In-situ laser-induced contamination monitoring using long-distance microscopy

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ABSTRACT

Operating high power space-based laser systems in the visible and UV range is problematic due to laser-induced contamination (LIC). In this paper LIC growth on high-reflective (HR) coated optics is investigated for UV irradiation of 355 nm with naphthalene as contamination material in the range of 10^{-5} mbar. The investigated HR optics were coated by different processes: electron beam deposition (EBD), magnetron sputtering (MS) or ion beam sputtering (IBS). In-situ observation of contamination induced damage was performed using a long distance microscope. Additionally the onset and evolution of deposit formation and contamination induced damage of optical samples was observed by in-situ laser-induced fluorescence and reflection monitoring. Ex-situ characterization of deposits and damage morphology was performed by differential interference contrast and fluorescence microscopy.

It was found that contamination induced a drastic reduction of laser damage threshold compared to values obtained without contamination. Contamination deposit and damage formation was strongest on IBS followed by MS and smallest on EBD.

Keywords: LIC, laser-induced contamination, contamination induced damage, high-reflective optics, coating techniques, long distance microscope, fluorescence, damage threshold

1. INTRODUCTION

The aim of these investigations is the qualification and evaluation of optics for long term space operation. One outstanding critical point which can drastically shorten the lifetime of space borne laser systems operating in the UV is laser-induced contamination. LIC is primarily induced by molecular contamination and it denotes the interaction of laser radiation with volatile molecules and the resulting formation of deposits on optical components [5]. Especially organic materials, even if present in small quantities, e.g. glues, adhesives, insulating materials, or circuit boards could contribute to LIC. By selection of suitable materials and preconditioning e.g. bake-out at elevated temperatures well above planned operating temperature the outgassing can be reduced but not totally prevented. LIC proved to be most critical, if the laser system is operated under vacuum conditions and it is becoming increasingly important the shorter the wavelength and the higher the fluences [8]. Although quite a lot of work on LIC was already done there is up to now no fundamental understanding of this phenomenon and it is still a serious risk for space based systems.

In general all optical elements in laser systems are coated for enhancement of their optical properties. But not all coating techniques are suitable for space applications. In corresponding LIDT tests it was demonstrated that optics which were coated by MS or IBS showed better performance than those coated by EBD. In former LIC tests with AR optics MS coated samples showed less contamination and higher reliability than EBD optics [8]. In this paper the examination of high-reflective coatings with regard to LIC is reported. The correlation between contamination, damage formation and optical performance is investigated. In particular the onset and further development of contamination induced damage is analyzed.

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2. TEST SETUP

2.1 LIC test bench

Fig. 1 shows the setup which was used to perform laser-induced contamination tests for space optics. Space conditions are simulated in the ultra-high vacuum (UHV) chamber. The contamination process is enforced by evaporating an organic contaminant into the UHV chamber. As contaminant naphthalene was chosen due to its high vapor pressure, and easy handling. The contamination chamber can be heated from outside by electrical heating bands for acceleration of the outgassing. By a needle valve the mass flow into the main chamber can be regulated and a temporally constant pressure can be adjusted. A partial pressure in the range of 10^{-5} mbar was used for LIC tests.

