The Sensitivity of the Structure and Properties of the Middle Carbon Steel to Electron Beam Hardening Conditions

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1. Introduction

The use of concentrated energy sources for steel surface hardening provides a short heating and cooling cycles leading to formation of fine-dyspersated structure of a high hardness and wear resistance.

The technology of electron beam hardening with sufficiently increased electron energy is relatively new. Electron accelerators are developed in Budker Institute of Nuclear Physics of Siberian Branch of Russian Academy of Sciences (BINP), where the steel hardening experiments are performed for few years [1–3]. On the basis of such the experiments, the technology of surface rail electron beam hardening was worked out. This technology allows significant hardness and wear resistance enhancement in comparison with hardening in plant conditions.

In this study, surface layers of samples of the middle carbon steel 50 have been hardened by the electron accelerator located at BINP. Steel 50 may be considered, in a sense, as a model material, which is well hardened on martensite and does not contain other alloy elements, except carbon, what allows detecting a basic mechanism of radiation influence on a structure, hardness and wear resistance in exposure zone. Structural peculiarities of irradiated zones were compared with temperature field simulation model during treatment process.

2. Experimental

ELV-6 accelerator provided by the device of electron beam extraction from accelerator vacuum system into atmosphere was used. In atmosphere, a beam starts to increase gradually in diameter due to electron dispersion. As the length of electron complete run in the air is about 6 m, a beam remains enough concentrated to heat surface metal layer for hardening at 10–15 cm distance from discharge outlet.

Electron energy in beam U was 1.4 MeV. Electron transit distance in atmosphere (the distance up to extraction hole) was chosen to be equal to 9 cm at corresponding 1.2 cm beam diameter. A track hardening conditions was used, i.e. a sample linearly transferred under fixed beam with controlled velocity v. When changing a beam current I within 2.53–8.35 mA and sample transfer velocity v from 1 to 7 cm/sec, five hardening conditions were set (Table 1). Sample transfer velocity was chosen so as a time of beam effect on each surface point was within 0.15–1.2 sec value range.

$$t_0 = d/v, \qquad (1)$$

where d is a beam diameter, v is a sample transfer velocity.

Beam current was set so as the same peak temperature 1300 °C was obtained at all conditions.

For comparative analysis of radiation conditions effect on surface layer structure the values t_0 and W were used. W is a surface energy density estimated by the formula

$$W = \frac{2(1-f_r)\cdot UI}{\sqrt{\pi}dv}, \qquad (2)$$

where f_r – coefficient of beam reflection from sample surface (in this case f_r=0,108), and coefficient is determined by the fact that power density distribution in electron beam cross-section is Gaussian. Microhardness distribution in the hardened layer was measured at 50 g load. Abrasive wear tests at unfixed abrasive particles friction (GOST 203.208-79) were performed.

Table 1. Steel 50 electron beam treatment conditions

Conditions #	v, cm/s	I, mA	t_0, s	W, kJ/cm^2
1	7	8.25	0.17	1.38
2	3	5.10	0.4	1.99
3	1.7	3.65	0.7	2.51
4	1.25	2.98	0.96	2.79
5	1	2.53	1.2	2.97

3. Metallographic analysis

In respect to radiation parameters effect onto structure and hardness in treatment zone the operating conditions were sorted as "fast" (t_0=0.1–0.3 s; W=1.1–1.7 kJ/cm^2), "average" (t_0=0.3–0.7 s; W=1.7–2.5 kJ/cm^2) and "slow" (t_0=0.7–1.2 s; W=2.5–3 kJ/cm^2).

If initial steel 50 structure is ferrite-pearlite, then after fast conditions hardening a highly refined martensite structure is formed. At average and slow conditions hardening there is grain growth in austenitizing temperature zone due to time of beam effect (1) increase. At radiated layer cooling a coarse-acicular martensite is formed.

An interface structure between hardened layer and basis material is important. At fast conditions it is practically straight line. Austenitizing process advances in passing above this line and does not advance in passing below it. Hardening boundary divides even separate grains.

