Publ. Astron. Obs. Belgrade No. 99 (2020), 129 - 132 *Contributed Paper*

TUNGSTEN AND ODS STEEL BEHAVIOR AT HIGH INTENSITY, 10^{15} W/cm^2, LASER IRRADIATION IN AIR AND VACUUM AMBIENCE: COMPARATIVE STUDY

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Abstract. The effects of high intensity, 10^{15} W/cm^2, laser radiation on tungsten (W) and oxide dispersion-strengthened (ODS) steel in ambiences of air and vacuum were studied. In both samples and mediums high intensity laser radiation induced morphological and chemical variations. Surface features and phenomena depend on the material characteristics and the ambience applied. Thus, crater depth was larger in vacuum then in air for ODS steel sample - ~55 µm vs. ~9 µm. Irradiation was accompanied with the appearance of plasma which can emit X-ray radiation. Chemical surface changes, particularly oxidation, were registered as well.

1. INTRODUCTION

The study of laser-material interaction is of particular interest in the last decade, primarily owing to modern applications, see Aliofkhazraei 2016. The use of intense ultrashort lasers, like femtosecond (fs) laser applied in this work, is essential due to creation of specific surface features. W and ODS steel considered here have extraordinary characteristics making them attractive for various applications, including nuclear complex (construction of fission and fusion reactors). In inertial fusion (IF) reactor both metals are serious candidates as the First Wall Materials (FWM), see Trtica 2018. FWMs are exposed to various fluxes like electromagnetic and thermal, thus the action of high intensity laser radiation can, in one approximation, simulate behavior of these materials inside the reactor, Montanari et al. 2017 and Trtica et al. 2020. The goal of this paper is to study the behavior of W and ODS steel under conditions of high laser intensity - 10^{15} W/cm^2 in air and vacuum. Variations of morphological features and chemical surface content were the primary aim.

2. EXPERIMENTAL

Tungsten sample (disc, diameter 25 mm, 3 mm thick) was produced by sintering process, with the grain size ~20-80 µm, using Ni/Cu and Ni/Fe binders. ODS steel (square, 10 mm × 10 mm, 0.4 mm thick) was synthesized by mechanical alloying and hot isostatic pressing in Ar, with composition (wt%) Cr(16):Al(3):W(1.5)-Y_2O_3(0.35) and Fe (balance). Average sizes of Y_2O_3 and pre-alloyed powders were 40 nm and 50 µm, respectively. Experimental setup is the same as in works Trtica 2018 and Trtica et al. 2020 - laser beam with 15 mm diameter was focused through lens (f=150 mm) perpendicularly on the sample. The fs laser was Ti:sapphire (PULSAR, Amplitude Technologies), wavelength 804 nm; pulse 60 fs; pulse energy ≤12 mJ; TEM_{00} mode; linearly, vertically polarized beam. Irradiations were performed at 1013 and $\sim 1\times10^{-4}$ mbar pressure in air and vacuum, respectively. Characterization was done by optical microscope, scanning electron microscope (SEM) with energy dispersive analyzer, and optical interferometric profilometry.

3. RESULTS AND DISCUSSION

Material surface changes by laser depend on various irradiation parameters - laser parameters (wavelength, pulse length, pulse count, intensity, etc.), as well as material properties (e.g. absorptivity) and ambience. Experimental work was focused on morphological and chemical effects induced on W and ODS steel surface in air and vacuum by fs-laser after the action of 100 pulses.

3. 1. IRRADIATION IN AIR AMBIENCE

The effects of fs laser on W and ODS steel at the pulse energy of ~5.2 mJ and intensity $\sim 10^{15}$ W/cm^2 are shown in Fig. 1. Generally, complex effects were detected: (a) crater like features in both samples, more prominent in ODS steel (Fig.1 A1-3 and B1-3); (b), surface cracking in the central zone, with additional grain fusion in case of W; (c) cross section of the craters was conical in both targets with similar depth, ~9 µm; (d) at the peripheral region more intense lifting of the material detected in W. Only in case of ODS steel laser induced periodic surface structures (LIPSS) were recorded. Also, hydrodynamic (HD) effects were much more prominent in case of W (Fig. 1 A3). Fundamentally, the process of fs-laser-metal interaction is complex and starts with free electrons absorbing the incident radiation, see Trtica et al. 2020. Further, the hot electrons cool down by diffusion and electron-phonon interaction leading to thermal equilibrium between lattice and electron subsystems. The dynamics of the system prior to this equilibrium can be described by two-temperature model. Finally, after several ps, laser-metal interaction can be considered a thermal process. If the initial laser intensity is sufficient, the ablation can take place on a time scale ≥100 ps. The ablated material cools rapidly in a space close to the target, and it can build up unique structures on the surface. Ablation mechanisms are diverse and they can comprise phase explosion, fragmentation, etc. Creation of LIPSS recorded in this experiment is a complex process as well, and one explanation includes the interference of incident laser beam with the so-called surface waves, scattered off the imperfections on the material and running along its surface.

At high laser intensities plasma was formed above the samples and it was expected to emit x-ray radiation. Chemical surface changes (central zone) were more prominent in case of ODS steel, i.e. [O] was 2.6% against 1.0% in W.

