Theory and Practice of Creation Highly Effective Combined Processes for Surface Hardening of Parts of Transport Engineering

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Abstract. A theoretical approach to the rational choice of technological combinations that allow to create optimal structures on the surface of steel products that can effectively resist wear and fatigue is considered. An example of a highly efficient combined process including laser alloying and nitriding is given. The application of the principles of the structural theory of strength makes it possible to purposefully form structures that can effectively resist complex multifactorial phenomena occurring in the surface layers, increasing the wear resistance and crack resistance, and, consequently, the reliability and durability of heavily loaded parts of transport equipment.

Introduction

Many parts of transport vehicles operate under wear and cyclic loads, when in the surface layers maximum stresses take place. Sensitivity to stress concentrators decreases when compressive stresses are created on the surface by hardening through various well-studied methods using induction, laser, electron beam heating, chemical-thermal treatment, surface plastic deformation, including ultrasound treatment or some other method.

At this stage of the development of surface engineering, the most promising direction is the designing of combined surface hardening technologies, which connect the action of concentrated energy flows, surface plastic deformation and classical diffusion processes such as nitriding, nitrocarburising, chromizing and etc.

Such complex and expensive processes can include two, three or more technologies, therefore their choice and sequence require the sound of technological solutions that ensure the specified properties of the product during operation. It is possible by calculating the expected structural state, and, consequently, the level of hardening. The accumulated knowledges on strengthening mechanisms based on dislocation theory can be successfully applied in the creation of combined processes.

The modern concepts of alloy hardening are based on the dislocation theory, according to which the increase in strength of metallic materials is a consequence of the interaction

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of dislocations with obstacles (dislocations, substructure elements, grain boundaries, dissolved atoms, dispersed particles). According to the basic provisions of the structural theory of strength, the main mechanisms of hardening are hardening by dissolved atoms of introduction or substitution, dislocations, grain and sub-grain boundaries, dispersed coherent or incoherent precipitations of excess phase particles.

In metals and alloys several strengthening mechanisms are usually realized simultaneously, and then the hardening of real metals is determined by the combined action of the listed mechanisms:

$$\sigma = \Sigma\sigma_i = \sigma_0 + \Delta\sigma_{s.s.} + \Delta\sigma_d + \Delta\sigma_g + \Delta\sigma_{s.} + \Delta\sigma_{disp.},$$

where σ_0 is the crystal lattice friction stress (Pyerls-Nabarro force); $\Delta\sigma_{s.s}$ - yield strength increment due to solid-solution strengthening; $\Delta\sigma_d$ - yield strength increment due to dislocation (deformation) strengthening; $\Delta\sigma_g$ - yield strength increment due to grain boundary strengthening; $\Delta\sigma_s$ - yield strength increment due to substructural strengthening; $\Delta\sigma_{disp}$ - yield strength increment due to dispersion strengthening.

The most favorable mechanisms that provide a combination of high strength with a sufficient margin of plasticity are grain boundary hardening σ_g, solid solution hardening $\sigma_{s.s}$ (if the alloying elements grinding the grain) and substructural hardening σ_s. Increasing the density of disorganized dislocations (σ_d), while increasing the strength, reduces the fracture toughness to the greatest extent. Dispersion strengthening (σ_{disp}) effectively increases the strength characteristics, and the negative effect of particles on fracture toughness characteristics can be minimized by adjusting the structure parameters by technological methods.

In [1], analytical relations are given that are convenient for calculating the predicted hardening from the implementation of each mechanism. Physical quantities and coefficients necessary for calculations are collected from reference books and scientific literature in tables. Information about the structural parameters necessary for calculating the predicted hardening, such as the density of dislocations, the grain (subgrain) size, the parameters of dispersed inclusions (diameter and distance between them), is available in modern digitalization conditions for almost any technology. On the basis of these relations, a method for calculating the hardening characteristics of metals and alloys was proposed, which makes it possible to predict the mechanical properties (yield strength and hardness) depending on the structural state of the alloy, considering the strengthening mechanisms involved [2].

The authors of this paper aim to show on a concrete example how the structural theory of strength is applied when choosing a technological combination for surface hardening of parts operating under conditions of intense wear and fatigue.

Materials and methods for conducting experiments

Carbon steels were treated with elements V, Cr, Mo, Al, etc. using laser radiation both in a pulsed mode and in a continuous mode with a power of 1 kW at a beam travel speed of 2 to 30 mm/s. Nitriding was carried out in an ammonia atmosphere at a temperature of 540...570°C for 3...6 hours.

Wear resistance tests were carried out on an installation for studying tribological properties according to the “roller-block” scheme under dry friction conditions with the determination of a stabilized friction coefficient. Tests for crack resistance under low-cycle loading were carried out on the ZD-10 installation, and under high-cycle loading - on the URS-20/30000 installation. Fractographic studies were carried out on a Jeol-U3 electron microscope.

Discussion of the results

As an example of the application of strength theory when choosing a technological combination, we present the surface hardening of law carbon steel using a technological combination that combines laser alloying and nitriding.

It is known that during laser treatment of a steel surface in the melting mode in the hardened zone due to shock-wave action, the dislocation density increases to $10^{10}...10^{12}$ cm^{-2} [3, 4]. To implement the grain-boundary hardening mechanism, it is possible to choose from the literature sources the modes under which an ultrafine-grained structure is formed.

According to the authors of [5], with an increase in the speed of the laser beam from 0.001 m/s to 10 m/s, the average grain diameter in steel 40Kh (0,4%C, 1%Cr) decreases from 15...20 μm to 0.1...0.5 μm. It is possible to obtain fine grains up to 2–5 μm in size with the help of various modifying additives, for example, V, Cr or Mo powder [6]. The second method is preferable, since another strengthening mechanism is implemented - the mechanism of solid solution strengthening by substitution elements.