At average conditions there is an interface tailing, which is connected with interchange of changed and not-changed structure areas. This indicates that carbon diffusion over the limits of pearlitic grains into ferrite does not advance to be performed and austenite, which is necessary for further hardening, is not formed. In the regions, where transformation performed, the intermediate with respect to martensite structure is observed.

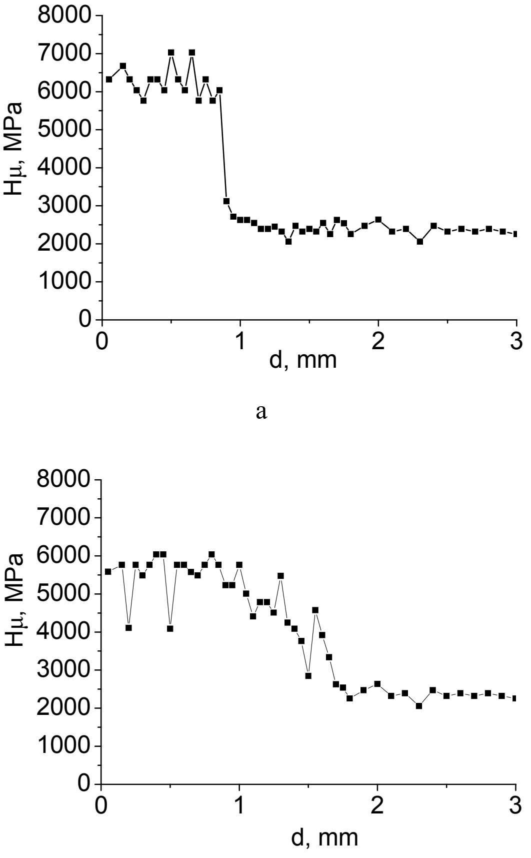
At slow operating conditions there is no distinguished interface between hardened and nonhardened areas. There is gradual reduction of hardening degree with forming of wide intermediate structure zone, i.e. from bainite to troostite-sorbite ones. That is connected with heat injection increase and heated metal cooling rate decrease. Further, there is a zone of particular austenitizing, where, together with the regions, which have been transformed, the initial ferrite grains are saved.

The characteristics of hardness, wear resistance and layer depth are connected with structural changes. When increasing operating time t_0 and surface energy density W, the average hardness values H_μ^{av} in martensite structure layer are decreased from 6500 to 5000 MPa. Layer depth l_A, which has underwent absolute austenitic transformation (there are no zones with initial structure), increases from 0.8 to 1.6 mm (Fig. 1, *a*, *b* and 2).

At fast conditions, an average hardness values are not changed according to hardened layer depth up to hardening boundary zone and, further, they sharply decrease, what is matched with a presence of sharp interface of hardened zone with basic metal (Fig. 1, *a*). At average conditions, there is intermediate zone on distribution curves. There the hardness values are changed gradually and there is more graded junction of properties. At slow conditions, a wide intermediate zone with gradual hardness decrease is observed. The width of this zone is up to 0.5–0.7 mm (Fig. 1, *b*), that is connected with disappearance of distinguished interface between hardened and unhardened zones at micrographs.

The hardened layer abrasive wear resistance tests have shown that at operating time increase abrasion index K_w values determined by experimental measuring of mass losses of investigated and reference patterns are gradually decreased from 8.52 to 2.14.

On the basis of experimental data the dependences of average values of micro-hardness H_μ^{av}, abrasion index K_w and full phase transformation depth l_A on surface energy density W were made. It turned out, that these dependences are of linear character (Fig. 2). Knowing the radiation parameters (U, I, v), this allows forecasting the properties of hardened layer for the given steel (or for a steel structurally similar to it) without additional investigations.



a

b

Fig. 1. Distribution of micro-hardness in cross-sections perpendicular to sample surfaces: a – conditions 1, b – conditions 5

Average operating conditions (t_0=0.3–0.7 sec, W=1.7–2.5 kJ/cm^2) are more effective. At these conditions sufficient thick hardened layer gradually passing into basis material is formed.

