Influence of laser radiation on structure and properties of steels and alloys

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Abstract. In present study, and laser alloying of different steels and laser cladding of Ti and SiC powders mixtures was carried out, and microstructure, as well as microhardness profile and wear properties were examined. Research of the influence of lasers alloying modes on the elastic and plastic characteristics of the surface was conducted. As a result of chemical reactions in the clad layer, a new phase (TiC) was synthesized during cladding process. The results showed that, in the clad layer, TiC was solidified to form dendrites in the clad zone. Produced coatings have high microhardness values in the upper and middle clad areas, about two time higher than clad matrix microhardness.

1. Introduction
Different ratios between power density and laser irradiation time are used in different laser applications. By varying power density and laser irradiation time and controlling the ratio between them, different applications are possible, for instance, drilling, welding, thermal hardening and cladding (figure 1). Laser surfacing techniques have been employed to form a ceramic-metal composite on conventional alloys for enhancing wear resistance [5,6]. Laser cladding by powder injection is the surface engineering method to produce high quality, metallurgically bonded and thick coatings on deficient substrates with a minimal heat input into the work piece. Usually, the main aim of laser cladding and alloying is to improve wear, impact and corrosion resistance properties of surfaces, by generating a protective layer. A complete description of the laser cladding and alloying process is rather complex, because of numerous of interactions (laser beam/powder stream, laser beam/substrate surface, powder stream/melt pool, powder stream/solid substrate, etc.) and physical phenomena (mass and heat transfer, fluid flow, phase transformations during rapid solidification, etc.) are present [1]. The present study aims at investigating the in situ synthesis of a TiC/Ti/Fe composite layer on lox-carbon steel by laser cladding using SiC and Ti powders as the starting materials, and analyzing the microstructures formed for different powder mixtures. Ti-based alloys possess high specific strength, excellent corrosion resistance and good high-temperature strength up to 400°C. These attractive characteristics have made Ti alloys important structural materials in the aircraft industry. However it is well known that Ti-based alloys have poor wear resistance with respect to abrasion, which imposes a limitation on these alloys for a wider range of applications [3, 2]. TiC has been widely used as the reinforced phase of composite materials because of its high hardness, high modulus and rather high flexural strength. In the past decade, the in-situ composite method has been extensively studied to produce composite materials. In this method, reinforcements are formed in the matrix by reaction between added pure elements or compounds, so the reinforcements are much more
compatible with the matrix and the interface is much cleaner than that of composites made by conventional technique [4].

Figure 1. Different ratios between power density, laser irradiation time and different laser applications.

2. Experimental procedures
Laser treatment was conducted on Trumpf DMD 505 industrial-scale machine. A nozzle transports powder coaxially to the CO2 5kW laser beam onto the molten pool created on the workpiece surface. 4 modular powder feeders can be used at the same time for powder mixing in situ the process and thus allowing manufacturing multimaterial multifunctional objects. The process is characterized by a minimal heat input into the workpiece. To prevent oxidation of the cladded layers, a protection skirt made of heat-resistant material is used. By comparing samples manufactured with and without protection skirt, we can observe a notable quality improvement. The substrate was low-carbon steel, with nominal chemical composition in wt. % is: 0.17-0.22 C, 0.40–0.60 Mn, Si less 0.05, Ni less 0.03, Cr less 0.03, P less 0.04, Cu less 0.03, balance Fe. Mixtures of SiC powder (135 µm) and Ti powder (60 µm) were thoroughly mixed by ball milling according to the ratios Ti/SiC = 6:4, 6:5 (wt%). The laser output power was varied between 4 and 5 kW, the laser beam scanning velocity was from 500 to 1000 mm/min, powder feeding rate was 75 g/min. During cladding process, monolayer coatings were produced (30x30 mm). Metallographic samples of the composite coatings were prepared using standard mechanical polishing procedures and were etched in HF:HNO3:H2O water solution in volume ratio of 1:1:8. Microstructure of the coatings was studied by optical microscopy (OM), scanning electron microscopy (SEM). The phases present in the cladding layer were identified by X-ray diffraction (XRD). The microhardness of the coating was measured with the load of 100 g by using a BUEHLER hardness tester machine.

3. Results and discussion

3.1 Laser alloying
Let us consider peculiarities of phase and structure transformation in steels under laser heating. Laser action zones have layer structure because of the fact that different layers were heated up to different temperatures. Generally, three layers can be distinguished. The first layer is the melted zone and corresponds to the hardening in the liquid state. In most cases, it has dendrite structure. The primary axes of the crystals are perpendicular to the bottom border of the melted zone. Martensite is the main structural element. As usual, carbides dissolve. The second layer corresponds to the hardening in the solid phase (without melting). The bottom border is determined by heating up to the critical temperature AC1. In this case, both complete and partly hardening is realized. The third layer is a transitional zone. Here the metal is heated below the critical temperature AC1. Microstructure and
hardness can vary depending on the initial structure of the steel. Figure 2 represents microstructure of steel 20X13 under pulsed laser radiation (E = 18 J, ΔF = 0).

![Figure 2. Microstructure of steel 20X13 under pulsed beam irradiation (E = 18 J, ΔF = 0).](image)

Laser treatment with melting is characterized by high cooling rate of the melted metal. Thus, the hardening if the liquid state occurs. The resulting structure has several peculiarities: a) the grains formed at primary crystallization have small sizes because of a large number crystallization centers. The distance between the dendrites axes of the second order substantially reduces. At the cooling rate of 106 °C/s and more they may disappear. Dendrite liquation reduces due to suppression of the separating diffusion at the crystallization front), b) formation of metastable structures is possible. They are oversaturated solid solutions and metastable intermediary phases, c) as a result of changes in the crystallization mechanism, anomaly structures may form such as stratification of eutectics and quasi-eutectics, amorphous and metal crystal structures.

