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Surface Structures Formed on AISI 420 Stainless Steel by Pulsed Laser Irradiation

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Abstract. The effects of TEA CO_2 laser radiation on AISI 420 stainless steel and formed surface structures are studied. The laser energy density of 45.0 J/cm^2 has modified the target surface. Qualitatively, the modifications of AISI 420 steel can be summarized as follows: change of color after action of one laser pulse; central zone of interaction in *crater* like form and *periphery zone of interaction* (for more than 10 laser pulses); appearance of *grainy* features and ablation rate of near 4 nm per laser pulse (action of 400 laser pulses); hydrodynamical effects like resolidified rim and droplets.

Introduction

Surface modification studies of metals by various types of energetic beams, including a laser beam, are of a great fundamental and technological interest. In this context, it must be emphasized that investigations of the laser beam interaction with various types of steel are highly interesting. The Nd: YAG and CO_2 (continuous-wave regime operation) are frequently used laser beams for this purpose [1,2,3]. Data about a pulsed transversely excited atmospheric (TEA) CO_2 laser beam interaction with steels, especially with AISI 420, are not sufficiently known in literature [4,5,6].

The stainless steel AISI 420 (American Iron Steel Institute classification) possesses desirable physicochemical characteristics: thermo-mechanical stability, high corrosion resistance, etc. It can be used in production of dental and surgical instruments, tools, plastic moulds and dies, etc.

The study of the TEA CO_2 laser effects on AISI 420 stainless steel was the main purpose of this work. During this investigation the TEA CO_2 laser typically emits infrared radiation at wavelength of about 10 microns. It must be pointed out that special attention was devoted to monitoring of the surface morphology on micro- and nano- scale.

Experimental

The AISI 420 stainless steel sample (thickness 1.5 mm and diameter of 15 mm) used in the experiment, prior to irradiation, was prepared by the standard metallographic procedure. This included polishing, rinsing and drying. The AISI 420 stainless steel sample possesses following chemical composition (Table 1).

Table 1 The chemical composition of AISI 420 stainless steel.

Element	C	Si	Cr	Mn	Fe
Concentration (wt.%)	0.20	0.95	13.00	1.30	balanced

Sample irradiation was done by a pulsed, UV preionized TEA carbon dioxide laser. The laser operated in the transverse fundamental mode regime - TEM_{00} mode, typically. Conventional $CO_2/N_2/He$ gas mixtures (1 atm) were used for laser pulses with a gain switched peak followed by a slowly decaying tail [6]. The laser output parameters can be found elsewhere [7,8,9] but some of the characteristic parameters, essential for this experiment, will be mentioned here: pulse laser energy density (fluence) 45 J/cm^2; laser pulse temporal shape- FWHM-about 100 ns (initial spike) and a tail with length of about 2 μs; spectral output - about 10.6 μm. Multi-pulse laser irradiation was performed in air atmosphere at a pressure of 1013 mbar and at a laser repetition rate of 2 Hz. The target was mounted on an x-y translation stage, at constant distance in z direction. [7,8], Fig. 1. Focusing of laser beam was done by KBr lens (focal length of 6.0 cm). The incidence angle of the laser beam in respect to the target surface was 90°.