4. Estimation of temperature fields

Estimation of temperature field in a sample was performed on the basis of Green function method. Sample thickness and heat loss from a surface due to radiation and convection were taken into consideration.

To form an analytical model of the process the material thermal characteristics, i.e. thermal capacity c and thermal conductivity a, were accepted to be constants. The values of these parameters were determined as simple average value from their reference value in the range from initial temperature up to the one similar to fusion temperature. They were found to be equal: c=0.66 J/g·K, a=0.085 cm^2/sec.

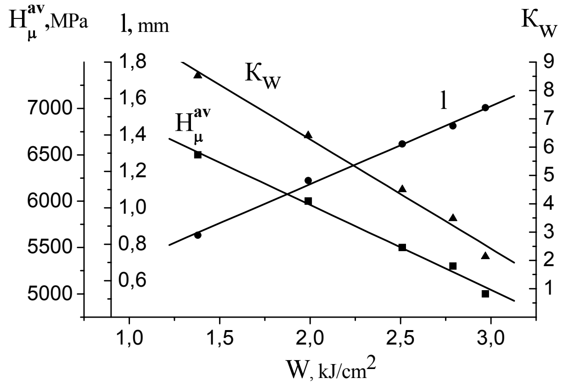


Fig. 2. Dependence of hardness H_μ^{av}, wear resistance K_w and hardened layer depth l_A vs surface energy density W

Variations of c and a values, which are particularly connected with their dependence on a temperature or with unreliable reference data, influence on calculation accuracy. Besides values c and a, estimation error may be connected with inaccurate value of beam diameter *d*. To decrease noted errors we performed the additional experiments in which the particular reference conditions with known temperature achieved in the treated layer were determined. As such conditions, the conditions of the beginning of sample surface fusion were chosen. Reference conditions were used to correct the temperature estimation by means of correction factor $K(\tau)$, which is a function of typical dimensionless parameter τ:

$$\tau = \frac{da}{v\delta^2}, \qquad (3)$$

where δ is effective beam penetration. Parameter τ is essentially a ratio of heat injection into material time (1) to the time δ^2/a of its outflow into matter due to thermal conductivity from a layer where it was introduced. In the range of values τ from 5 to 50 correction factor $K(\tau)$ monotonically increases from 0.75 to 0.95.

The final formula for temperature field is:

$$T(x,y,t)=T_{н}+K(\tau)\cdot(T_0(x,y,t)+T_1(x,y,t)+T_2(t)), \qquad (4)$$

where *x*, *y*, *t* are coordinates inside a sample and current time, T_i is initial sample temperature. Term $T_0(x,y,t)$ shows a temperature distribution in semi-infinite solid without taking into account sample thickness, $T_1(x,y,t)$ appears due to surface material lying opposite irradiated one. In its turn, it consists of few terms, which are the same form with $T_0(x,y,z,t)$. Each term takes into account one of a heat source mirror image. Term $T_2(t)$ is negative itself and estimate a heat loss from the surface due to heat radiation and convection. Coordinate *z* is not included in (4) as *z* is accepted to be equal to zero in investigated sample cross-section.

The calculation results of temperature-time relationships for "quick" and "slow" conditions 1 and 5 is shown in Fig. 3.