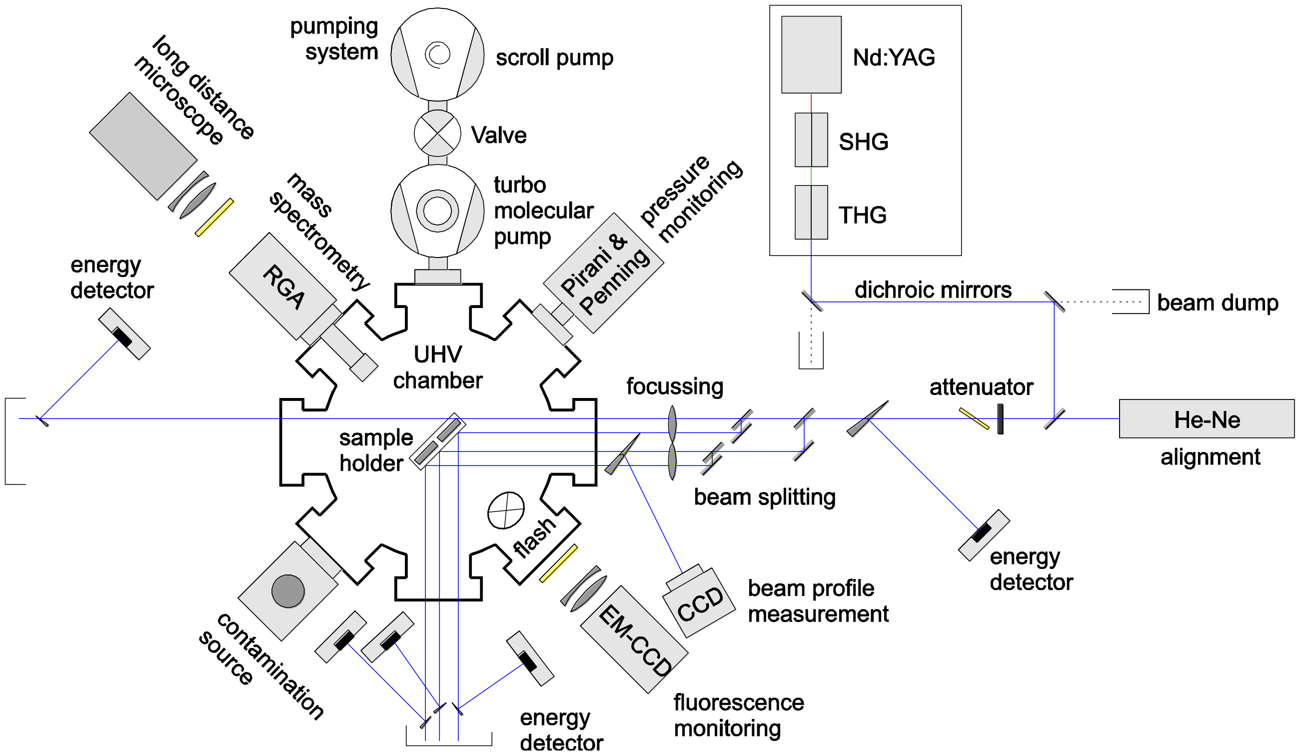

Figure 1: Laser-induced contamination test bench for testing HR coated optics.

As UV laser source a pulsed Nd:YAG laser with subsequent frequency doubling and tripling unit is used at 355 nm. The pulse frequency is 1000 Hz with a pulse width of 10 ns and pulse energy up to 1.9 mJ. The beam is split into four identical beams to allow tests of three different samples simultaneously under identical conditions. One beam is used for reference. A moveable sample holder allows performing several tests successively without breaking the vacuum.

Focusing lenses ensure that on the chamber windows the beam diameter is larger and consequently the energy density is considerably lower than on the optical samples. This ensures that contamination is mainly formed on the optical samples and not on the windows. The beam diameter is about 260 µm on the sample plane.

2.2 Experimental

Different monitoring units are available for investigation of contamination and damage occurrence. Energy detectors record the reflectivity of each sample. To investigate damage formation a long distance microscope is installed to monitor the sample inside the UHV chamber during irradition. It consists of a Maksutov-Cassegrain Catadioptric lens design in combination with a single lens reflex camera. To resolve even small damage under sufficient contrast the optical sample needs to be illuminated. A flash is triggered by the camera and illuminates the sample from the back. The long distance microscope is mounted in front of the UHV chamber window. By an appropriate filter unwanted, scattered

UV light from the laser source is blocked. The microscope is focused onto the front side of the HR coated samples and the images are recorded in-situ during LIC tests. An optical resolution down to 10 µm is possible with this setup.

For damage investigation reflectivity measurements are used and compared with surface micrographs recorded by the long distance microscope. For comparison of tests with different contamination pressure and fluence a break point is defined. This is the time where the reflectivity drops below 95 %.

To analyze LIC deposits with high spatial resolution all samples are investigated after the tests by fluorescence microscopy. Organic materials show high fluorescence and in former tests it was shown that the fluorescence scales with deposit thickness [3]. All FM images were taken with same magnification and exposure time in stitching mode. Each image is a mosaic combined of several images by the microscope software. The fluorescence line scans show background corrected results.

All tested coatings (EBD, MS, IBS) are made by the same manufacturer on fused silica substrates (1'' diameter). All coatings have a SiO_2 top layer and are made for an angle of incidence of 45° at 355 nm.

