Plastic deformation hardening of iron-nickel alloys

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Abstract. The purpose of the study is to determine the influence of the structural state of the surface layer on the possibility of enhancing the properties of heavy-loaded parts, including gear wheels, by plastic deformation. Plastic deformation was carried out by shot-blasting treatment. Since the behavior of the structure of the carburized layer of gear wheels is very complex, single-phase iron-nickel alloys were studied as model alloys. It is shown that the contact fatigue strength and other operational properties of parts can be improved if we apply shot-blasting treatment in optimal conditions. After the latter should be low-temperature tempering, causing strain aging. The positive effect of such complex processing is associated with the formation of a favorable substructure - a substructure of martensite with high resistance to local microplastic deformation.

Introduction
Changes in the structure and properties of the carburized layer during shot-blasted treatment (ST) of gear wheels are very complex. The latter is explained by the multiphase structure of the carburized layer, containing martensite, residual austenite and different carbides. Each of them contributes to the changes occurring during plastic deformation. It is known [1-3] that the martensitic matrix of the carburized layer has the greatest influence on the surface properties. As mentioned above, the study of the behavior of the substructure of the martensitic matrix is complicated by the influence of the other two phases. In this connection, in the present work, single-phase iron-nickel alloys were used, the martensite of which has approximately the same martensitic transformation temperature as the martensite of carburized layer [4-6].

In this work, as a model alloys, we used a carbon-free (C < 0.03%) alloy of iron with Ni – Ni22, as well as an iron-nickel alloy with carbon – C0.25Ni20. The alloys are chosen to study the role of carbon atoms in ST and subsequent tempering. In an alloy with carbon, the nickel content was reduced to compensate for the effect of carbon on the martensitic transformation temperature.

Materials and methods of the experiment
The material used for the test were two iron-nickel alloys – carbon free and with carbon: Ni22 (0.03% C, 22% Ni, the remainder is iron) and C0.25Ni20 (0.25% C, 20% Ni, and the remainder is iron).

The research objects passed through, hardening in oil (from \( t = 860-880 ^\circ C \)), cold treatment \(( t = -70 ^\circ C, 40 \text{ min} )\), low-temperature tempering \(( t = 180-200 ^\circ C, 1 \text{ h} )\). After such treatment the plastic deformation (shot-blasting by shot \( d = 0.2 \text{ mm} \)) and low tempering \(( t = 100...200 ^\circ C, 2 \text{ h} )\) was carried out. The duration of shot blasting of the surface element \( \tau_{el} \) was changed from 1 to 6 minutes.

PHILIPS autopower diffractometer was used for measuring the width of the interference line \( B(220), \text{ mrad} \) in cobalt \( K_{\alpha} \)-radiation. «JEM-200» scanning electrical microscope was used for...
observations and taking photographs of the structure. The relaxation effect $\Delta \sigma$, $N/mm^2$, equal to the difference between the initial stress and voltage at the end of the test, was calculated from the residual strain. Similarly investigated the electrical resistance of the alloys.

The contact fatigue strength $N_{50} = 10^6$, cycle specimen is a roller of 30.2 mm in diameter and 18.5 mm in length. This specimen is rolled reciprocally with a fatigue tester with a slip ratio of 20% ($\sigma_{z, \text{max}} = 2100\ MPa$, $t = 110\ ^\circ C$).

**Experimental results and discussion**

The electron-microscopic analysis of thin foils showed that the initial structure of iron-nickel alloys is close to that of the carbonized layer. It is a mixture of twinned martensite crystals and finer crystals of packet dislocation martensite (Fig. 1a, d). The basic difference is that the structural carbonized layer is characterized by a larger percentage volume of twinned martensite.

The special features of the initial structure of the hardened alloys being investigated are the high density of dislocations and the heterogeneity of elastic distortions of the solid solution of the crystal lattice. This is indicated by the high value of the width of the interference line (220) (Table 1). Broadening of the interference line of C0.25Ni20 alloy as compared with the carbonless Ni22 alloy is more intense, which is linked with the martensite lattice tetragonality and its concentration of heterogeneity.