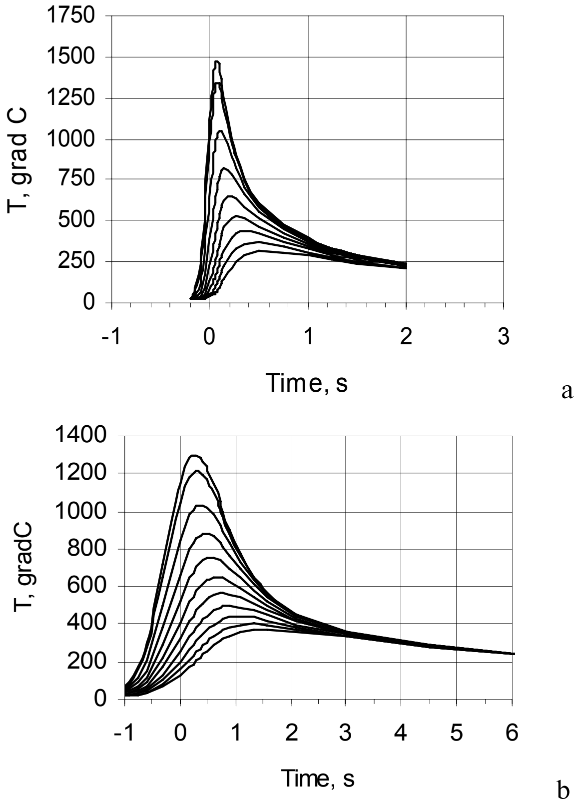


Fig. 3. Temperature-time relationships at different depth from a surface: a – conditions 1, depth step for two neighbors curves corresponds to 0,4 mm; b – conditions 5, depth step for two neighbors curves corresponds to 0,5 mm

5. Calculated data comparison with the experiment

For each operating conditions of steel 50 hardening (Table 1) the temperature fields were estimated and temperature-time relationships were made at different depth from sample surface.

The distributions of peak temperatures versus distance from the surface were graphed at separate diagrams for each conditions. Those distributions are interesting for comparison with actual along material depth distributions of structural zones such as martensite zone, mixed structure zone and heat-affected zone.

In usual heat treatment practice for hypoeutectoid steel austenitizing a heating 30–50 °C higher than Ac_3 is used. For steel 50 the temperature in point Ac_3 is 750 °C [4].

Assuming that austenitizing take place at 750 °C and using the dependences of peak temperatures versus depth from the sample surface mentioned above, one can determine a theoretical depth of austenitic transformation l'_A.

The depths determined in such a way for the five radiation conditions are 1.1; 1.4; 1.7; 1.9 and 2.0 mm. The depths l_A obtained by the experiment are less and equal to 0.85; 1.15; 1.35; 1.45 and 1.55 mm.

Observational difference is explained by diffusion nature of austenitizing the performance of which requires a time. Though originally the austenite nucleuses are formed by shift way, their further growth is connected with the diffusion of carbon atoms, which are migrate into austenitic regions at cementite plates dissolution. Besides, an additional time is required to homogenize austenite, which is non-homogeneous by carbon content.

It is known [4], that a time necessary for austenite formation at temperatures similar to 750 °C is few minutes. In our case, electron beam effect time t_0 in each point of the surface did not exceed 1,2 sec (Fig. 3). To realize a transformation in such a short-term operating condition a noticeable overheat promoting significant diffusion acceleration is necessary.

By experimental data of l_A depths in accordance with diagrams of dependences of peak temperatures on a distance up to a surface we have found temperatures T_A corresponding to them at austenitizing zone boundary. On average, they were found to be 100–150 °C higher than a temperature in the point Ac_3 at equilibrium state diagram for steel 50. By increasing operating time t_0 a small reduction of temperature T_A is observed.

It is evident, that a further increase of operating time and selection of slow processing speed for realization of phase recrystallization in conditions similar to equilibrium state diagram would lead to significant increase of heat injections together with simultaneous growth of hardened layer and significant decrease of hardness inside it.

Conclusion

1. Irradiation by electron beam extracted into atmosphere is high-performance method of surface steel layer hardening. The method allows combining the deep treatment zone depth with significant enhancement of hardness and wearing resistance. Hardening effect is connected basically with martensite transformation process and formation of highly refined martensite structure.
2. At steel 50 radiation treatment a martensite dispersivity, a hardened layer depth, interface zone thickness, a hardness and wear resistance are determined by electron beam effect time t_0 and injected radiation energy density W. There are linear dependences H_μ^{av}, K_w and l_A on W. The most effective conditions are the "average" operating conditions (t_0=0.3–0.7 sec, W=1.7–2.5 kJ/cm^2) at which the sufficient length hardened layer gradually passing into basis material is formed.
3. Estimation of temperature-time relationships in beam operation zone and comparison of calculation data with experimental results shows that austenitizing process in steel layer being hardened and achievement of satisfactory hardening level require no less than 100–1500 °C overheat relatively to the point Ac_3 of equilibrium state diagram.

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