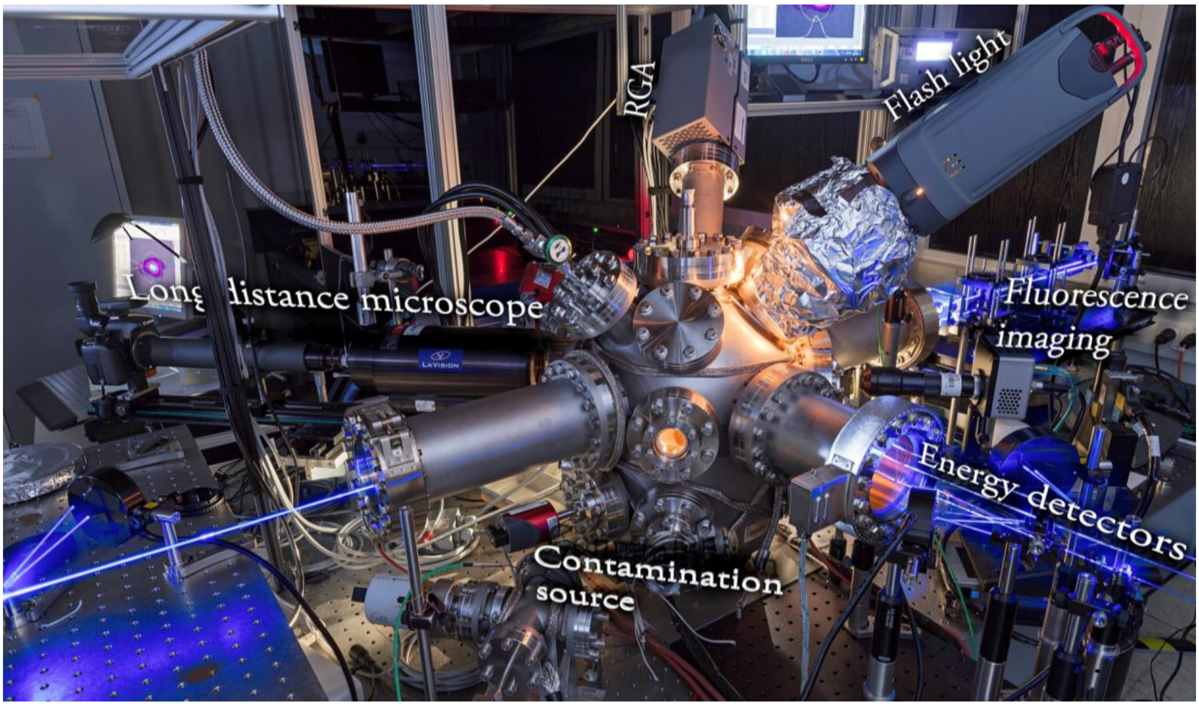

Figure 2: UHV chamber equipped with various sensors for process monitoring.

3. RESULTS

3.1 Deposit formation

To investigate the deposit growth as a function of time the laser radiation time was varied for tests on different sample positions by moving the sample holder and while keeping same contamination conditions. Top image on Fig. 3 shows fluorescence for EBD, middle for MS and bottom for IBS samples. From left to right the laser irradiation time increases from 15 min up to 60 min. Laser fluence was 300 mJ/cm² and contamination pressure was $2x10^{-5}$ mbar naphthalene. No contamination induced damage was observed during these tests due to short laser irradiation time. The line scans in Fig. 4 are taken from FM images across the center of deposits. These profiles show the fluorescence level after laser irradiations of 15 min, 45 min and 75 min on EBD, MS and IBS samples.

