The concept of structural steels surface hardening for tribo-joint elements

O V Chudina and Yu M Luzhnov

Moscow Automobile and Highway State Technical University (MADI), 64, Leningradskiy prospect, Moscow, 125319, Russia

E-mail: Chudina_madi@mail.ru

Abstract. The concept of surface hardening of structural steels is proposed on the basis of the structural theory of strength and the Charpy principle at the macro- and microgeometric levels for the purposeful formation of a structure that can effectively resist wear and fatigue. An intellectual approach to the rational choice of technological combinations capable of maximally realizing the dislocation, substructural, grain-boundary, solid solution and dispersion mechanisms of steel hardening, which makes it possible to create optimal structures on the surface of tribo-interface elements, is described. As an example of such an approach, the surface laser alloying of structural steels with nitride-forming elements with subsequent nitriding was investigated; an increase in surface hardness, strength, wear resistance by 15 times and fatigue strength by 1.5 times compared with the initial parameters of steels was shown.

1. Introduction

The service life of the friction unit is determined by the optimal design solution, accurate calculation of real loads, as well as the selected material and the method of hardening of the tribo mating parts operating in specific operating conditions. Depending on the operating conditions, complex and interdependent multifactorial phenomena occur on the surface of the tribo-interface elements.

In the zone of frictional contact, under the influence of loads, a friction force arises, and, due to the rupture of metal bonds in places with the highest stress concentration, free energy is released. Moreover, with an increase in the friction force, the activation energy increases and it is spent primarily on the release of heat and change in the shape of the body. As the temperature rises, diffusion phenomena are also accelerated, which leads to significant changes in the structure of surface layers, up to phase transformations. At the first stage of the friction process, an increase in the dislocation density leads to some hardening of the metal surface. However, with the further development of plastic deformation, critical accumulations of dislocations are observed in some areas of the surface, which are the cause of the appearance of surface and subsurface submicrocracks, which, while developing, block the channels of dislocation advance and form a branched system of cracks, which ultimately leads to fatigue failure.

Since in the process of friction these surfaces interact with each other directly or through a lubricating medium, the energy released in the frictional contact zone also activates physicochemical processes, such as oxidation and reduction reactions, adsorption of elements from the environment, electrification and others related to them. phenomena. In real frictional contact, as a rule, all these processes proceed simultaneously [1].
A decrease in the adverse effect of these factors is associated with the creation of dissipative compatible structures capable of adaptability, self-organization and efficient energy dissipation [2, 3]. The available information about such structures is rather empirical. In particular, research was carried out on some pairs of friction, which, with a certain type of lubricant in the process of mutual movement, could adapt to each other, providing a given durability without damaging the friction surface.

Analysis of literary sources indicates the absence of a systematic approach to the purposeful creation of materials for tribosystems.

An important role in reducing the effect of friction processes on the reliability and durability of machine parts is assigned to designers who perform calculations to quantify the critical stresses arising during operation. However, they cannot consider the entire spectrum of dislocation processes and related problems of the structural strength of materials.

Therefore, the solution of such a complex problem is possible on the basis of the joint use of the achievements of metal physics and fracture mechanics through scientific design and purposeful formation of dissipative structures capable of efficiently dissipating the energy generated in the friction contact zone and resisting its destructive effect on the surface of parts.

In this regard, an urgent problem is the development of the concept of surface hardening of structural steels for tribosteel elements based on the structural theory of strength by purposeful application of known hardening technologies or their combinations in order to increase the structural strength of materials operating under wear conditions.

Structural strength is expressed by indicators of mechanical properties, which are conventionally combined into two groups: a reliability group and a durability group.

The criteria for the reliability of materials are impact strength, fracture toughness (survivability, critical crack opening, etc.), and the criteria for durability are wear resistance, fatigue strength, contact endurance, corrosion resistance, etc.

Many machine parts operate under conditions of wear and alternating loads, at which maximum stresses arise in the surface layers, where stress concentrators are concentrated [4]. The sensitivity to them is sharply reduced when residual compressive stresses are created on the surface by hardening by induction, laser, electron-beam heating or chemical-thermal treatment, vibration rolling, including ultrasonic or in some other way.

All characteristics of structural strength are structurally sensitive, and therefore the way to increase the operational properties is associated with the development of such strengthening technologies that would lead to the creation of heat-resistant structures with high hardness and strength, providing the design level of reliability and durability of structures. The formation of the optimal structural state of metallic materials, which provides a high level of reliability and durability of products, is most fully realized on the basis of the application of the principles of dislocation hardening theory [5].

