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Laser Hardening of 4X5MФC Die Steel

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Abstract—The hardening of 4X5MФC die steel by a powerful fiber laser is considered. It is found that the hardness of the surface layer after laser treatment is 62–64 *HRC* and the depth of the hardened layer is 1 mm. Ultrafine structure such as a white layer is formed at the surface.

Keywords: laser hardening, structure, hardness, nitriding, steel

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One challenge in manufacturing is the production of high-strength components from tool steel [1]. Gas nitriding in ammonia is used for surface hardening of dies at OAO KamAZ. That increases the hardness of the surface layer, the fatigue limit, and the wear resistance of the steel [2].

The complex nitrides and carbonitrides formed in the nitriding of 4X5MФC die steel increase the hardness but reduce the thickness of the hardened layer, forming brittle nitride phases. Therefore, this method requires considerable expenditures of energy and time (36 h). Laser technology permits the creation of a surface layer (thickness 1 mm) of hardness up to 62–64 *HRC* on dies without the formation of brittle compounds between the hardened layer and the base. In addition, laser hardening takes only a few seconds [3]. A fiber laser is most effective for such treatment, since its efficiency is 2.5 times that of other lasers [4]; the laser beam is 3–5 times brighter; and the laser life is twice that of CO-2 lasers [5]. Laser hardening is also used to increase the corrosion and wear resistance [6].

We now compare the surface structure and properties of samples of 4X5MФC die steel after laser hardening and nitriding in ammonia and also determine the influence of the laser power on the hardening depth, the structure of the hardened layer, and the microhardness.

The 4X5MФC steel considered is used to produce small hammer dies; it is characterized by troostosorbite structure (Fig. 1). The hardness of 4X5MФC steel is 46 *HRC*; in the surface layer, the microhardness $H_\mu \approx$ 4600 MPa.

The composition of 4X5MФC steel is as follows: 0.32–0.4% C, 4.5–5.5% Cr, 0.2–0.5% Mn, 1.2–1.5% Mo, <0.03% P, <0.03% S, 0.9–1.2% Si, and 0.3–0.5% V. The nitriding temperature is 520–540°C; the degree of dissociation of the ammonia is 30–40%. The total nitriding time is 36 h [2].

We use a 2-kW fiber laser with wavelength 1064 nm, at different beam speeds.

The optical head of the laser scans the laser radiation normal to the motion; a galvanic deflector produces the row displacement.

After nitriding and laser hardening, samples are taken from the die for metallographic study. The sample surface is ground and also subjected to coarse and fine polishing.

Nitric acid is used for chemical etching of the microsections. The Rockwell hardness is measured by an HR150A instrument and the microhardness by an HX-1000TM instrument. The surface structure of the samples is determined by means of an Axiovert 200M inverted microscope. Electron-microscope images of the sample surfaces are obtained by means of an Auriga CrossBeam system.

The power of the laser beam varies from 100 to 1500 W. With constant speed of the laser beam and width of the laser spot (11 mm), the maximum relative hardness (the ratio of the hardness *HRC* of the hard-

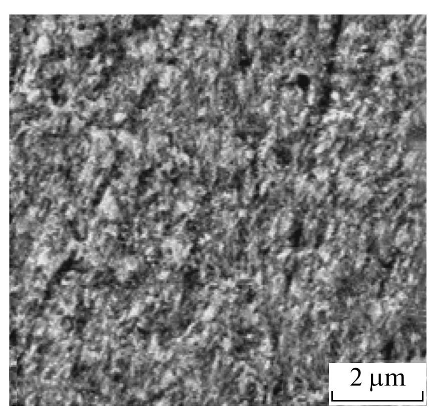

Fig. 1. Structure of 4X5MФC steel.

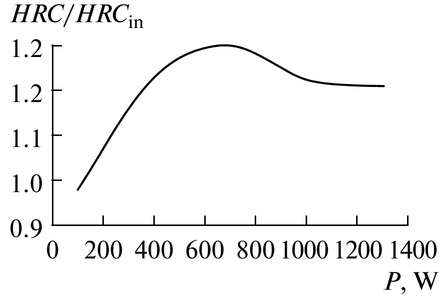

Fig. 2. Dependence of the relative hardness HRC/HRC_{in} of the surface layer on the laser-beam power *P*.

ened layer and the hardness HRC_{in} of the initial material) corresponds to laser power of 700 kW (Fig. 2).

With low laser power (around 100 W), the surface is softened. Then, with increase in power, the hardness begins to rise. Later it falls but remains above the initial value (Fig. 2). In Fig. 3, we show the microstructure of the surface layers after nitriding (a) and laser hardening (b).

In the nitrided sample, a hardened layer is observed to a depth $h = 0.2$ mm (Fig. 3a); bands of brittle nitride are present. In the laser-hardened sample, rather than the structure formed by chemical etching, we observe a white layer (Fig. 3b).

In Fig. 4, we show sections corresponding to the transition between the base and the hardened layer after nitriding and laser hardening. In nitriding, these sections are the nitride zone and the diffusional sublayer (Fig. 4a). Carbonitrides and nitride phases form the nitride zone, while the diffusional sublayer consists of a solid solution in α phase with nitride inclusions. The nitride layer consists of γ' phase and ε phase; that creates internal stress at the phase interface and produces brittleness and peeling of the hardened layer in operation [2]. For 4X5MΦC steel, the thickness of the nitride zone is 0.1–0.2 mm.

