Journal of Engineering Physics and Thermophysics, Vol. 70, No. 3, 1997

A MODEL OF THERMAL EFFECTS ON THE RESISTANCE OF STEELS TO CRACKING

V. E. Zhogolev and Yu. G. Romanov

UDC 621.78

We consider an example of processing of the results of laboratory tests that reflect the change in the conditions of the formation of cold cracks associated with tempering of martensite structures on reheating. The processing is carried out using a proposed model of thermal effects on the resistance of steels to cracking.

Carbon and alloyed steels owe their application in producing welded parts and constructions to their adequate weldability [1, 2]. Most dangerously, insufficient weldability results in the formation of cracks in the metal of a seam and in the zone near the latter. Among weld defects, more than half are cold cracks formed in the process of steel cooling after welding at temperatures below 150°C or within a few days. The initiation and development of cold cracks is associated with the structural state of the steel, the concentration of diffusionally mobile hydrogen C_H in it, and tensile stresses of the first kind σ_t [3]. The critical combination of the indicated factors is used as a criterion for the formation of cold cracks. An increase in σ_t and C_H leads to a decrease in the resistance of steels to cracking. At a fixed value of the stress σ_t the magnitude of the critical concentration of hydrogen C_H, above which cold cracks appear, can be used as a quantitative characteristic of the property of steel in a specific structural state.

An important characteristic of the structure of a metal from the viewpoint of the formation of cold cracks is its phase composition [3] (the relationship between martensite, bainite, and ferrite-pearlite). The martensite structure shows the greatest tendency toward the formation of cold cracks. This structure is typically formed in carbon and alloyed steels at the high rates of metal cooling often observed in the conditions of multilayer welding or root run surfacing. In subsequent runs the region of martensite structure formed is subjected to heating in a wide range of temperatures. In the present work we investigate a situation encountered in practice when the maximum temperature of reheatings in this region does not exceed the lower limit of the intercritical interval. In this case the tempering of martensite occurs, which is accompanied by structural conversions, phase evolutions, and other processes. As a result, the resistance of steel to the formation of cold cracks varies. Some information concerning the effect of reheating on the conditions of the initiation of cold cracks can be obtained from the laboratory tests described in [3]. There, measurements were made of the change in the critical concentration of hydrogen C_H as a result of thermal effects of various intensities and durations. However, in such tests a particular form of thermal cycles is specified, and, therefore, a question arises as to how the data obtained can be used for predicting the conditions of the initiation of cracks in steel after different thermal effects encountered in practice. This is important for optimizing the conditions of welding, surfacing, and thermal treatment.

We also consider an example demonstrating the processing of the results of laboratory tests that reflect the change in the conditions of the initiation of cold cracks due to the tempering of martensite structure on reheating. The processing was carried out using the proposed model of thermal effects on the resistance of steels to cracking. As a result, we found indeterminate parameters of the model that subsequently allow us to predict the conditions for the formation of cracks in a given steel after repeated thermal cycling of arbitrary form.

Experiment. Our laboratory tests were run at the Bauman Moscow State Technological University following the experimental procedure of [3] adapted for the conditions of multilayer welding. Specimens of 30KhN3M2FA steel of size 1.5 × 10 × 100 mm were investigated in succession. First, each specimen was subjected to the same

Institute of Nuclear Synthesis, Russian Scientific Center "Kurchatov Institute," Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 70, No. 3, pp. 476-479, May-June, 1997. Original article submitted February 2, 1995; revision submitted December 21, 1995.

 1062-0125/97/7003-0468$18.00

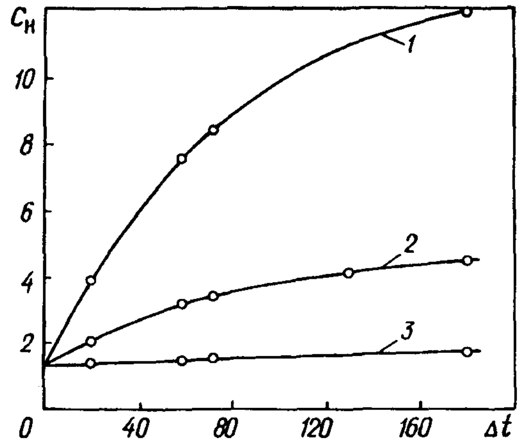

Fig. 1. Critical concentration of hydrogen C_H (cm^3/kg) versus duration of thermal cycle Δt (sec) at different temperatures T_0: 1) $T_0 = 873$ K; 2) 673; 3) 573.

thermal cycle, which simulated the first half-wave of heating of multilayer welding and ensured martempering of the steel. Next, we carried out repeated heating in which the temperature was decreased linearly with time t:

$$T(t) = T_0 - \Delta T\, t/\Delta t;\ \ \Delta T = 200\ \text{K},\ \ 0 < t < \Delta t. \tag{1}$$

