Analysis of optical spectra from steel samples exposed to pulsed plasma streams

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Abstract. In the reported studies the attention was focused on an analysis of optical spectra of the visible radiation emitted from stainless steel (SS) samples exposed to intense pulses from a ND:YAG laser or pulsed plasma streams produced by a Rod Plasma Injector (RPI) IBIS. Operational regimes of the RPI IBIS facility, which can generate intense deuterium-plasma streams, were studied and corresponding energy fluxes were determined. Optical emission spectra from the laser- or plasma-irradiated SS samples were recorded at different energies supplied. It was proved that intensities of the emitted spectral lines of Fe I and Cr I species depend strongly on deuterium-plasma energy deposited upon the irradiated target.

1. Introduction

The austenitic stainless-steel (SS) is a very good material to construct different parts of plasma facilities, e.g. vacuum chambers, in-vessel components, diagnostic ports, etc. Several years ago, it was recommended that the main constructional material of the ITER facility should be of the SS type [1]. Therefore, it was of interest to investigate behaviour of SS samples under irradiation by intense plasma streams, and to study damages caused by plasma containing fast electrons and ions (particularly fast deuterons and protons). The main question was to investigate which SS type is the most resistant to erosion induced by plasma impacts. It was known that the optical emission spectroscopy can deliver important information about dynamics and parameters of the investigated plasma streams. Such data are of primary importance for research on the interaction of plasma streams with various targets. Therefore, new experiments have been undertaken for different SS types, using intense laser pulses and pulsed plasma streams.

2. Experimental setup and diagnostics

Detailed investigations were carried out for two types of SS samples. A chemical composition of them is given in a Table 1.

Table 1. Chemical composition of the investigated SS types.

| Main elements [%] | SW7 | S316/316L |
|------------------|-----|-----------|
| Cr               | 3.5-4.5 | 16-18      |
| Ni               | 0.4  | 10-14      |
| Mo               | 4.5-5.5 | 2-3        |
| W                | 6-7  | -          |
| Fe               | basic | basic      |
Irradiation tests of the chosen SS samples of dimensions 3 x 2 x 0.2 cm\(^3\) were performed within two different experimental facilities. In the first experiments the samples were exposed to laser pulses only, and during the main experiments they were irradiated by intense deuterium plasma streams.

During the first experimental series the SS samples were placed at the centre of the vacuum chamber and irradiated by intense pulses from a Nd:YAG laser of the LOTIS TII type, which operated at \(\lambda_{\text{l}} = 1064\) nm and delivered 3 ns-pulses of energy from 0.1 J to 0.5 J. The laser beam was introduced at an angle of 30\(^\circ\) to the target normal and focused (by means of achromatic lenses with \(f = 42\) cm) to the spot of 1 mm in diameter. Optical observations were carried out at an angle of 30\(^\circ\) to the target normal, through a quartz collimator and an optical cable. Spectroscopic measurements of the visible radiation, which was emitted from plasma produced during the interaction of a laser beam with the target, were performed by means of a Mechelle®900 optical spectrometer. It was able to record optical spectra in the wavelength range from about 300 nm to 1100 nm, at expositions varied from 100 ns up to 50 ms.

The main experimental studies have been performed within the RPI-IBIS facility equipped with molybdenum (Mo) electrodes [2-4], which were powered from a condenser bank charged to \(U_{0} = 28\) kV. The peak discharge current amounted to \(I_{\text{max}} = 550\) kA. The operational mode of the device was varied by changes of a time delay between the gas puffing and the application of a high-voltage pulse. In order to record optical emission spectra in the RPI-IBIS facility the use was made of the same Mechelle®900 spectrometer, which observed the irradiated sample through a quartz collimator and an optical cable. The positioning of the SS target, which was placed at a distance of about 20 cm from the electrodes outlet, as well as typical discharge traces are shown in Figure 1.

![Figure 1](image)

**Figure 1.** Location of a SS target inside the RPI-IBIS vacuum chamber (a), and a temporal correlation of the voltage \(U_{d}(t)\) and current \(I_{d}(t)\) traces with a pulse used to trigger the Mechelle-900 spectrometer (b).

### 3. Experimental results and discussion

#### 3.1. Results of the irradiation of the SS samples by laser pulses

During the preliminary experiments the investigated SS samples were exposed to focused Nd:YAG laser pulses of the same duration (3 ns), but different energy which was equal to \(E_{\text{l}} = 0.15\) J, 0.2 J, 0.3 J and 0.44 J. Since the samples were irradiated under vacuum conditions, at the background pressure \(p_{0} = 6.8 \times 10^{-5}\) mbar, the radiation emitted from laser-produced plasma had an optical spectrum composed of the spectral lines originated only from components of the irradiated target-material. There were no lines from other materials and impurities which are often observed during experiments with pulsed plasma streams.

