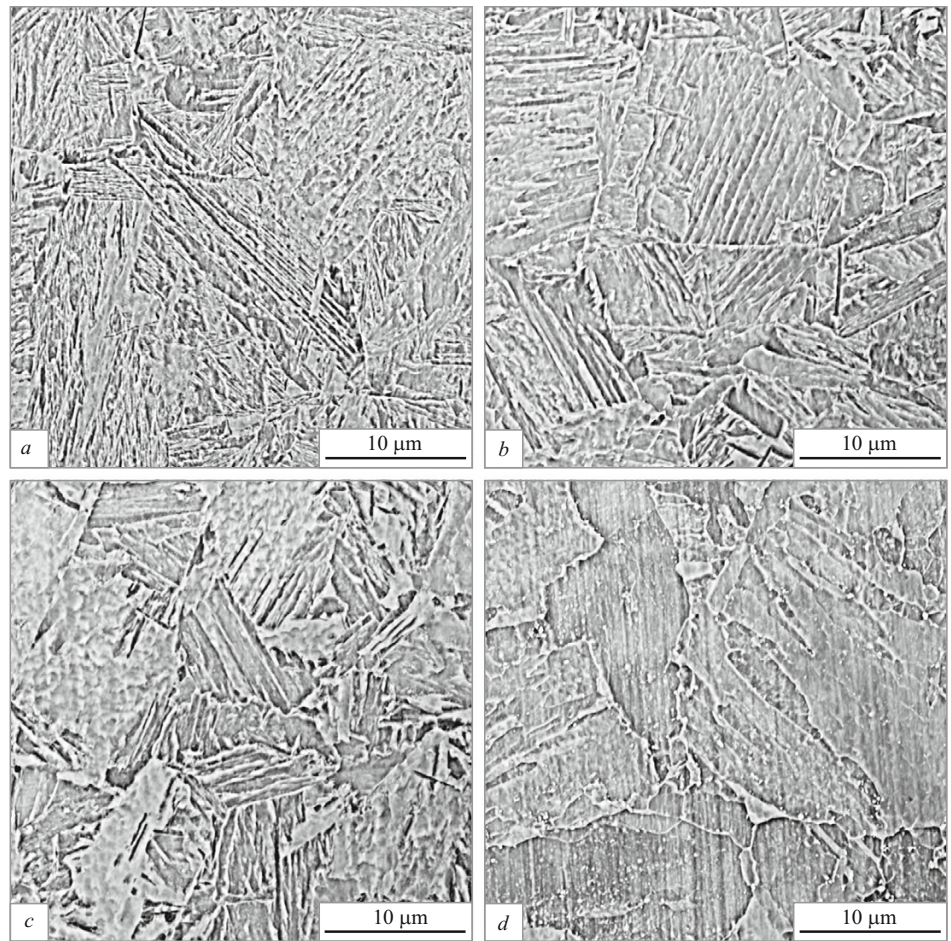


Fig. 1. Microstructure of steel 09G2S (SEM) after quenching and tempering at 200 (a), 400 (b), 500 (c) and 650°C (d).

After the heat treatment the specimens were subjected to dynamic tests in a KM-30 pendulum impact machine. The specimens of type 15 (GOST 9454–78) were divided into two groups; in the first group we varied the relative crack length $\lambda = 0.25 - 0.7$ ($\lambda = l/b$, where l is the total length of the base notch and the crack and b is the width of the specimen). On the specimens of the second group we imposed additional side V -notches 1 mm deep and varied the relative crack length $\lambda = 0.3 - 0.65$ [17]. Initial fatigue cracks of various lengths were deposited using a Drozdovsky vibrator. After the tests we plotted the dependences of KCT on λ and used them to determine the parameter $KCT^* \equiv G_{lc}^d$. Then we plotted the diagrams of dynamic crack resistance for the steel studied.

We studied the PSZ in the region of the start of propagation of dynamic cracks by the method of systematic measurement of microhardness [18] on fragments of fractured specimens with various relative lengths of fatigue crack $\lambda = 0.45 - 0.55$.

The stages of preparation of specimens and the specific features of the method of evaluation of the parameters of PSZ are described in detail in [5].

The strength and ductility parameters were determined on short cylindrical specimens of type 3 with initial diameter

3 mm in accordance with GOST 1497–73 with the help of an INSTRON-SATEC 300 LCX universal hydraulic machine for static tests. The results were processed and the diagrams plotted using the “Bluehill” software for 5 specimens for each treatment mode.

