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# INCREASE OF RELIABILITY OF LOADED MACHINE PARTS BY SURFACE MODIFICATION USING METHODS OF LASER TREATMENT

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## ABSTRACT

This article discusses the issues of increasing the reliability of loaded machine parts by modifying the surface using laser heating. In order to increase the durability of vehicle differential axle a method of surface modification has been considered, which combines advantages of discrete alloying of steel surface upon laser heating, diffusion metallization, and nitriding. Combined technology of surface strengthening of engineering steels is proposed, which is comprised of laser alloying with chromium, subsequent diffusion metallization and nitriding in environment of dissociated ammonia. It is demonstrated that preliminary local alloying makes it possible to decrease processing temperature and to obtain diffusion layer thickness in two times higher in comparison with conventional procedures. Nitriding of surface alloyed steel 40Kh (0, 4%C, 1%Cr) increases microhardness of strengthened layer up to 17.5 GPa, promotes formation of transient layer which positively influences on wear resistance of parts, increases their durability.

**Keywords:** laser alloying, diffusion metallization, nitriding, steel, microstructure, microhardness.

## INTRODUCTION

Increasing of reliability and durability of machine parts is an urgent concern of modern engineering. Reliability is determined by capability to maintain operational properties in predetermined limits and to perform specified functions within required time interval. Reliability is stipulated by fail-free operation of part, long operation lifetime as well as maintainability.

Fail-free operation is the property of a part to maintain its operability within preset time interval - time between failures without forced interruptions.

Durability is the property of a part to maintain its operability including required pauses for repair and maintenance. Ultimate state of part operation specified in engineering documentation is stipulated by impossibility of its further operation due to decrease in efficiency or safety requirements. Increased durability is a basis of improved reliability.

Operation reliability is mainly determined by engineering strength of materials of machine parts which combines the set of mechanical properties being in maximum correlation with operational strength of part. In order to estimate reliability of items made of metals the following properties of engineering strength are applied: impact viscosity, failure viscosity (failure survival, critical crack opening and others). The criterion of durability is comprised of parameters of fatigue limit, wear resistance, corrosion resistance, creeping and others, characterizing gradual accumulation of irreversible damages in material causing its destruction as consequences of these damages.

The mentioned material properties depend on engineering design. The required level of these or those properties is achieved by means of strengthening procedures, which form the required structure in alloys providing their engineering strength and, hence, improved reliability and durability of item in general.

Durability of machine parts operating as friction couples is mainly based on their wear resistance under operation conditions. According to statistic data, from 80% to 90% of machine parts fail due to their surface wear with subsequent loss in accuracy, decrease in efficiency, it can cause fatigue failure due to increased amplitude of varying loads. Fatigue wear (contact fatigue) is the cause of failures of heavy loaded items: gear and worm wheels, rolling bearings, rails, wheels and so on.

Wear resistance of steel part is mainly determined by its surface state and surface layer structure. Wear resistance is improved by various procedures of surface strengthening, including laser alloying, nitration, metallization and others [1-4].

Essential parts which should possess high impact viscosity are often fabricated of alloyed steels. In order to provide wear resistance their surfaces are strengthened, in particular, by thermo-chemical treatment (carburizing, nitriding, carbo-nitriding, boriding, oxy-nitriding and others) [5-6]. Loaded machine parts operating under tension and torsion (axles, shafts and so on) experience alternating (cyclic) loads, herewith, maximum stresses occur in surface layers, where stress concentrators are located. The material sensitivity to stress concentrators can be decreased by residual compression stresses on surface. This can be achieved by certain methods of thermo-chemical treatment, in particular, by laser heating [1] which creates high level of compression stresses on surface, thus increasing fatigue limit.

One of essential loaded parts of a vehicle is differential axle. In general, differential axles are fabricated of carbon steels, grades 35, 40, 40Kh, 38KhGS, and are exposed to regular thermal processing - enhancement, after such strengthening mechanical machining is not required. After quenching and high tempering, the obtained structure of granular sorbite is characterized by increased impact viscosity.

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Vehicle lifetime decreases due to failures of differential axles; the loads of differential axles of sports cars are especially high. Thus, the racing car designed in the MADI Center of engineering art could not finish the race due to early failure of differential axles. Analysis of the failed axles according to the procedure of metal testing [7] demonstrated that the main reason of the failure was surface wear of spline coupling. Insufficient hardness and wear resistance of granular sorbite structure lead to fast wear of spline coupling surface. Hardness and wear resistance can be improved by surface modifications allowing obtaining surface layer characterized by properties of high alloy steel. Surface alloying is performed by diffusion metallization or by methods assuming the use of highly concentrated power sources (laser, ultrasound or plasma processing) [1, 8-10]. Chromium, vanadium, titanium, molybdenum and other materials are used as alloying elements.