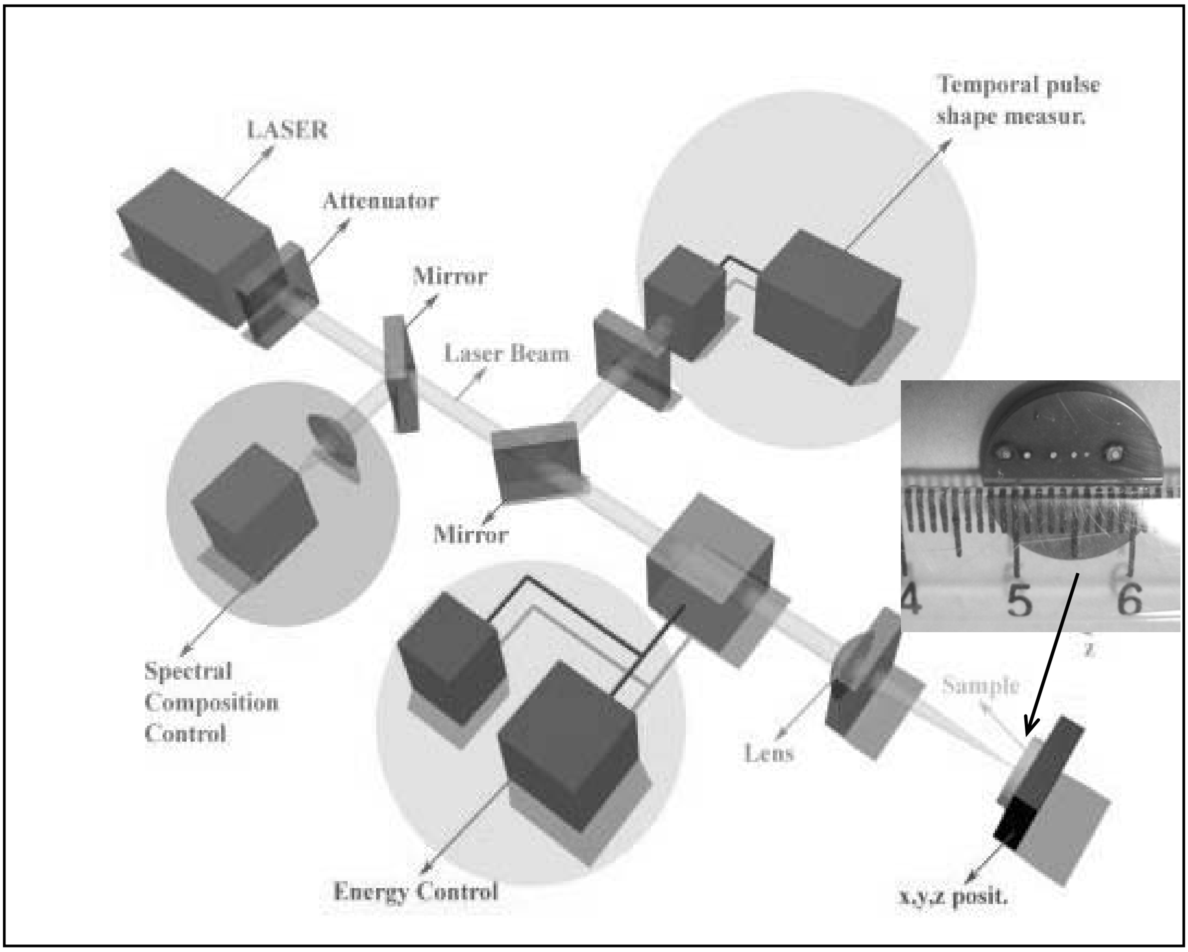

Fig. 1 Experimental set up for laser sample irradiation.

Various analytical techniques were used for the characterization of the coating surface. The surface morphology was examined by an optical microscope (OM) and by a scanning electron microscope (SEM: JEOL-JXA). A profilometer (Taylor–Hobson: Talysurf 2) served to measure surface roughness and topographic changes in irradiated region. It can define the geometry of the ablated areas. Reflectivity characterization for the spectral region of 2.5–25 μm was carried out by infrared spectrophotometer (SPECORD).