Experimental data [7, 8] and calculations of dispersion strengthening [9] show that the highest level of hardening is achieved by particles of nitrides of various elements coherent with the matrix. Therefore, the next step is nitriding, and the temperature and duration of the process, chosen according to the criterion of coherence of dispersed nitrides, are 540ºC for 3.5 hours.

When combining the processes of laser alloying and nitriding, a synergistic effect is manifested, since, firstly, heating steel with a high dislocation density leads to polygonization and the formation of a cellular substructure, that is, the substructural mechanism is additionally switched on, and secondly, at a nitriding temperature of 540°C unfavorable tensile stresses that have arisen at the border with the base after laser exposure are removed.

Another important advantage of the surface with nitride hardening is its high heat resistance (up to 600°C), which is important for products operating at high speeds, at elevated temperatures and loads, while martensitic structures obtained by traditional heat treatment (quenching and tempering), decompose with loss of strength even at 250°C.

Thus, the combination of two complementary and increasing the efficiency of each other technologies, consisting in laser alloying (LA) of carbon steels with nitride-forming elements followed by nitriding (LA + N), allows you to use the maximum possible number of strengthening mechanisms and purposefully create a structure capable of resisting wear and fatigue.

The total calculated hardening effect for various alloying elements is in good agreement with the experimental data, and, after recalculating the yield strength to microhardness through a factor of 0.33 [10], it is 21000 MPa for zones alloyed with aluminum followed by nitriding, 18,500 MPa with vanadium, and 18500 MPa with chromium - 18000 MPa, molybdenum - 12000 MPa

Tribological tests of samples hardened with non-overlapping tracks, as shown in Figure 1, under dry friction conditions showed the results presented in Table 1.

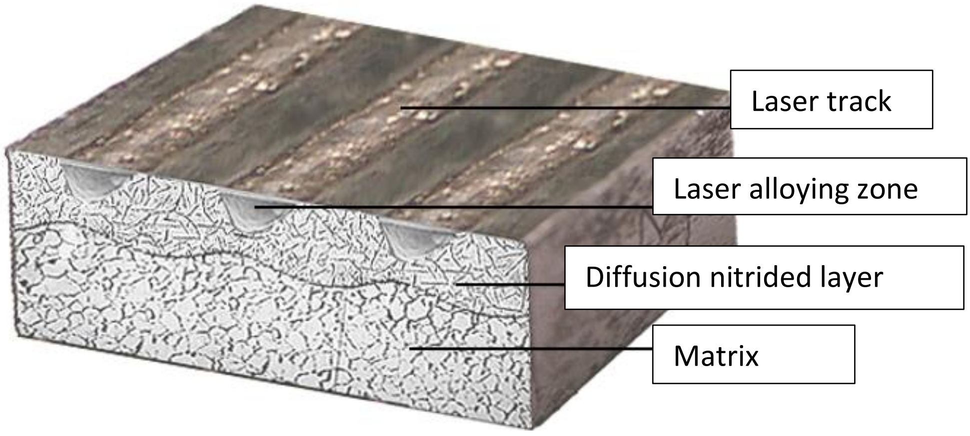

Fig. 1. Formation of a hardened layer on a steel surface during laser alloying followed by nitriding

Table 1. Effect of laser alloying and nitriding on the tribological properties of steel (0,2%C)

Type of alloying element (AE)	Hardness after LA, (MPa)	Hardness after LA+N, (MPa)	Wear resistance after LA, Δm, (mg/km)	Wear resistance after LA+N, Δm, (mg/km)	Coefficient friction after LA	Coefficient friction after LA+N
without AE	2500	2600	30	23	0,3	0,26
Al	4000	21000	11	1,2	0,24	0,07
Cr	5800	17000	10	3,8	0,23	0,08
V	5900	18500	8	1,9	0,23	0,16
Mo	8500	11000	6	7,3	0,18	0,06

Table 1 shows that laser alloying with all the elements under study reduces the wear of samples compared to normalized steel 20 (0,2%C) by 2–5 times, depending on the type of alloying element. The greatest surface wear is observed on samples alloyed with aluminum, and the smallest - with molybdenum. This is explained, on the one hand, by the higher hardness of the surface alloyed with molybdenum (8500 MPa), and, on the other hand, by the low coefficient of friction due to oxides (secondary phases) formed in the contact zone, which play the role of a lubricant in the friction process. Subsequent nitriding increases the wear resistance of steel 20 alloyed with vanadium by 15 times. Alloying with aluminum gives even higher tribological performance, but the heat resistance of such layers is somewhat lower compared to other elements. Comparative wear tests of nitralloy (0,38%C, 2%Cr, 1%Mo, 1%Al) nitrided under similar conditions, showed that steel 20 after combined treatment has 1.5 ... 3 times greater wear resistance.

Another important tribological surface property during friction is fatigue strength. In this work, cyclic tests were carried out under conditions of high-cycle loading with a frequency of 200 Hz and under conditions of low-cycle loading with a frequency of 0.1 Hz in order to determine the growth rate of a fatigue crack and the threshold value of the stress intensity factor, below which the crack does not develop.

Conclusions

During laser alloying and subsequent nitriding, a structure is formed on the steel surface, strengthened by dispersed particles of nitrides of alloying elements, which makes it difficult to initiate a crack and contributes to its effective inhibition, especially at an early stage of growth, and the contribution of the dislocation hardening mechanism is significantly reduced.

Thus, the application of the principles of the structural theory of strength makes it possible to purposefully form structures that can effectively resist complex multifactorial phenomena occurring in the surface layers, increasing the wear resistance and crack resistance, and, consequently, the reliability and durability of heavily loaded parts of transport equipment.

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