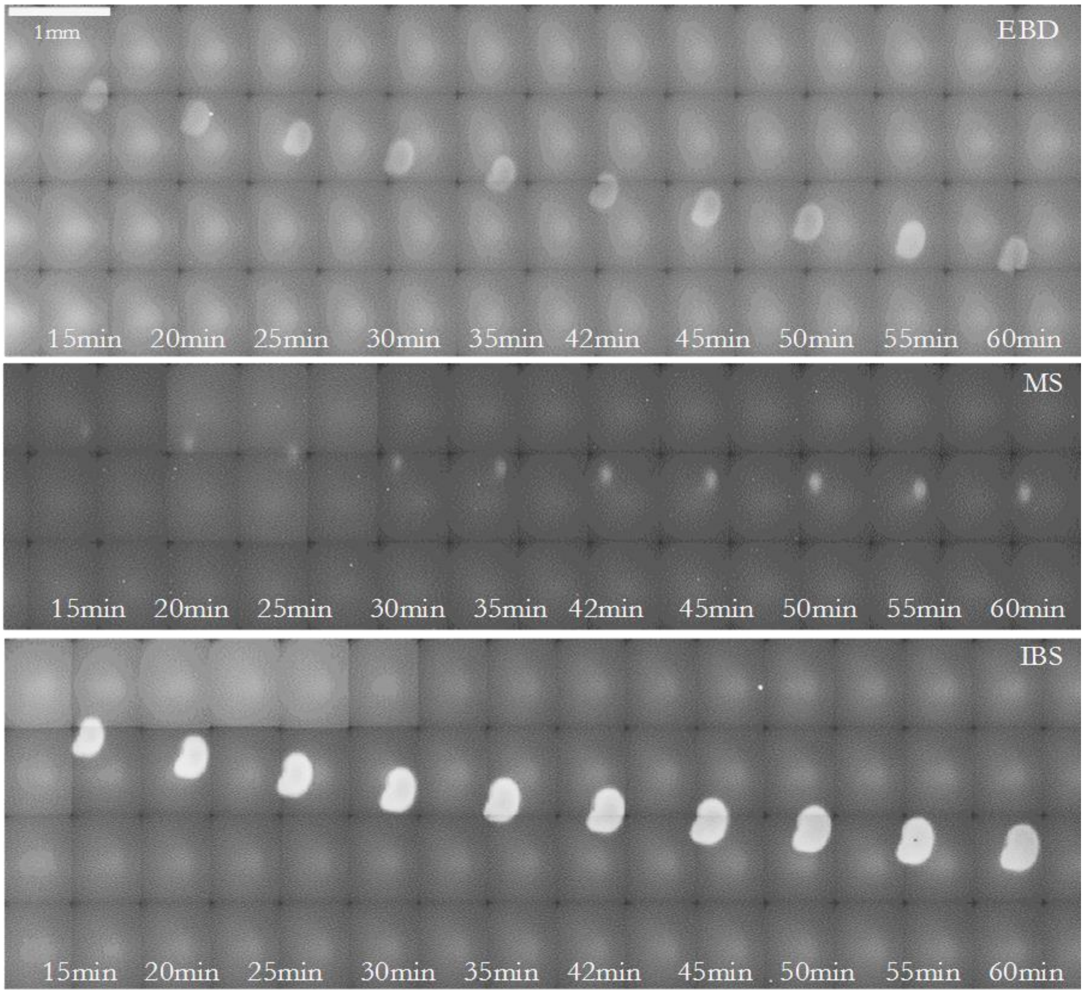

Figure 3: Fluorescence micrographs after LIC tests show deposit formation. Laser irradiation time varied from 15 min up to 60 min. Fluence was 300 mJ/cm² with contamination pressure of 2 x10^{-5} mbar.

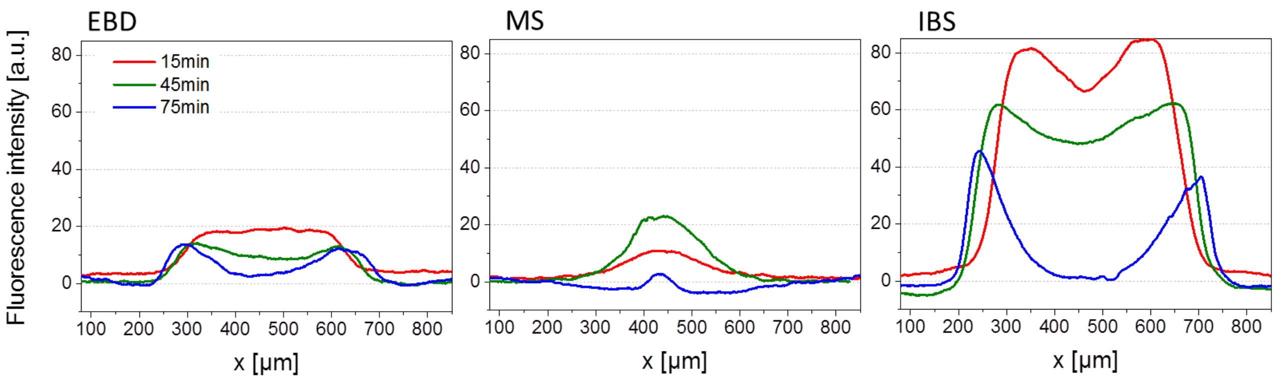

Figure 4: Fluorescence line scans of LIC tested samples after 15, 45 and 75 min.

For IBS sample fluorescence intensity is considerably higher than for EBD and MS samples. For all three samples the fluorescence intensity decreased in the center of the beam for higher irradiation time, indicating that there is a competitive ablation or transformation to non-fluorescent material. For IBS and EBD samples doughnut shaped deposits are clearly visible, but for MS sample the shape remains Gaussian like for investigated irradiation time up to 75 min. The surface covered by contamination on MS samples is smaller with a diameter of about 150 µm than on EBD samples with about 300 µm and IBS samples with about 400 µm.

3.2 Damage threshold

During several long term tests, which were run up to 30 hours, contamination induced damage was investigated in dependence on fluence and contamination pressure. Figure 5 shows as an example the reflectivity of the HR samples coated by EBD, MS and IBS in dependence on irradiation time for a test with a fluence of 900 mJ/cm² and a contamination pressure of 4 x10^{-5} mbar. For IBS sample the reflectivity decreases much earlier than for EBD or MS samples. Ex-situ investigations verified that damage occurred. The comparison of the breakpoints shows that EBD samples always performed best followed by MS and IBS samples (Fig 6).