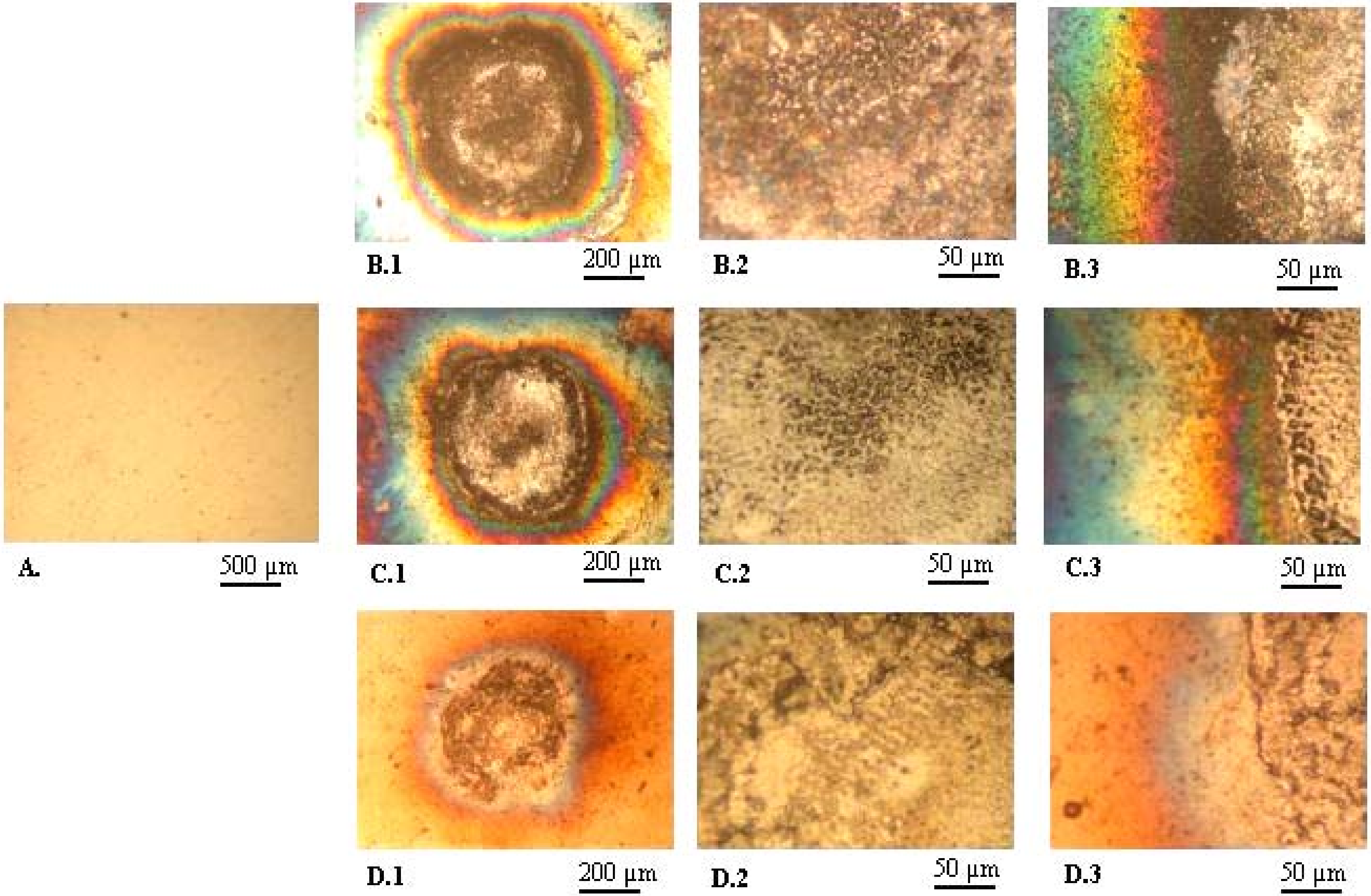

Fig. 2 A- AISI 420 stainless steel before laser irradiation. Analysis was carried out by optical microscopy. B, C and D- the steel after irradiation with TEA CO_2 laser. Laser energy density- 45 J/cm^2. (B1, C1 and D1- entire spots after 400, 100 and 10 cumulative laser pulses; B2, C2 and D2 center and B3, C3 and D3 periphery of the modified areas, respectively).

Results and Discussions

Laser induced AISI 420 morphological changes showed dependence on beam characteristics: primarily on the energy density, peak power density, pulse duration and the number of pulses. Morphological changes of AISI 420, applying 1 to 400 successive laser pulses, were analyzed. In Fig. 2, action of 10, 100 and 400 accumulated TEA CO_2 laser pulses are presented. Laser radiation energy densities of 45.0 J/cm^2 induce significant steel surface modifications. The induced alteration can be presented as follows: (i) creation of crater like features in all three cases, Fig. 2. B1,C1,D1, (ii) formation of corrugated surface structure in the central part of irradiated area (Fig. 2. B2,C2,D2), and (iii) creation of three periphery zones with appearance, on further periphery, of hydrodynamical effects, Fig. 2. B3, C3, D3.

