LIDT Modification Following Debris Damage

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Abstract

Since its initiation in 2002, the TAP parabola has seen a rapid deterioration of its protected silver coating, leading to multiple re-coatings. In this study, we aim to understand the reasons behind the deterioration of the parabola coatings and the continuing reduced lifetime, even when recoated. We performed tests on three types of coatings; protected silver, protected gold, and dielectric, finding that the protected silver coating was the most susceptible to Laser Induced Damage (LID) follow exposure to target debris.

Introduction

In solid target interactions debris is ejected from the target from many different mechanisms but can generally be categorised under "soft" coatings or "bullet-like" fragments. The latter of these can penetrate surface coatings and cause damage to the optical substrates due to high impact velocities. Much of this damage is observed as small pinholes in the optical coatings but with thicker targets damage has been observed on the millimetre scale. Target fragments can easily penetrate through tens of microns of material as can be seen in figure 1.

Debris Protection

Protection against target debris has typically relied on debris shields or pellicles. In the case of the TAW facility on the Vulcan Laser these are in the order of 0.5 - 1mm thick. For lower energy laser systems where the bullet-like debris is significantly reduced pellicles can be much thinner as primarily protect against only the soft coatings.

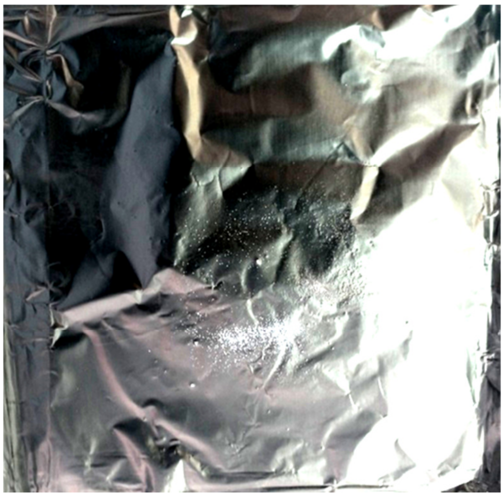


Figure 1. Debris holes penetrating 150μm aluminium foil placed inside the TAW interaction chamber, 300mm from target normal rear.

For the Gemini facility thicknesses in the order of a few 10's to 1000's μm are used. Large (0.5 - 1m diameter) optics such as those on the Vulcan Petawatt Facility (TAP) are extremely difficult to guard from debris because the thickness required for shield stability - whilst still able to withstand the bullet-like debris has a significant negative impact on the transmitted beam. The debris shield has to reach a compromise in thickness that allows it to be thick enough to stop large fragments of debris, but also thin enough to avoid non-linear phase shift (B-integral) issues and pulse stretching. At apertures approaching that of the TAP parabola (600mm beam diameter) high-quality thin substrates are virtually impossible to obtain and are extremely expensive.

Optical Coatings

The three main choices for optical coatings are dielectric, protected gold, or protected silver. One of the advantages of metallic coatings is that they can be stripped and recoated, whereas dielectrics require a full re-polish of the optical substrate, greatly increasing costs. The challenges that each coating has to conquer include, but are not limited to; a high reflectivity bandwidth over the full angle range of the parabola, a high LIDT [1,2], vacuum compatibility, low stress coating and good adhesion properties. With no angularly dependant bandwidth/reflectivity issues and a naturally low optical coating stress the metallic coatings are typically more appealing provided the LIDT constraints can be met. In-house LIDT testing carried out in the Astra TA2 facility [3] were able to confirm data provided by companies, the results of which are shown in figure 2. From this data it is clear that dielectric mirrors achieve the highest LIDT followed by silver and then gold. Similar data for operation at longer (ps) pulse durations confirmed that protected silver is the best *metallic* coating option based on LIDT. For the above reasons protected silver coatings were chosen for the parabolas in both TAP and Gemini.

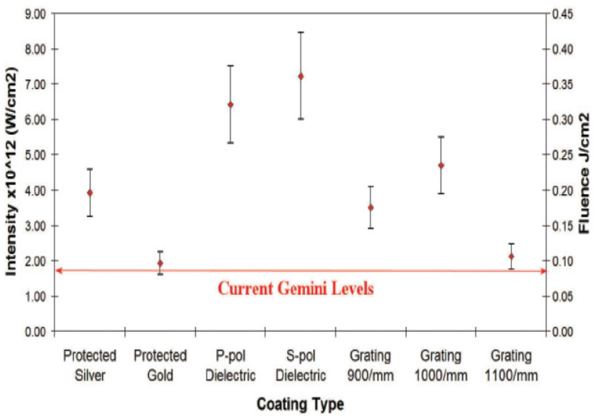


Figure 2. LIDT data taken in-facility (Streeter et al) [1] on ATA2. LIDT at picosecond pulses are slightly different but follow the same trends.