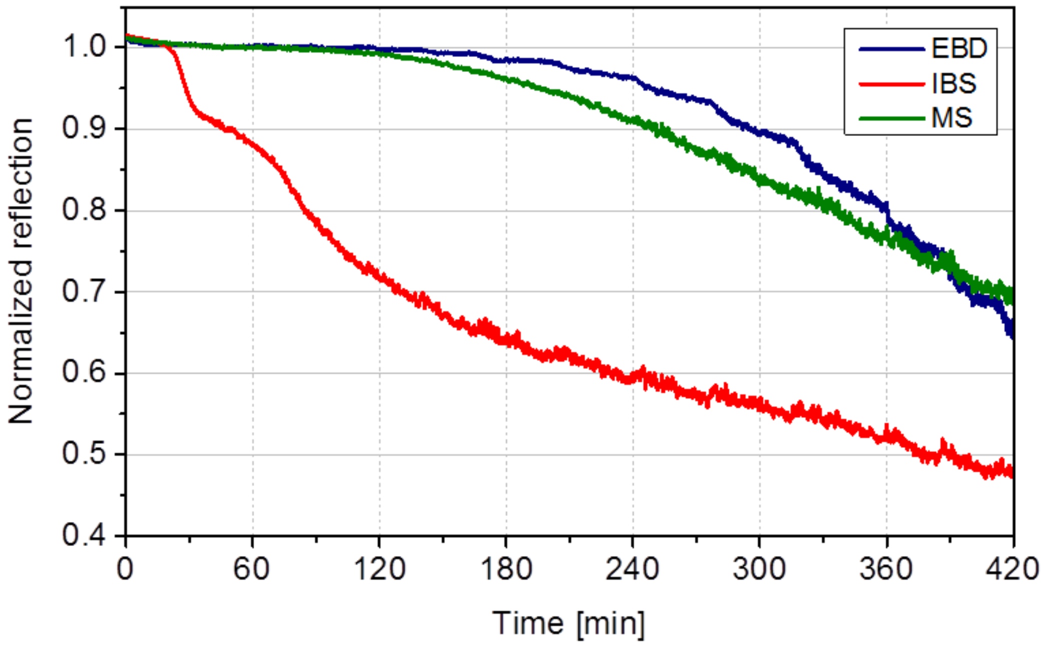

Figure 5: Normalized reflection measurement of the EBD, MS and IBS samples during a LIC test. Test conditions are H_{peak} = 900 mJ/cm², with a contamination pressure of p = 4 x10^{-5} mbar.