According to the structural theory of strength and fracture mechanics, strength is understood as the ability of a material to resist the movement of dislocations. This means that in order to increase the strength of metallic materials, it is necessary to slow down the movement of dislocations, that is, to create barriers in the path of their movement. Other dislocations, microstresses arising in solid solutions in the presence of alloying elements, grain boundaries, dispersed particles, coherent or incoherent with the matrix lattice, can be such barriers in the structure.

An analysis of the existing dislocation theories shows that the main hardening mechanisms that provide an increase in the plastic flow stress are hardening by dissolved interstitial or substitutional atoms, dislocations, grain and subgrain boundaries, and dispersed particles. Then the strengthening of real metals is determined by the combined action of the listed mechanisms:

\[ \sigma_f = \sigma_0 + \Delta \sigma_{s.h} + \Delta \sigma_d + \Delta \sigma_y + \Delta \sigma_g + \Delta \sigma_{p.h} \]

where \( \sigma_0 \) is the frictional stress of the crystal lattice (Peierls-Nabarro force); \( \Delta \sigma_{s.h} \) - an increase in the yield strength due to solid solution hardening; \( \Delta \sigma_d \) - increase in yield strength due to dislocation (strain) hardening; \( \Delta \sigma_y \) - increase in the yield point due to grain-boundary hardening; \( \Delta \sigma_g \) - increase in the yield stress due to substructural hardening; \( \Delta \sigma_{p.h} \) - an increase in the yield strength due to precipitation hardening.
The most favorable mechanisms that provide a combination of high strength with a sufficient margin of plasticity are grain boundary hardening $\sigma_g$, solid solution hardening $\sigma_{s.h.}$ (if alloying elements refine the grain) and substructural hardening $\sigma_s$. An increase in the density of unorganized dislocations ($\sigma_d$), increasing strength, to the greatest extent reduces the fracture toughness. Dispersion hardening ($\sigma_{p.h.}$) effectively increases the strength characteristics, while the negative effect of particles on the fracture toughness characteristics can be minimized by adjusting the structure parameters by technological methods.

On the basis of the implementation of certain strengthening mechanisms by purposeful formation of the structure by technological methods, it is possible to obtain the required characteristics of structural strength for parts operating under specific operating conditions. Using various technological combinations, you can use the maximum number of strengthening mechanisms and form a structure with high and ultra-high physical and mechanical properties [6, 7]. The main technological methods for the implementation of the most important hardening mechanisms are plastic deformation, especially with the use of ultrasound, quenching for martensite, laser processing, mainly with fusion and addition of carbide and nitride-forming alloying elements, chemical-thermal treatment, especially nitriding, etc. with surface fusion, dislocation, solid solution, grain boundary and substructural mechanisms are realized. However, calculations show that the greatest contribution to the overall level of hardening is made by the dispersion mechanism, especially by particles of nitrides of alloying elements coherent with the matrix. Such a mechanism can be realized by nitriding if laser alloying with nitride-forming elements is carried out beforehand [7]. At the same time, heating during nitriding to a temperature of 540 °C relieves unfavorable tensile stresses arising at the border with the main one after laser exposure, leads to polygonization and the formation of a cellular substructure and, unlike other types of chemical-thermal treatment, does not lead to deformation of the product, while maintaining core structure unchanged.

An important advantage of a nitride-hardened surface is its high heat resistance (up to 600 °C), which is important for products operating at elevated temperatures or under conditions of wear at high speeds, while martensitic structures obtained by traditional heat treatment (quenching and tempering), disintegrate with a loss of strength already at 250 °C.

Thus, the combination of two mutually complementary technologies that increase the efficiency of each other, consisting in laser alloying (LA) of carbon steels with nitride-forming elements followed by nitriding, will make it possible to use the maximum possible number of strengthening mechanisms and purposefully create a structure that can withstand wear and fatigue.

The aim of this work is to implement the proposed concept of surface hardening of structural steels for tribo-joint elements using the example of a combined technology, which consists in laser alloying of the surface with nitride-forming elements and subsequent nitriding, and also to study its effect on the main parameters of structural strength characterizing the reliability and durability of parts, such as surface hardness, wear resistance and crack resistance.

