Effect of Laser Alloying on the Mechanism of Steel Fracture Under the Cyclic Loading

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INTRODUCTION

There are many reports dealing with laser alloying of part surfaces to increase their wear resistance. Anyhow, little attention has been paid to laser alloying of surface to improve corrosive and mechanic characteristics in particular under cyclic loading.

This paper concerns increase of low-cyclic fatigue by means of laser alloying. It is of interest as in the result of laser treatment micro-and macro surface relief considerably deteriorates. Surface layer cracking (Fig.1) due to high tensile stresses can occur in the zone of laser alloying (flashing) while cooling. Moreover, heterogenous structure formation leads to concentration of stresses in the surface layer.

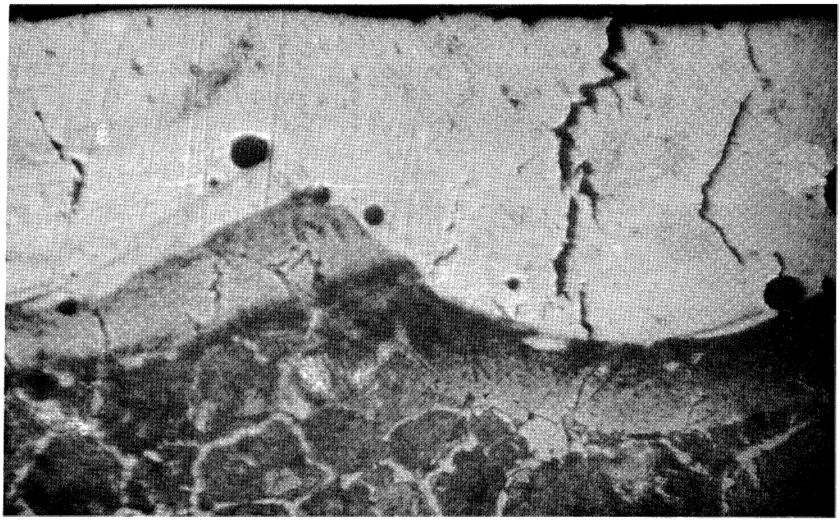


Fig.1. Surface layer structure of specimen made of copper alloyed steel 45 after testing under low-cyclic loading with NaCl effect

Plane specimens were tested for low-cyclic fatigue under controlled stresses and deformations as well as cylindrical one tested for high-cyclic fatigue both in the air and in 3% NaCl aqueous solution.

Main purpose of the paper was to clear out physical nature of the loss of the metal structure strength because of laser alloying and elaborate measures to increase cyclic durability of steel.

EXPERIMENTAL PROCEDURE

Normalized medium-carbon steel 45 was used for investigation. Plane specimens (10x5 mm) with effective length 40 mm were under fatigue test on four-position machine, alternating pure bending at 0.11 Hz. Our methods (Blednova, 1987) were used to determine stresses under elastic deformations and their continuous control while testing. Standard specimens (effective diameter 10 mm)were tested for high-cyclic fatigue when bended while 50 Hz rotating on testing machines (UKI).
For surface flashing and alloying "Quantum-12" pulse-operating laser installation was used. Prior to laser treatment surface layer was covered with synthetic resin adhesive paste containing metal powders. Modes of laser treatment: impulse energy 2.5÷4 J; frequency 10 Hz; spot diameter 0.5÷1 mm; spot overlap 30÷80%; speed of part movement 2.5 mm/s; pulse duration 2-5 ms; depth of penetration up to 0.3 mm.

Test was realized as per programme "KURP-4" for 3 and 4 variables (pulse frequency, pulse energy, number of runs, speed of part movement). Cyclic longevity determined depending on the said parameters, in case of laser alloying was estimated with the same parameters, m.p. including. Significance of regressive equation coefficients was evaluated using Student t-test and as to its adequacy - by Fisher's ratio test. Optimization problem prompted us to obtain optimum parameters of treatment to attain required longevity.

Experimental results

Irreversibility of metal damage resulting from laser pulses effect (Fig.2) is evidenced by drop of specimen load-carrying capacity under low-cyclic stressing with the first cycles of loading.