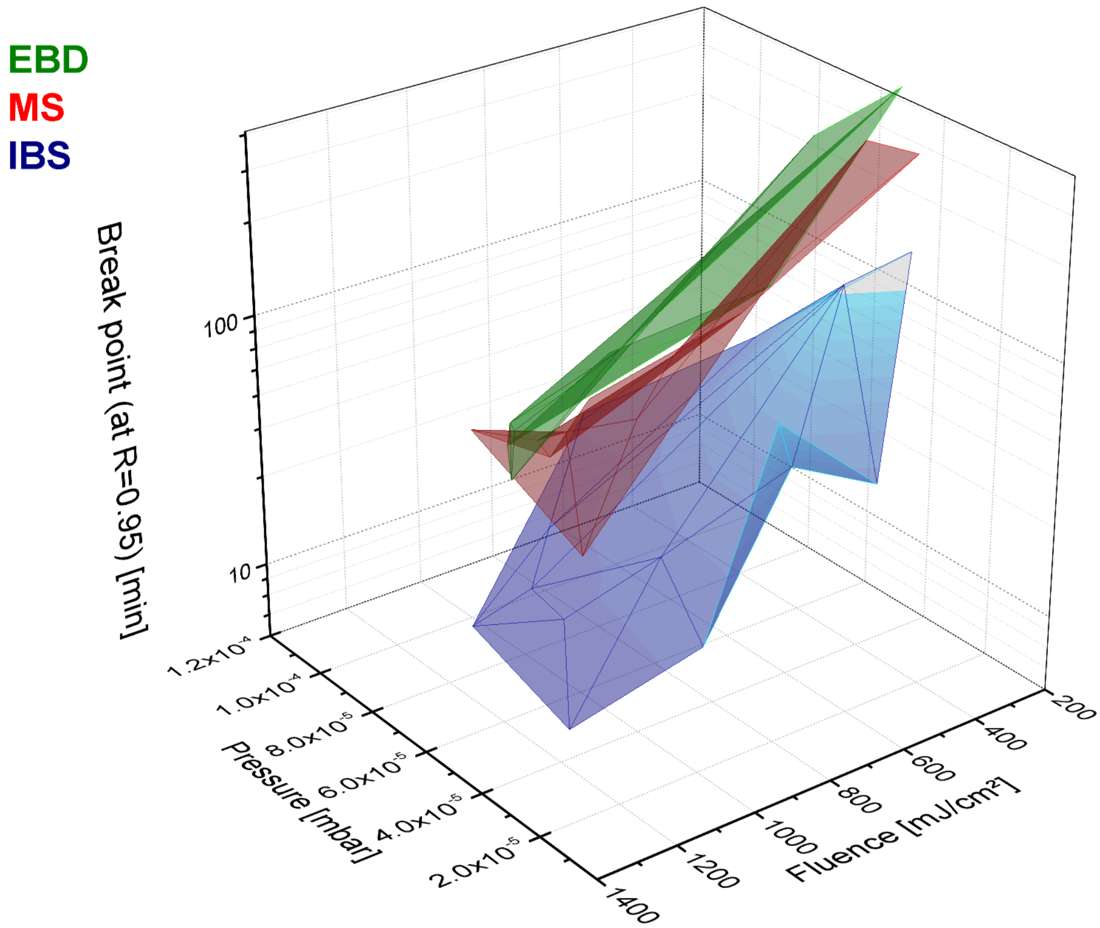

Figure 6: 3D-plot of the break point in dependence on fluence and contamination pressure for EBD (green), MS (red) and IBS (blue) samples.

3.3 Contamination induced damage

For in-situ monitoring of damage formation and dynamic the long distance microscope was used. Figure 7 shows the relation between LDM micrographs and reflectivity for a test with EBD coated HR sample. It was tested with a fluence of 400 mJ/cm² and a contamination pressure of $p = 3.1 \times 10^{-5}$ mbar. After 10 hours damage becomes visible. A couple of locally spread spots appear with a size of about 10 µm each. This has only a slight effect on the reflection loss, which decreased to 98 %. By ex-situ investigation with atomic force microscopy it was demonstrated that these damages are small holes in the coating. These small damages appear to start at almost the same time and are spread within the area of the beam spot. By further these small spots merge until they form a large damaged area after 24 h.