The visible radiation emitted from plasma produced in the near-target region, due to erosion of laser-irradiated samples, was recorded by means the Mechelle®900 spectrometer described above. Some examples of the recorded optical spectra are presented in Figure 2.
Figure 2. Part of the optical spectrum from plasma produced from the SW7 samples irradiated by laser pulses of different energy (a) and another part of the optical spectra obtained from different SS samples irradiated by laser pulse of similar energy (b).

The optical spectra presented in Figure 2a, as recorded for plasma created by surface erosion of the SW7 samples, showed that the near-surface plasma production and intensity of its radiation depended considerably on laser pulse energy. There were identified distinct spectral lines originated from Fe I species (because iron was the main component of the SS samples), as well as intense lines of W I – 411 nm, Mo I – 418 nm, and Cr I – 432 nm (originated from other sample-components). As expected, intensities of all the mentioned spectral lines increased with an increase in laser pulse energy.

A comparison of the optical spectra obtained from SW7, S316 and S316L samples exposed to laser pulses of comparable energy, as presented in Figure 2b, showed that intensity of the plasma radiation from the S316L sample was about 1.5 times lower than that from the SW7 sample. In the case of the S316 sample the optical emission was still lower in spite of the fact that laser-pulse energy was about 10% higher. Hence, one could conclude that the S316 sample has higher resistance to erosion induced by a laser impact. Therefore, it was reasonable to check whether this effect occurs also when the chosen SS samples are exposed to pulsed plasma streams impinging upon the target surface.

3.2. Results of irradiation of the SS samples by pulsed plasma streams

The main experiments on the erosion of the SS samples were performed within the RPI-IBIS facility described above. The optimal operational mode of this device was found on the basis of the optical emission spectra presented in Figure 3.

Figure 3. Optical emission spectra of pulsed plasma streams generated within the RPI-IBIS facility, which were recorded for different operational modes.
Earlier experiments with the RPI-IBIS facility showed that the operational mode could be modified by a change of a time delay $\tau$ of the discharge ignition in relation to the gas injection [2-4]. In order to expose the SS samples to clean deuterium plasma streams a so-called PID mode was chosen at $\tau = 215 \mu$s, and plasma energy-flux density equal to 8 J/cm$^2$. On the basis of the optical spectra, analyzing a linear Stark effect of D-lines, the Voigt contour fitting and the know formula $\Delta \lambda_{1/2} \approx n_e^{2/3}$ [5], it was estimated that the electron density of a freely-propagating plasma stream was $(1.1-2.2) \times 10^{15}$ cm$^{-3}$.

During the main experimental session the chosen S316 sample was irradiated in the RPI-IBIS facility, and the optical spectrum from near-surface plasma was recorded, as presented in Figure 4a. For a comparison a SW7 sample was also irradiated under the identical experimental conditions, and the corresponding spectrum was obtained, as shown in Figure 4b.

From the spectra in Figure 4a one could easily see that during interactions of a deuterium plasma stream with the S316 target there were emitted many spectral lines of Mo I, Fe I and Cr I, which evidently originated from the eroded material. In that case the electron density of near-surface plasma (integrated over the whole discharge period) amounted to $(3-7) \times 10^{15}$ cm$^{-3}$. During discharges when the spectrometer exposition time was shorter (e.g. 5 $\mu$s) the electron density amounted $5 \times 10^{16}$ cm$^{-3}$.

A comparison of the spectra shown in Figure 4b confirmed that intensities of the observed spectral lines from the S316 sample were about twice lower than those from the SW7 target. It should here be noted that intensity of the Mo I - 455.8 nm line, which originated from the Mo-electrode erosion, remained unchanged for experiments with both types of the SS samples.

4. Summary and conclusions

Interactions of laser pulses and pulsed plasma-streams with different austenitic stainless-steels (SW7 and S316/316L) were investigated. The operational regimes of the RPI-IBIS facility were controlled and corresponding plasma energy flux densities were measured. During irradiations of the chosen samples many spectral lines from iron and other target-components were recorded. The samples of the S316/316L type showed higher resistance to erosion than the SW7 samples.

Therefore, for the construction of plasma facing components it was recommended to use the S316/316L stainless-steel. It was also proved that the RPI-IBIS facility may be applied for research on interactions of plasma streams with materials at power fluxes amounting to 5 MW/cm$^2$.

References
[1] D. Stork, S.J. Zinkle, Nucl. Fusion 57 (2017) 092001 (9pp).
[2] M.J. Sadowski, J. Baranowski, et al., Appl. Surface Science 238, Issues 1-4 (2004) 433-437.
[3] J. Piekoszewski, J. Stanislawski, et al., Czech. J. Phys. 54, Suppl. C (2004) C217-C222.
[4] E. Skladnik-Sadowska, K. Czaus, et al., Nukleonika57, No 2(2012) 193–196.
[5] Plasma Diagnostic Techniques, Edit. R.H. Huddleston, S.L. Leonard (Academic Press, 1965).