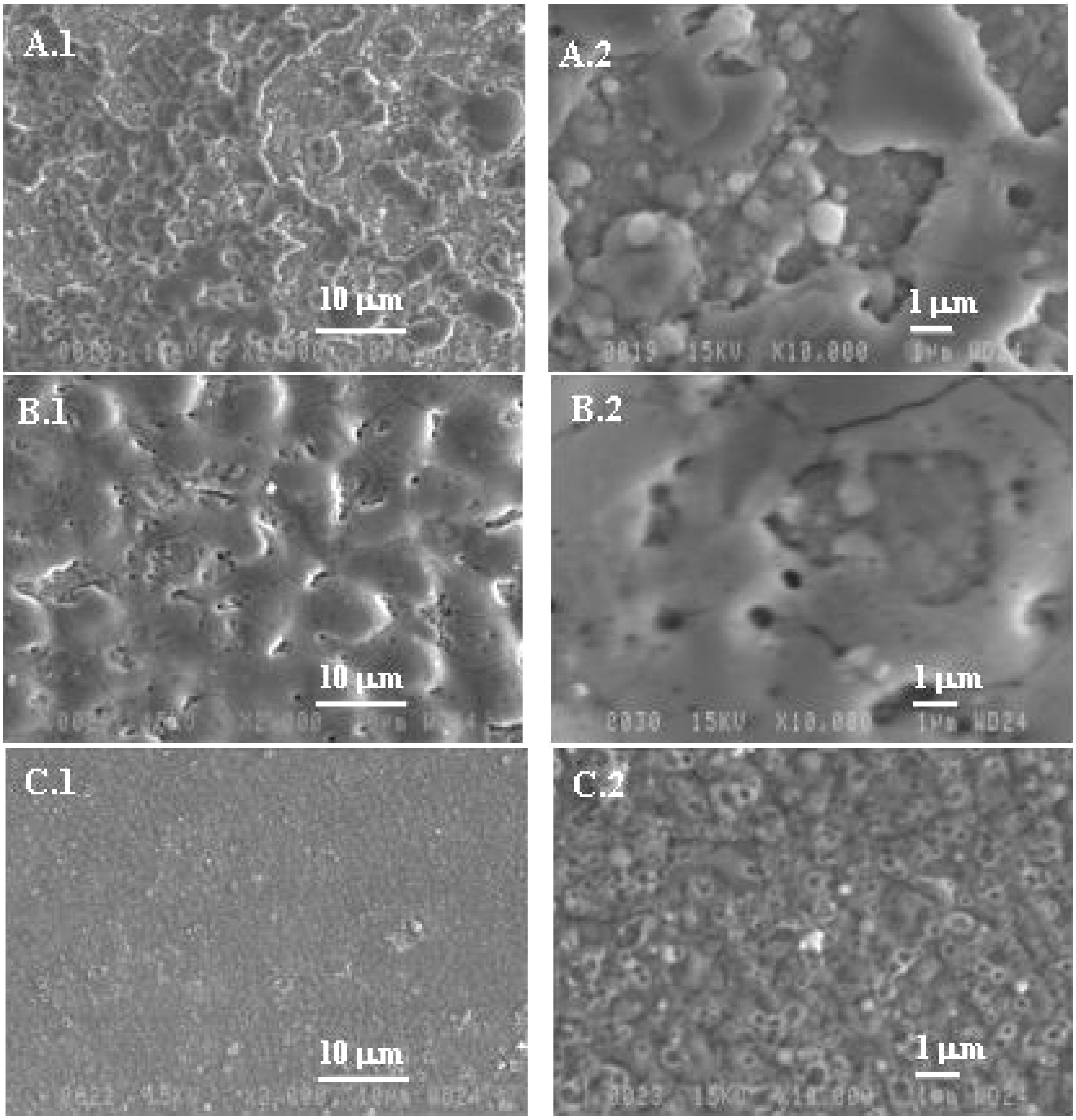

Fig. 3 The SEM image of AISI 420 steel after TEA CO_2 laser irradiation. Laser operation conditions: TEM_{00} mode; F = 45.0 J/cm^2. A-effects of 400, B-effects of 100 and C-effects of 2-laser pulses action. (A1,B1, C1–center of the damaged area and A2, B2, C2 periphery, in that order).

More detailed analysis of the laser action onto AISI 420 sample was carried out by SEM (Fig. 3). SEM analysis, Fig. 3 A2, confirms that laser action on the sample produced nano-, i.e. sub-micron structures. The registered features possess different grain sizes from 100 nm to one micron. These structures typically appeared after action of more than 100 laser pulses (at the crater bottom).

Relatively significant damage of the target implies that the sample possesses high absorptivity. The reflectivity measurement of the sample confirmed this assumption. Reflectivity value of the sample, prior to laser irradiation, was about 70% at 10.6 µm- (emission line of TEA CO_2 laser). Relatively high absorptivity of the target implies that the coupling between laser radiation and target was efficient.