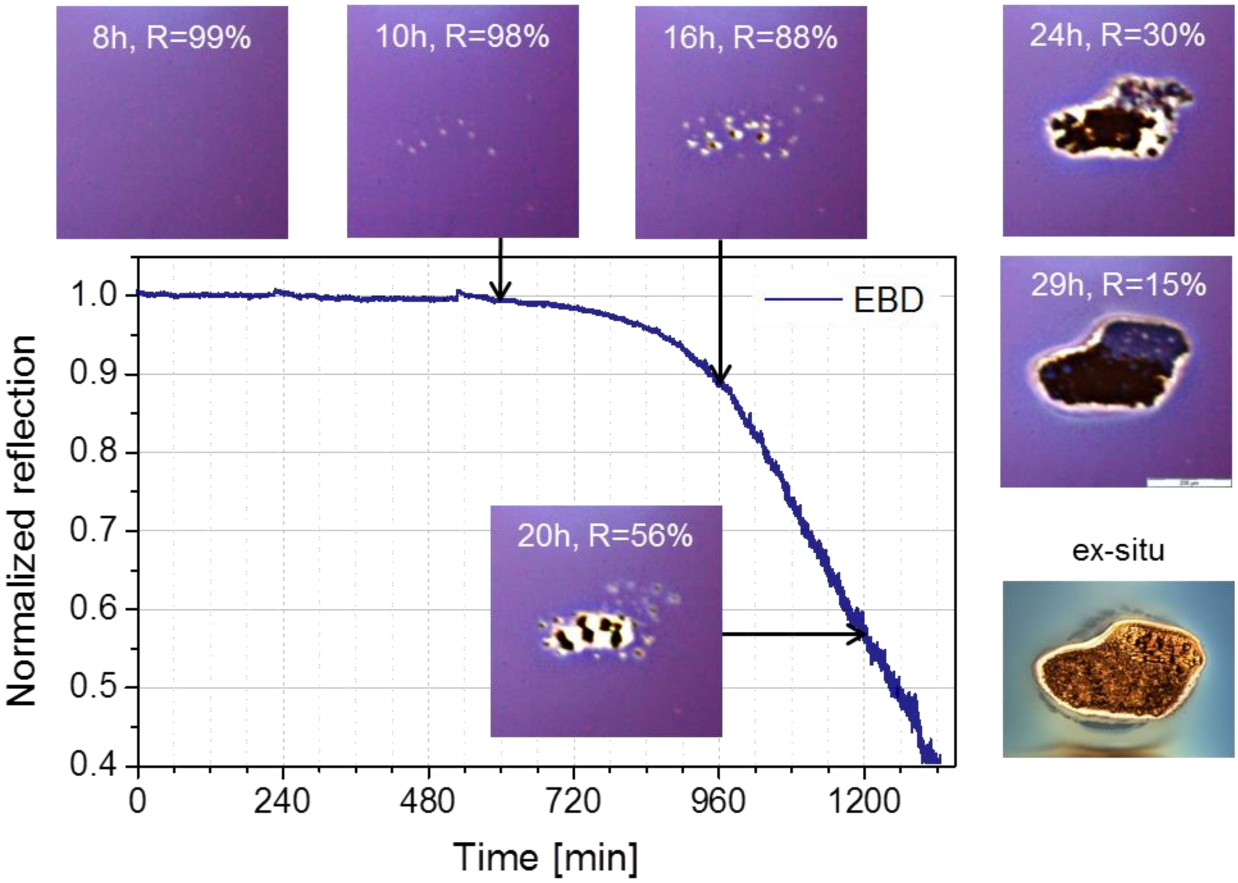

Figure 7: Normalized reflection measurement of the EBD sample during a LIC test. Test conditions are H_{Peak} = 400 mJ/cm² with a contamination pressure of p = 3.1 x10^{-5} mbar. After 10 h (36 mio. shots) of irradiation the reflection starts to degrade and in-situ long distance microscope images show damage growth. In addition ex-situ DIC micrograph is shown.

The MS coated optic was tested at a fluence of 660 mJ/cm² and a contamination pressure of 1 x10^{-5} mbar. MS samples show a different contamination shape than IBS and EBD samples (see Figure 4). But the damage morphology is similar to EBD samples, seen in Fig. 7. Damage starts to occur with a couple of small spots within an area of 200 µm x 250 µm after 8 h of irradiation. The reflection decreased just slightly by 1 %. These spots are about 10 µm in diameter and are holes like those found at EBD samples. They are getting larger by time until they merge after 22 h resulting in a decrease of the reflectivity down to 85 % (Fig. 8).

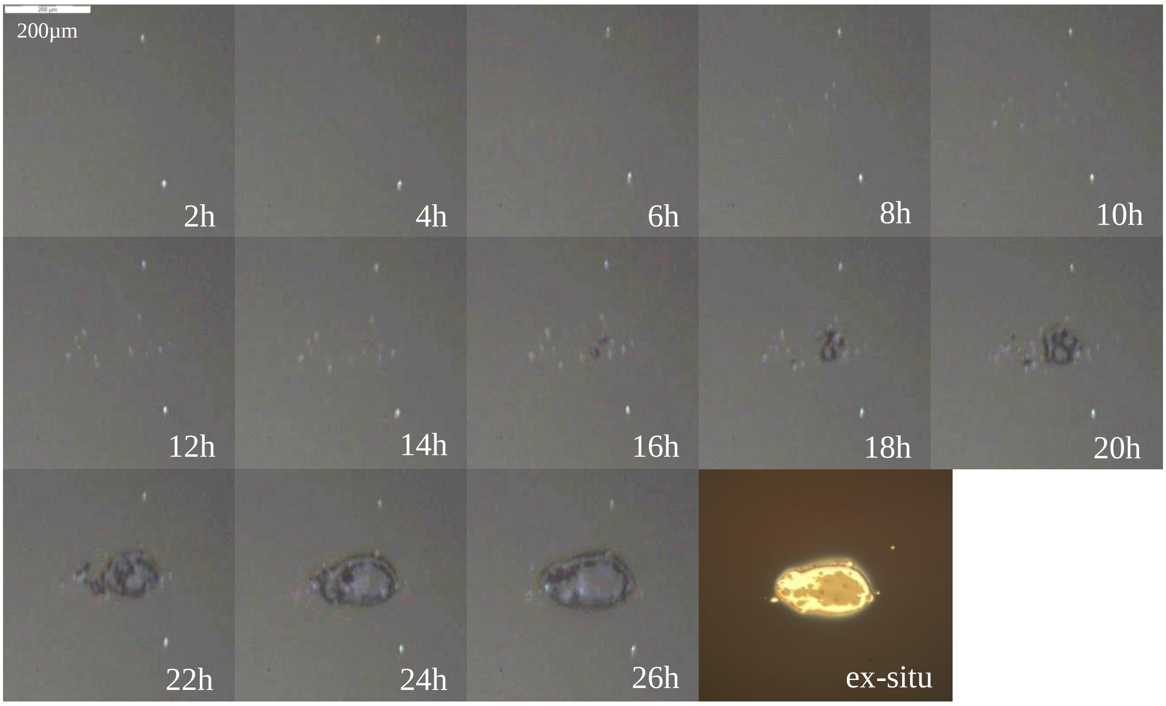

Figure 8: In-situ long distance microscope images of MS sample during LIC test and ex-situ DIC micrograph made after the test. Sample tested at a fluence of 660 mJ/cm² and a contamination pressure of 1 x10^{-5} mbar.