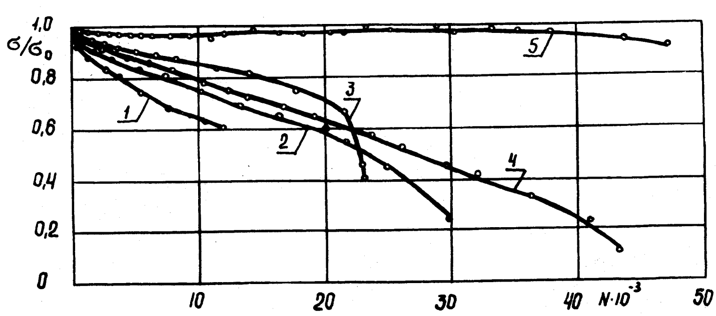


Fig.2. Drop of load-carrying capacity of specimens made of steel 45 after surface laser alloying at ε_a = 0.2 %

1. alloying W (NaCl) 2. alloying Mo (air)
3. normalizing (NaCl) 4. alloying Cr (NaCl)
5. normalizing (air)

The fig.2 shows that while alloying steel 45 by chromium and molybdenum a complete fracture takes place just after loss of load-carrying capacity has achieved 80 %. This drop is explained by multi-point formation of defects.

One should pay attention to abnormal processes of crack development in the direction coinciding with that of maximum normal stresses. It is due to the cyclic stresses in the shell created by laser alloying caused by lateral cyclic deformation. Such stresses combined with residual tensile ones lead to cracking (Fig.3).

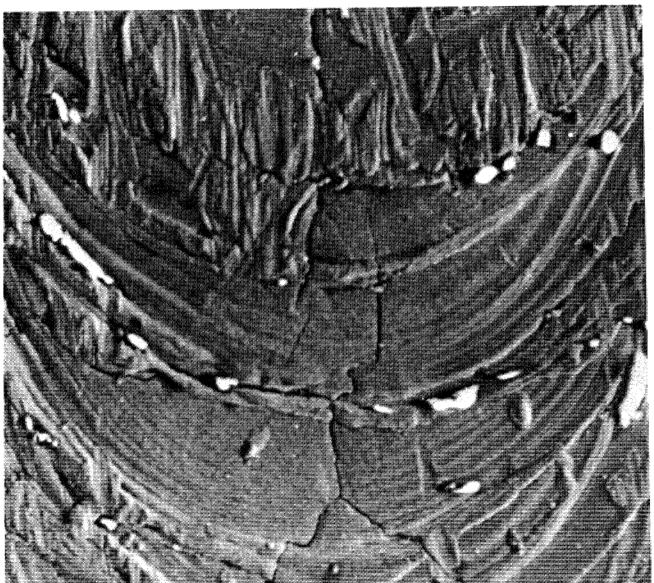


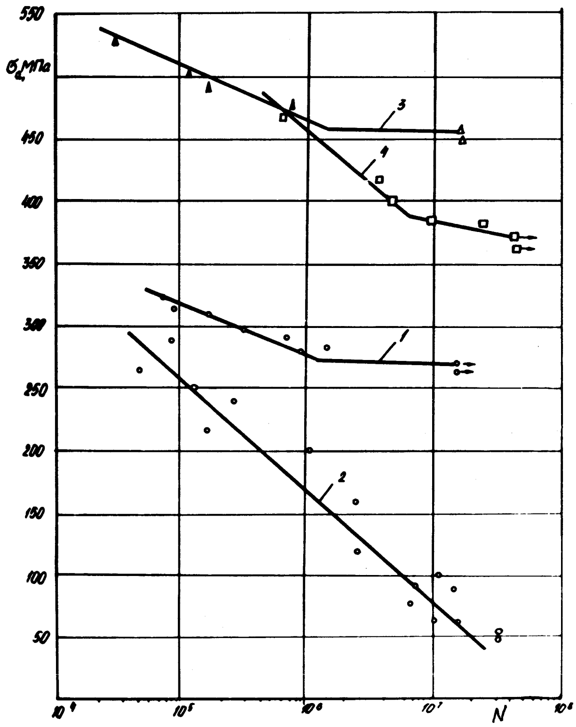
Fig.3. Specimen surface after chromium alloying and testing under cyclic loading (ε_a = 0.2 %)

Cyclic longevity drop relationship for different alloying elements Cr-Ni-Cu-Cu corresponds to cyclic longevity $50\cdot10^3$, $20\cdot10^3$, $5\cdot10^3$, $2{,}5\cdot10^3$ cycles when ε_a = 0.2 %.
To prevent loss of steel strength in laser alloying there have been made attempts to use combined methods of strengthening including laser alloying, heat treatment and surface plastic deformation. Standard specimens made of normalized steel 45 for high-cyclic tests were subjected to pulse mode alloying by means of chromium at 10 Hz and part movement speed 0.25 mm/rev., with double laser penetration having been used. This procedure was followed by steel tempering at T = 300°C and roller running at P = 800 N upon roller.

Tests at 50 Hz showed (Fig.4) that fatigue range of steel 45 treated as indicated was increased by 40 % and limited fatigue range based on $5\cdot10^7$ cycles in NaCl solution increased sevenfold being equal to 375 MPa (curve 4). Preliminary thermal improvement with low tempering results in steel 45 fatigue range increase up to 450 MPa after laser chroming.