The structure was studied on laps prepared on transverse sections of impact specimens. The etchant was a 4% solution of nitric acid in ethyl alcohol. The etched microsections were studied under an GX-51 Olympus light microscope at a magnification of $\times 100 - 1000$, a Phenom ProX Scanning electron microscope (SEM) at a magnification of $\times 1000 - 15,000$ at an accelerating voltage of 15 kV. The fine structure was studied under a JEM-200CX electron microscope at an accelerating voltage of 160 kV.

Then we performed a joint analysis of the results of the evaluation of KCT^* and of the sizes of the PSZ (r_{PSZ}^*) and other parameters of the steel.

RESULTS AND DISCUSSION

The metallographic analysis of steel 09G2S after quenching from 925°C and subsequent tempering at 200°C shows that its structure is represented by lath (dislocation)

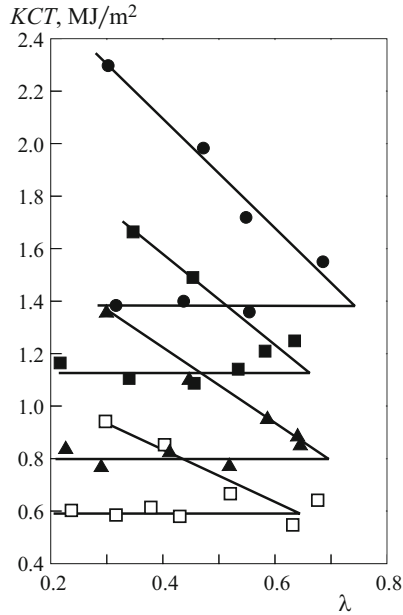


Fig. 2. Diagrams of dynamic crack resistance of specimens of steel 09G2S quenched and tempered at 650 (●), 500 (■), 400 (▲) and 200°C (□) (KCT is the impact toughness of specimens with deposited crack; λ is the relative crack length).

martensite (Fig. 1a). After the tempering at 400°C the substructure of the martensite is preserved on the whole. At the same time, steel 09G2S at this temperature undergoes processes that lower the dislocation density and cause decomposition of the supersaturated solid solution yielding cementite-type carbides [19] (Fig. 1b). After the tempering at 500°C the substructure of the martensite is preserved only partially (Fig. 1c). The processes of polygonization, primary recrystallization and further decomposition of the solid solution occurring in steel 09G2S at 500°C and yielding carbide particles produce a structure describable as high-tempered martensite. After the high-temperature tempering (650°C) the structure is represented by volumes that have undergone secondary recrystallization and contain ferrite polyhedrons over 10 μm in size and volumes of incomplete secondary recrystallization (Fig. 1d). These volumes have a cellular substructure formed during the primary recrystallization and polygonization.

TABLE 1. Impact Toughness, Strength, Size of PSZ, and Criteria of Dynamic Crack Resistance of Steel 09G2S

$t_{\text{temp}}, ^\circ\text{C}$	$KCT, \text{MJ/m}^2$	$KCT^*, \text{MJ/m}^2$	λ^*	σ_r, MPa	$\sigma_{0.2}, \text{MPa}$	$r_{\text{PSZ}}^*, \text{mm}$
200	0.90	0.60	0.64	845	727	0.8 – 0.85
400	1.40	0.80	0.68	790	647	1.2 – 1.25
500	1.80	1.10	0.65	680	577	1.7 – 1.75
650	2.30	1.35	0.74	600	510	2.05 – 2.1

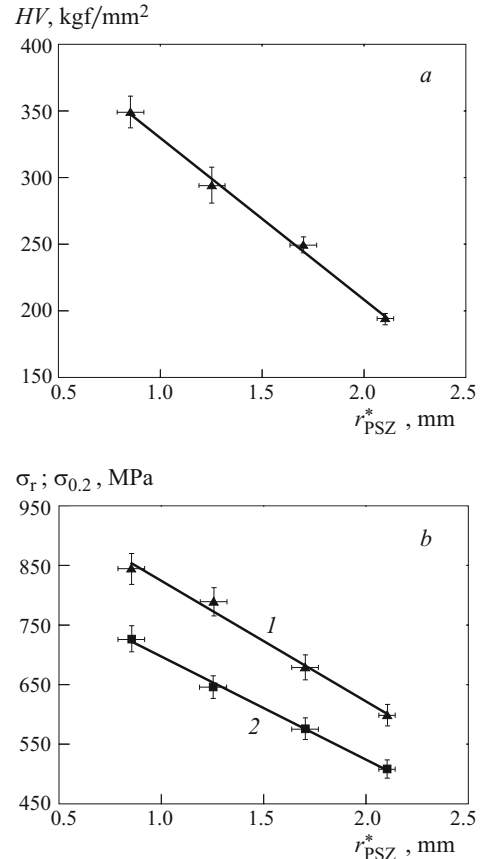


Fig. 3. Microhardness of the matrix material (a), ultimate strength (1) and yield strength (2) (b) as a function of the size of the plastic strain zone r_{PSZ}^* .