Figure 9 shows LDM micrographs for a LIC test with an IBS sample at a fluence of 360 mJ/cm^2 and a contamination pressure of 3.5x10^{-5} mbar. Unlike to the tests with EBD and MS samples the damage on IBS sample starts from the center of the beam at it expands uniformly to the edges of the laser beam spot.

These tests have shown that damage morphology changes with different coatings and give a hint that different physical properties of the coatings drive the contamination induced damage.

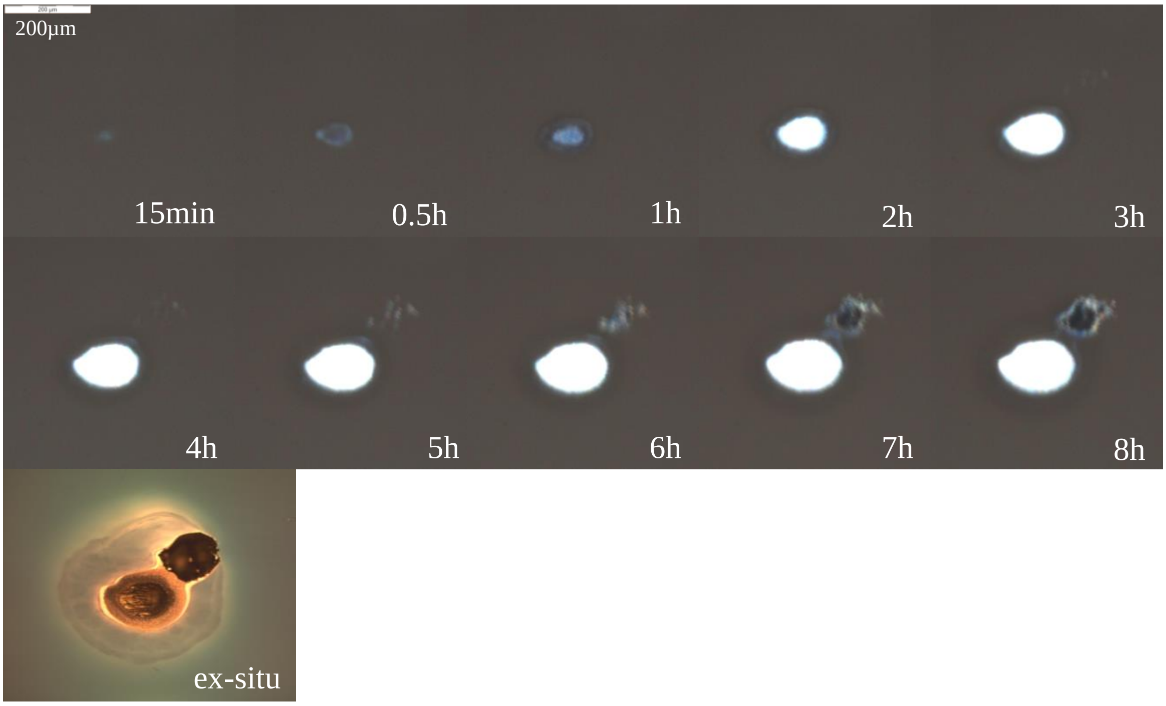

Figure 9: In-situ long distance microscope images of IBS sample during LIC test and ex-situ DIC micrograph made after the test. Sample tested at a fluence of 360 mJ/cm² and a contamination pressure of 3.5 x10^{-5} mbar.

4. SUMMARY

In this study, we presented investigations of UV laser-induced contamination in the presence of naphthalene in the order of 10^{-5} mbar contamination pressure. The tests were performed with a pulsed laser at a wavelength of 355 nm. These tests revealed a drastic reduction of damage threshold by contamination by more than one order of magnitude. Coating process has a great influence on contamination growth and damage behavior. Contamination deposit was strongest on IBS followed by MS and smallest on EBD. Damage starts first on IBS then MS and last on EBD samples. Former tests with AR coatings showed higher resistence of MS coatings relative to EBD. Onset of damage formation was observed in-situ by long distance microscope and revealed that contamination induced damage starts with small localized spots with a size of ≤10 µm on MS and EBD samples. Contamination induced damage on IBS samples always starts from the center of the beam. Damage formation depends on fluence, partial pressure of contaminant and coating type.

5. ACKNOWLEDGEMENT

The work was performed with kind support by ESA/ESTEC under Contract No. 4000102602/11/NL/CP "Optical components materials and process development and validation for high power space borne lasers"

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