Surface Layer Model After Laser Alloying

In laser alloying following effects were observed to lead to loss of structure strength: As a result of laser impact heterogenous mechanical mixture with weaker interatomic bonds was formed. The intensity of fracture was shown to increase with decrease of alloying elements melting point. This can be explained as being due to the effect of plasticizing harder metal by softer one on the basis of barrier-and dislocation mechanism of plastic deformation transfer (Chayevsky, 1963);In crystallization residual tensile stresses may arise being considerable enough to form crack surface.



1.normalizing (air)
2.normalizing (NaCl)

3,4-laser alloying by chromium, tempering at T = 300°C, roller running at P = 800 N;
3 - air; 4 - NaCl

Fig.4. Endurance curves of steel 45 after thermal deformation and laser treatment

Initially, at pure bending of specimen there appears linear stressed state in surface layer (Fig.5). Following laser alloying takes place volumetric stressed state which can be reduced to the plane one neglecting pressure of the formed layers on each other.

Residual tensile stresses arise after laser alloying. Compres - sive stresses σ^{I} from bending moment and tensile stresses σ^{II} from lateral deformation of specimen are applied on the above mentioned ones. Tensile stresses from bending loading and compressive stresses from lateral deformation of specimen σ^{II} which are applied on residual ones σ' arise in the bottom of specimen. In cyclic loading stresses σ^{II} and σ^{I} periodically change their value in symmetric cycle and summary stresses change in pulse cycle. It is this unfavourable combination of main stresses under plane stressed state which can lead to considerable values of similar stresses causing microcracking under alloyed layer and intensive drop of the specimen load-carrying capacity.

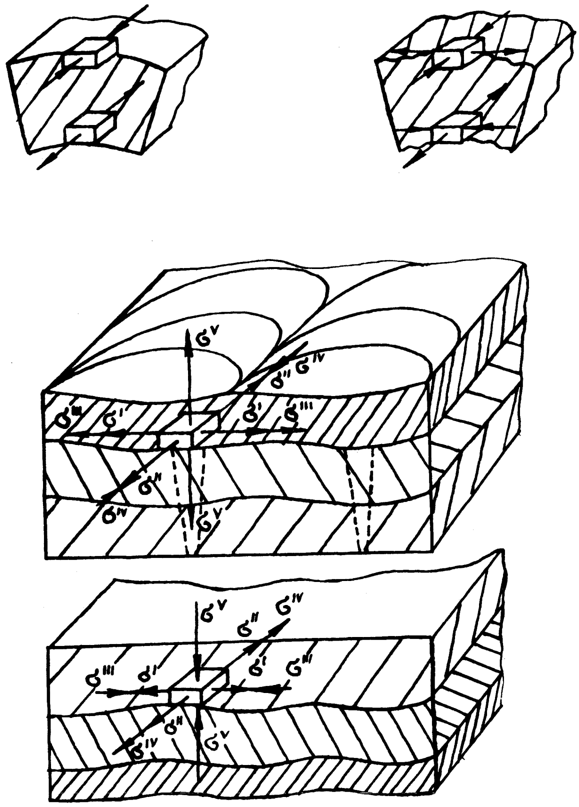


Fig.5. Diagram of surface layer stressed
state after laser alloying

Earlier an equation was proposed (Blednova, 1986) to determine cyclic longevity in energy form

$$\sigma \varepsilon_{pa} N^{p} = \alpha Q \qquad (1)$$

where σ - amplitude of stresses

ε_{pa} - half a width of hysteresis loop

N - number of loading cycles

Q - energy capacity of metals and alloys

α - thermomechanic coefficient

p - factor

Neglecting σ^{V} the equation (1) becomes

$$\sigma_1 \varepsilon_{pa_1} (1 + \mu \nu) N^{p} = \alpha Q \qquad (2)$$

where σ_1 - amplitude of main stress

ε_{pa_1} - amplitude of plastic deformation in the direction of specimen axis

ν - Poisson's ratio

$\mu = \frac{\sigma_2}{\sigma_1}$ - ratio of amplitudes of main stresses

Energy criterion $\mathcal{L}Q$ does not depend on the type of stressed state. Value $Q = \int_T^{T_s} c_p \, dT + L$ can be estimated for any binary alloy.

As seen from Eq.(2) with μ = 1 and ν = 0.5, energy expenditures for microplastic deformation per cycle are one and a half times more than in material without residual tensile stresses, which essentially reduce cyclic longevity.

CONCLUSIONS

1. Laser alloying leads to loss of metal structure strength. 2. For the structure to be strengthened roller running and low tempering are necessary after laser alloying. 3. There is suggested model of surface layer after laser alloying as well as the equation of low cyclic fatigue enabling to determine cyclic longevity.

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