2. Materials and methods
Carbon steels were treated with elements V, Cr, Mo, Al, etc. using laser radiation both in a pulsed mode with a radiation power of 24 J 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. Tests for wear resistance were carried out on an installation for studying tribological properties according to the "roller-block" scheme under dry friction conditions with the determination of the stabilized coefficient of friction. Crack resistance tests under low-cycle loading were carried out on a ZD-10 installation, and under high-cycle loading - on a URS-20/30000 installation. Fractographic studies were carried out using a Jeol-U3 electron microscope.

3. Results and discussion
In order to implement the maximum possible number of strengthening mechanisms, when choosing a matrix material, the type of alloying elements and technological parameters of laser alloying and
subsequent nitriding, we were guided by the fact that the alloying elements had a high affinity for nitrogen, and also increased the solubility of nitrogen in ferrite. With these requirements in mind, V, Cr, Mo and Al were selected. Their optimal concentration in the alloying zone was determined depending on the ability to uniformly distribute in the iron matrix during laser alloying (Fig. 1).

The thickness of the alloyed zone is determined by the maximum possible thickness of the nitrided layer, which in most cases for alloyed steels does not exceed 600 µm (Fig. 2).

Steels with a carbon content of 0.2 ... 0.3% C are preferred as the matrix material. With a higher carbon content, the efficiency of the combined technology is somewhat reduced, since the alloying elements are partially bound into carbides and do not participate in the formation of nitrides.

The conducted studies of the influence of laser alloying parameters made it possible to establish the optimal technological modes of both pulsed and continuous radiation, at which the above requirements are satisfied.

Metallographic, X-ray diffraction and micro-X-ray spectral analysis showed that under optimal technological conditions in the zone of laser alloying with vanadium, chromium and aluminum, a structure of doped ferrite with an extremely fine grain of 2 ... 5 µm is formed (Fig. 3), which leads to an increase in microhardness up to about 6000 MPa. Doping with molybdenum in the structure may precipitate intermetallic phases, which increase the microhardness of the hardened layer to 11000 MPa. After nitriding at T = 540 °C for 3 hours of the laser-doped surface of V, Cr and Mo, in the hardened layer, as a rule, a single-phase structure of a α-solid solution doped with nitrogen is formed without inclusions of nitride particles.

Figure 1. Distribution of vanadium in the laser alloying zone

Figure 2. Microstructure of steel 20 after laser alloying with chromium, x100
In zones doped with Al, a two-phase structure $\alpha + \gamma'$ - phase (Fe, Al)$_4$N is formed. Such processing provides a significant increase in microhardness: LA (Al) + N up to 21000 MPa, LA (V) + N up to 18500 MPa, LA (Cr) + N up to 18000 MPa; LA (Mo) + N up to 12000 MPa. The increase in hardness is explained by the fact that after nitriding, the mechanism of solid solution hardening with nitrogen is additionally activated. When nitriding steels laser-alloyed with aluminum, the microhardness is maximum, since in this case the mechanism for increasing the strength combines the components of both solid solution and precipitation hardening with the $\gamma'$-phase (Fe, Al) $_4$N.

An increase in the duration of the nitriding process to 6 hours or aging leads to the release of nitrides of alloying elements fully or partially coherent with the matrix and, as a consequence, to an additional increase in hardness. It has been experimentally established that the maximum level of hardening is achieved after aging at a temperature of 250 °C for 0.5 ... 1 h due to the release of dispersed particles of the optimal degree of coherence.

Calculations show that the most significant contribution is made by two mechanisms: solid solution - by nitrogen and dispersion - by particles of nitrides of alloying elements. The contribution of solid solution hardening with nitrogen is especially high in Fe-Cr alloys, which is explained by the strong influence of chromium on increasing the solubility of nitrogen in ferrite.

The proportion of solid solution hardening with an alloying element is very small: no more than 5%. Grain-boundary hardening is more significant in Fe-Mo alloys (7 ... 10%) in comparison with other alloys, which is explained by a finer-grained structure. The contribution of dislocation hardening, as well as grain-boundary hardening, significantly decreases after nitriding to 1 ... 6%.

The role of precipitation hardening in combined processing is maximal. It is the greater, the higher the thermodynamic stability of the nitride (in the series Mo$_2$N→Cr$_2$N→VN); upon strengthening with vanadium nitrides, its contribution reaches 83%. Moreover, the level of hardening by coherent particles is significantly higher than by incoherent ones.