Plotting the diagrams of dynamic crack resistance (Fig. 2) and analyzing the latter we determined the characteristics of impact toughness and dynamic crack resistance of the steel. It turned out that the specific energy of crack propagation in the plane stress condition (PSC) is in all cases higher than the energy of crack propagation in the state of plane strain (KCT^*). Both KCT and KCT^* grow with the tempering temperature.

The characteristics of the strength and of the dynamic crack resistance of the material, as well as the size of the PSZ for each tempering temperature are presented in Table 1.

Figure 3a presents the results of a joint analysis of the data obtained by systematic measurement of the microhardness [5] on specially prepared fragments of impact specimens after quenching and tempering at 200, 400, 500 and 650°C. It can be seen that the interrelation between the level of the microhardness of the matrix material and of the size of the PSZ is describable by a linear law (see Eq. (1) below). Figure 3b presents a plot reflecting the interrelation between the ultimate strength, the yield strength and the value of r_{PSZ}^* . We can see a linear decline of the ultimate strength (Eq. (2)) and of the yield strength (Eq. (3)) with growth in r_{PSZ}^* in the start region observed upon elevation of the tempering tem-

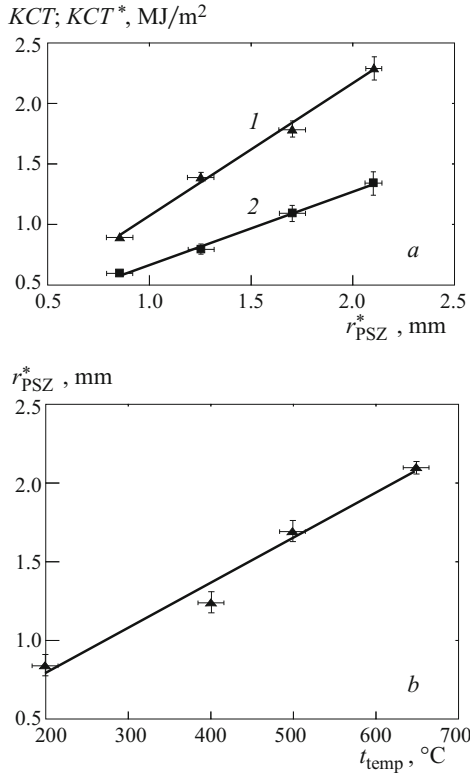


Fig. 4. Parametric dependence of KCT (1) and KCT^* (2) on r_{PSZ}^* (a) and of r_{PSZ}^* on t_{temp} (b).

perature from 200 to 650 $^{\circ}\text{C}$. The equations below characterize the relations of the characteristics mentioned, i.e.,

$$HV = -121.2r_{PSZ}^* + 451.3, \quad (1)$$

$$\sigma_r = -201.5r_{PSZ}^* + 1026, \quad (2)$$

$$\sigma_{0.2} = -171.5r_{PSZ}^* + 868.2. \quad (3)$$

Figure 4 presents dependences of the dynamic crack resistance and of the impact toughness on r_{PSZ}^* (a) and of r_{PSZ}^* on the tempering temperature (b). The following equations characterize the relations of these characteristics, i.e.,

$$KCT^* = 60.76r_{PSZ}^* + 6.621, \quad (4)$$

$$KCT = 109.3r_{PSZ}^* - 1.289, \quad (5)$$

$$t_{temp} = 344.1r_{PSZ}^* - 70.18. \quad (6)$$

It can be seen from Fig. 4a that the dynamic crack resistance and the impact toughness grow linearly with r_{PSZ}^* , and this dependence is describable by equations (4) and (5) respectively. The dependence of r_{PSZ}^* on the tempering temperature of steel 09G2S is also linear (Fig. 4b) and is describable by Eq. (6).