Shot-blasting treatment introduced noticeable changes into the intercrystalline structure of both carbon iron-nickel and carbonless martensite. Absorption of elastic energy of deformation by the surface layer is accompanied by a sharp reduction of the interference line width (see Table 1),

![Figure 1](image-url)
especially in a short duration of ST. At a surface element treatment, duration $\tau_{el} = 1$ min, it is minimum.

### Table 1. Properties of iron-nickel alloys

| $\tau_{el}$, min | $B(220)$, mrad | $N_{50}$, $10^6$, cycle | $\Delta\sigma$, N/mm$^2$ | $\Delta\rho/\rho_0$ |
|------------------|----------------|-------------------------|-------------------------|-------------------|
| Ni22             |                |                         |                         |                   |
| 0                | 100            | 0.5                     | 20                      | 0.40              |
| 1                | 80             | 1.0                     | 10                      | 0.40              |
| 3                | 85             | 0.8                     | -                       | 0.40              |
| 6                | 90             | 0.5                     | 25                      | 0.40              |
| C0.25Ni20        |                |                         |                         |                   |
| 0                | 120            | 2.0                     | 31                      | 0.60              |
| 1                | 70             | 4.0                     | 25                      | 0.55              |
| 3                | 75             | 3.5                     | -                       | 0.50              |
| 6                | 80             | 2.0                     | 40                      | 0.42              |

Legend: $\tau_{el}$ – duration of shot-blasting treatment of a surface element; $B$ – the width of the martensite interference line (220); $N_{50}$ – contact fatigue strength; $\Delta\sigma$ – relaxation effect; $\Delta\rho/\rho_0$ – the measurements of the electrical resistivity.

The crystal lattice of carbonless martensite is not tetragonal. The reason for the reduction of its interference line width can only be the reduction of the level of hardening microstresses. The process responsible for this reduction is the change in the dislocation structure. Plastic strain causing the formation of new defects of the crystalline structure stimulates their interaction with those already existing [7-9]. As a result of such interaction taking place in the conditions of local heating stretched (within one grain) dense dislocation accumulations are formed. Between accumulations there are regions with relatively low dislocation density (Fig. 1b, e).

The parameter controlling such a fragmented structure is the kinetic shot energy ($E$) depending on the duration of processing. In iron-nickel alloys, as follows from electron-microscopic investigations, the fragmented structure is formed in hardening with shot energy $E = 20$ kJ/m$^2$ ($\tau_{el} = 1$ min).

The effect of reduction in the interference line width for the 25N20 alloy containing carbon is greater than for the carbon-free Ni22 alloy which suggests an additional contribution to the change of this characteristic by martensite decomposition (i.e., reduction of its tetragonality) and redistribution of carbon atoms in the crystal lattice.

The reflection of the processes of changing the structure of martensite is the formation of high residual compressive stresses ($400$ N/mm$^2$) in the surface layer of both alloys and an increase in the surface microhardness (by $30$ N).

Comparison of Table 1 and Fig. 1 data shows that after hardening in modes that cause a width of the interference line decrease and the fragmented structure formation, the contact fatigue strength increases. At the same time, the contact fatigue strength of an alloy with carbon after ST is higher than that of a carbon-free alloy. This indicates a positive effect of carbon on the contact fatigue strength, the atoms of which, accumulating on dislocations, cause their fixation.

The formation of a favorable substructure under the ST mode, which provides increased durability, is also evidenced by the results of tests for relaxation resistance (see Table 1), which was carried out with static bending. Stress relaxation is associated with the movement of dislocations under the action of local stresses, therefore, the degree of mobility of dislocations can be judged by the relaxation effect ($\Delta\sigma$) equal to the difference between the initial stress and stress at the end of the test, calculated from the residual strain. The relaxation effect, decreasing at $\tau_{el} = 1$ min (see Table 1), increases with a further increase in the duration of shot-blasting treatment of both alloys.

The results of measurements of the electrical resistivity $\rho$ (see Table 1) confirm the decomposition of martensite in an alloy containing carbon C0.25Ni20. In which this process takes place during ST along with stress relaxation. At the same time, in a carbon-free alloy Ni22, the electrical resistivity
practically does not change, since only stress relaxation can occur in it.