Steel specimens with the same $T_0 = T_0^i$ and $\Delta t = \Delta t^i$ composed one batch with number i. Then each specimen was saturated with hydrogen, whose amount was regulated by the time of holding the specimen in an electrolytic cell. At the final stage it was kept for 20 h under mechanical loading equal to the conventional limit of the yield stress of the material. Out of each batch we selected the cracked specimen with the smallest content of hydrogen, whose amount was measured on a special setup. Thus, we determined the critical concentration of hydrogen C_H^i for all of the thermal cycles. It should be noted that we also found the value $C_H^0 = 1.35$ cm^3/kg in the absence of reheating ($\Delta t^0 = 0$). The dimension used in the work for C_H has the meaning of the hydrogen volume under normal conditions which is liberated from a unit mass of steel on heating. The dots in Fig. 1 show the experimental values of C_H^i as a function of Δt. The experimental accuracy of the measurements was $\delta C_H = \pm 0.1$ cm^3/kg.

Model. The experiment was designed so that it revealed the change in the resistance of steel to the formation of cold cracks on tempering of the martensite structure during reheating. Saturation with hydrogen was performed after the thermal effect before slow breakdown testing. We assume that the appearance of cold cracks does not depend on the prehistory of hydrogen ingress into the metal; only its resultant concentration and the existing mechanical stress are of importance. A certain justification for such an assumption is the fact that the change in the order of metal saturation with hydrogen leads to not more than a 15%-difference in the change in the critical value of ΔC_H. Thus, tempering of the martensite structure on reheating is a more important factor. It is natural to assume that the set of critical values of C_H that correspond to different possible states of the martensite structure is limited:

$$C_H^{\min} \le C_H \le C_H^{\max}. \tag{2}$$

Here, it should be understood that $C_H^{\min}$ and $C_H^{\max}$ depend on the value of σ_t.

Let us introduce into consideration the dimensionless variable y, so that

$$C_H = (1 - y)\, C_H^{\min} + y C_H^{\max}. \tag{3}$$

In the model suggested it is assumed that the time change in the characteristic of the state of steel $y(t)$ is described by a linear differential equation:

$$dy/dt = \alpha - y(\alpha + \beta),\ \ y(0) = y_0. \tag{4}$$

Here y_0 is the initial value; the coefficients of the equation depend on the absolute temperature $T(t)$ in the following way:

$$\alpha(T) = f\,T^{-2}\exp(-T_\alpha/T),\quad \beta(T) = f\,T^{-2}\exp(-T_\beta/T). \tag{5}$$

Functional Relationship. The model involves five indeterminate parameters C_H^{min}, C_H^{max}, f, T_α, T_β, and the characteristic of the initial state of the steel y_0. The model parameters can be found by processing experimental data. To perform the processing, it is necessary to know the functional relationship between the critical concentration of hydrogen C_H and the form of the thermal cycle. We will determine it from the solution $y(t)$ of differential problem (4) in the form of the quadrature:

$$y = \exp\left(-\int_0^t (\alpha+\beta)\,dt'\right)\left\{y_0 + \int_0^t \alpha\exp\left(\int_0^{t'}(\alpha+\beta)\,dt''\right)dt'\right\}. \tag{6}$$

From this, by the end of the thermal cycle we obtain $y_1 = y(\Delta t)$:

$$y_1 = y_0 + (\bar{y} - y_0)\left\{1 - \exp(-(A+B)\,\Delta t)\right\}; \tag{7}$$

$$A = \int_0^{\Delta t} \alpha dt/\Delta t,\quad B = \int_0^{\Delta t} \beta dt/\Delta t; \tag{8}$$

$$\bar{y} = \int_0^{\Delta t} \alpha\exp\left(-\int_0^{\Delta t}(\alpha+\beta)\,dt'\right)dt \Big/ \left\{1 - \exp(-(A+B)\,\Delta t)\right\}. \tag{9}$$

We note that A and B are independent of the duration of the thermal cycle Δt. If we take into account that the temperature in the experiments decreased from T_0 to $T_1 = T_0 - \Delta T$ $(dT/dt = -\Delta T/\Delta t)$, then we can rewrite Eq. (8) as

$$A = \int_{T_1}^{T_0} \alpha dT/\Delta T,\quad B = \int_{T_1}^{T_0} \beta dT/\Delta T. \tag{10}$$

In this case, for the functions $\alpha(T)$ and $\beta(T)$ of form (5) the integrals are taken analytically. Further, instead of complex expression (9) for $\bar{y}$ we will use the formula

$$\bar{y} = A/(A+B). \tag{11}$$

Expression (11) in the limit of small and large values of Δt coincides with Eq. (9). The duration Δt is considered to be large if there is saturation $y_1 = \bar{y}$. The substitution of Eq. (7) into Eq. (3) gives the functional relationship needed.