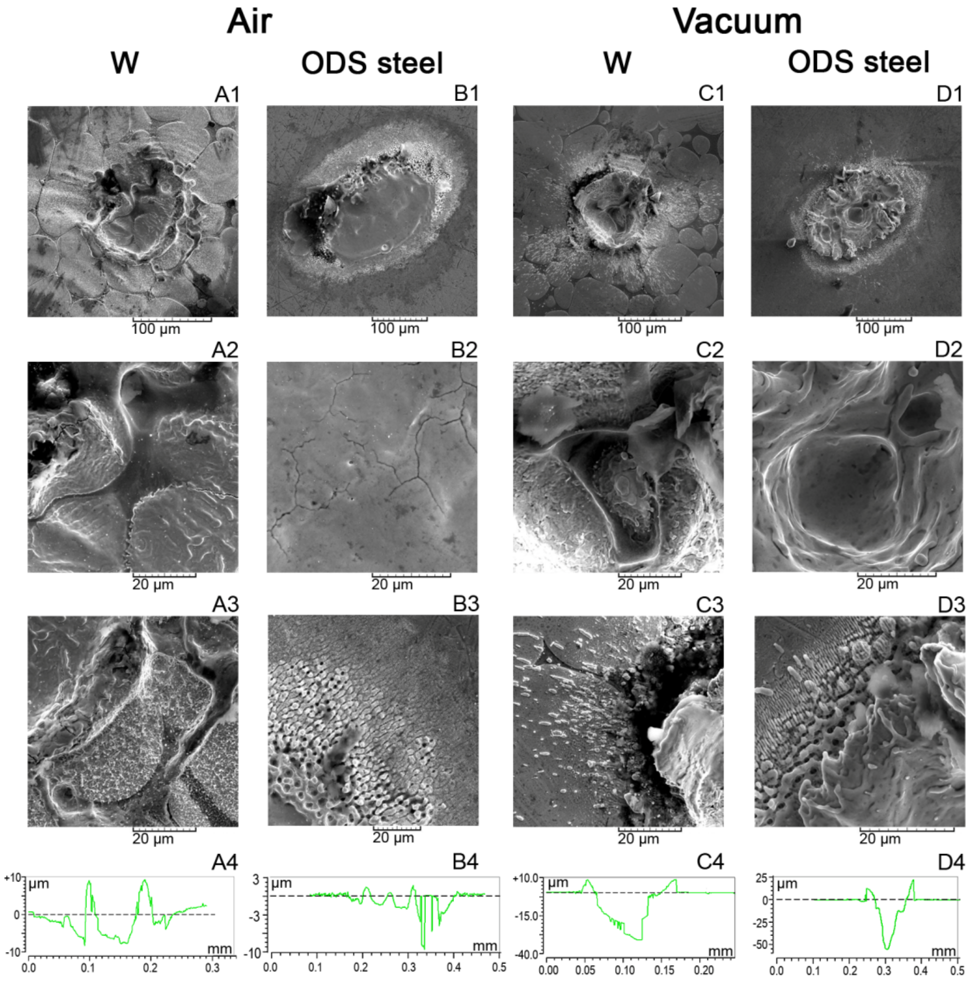

Figure 1: SEM and 2D profilometric analysis of W and ODS steel after action of laser pulses in air and vacuum. Energy ~5.2 mJ, intensity ~10^{15} W/cm^2.

3.2. IRRADIATION IN VACUUM AMBIENCE

In the main, modifications of both targets in vacuum are more pronounced than in air which is explained by better coupling of laser radiation with the surface.

Changes are as follows: (a) in the central zone, grain fusion is present in W - Fig. 1 C2, while violent structure was obtained in ODS steel (Fig. 1 D2). Crater depth was more prominent in steel, i.e. ~55 μm vs. ~33 μm in W; (b) lifting of the material on the periphery was more prominent in steel, while HD effects were dominantly observed in W. LIPSS are registered only on steel. Also, in vacuum ambience, at the intensity used, plasma was generated above both samples. Chemical analysis (central zone) showed that oxidation was absent in case of W while at ODS steel surface it was strong, in the interval from ~2 to ~36%, probably caused by redistribution of oxygen which is initially present in the sample.

4. CONCLUSION

Study of fs laser-target (W and ODS steel) interaction in air and vacuum was presented. It was shown that applied laser pulse energy of ~5.2 mJ, intensity 10^{15} W/cm^2, induced distinguishing surface features and phenomena. Generally, they are in strong correlation with sample type and ambience: (i) in both targets crater like damages were registered with crater depth larger in ODS steel, ~55 μm, vs. ~33 μm for W in vacuum. Also, damages were always more prominent in vacuum. In the peripheral area specific changes were registered such as HD effects, LIPSS; (ii) irradiation was accompanied with the appearance of plasma which can emit x-ray radiation; (iii) chemical surface changes, particularly oxidation, were registered in air as well as in vacuum but only in ODS steel. The results could contribute to better understanding of the behavior of nuclear reactor materials under high fluxes that can be simulated by laser intensities applied here.

Acknowledgements: The research was sponsored by the: (i) Ministry of Education, Science and Technological Development of the Republic of Serbia, project 172019; (ii) IAEA project "Pathways to energy from inertial fusion: Materials beyond ignition"; (iii) ESIF and the Czech Republic, the Project Center of Advanced Applied Science [CZ.02.1.01/0.0/0.0/16_019/0000778] - through The Operational Program. Research, Develop. and Education and, (iv) Czech Ministry of Education, Youth and Sports [project LTT17015].

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