Diffusion metallization is an efficient method of surface modification, though, with certain significant disadvantages. Due to low diffusion mobility of alloying elements in iron, the steel items should be processed at high temperatures (950…1050°C). Moderate thickness of metallized layer (50…70 µm) could be attributed to the same reason. The concentration of alloying element usually decreases sharply at the interface between surface layer and core area which leads to unfavorable stresses in boundary region. High processing temperatures cause intense grain growth and increase the risk of item deformation. The required additional thermal and mechanical processing makes the process more complicated.

Advantages of surface alloying upon laser heating include possibility to obtain alloyed diffusion layers of significant thickness: up to 300 µm upon pulsed action and up to 700…800 µm upon continuous laser action. Uniform distribution of alloying element is achieved in the area of laser action. High microhardness of alloyed areas is stipulated by generation of non-equilibrium structures due to high rates of heating and cooling. The drawback of laser processing is the resulted specific residual stress diagram. Residual tensile stresses at the boundary of laser action and the base are unfavorable and can lead to cracking during part operation. Attempts to decrease stresses by additional heating inevitably result in strength degradation: hardness of strengthened layers deceases due to transformations of non-equilibrium phases. It is possible to adjust the distribution of residual stresses and to retain strengthening by nitriding of laser alloyed steels [1]. Moreover, wear resistance is improved due formation of disperse nitrides of alloying elements according to disperse strengthening of nitrated layer in high alloy steels.

This work discusses the surface modification combining advantages of discrete alloying of steel surface upon laser heating, diffusion metallization and nitration in order to improve durability of differential axle.

## METHODS

The tests were performed with items made of steel, grade 40Kh; their surface was preliminary machined, including finishing and degreasing by acetone.

Laser alloying and diffusion metallization were performed by slip method: saturation from suspensions. Chromium was selected as alloying element; it is characterized by sufficient diffusion mobility in iron and can form stable nitrides upon interaction with nitrogen.

Slip suspension is comprised of a powdered alloying element (Cr), a halide ($CrCl_2$) aiming at acceleration of transport reactions, and a binder (Zapon lacquer). The suspension was mixed with powdered activated coal in order to prevent formation of oxide film which decelerates metallization. The slip powder layer was applied onto surface with controlled thickness.

Laser processing was performed using a Kvant-15 pulse laser at pulse power of E = 15 J, pulse duration of 4 ms, and laser beam defocusing extent of $\Delta F = 0$. With the selected parameters the diameter of areas of laser strengthening (d) was 1 mm.

After laser processing the integrity of violated slip powder layer was restored. Diffusion metallization was performed in induction furnace in dissociated ammonia environment at 735°C in 3 h, subsequent cooling was performed in furnace. Nitration was performed at 570°C in 3 h in ammonia environment with dissociation extent of 30%.

The processed samples were used for preparation of transversal metallographic polished microsections using conventional sampling procedure. The section microstructures were analyzed using a Carl Zeiss Axiover 25CA optical microscope after etching in 4% $HNO_3$ solution in ethanol.

Microhardness was measured on transversal microsections according to regular procedure using a PMT-3 microhardness meter at the load of 50 g with the increment of 20 µm.

## RESULTS

Metallographic study demonstrated that after processing comprised of laser alloying and subsequent diffusion metallization, it is possible to observe modified layer with the thickness up to 100 µm in steel, grade 40Kh (Figure-1a). In reference sample of steel, grade 40Kh, after metallization using the same modes but without laser alloying, the layer thickness did not exceed 40 µm (Figure-1b).

The influence of geometry of steel surface, discretely strengthened by laser processing, on growth kinetics of alloyed layers upon subsequent diffusion metallization was analyzed. With this aim the number of areas of laser alloying N per unit surface area S was varied from 0 to 10 unit/cm$^2$. Analysis of the obtained results (Table-1) demonstrated that preliminary discrete laser alloying with the area density of 4 unit/cn$^2$ before thermal diffusion metallization increased the thickness of strengthened layer by two times (up to ~80 µm).

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**Table-1.** Thickness of strengthened layer (h) upon thermal diffusion metallization with laser treatment as a function of density of laser alloying areas (N).

| N, unit/cm$^2$ | h, µm |
|---|---|
| 0 | 40 |
| 4 | 80 |
| 6 | 120 |
| 8 | 120 |

With increase in the density of areas of laser alloying from 4 unit/cm$^2$ to 6 unit/cm$^2$ the thickness of strengthened layer increases to ~ 120 µm, but it does not increase upon further increase in the density. Therefore, the processing with the density of areas of laser alloying equaling to 6 unit/cm$^2$ should be considered optimum, since its further increase does not lead to significant increase in the thickness of strengthened layer.

Microhardness of surface layer significantly increases after processing, it is comparable with that of quenched alloyed steel and equals to 12 GPa. The depth of layer of effective strengthening (with the hardness higher than 5 GPa), measured by microhardness distribution profiles, upon laser processing before metallization increases by two times (from 60 µm to 120 µm). The drawback of metallization without preliminary laser alloying is sharp drop of microhardness, which creates stress gradient at the layer interface and can lead to its pitting during operation. Laser processing provides smoother microhardness distribution profile due to more intensive progress of diffusion.