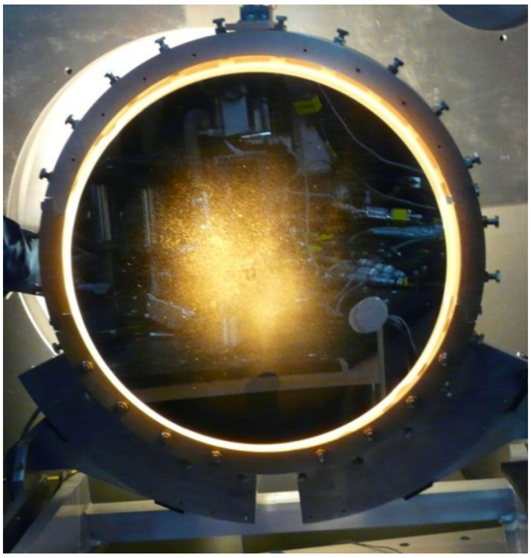
Observations

Over the first 10 years of TAP operations the parabola has been switched between the 2 available substrates 5 times. Each of the substrates was in operation for approximately 3 years before their respective first recoating. With no debris protection, small pinholes were observed throughout the parabola coating, observable via high brightness illumination behind the substrate (figure 3a). However, the overall parabola reflectivity and focal spots did not appear to be greatly affected and the switch between parabolas was only initiated once beam imprints were observed on the coating (figure 3b). Following each subsequent recoating the parabola lifetime dropped significantly.

Theory

The rapid deterioration of the silver parabola is believed to be due to debris primarily removing the protective layer over the silver coating. This exposes the silver layer to the external environment which causes oxidation of the silver. The LIDT of oxidised silver is calculated to be ~ 50x lower than the natural protected silver coating (around 0.08 Jcm^{-1}). With such a low LIDT the oxidised silver immediately damages causing material blow-off and further damage to the surrounding protective layers – exposing further localised exposure of the silver coating to the atmosphere. This process creates a growth of the damage site from a small pin-hole into an expanding damage site. Since the localised damage is through the lowered LIDT the appearance is of laser beam damage whereas in fact it is generated through this loss of the silver protective layer.

During recoating, the entire coating is etched away leaving only the substrate. The substrate has surface damage from the target debris which has penetrated the 100's nm silver and protective overcoat. With a simple recoat, no surface polishing is undertaken and the new coating layers are directly applied to the damaged substrate. This creates coating imperfections where some areas – predominantly on the impact crater walls and floor – are left with minimal or no protective layer. Within these areas the lower LIDT from silver oxide exists and the overall damage process restarts.



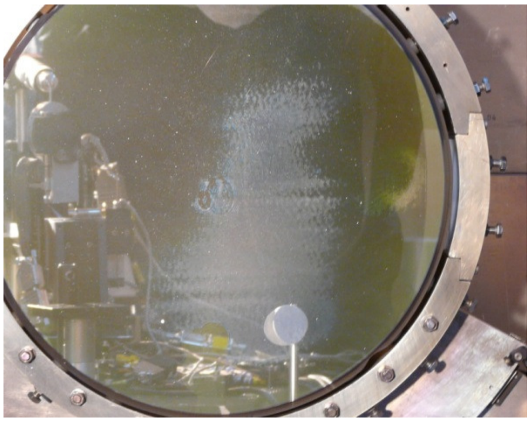


Figure 3. Images of the TAP final focussing parabola. The top image shows the presence of the pinholes *when illuminated from behind*, and the bottom image shows the parabola unilluminated to display the beam damage to the coating .

Testing

For the purposes of this study, we chose to 'degrade' a set of mirrors (protected gold, protected silver and dielectric) through exposure to severe target debris from a long-pulse laser interaction. Such large scale damage should reproduce the long term damage observed but over a much shorter timescale. A set of 3 mirrors, each 2" diameter were placed in the TAW interaction chamber at a distance ~250mm from target and at 14.6° to target normal. The mirrors were configured so that they were equidistant from the interaction. Half of each mirror was covered by a 1mm thick aluminium plate to protect from debris and thus act as a control surface. The mirrors were inside the TAW interaction chamber for seven long pulse shots onto iron and tantalum targets with energies ranging from 390.2J to 688.2J. The average energy of the shots was 576.5J. Following the exposure to target debris the aluminium shields were rotated 90º so that half of the damaged and half of the undamaged areas could be exposed to an irradiating laser beam. This arrangement sectioned the mirrors into 4 distinct quadrants – a) unexposed, b) laser only, c) debris only and d) both debris and laser. The mirrors were then exposed to Laser irradiation through 4 laser shots in TAW (~1ps) with moderate energy densities as detailed in table 1.