Therefore, to achieve the maximum level of hardening, it is necessary to ensure the formation of a structure with dispersed particles of nitrides of alloying elements, which are in the optimal degree of coherence with the matrix, which is controlled by optimizing the technological parameters of the combined processing at each stage. Combined processing allows you to increase a whole range of structural strength indicators.

Wear tests have shown that the wear resistance of steel 20 after combined treatment is 15 times higher than that of normalized steel 20, and 1.5 ... 3 times higher than the wear resistance of nitrided nitralloy 38Kh2MYuA. High indicators of wear resistance are explained not only by the high hardness of the surface layer, but also by the formation of a Charpy-type relief on the surface, which significantly reduces the coefficient of friction. Moreover, the Charpy principle is realized both at the macrolevel with 50% filling of the surface with hardened zones, and at the micro- and nanolevel due to the creation of a structure inside the crystal, consisting of a soft and plastic $\alpha$-solid solution and solid fine particles of nitrides of alloying elements. Well-known low friction antifriction materials such as babbits and cast...
bronzes have a similar structure. The best results are achieved by alloying with aluminum, vanadium and chromium, followed by nitriding (Fig. 4).

Cyclic tests under high-cycle loading with a frequency of 200 Hz for samples subjected to laser treatment showed a decrease in the growth rate of a fatigue crack and an increase in the threshold value of the stress intensity factor $K_{\text{ic}}$, below which the crack does not develop. Subsequent nitriding shifts the kinetic diagrams of fatigue fracture even more to the right.

![Figure 4. Wear of steel 20 after: 1 - normalization, 2 - nitriding, 3 - LA (Al), 4 - LA (Cr), 5 - LA (V), 6 - LA (Mo), 7 - LA (Mo) + N, 8 - LA (Cr) + N, 9 - LA (V) + N, 10 - LA (Al) + N, 11 - steel 38X2MIOA after nitriding](image)

Tests under low-cycle loading with a frequency of 0.1 Hz when laser "tracks" are applied to a steel surface with overlapping, the rate of growth of a fatigue crack increases, and subsequent nitriding improves this characteristic to the level of the original sample. When laser "tracks" are applied without overlapping, followed by nitriding, the crack resistance of low-carbon steels increases by 1.5 times. The kinetic diagrams in this case have an unusual form (Fig. 5), which, however, fully corresponds to the internal mechanisms of fatigue failure of such heterophase samples. An unstable crack growth is observed, the accelerations of which alternate with periodic deceleration. The best results under high-cycle loading are achieved by alloying with molybdenum, and under low-cycle loading - with vanadium and chromium.

Fractographic studies have established that in the fracture of steels hardened by the combined LL + N technology, viscous components are observed (Fig. 6, b), while after laser alloying, the fractures of steel 20 have a pronounced brittle character (Fig. 6, a), which due to the significant contribution of the dislocation mechanism to the overall level of hardening.
During laser alloying and subsequent nitriding, a structure is formed on the steel surface, strengthened by dispersed particles of nitrides of alloying elements, which complicates crack initiation and promotes its effective deceleration, especially at the early stage of growth, and the contribution of the dislocation hardening mechanism decreases significantly.

Thus, on the basis of experimental studies of the influence of the modes of each stage of the combined technological process and the tests of the samples on wear resistance, crack resistance, technological modes have been determined that make it possible to increase the service life of products by 1.5 ... 1.8 times operating under conditions of intense wear, dynamic and cyclic loads at elevated temperatures (shafts, gears, tools, dies, punches for cold and hot deformation, spindles of rolling bearings, lead screws, sleeves, parts of the caliper group, etc.).
Figure 6. Fractograms of fatigue failure of steel 20 after: a) LA (V); b) LA (V) + N

4. Conclusion
1. The concept of surface hardening of structural steels is proposed, which consists in applying the principles of strength theory for the purposeful formation of structures capable of effectively resisting complex multifactorial phenomena occurring in the frictional contact zone, increasing wear resistance and crack resistance.
2. An intellectual approach to the rational choice of technological combinations capable of maximally realizing dislocation, substructural, grain-boundary, solid solution and dispersion mechanisms of steel hardening, allowing to create optimal structures on the surface of tribo-interface elements, is described.
3. Using the example of the technology of surface laser alloying of structural steels with nitride-forming elements followed by nitriding, an increase in surface hardness, strength, wear resistance by 15 times and fatigue strength by 1.5 times compared with the initial parameters of steels is shown.

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