Nitriding after laser processing and metallization additionally increases effective thickness of diffusion layer (Figure-1c), activates diffusion of alloying element into the depth and leads to formation of disperse nitrides. The thickness of layer of effective strengthening (with the hardness above 5 GPa) is about 300 µm which is significantly higher than that after processing without final nitriding.

Nitriding increases the surface microhardness up to 17.5 GPa (Figure-2) which is comparable with that of high strength nitride phases. The high hardness (about 13 GPa) under the metallized layer exists at the depth up to 170 µm due to disperse strengthening by chromium nitrides.


a) b) c)

**Figure-1.** Microstructure of steel, grade 40Kh, after laser alloying and metallization (a), after metallization without laser processing (b), and after combined processing with final nitriding (c).

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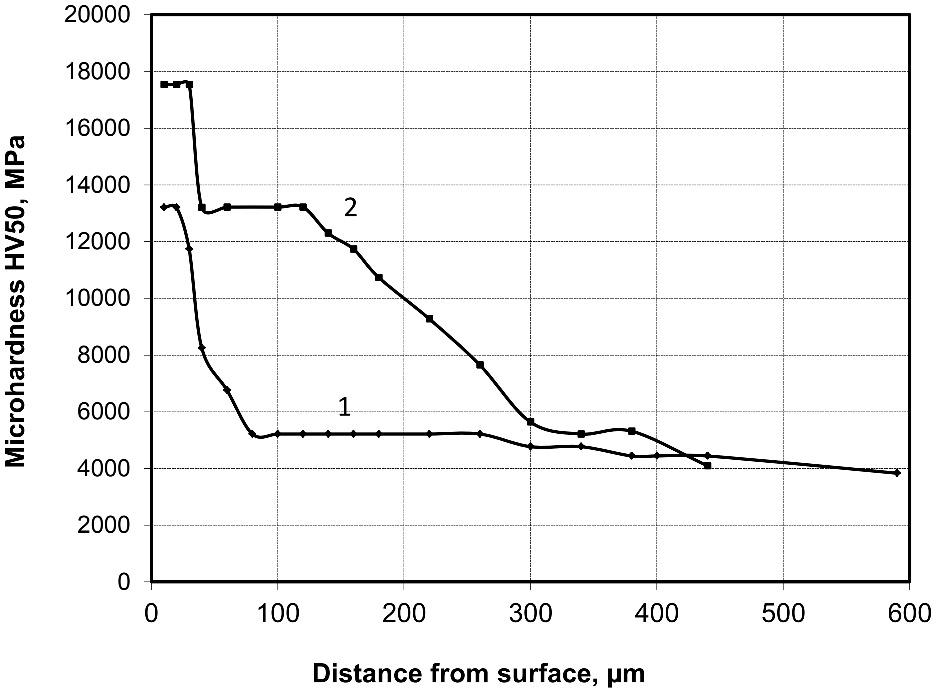


**Figure-2.** Microhardness profiles in steel, grade 40Kh: 1- metallization without laser processing, 2- laser processing + metallization + nitriding.

## DISCUSSIONS

In the considered combined method of surface modification, the laser processing is a preliminary stage which provides creation of discrete alloyed areas.

Upon surface strengthening of spline couplings of differential axles, the size of overlaps resulting from laser processing is highly important, since finishing processing is not specified. In order to minimize surface roughness, the mode of laser processing was selected with minimum remelting depth.

Final nitriding promotes achievement of higher level of strengthening. Subsequent heating provides diffusion of alloying element from the areas of laser alloying both along and into the depth of items. Herewith, the source of alloying element is both the slip powder layer and the alloyed areas obtained upon laser processing. Preliminary formed alloyed areas promoted decrease in metallization temperature to 700°C and reduction of saturation time to 3 h.

During metallization the halide in slip substance is decomposed into ions of halogen and chromium as follows:

$$CrCl_2 + Fe \leftrightarrow Cr + FeCl_2 \uparrow \quad (1)$$

As a consequence, diffusion alloyed layer is formed across overall surface irrespective on complexity of its geometry. Formation of transient layer promotes decrease in residual stresses which is impossible upon processing without nitration. Improved wear resistance and score resistance, ability to wear-in, decrease in attrition coefficient are the consequences of formation of surface layer of nitride ε-phase during nitriding.

The proposed method of surface modification of steel, grade 40Kh was applied for strengthening of differential axles of Formula–Hybrid MADI sports car. After installation of processed differential axles onto the sports car the operation lifetime increased by 1.5 times (more than 600 km of fail-free run in comparison with 400 km without processing).

## CONCLUSIONS

a) Combined technology of surface strengthening of parts made of engineering steels is proposed, which is comprised of discrete laser alloying, diffusion metallization, and nitriding.
b) It is demonstrated that preliminary local alloying makes it possible to decrease processing temperature, to reduce metallization time and to obtain diffusion layer thickness by two times higher in comparison with conventional procedures.
c) Nitriding of surface alloyed steel, grade 40Kh, increases microhardness of strengthened layer up to 17.5 GPa, promotes formation of transient layer, which improves wear resistance of parts and increases their durability.

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