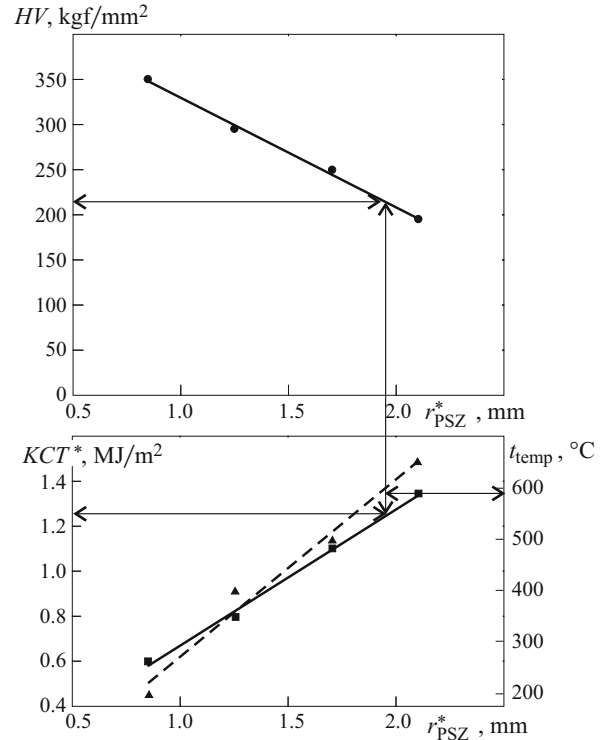


Fig. 5. Example of graphical solution of equations (1), (4), (6): \bullet) dependence $HV - r_{PSZ}^*$; \blacksquare) dependence $KCT^* - r_{PSZ}^*$; \blacktriangle) dependence $t_{temp} - r_{PSZ}^*$.

Thus, the interrelation of the impact toughness, dynamic crack resistance, microhardness, strength characteristics, tempering temperature, and sizes of the PSZ allows us to speak of a mathematical model represented by the system of Eqs. (1) – (6). An analytical or graphical solution of this system will allow us to predict the level of the fracture energy G_{lc}^d , the hardness, the tempering temperature, the impact toughness and other characteristics of steel 09G2S in different structural states on the basis of one known parameter of the list.

To check the adequacy of the model for predicting properties we chose a tubular billet from steel 09G2S [20] with chemical composition differing somewhat from that of the steel studied within the standardized range, namely (in wt.%): 0.11 C, 0.50 Si, 1.26 Mn, 0.22 Cr, 0.18 Ni, 0.14 Cu, 0.14 Mo, 0.005 S, 0.017 P. The billet was treated by water quenching from 920 $^{\circ}\text{C}$ and tempering at 570 $^{\circ}\text{C}$. The heating for the quenching and for the tempering was conducted in a SShTsM 6.12/9 shaft furnace.

To check the possibility of prediction of the properties of the test material we measured its microhardness. As an example, we present in Fig. 5 a graphical interpretation of linear equations (1), (4) and (6). The arrows present a graphical solution of the system of three linear equations at a known value of the microhardness of the test material. It is important that to make the prediction of the parameters more accurate we should perform computation by the formulas

TABLE 2. Results of Tests of the Chosen Material and Their Deviation from Computed Data

Data	t_{temp} , °C	KCT , MJ/m ²	KCT^* , MJ/m ²	σ_r , MPa	$\sigma_{0.2}$, MPa	HV , kgf/mm ²
Experiment	570	2.10	1.24	650	520	220
Computation	587	2.07	1.23	641	540	–
Relative error, %	3	1	< 1	1	4	–

given above. A graphical solution is approximate and may be used for qualitative estimation of variation of the properties of the material.

Table 2 presents the control parameters obtained experimentally and computationally for the tubular billet of the test material.

The computed and experimental data matched well enough and deviated by at most 5%.

However, we should note that in the case of such embrittling factors as susceptibility of the material to temper brittleness of kinds I and II, elevated content of harmful impurities both standardized and not standardized, and phase transformations developing in large volumes of the material during the process of fracture the method in question is less efficient.

CONCLUSIONS

1. We have established interrelation of the impact toughness, dynamic crack resistance, microhardness, ultimate strength, yield strength, and size of the plastic strain zone (t_{PSZ}^*) in the region of start of dynamic crack of steel 09G2S. These characteristics of the steel vary linearly in the range of tempering temperatures from 200 to 650°C.

2. We have developed a mathematical model based on linear equations for predicting the level of dynamic crack resistance and other parameters of steel 09G2S.

3. The suggested model has been checked and exhibited good convergence of the experimental and computed data.

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