The TEA CO_2 laser interaction with the AISI 420 stainless steel sample was accompanied by appearance of plasma in front of the target. A form of spark-like plasma was typically observed.

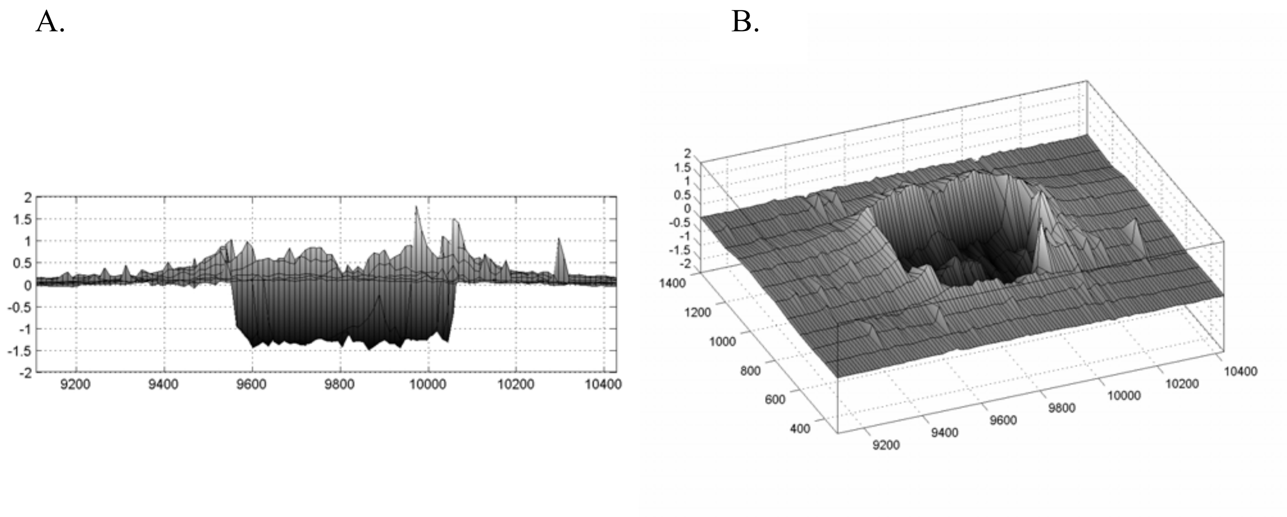

Fig. 4 Profilometer analysis, A- 2D view, of AISI 420 stainless steel after action of 400 cumulative laser pulses (x, y and z are in microns) and B- 3-D view of the same irradiated area.

Generally speaking, the energy absorbed from the TEA CO_2 laser beam is converted into thermal energy, which generates a series of effects such as melting, vaporization of molten material, dissociation or ionization of vaporized material and shock waves in vapor and in the solid [8]. It can be assumed, that a relatively high temperature was reached over the surface, which is probably responsible for steel damage/ablation. Profilometer analysis of the damaged areas confirmed crater like forms induced by irradiation, especially visible after action of 400 laser pulses, Fig. 4. The depth of crater can be estimated to be 1.5 microns (Fig. 4.), so that rate of ablation was near 4 nm per laser pulse. In addition, the ratio of the crater missed material volume (V_1= 2.48 x10^{-3} μm^3) to the material volume registered above the surface on periphery (V_2= 2.38 x10^{-3} μm^3) is ≈1. Materials redistribution, in this case, is in strong correlation with the processes on the target surface.

Conclusion

The morphological changes of AISI 420 stainless steel, induced by the TEA CO_2 laser, have been presented. The laser energy density of 45.0 J/cm^2 modified the target surface. The action of the laser, generally leads to surface damage/ablation with appearance of crater-like forms. The depth of crater-like feature, after irradiation with 400 laser pulses, was about 1.5 microns. Qualitatively, the modifications of AISI 420 stainless steel sample can be summarized: *in the central zone of* *interaction* - non-uniform features with appearance of crater forms; also registration of nano-grains; *in* the *periphery zone of interaction* - appearance of three damaged areas and change in sample color. This suggests that chemical modification such as oxidation was probable. In addition, hydrodynamical effects like resolidified rim and droplets can be detected.

Acknowledgments

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