Processing of Experiment. We will use the obtained functional relationship for processing the previously cited laboratory tests. In the experiments we measured the critical concentrations of hydrogen C_H^i for each of $N = 12$ thermal cycles with the parameters Δt^i and T_0^i. On the other hand, these parameters can be set to correspond to the values of the model function $C_H(\Delta t^i, T_0^i)$. In addition to two arguments, the model dependence also involves six parameters. The processing consists in determining these parameters by the least-squares method, which involves a search for the minimum of the functional W:

$$W = \sum_{i=0}^{N}\left[C_H^i - C_H(\Delta t^i, T_0^i)\right]^2. \tag{12}$$

Here $i = 0$ corresponds to the absence of a repeated thermal cycle. As a result of minimization by computer, we found the following values of the parameters: $y_0 = 0.0131$, $C_H^{min} = -1.57$ cm^3/kg, $C_H^{max} = 222$ cm^3/kg, $f = 3570$

$K^2 \cdot sec^{-1}$, $T_\alpha = 3290$ K, $T_\beta = 1260$ K. The result $C_H^{min} < 0$ should be understood as the possibility of such a state of steel when cold cracks appear at a given mechanical stress even without hydrogen.

Figure 1 presents the model functions $C_H(\Delta t)$ for different temperatures T_0. They were calculated with the use of the parameters found. We see that the experimental data fall well on these curves. For example, the deviation from C_H^0 amounts to only 0.02 cm^3/kg. Analogously, we can predict the critical value of C_H after any reheating. The difference is that integrals (8) are calculated for the selected function $T(t)$. Moreover, if the initial state of the steel differs from the laboratory one, then, to determine y_0, we need additional measurement of C_H^0 or its estimation.

FINAL REMARKS

1. The model suggested is phenomenological. If was formulated in such a way that for a small number of parameters one could describe a certain set of experimental data.

2. In the present work we consider a case of fixed loading σ_t. For processing tests with different values of σ_t the model can be generalized by introducing the functions $C_H^{min}(\alpha_t)$ and $C_H^{max}(\alpha_t)$.

3. The model is constructive, because it provides a functional relationship for any repeated thermal cycle.

4. The functional relationship can be regarded as a successful means of data approximation. For example, the quadratic polynomial of two variables Δt and T_0 at the optimum values of its six coefficients does not provide the same accuracy for our case.

5. The presented example of processing the results of tests can be considered as a check of the hypothesis that the model describes the changes in the conditions of the formation of cracks. This hypothesis does not contradict the initial base of data, since the model curves lie within the limits of experimental accuracy.

6. In constructing the model we used analogies with certain physical processes. In particular, this was reflected in the adopted form of the functions $\alpha(T)$ and $\beta(T)$ in Eq. (5). It corresponds to a slow change in the properties of steel at room temperature.

Conclusion. A model of thermal effects on the resistance of steels to cracking is suggested. It may serve as a basis for processing the results of laboratory tests, allowing one to determine six model parameters. Subsequently it makes it possible to predict the conditions for the appearance of cold cracks after reheating cycles of arbitrary form.

NOTATION

C_H, concentration of hydrogen in steel; C_H^i, critical concentration of hydrogen after thermal cycle with number i; ΔC_H, change in critical concentration of hydrogen; δC_H, accuracy of measurements of critical concentration of hydrogen; C_H^{min}, C_H^{max}, lower and upper limits of possible change in critical concentration of hydrogen (parameters of model); f, parameter of model which has the dimension of inverse time; t, current time of thermal cycle; Δt, duration of thermal cycle; Δt^i, duration of thermal cycle for test with number i; T, absolute temperature; T_0, temperature of steel at beginning of thermal cycle; T_0^i, its value for test with number i; ΔT, change in temperature during thermal cycle; T_α, T_β, model parameters having the dimension of temperature; y, dimensionless characteristic of state of the steel; y_0, y_1, its values at beginning and at end of thermal cycle; $\bar{y}$, level of saturation y in long thermal cycle; A, B, intervals from α and β; W, functional of least-squares method; σ_t, mechanical tensile stress.

REFERENCES

1. É. L. Makarov (ed.), Welding and Welded Materials Reference Book, Vol. 1 [in Russian], Moscow (1991).
2. É. L. Makarov, Strength and Diagnosis of Welded Constructions, All-Union Scientific-Technical Conference, 18-21 November, Tver', Abstracts of Papers [in Russian], Moscow (1991).
3. É. L. Makarov, Cold Cracks in Welding of Alloyed Steels [in Russian], Moscow (1981).