After laser hardening, three characteristic zones may be seen in the microsection (Fig. 4b).

The first zone has ultrafine structure. This is the white layer, consisting of small martensite needles (sometimes known as hardenite). Because of high-

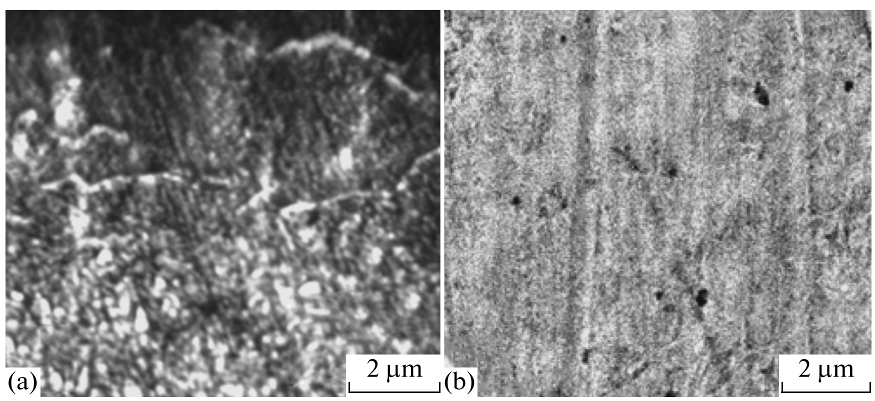

Fig. 3. Microphotographs of the hardened surface layers after nitriding (a) and laser hardening (b).

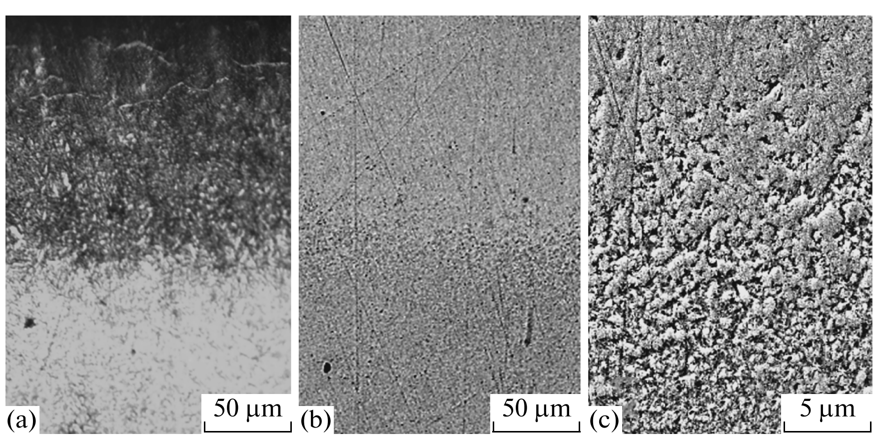

Fig. 4. Microphotographs of a transverse section of 4X5MΦC steel after nitriding (a) and laser hardening (b, c).

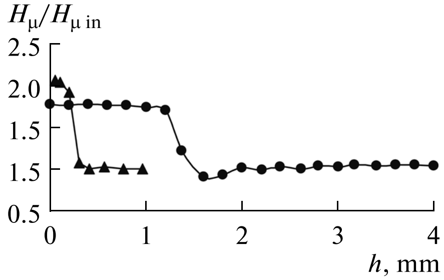

Fig. 5. Distribution of the relative microhardness $H_\mu/H_{\mu\,in}$ over the depth h of the surface layer in nitriding (▲) and laser hardening (●).

speed laser heating and rapid cooling as heat travels into the depth of the metal, numerous crystallization centers are created and the structure that forms is fixed. Research shows that the depth of the hardened layer $h \approx 1.2$ mm.

The softer second zone (the thermal-influence zone) consists of fragments of the initial structure, carbides, and some martensite (Fig. 4c). The structure of these fragments is larger than in the first zone. The width of the transition zone is about 20 μm. Insufficient energy penetration into the depth of the metal creates the thermal-influence zone, with its reduced hardness.

The third zone consists of the initial structure.

In Fig. 5, we show the distribution of the relative microhardness (the ratio of the microhardness H_μ of the hardened layer and the microhardness $H_{\mu\,in}$ of the initial material) on the depth h of the surface layer in nitriding and laser hardening.

Comparison shows that, after nitriding, the hardness of the surface layer is 12.5% higher than after laser hardening. However, the high hardness does not always ensure high resistance of the material to impact loads at high temperatures, such as those experienced by dies. The nitride phases formed lead to embrittlement of the structure. By contrast, laser hardening with high-speed quenching produces a hardened layer 5–6 times broader than in nitriding, without embrittling phases. The same hardness is retained in a surface layer of width up to 1 mm. This indicates low internal stress at the phase boundary and rules out brittleness and peeling of the hardened layer in the course of operation.

Summarizing, our findings confirm that a fiber laser may be used to harden 4X5MΦC die steel. Such laser treatment is characterized by low energy consumption and high productivity.

Thus, the hardening of the steel depends on the power of the laser beam. At 700 W, the hardening of the surface layer is greatest; at 100 W, the surface layer is softened.

Microstructural data show that the structure becomes smaller on hardening, and ultrafine martensite structure (hardenite) is formed.

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