With an increase in the time of deformation, the density of defects increases, causing an increase in the overall level of micro distortions, as evidenced by an increase in the width of the interference line (220) and an increase in the relaxation effect (see Table 1). An increase in the level of micro distortions causes a decrease in the resistance of the alloy to the nucleation of fatigue cracks and, accordingly, of contact fatigue strength.

Thus, the effect of shot-blasting treatment of optimal duration ($\tau = 1 \text{ min}$) is due, along with the strengthening of the surface and the creation of residual compressive stresses, a change in the structure of martensite with the formation of a stable fragmented structure. The result of these changes is an increase in the resistance of microplastic deformation, an obstruction of the process of the emergence and development of contact fatigue cracks.

An effective way to change the substructure and improve the properties of an alloy that is deformed in optimal conditions is the use of subsequent low-temperature tempering [10-13]. In alloy Ni22, such tempering leads to a decrease in the width of the interference line (Table 2) and a decrease in the relaxation effect (Fig. 2). For a carbon-free alloy Ni22, these changes during heating are explained only by the development of processes of relaxation of micro-distortions, which positively affects on the contact fatigue strength (Fig. 3).

**Table 2.** The width of the martensite interference line $B(220)$, mrad of iron-nickel alloys after-hardening tempering $t$, °C (2 hr)

| $t$, °C | $B(220)$, mrad |
|--------|----------------|
|        | Ni22 | C0.25Ni20   |
| 20     | 70   | 80           |
| 100    | 65   | 70           |
| 130    | 60   | 74           |
| 160    | 55   | 70           |
| 190    | 52   | 70           |
| 220    | 50   | 70           |

**Figure 2.** Dependence of the relaxation effect $\Delta \sigma$ of iron-nickel alloys Ni22 (1) and C0.25Ni20 (2) on the tempering temperature $t$ after shot-blast treatment (ST).

When the C0.25Ni20 alloy is heated, the decrease in the width of the interference line is more significant than that of the Ni22 alloy (see Table 2). This indicates a decrease in the tetragonality of martensite due to the release of carbon atoms from its lattice as a result of the development of deformation aging. Accumulating on dislocations, carbon atoms increase the resistance of the substructure to destruction during subsequent loading and, consequently, to an increase in contact fatigue strength (see Fig. 3). However, deformation aging has a dual effect. On the one hand, it
increases the resistance of microplastic deformation, and on the other hand, it reduces the dislocation mobility, complicates stress relaxation. Deformational aging and stress relaxation intensify as the tempering temperature rises [14-16]. It should be noted that, due to the high density of defects in the crystal structure, which greatly accelerates the migration of carbon atoms to dislocations, strain aging under these conditions should take precedence. The interaction of opposite processes leads to the fact that the most stable structure is formed at a low tempering temperature \( t = 130 \pm 10 \, ^\circ C \), which corresponds to the minimum relaxation effect. As can be seen from Fig. 3, tempering at \( t = 130 \, ^\circ C \) for 2 h maximizes the durability of the C0.25Ni20 alloy under heating conditions. Electron-microscopic studies have shown that after tempering at \( t = 160 \, ^\circ C \), the boundaries of the cells in martensite of the C0.25Ni20 alloy become more distinct (see Fig. 1f) probably due to the accumulation of carbon atoms on them. The absence of carbon in the Ni22 alloy causes the disappearance of fragmentation after tempering at \( t = 160 \, ^\circ C \) (see Fig. 1c), Whereas in the C0.25Ni20 alloy with carbon the fragmentation is eliminated during tempering at temperatures above \( t = 200 \, ^\circ C \).

Conclusions

1. The changes in the martensite substructure of the surface layer have a determining effect on the contact fatigue strength of Ni22 and C0.25Ni20 alloys subjected to shot-blasting treatment (ST).

2. An increase in the contact fatigue strength of iron-nickel alloys is attained in a narrow range of ST regimes, which ensure alongside with strengthening and creation of high residual compressive stresses a more stable structure, being characterized by a lowered level of microdistortions and low mobility of dislocations.

3. It is recommended to combine the shot-blasting treatment of iron-nickel alloys with subsequent low-temperature annealing at which martensite hardening takes place as a result of strain aging and reduction of microdistortions which facilitate increase of resistance to contact fatigue.

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