### 3.2 The effect of laser alloying on steel hardness

Now our concern will be methods of laser alloying. The table 1 represents the effect of laser alloying on steel hardness. In laser alloying a zone of the surface is heated above the melting temperature, then alloying component are introduced into the melted zone. Figure 3 shows microhardness distribution into the depth of the alloyed zone after laser cementation of steel 12X13 (E = 9 J, δ = 0.4 mm, ΔF = 0).

### Table 1. Effect of Laser Alloying on the Microhardness of Carbon Steel (0.4%C, 1%Cr)

| Class (Type) Alloying Components | Alloying Components | Microhardness, MPa |
|----------------------------------|--------------------|-------------------|
| Nonmetal Elements                | Boron              | 10000-20000       |
|                                  | Graphite           | 10000             |
|                                  | Nitrogen           | 9500              |
| Metals                           | Chromium           | 8000              |
|                                  | Titanium           | 4000-4500         |
| Chemical compounds:              |                    |                   |
| Carbides                         | Boron carbide      | 9500-11000        |
|                                  | Titanium carbide   |                   |
|                                  | Vanadium nitride   |                   |
| Nitrides                         | Aluminum nitride   | 10000-12000       |
|                                  | Zirconium nitride  |                   |
Based on experimental research, phase diagrams were constructed. They show existence of zones of structures of various types depending on laser energy and powder layer thickness. The influence of laser cementation conditions on structure and microhardness of melted zones of steel 12X13 ($\Delta F = 0$) is shown on figure 4.

**Figure 3.** Microhardness distribution into the depth of the alloyed zone after laser cementation of steel 12X13 ($E = 9 \text{ J}, \delta = 0.4 \text{ mm}, \Delta F = 0$).

**Figure 4.** Influence of laser cementation conditions on structure and microhardness of melted zones of steel 12X13 ($\Delta F = 0$).

3.3 Evolution of wear rate of the hardened samples
Wear rate of samples after laser treatment is by 2-2.5 time lower than that of samples from the similar steels after conventional thermal treatment, experiment had been held on SMC-2 machine. Laser alloying leads to much more noticeable decrease of wear rate. This is shown on figure 5.
Figure 5. Evolution of wear rate of the hardened samples on SMC-2 machine: 1-volume hardening and tempering, 20X13 steel, 2- volume hardening and tempering, 40X13 steel, 3-LCT with melting, 20X13 steel, E=30J, 4- LCT with melting, 40X13 steel, E=30J, 5- gas cementation, 12X13 steel, E=30J, 6-LA (C), E=20J, d=0.05, steel 20X13, 7-LA (Si), E=11J, d=0.2, steel 20X13, 8-LA (C), E=8J, d=0.3, steel 20X13.

Wear resistance and abrasive wear versus hardness of the alloyed surface had been measured. The tests showed than the laser alloying increases microhardness of the samples. Friction coefficient and wear rate decreased. As to abrasive wear, the optimal conditions are those that provide the maximum hardness without cracks and pores. The results are presented on figure 6.

Figure 6. Wear resistance and abrasive wear versus hardness of the alloyed surface: 1-annealing, 20X13 steel, 2- conventional thermal treatment, steel 20X13, 3-traditional heat-treatment, steel 40X13, 4-LCT with melting, 20X13 steel, E=30J, 5- LA with melting, 40X13 steel, E=30J 6- laser cementation, 12X13 steel, 7- gas cementation, 12X13 steel, 8- LA (C), E=20J, d=0.05, steel 20X13, LA (Si), E=11J, d=0.2, steel 20X13, 9-LA (C), E=8J, d=0.3, steel 20X13.

3.4 Laser cladding
The purpose of current study is production of fine and uniformly distributed TiC in the cladd layers. TiC has been widely used as the reinforced phase of composite materials because of its high hardness. The majority of reinforced phases are directly added into coating materials. Figure 7 presents powder characteristics used in our research. The average Ti and SiC powder particles size is about 50 µm. The substrate was low-carbon steel.
Phase analysis of the coating indicates that the dark precipitations in the cladded layer are Titanium Carbide. It is shown on figure 8.

**3.5 Microstructure and microhardness profile of the clad layers**

Microstructure of the clad layers is presented at figure 9. When the cladding velocity increases (in case of both 4 and 5kW laser power), more fine TiC precipitations are formed. In general, carbide inclusions are uniformly distributed in the coating.
The microhardness profile across the clad samples is shown at figure 10. Powder feeding rate \( Pd = 11.9 \text{g/min} \). Microhardness values are notably higher in case of \( 11.9 \text{g/min} \) powder feeding rate, than in \( 9.6 \text{g/min} \).

**Figure 10.** Microhardness profile across the clad samples, \( Pd = 11.9 \text{g/min} \).

4. Conclusions
Research of the influence of lasers alloying modes on the elastic and plastic characteristics of the surface indicated that laser doping reduces microplasticity surface-treated steels. Structures formed by laser-hardening and consisting of martensite, residual austenite and a large quantity of carbide phase have the smallest research microplasticity. Laser-hardening modes, leading to a large of carbide phase in the band structure of doping leads to increasing of heat resistance at \( 300^\circ \text{C} \) compared with
gas cementation. Doping of silicon increases heat resistance of hardened zones on 500S. Study of the electrochemical corrosion kinetics of the investigated steels by using potentiodynamic method in 3% solution of NaCl showed that Laser-hardening does not degrade the corrosion resistance compared with the traditional heat treatment, which is explained (as its shown by electron microprobe analysis results), by distribution of chromium in terms of area doping with high degree of homogeneity. Also, the possibility of hard and wear-resistant coatings formation from the Ti and SiC powders was demonstrated.

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