Shot Number	Energy (J)	Energy Density (Jcm^{-2})
1	50	0.125
2	61	0.1525
3	31	0.0775
4	37.4	0.0935

Table 1. Data from the laser shots that the mirror array was subject to. Energy density calculated from mean diameter of the short pulse beam (200mm).

Results/Analysis

Figure 5 shows images of each of the mirrors after exposure to debris. Craters and scratches are observable deep into the substrate. The dielectric mirror was badly damaged on the unprotected side, showing signs of stress fractures in the coating. Marks on the control (right) side of the mirror were caused by handling (fingerprints and scratching) and the aluminium shield. On the silver mirror, the exposed side has suffered even damage across the surface and almost entirely removing the protective layer. On the gold mirror, the exposed surface was damaged severely - the top coating layer was completely removed and the undercoating was badly damaged too. Marks on the control surface were a result of handling.

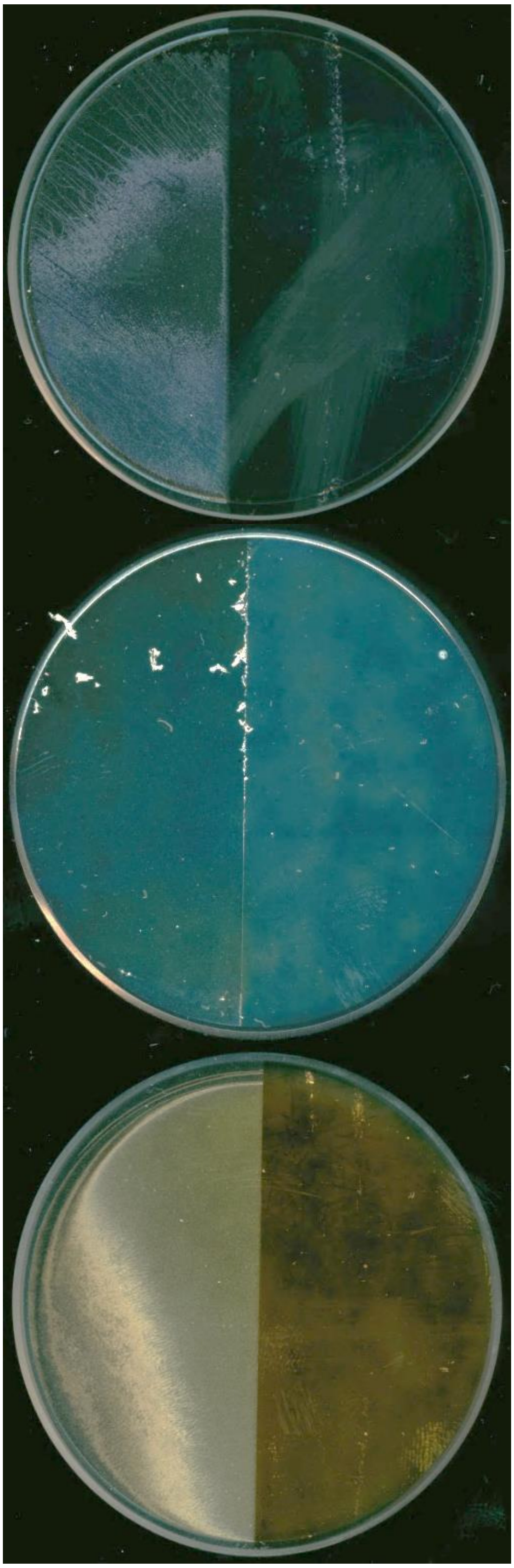


Figure 5. The mirrors after the 'roughing' stage of the experiment. From top to bottom: dielectric, silver, gold. On each mirror, the left hand side is the unprotected half.

The images of the mirrors after exposure to the short pulse beam are shown in figure 6. The dielectric mirror showed no noticeable difference before and after the second stage of the testing, demonstrated by the unchanged marks on the surface of the mirror. The effects on the silver mirror are far more obvious. The quadrant which underwent the double exposure was subject to significant damage, removing almost all of the remaining coating. The undamaged, shot surface showed no changes. The gold mirror was unaffected by the second stage; the only noticeable change is a line across the two surfaces, caused by the aluminium shield.

Figure 6. The mirrors after the second stage of the study. From top to bottom: dielectric, silver, gold. The dielectric mirror had its top left quarter 'roughed' and exposed to the beam. The silver and gold mirrors both had the double exposure to their bottom left quarters.

Conclusions

All three mirror types tested were subject to severe damage through laser-generated target debris. The mirrors were then irradiated by a short pulse laser at fairly low energy densities – well below the specified damage thresholds of the optical coatings. The silver mirror was the only coating showing significant changes following both the debris exposure and laser. The experimental data appears to verify the working theory and has shed light on the previously unexplained reasons for the deterioration of the TAP parabola. Based on this study, the option for silver coated optics in high-debris areas needs careful consideration for lifetime and costs versus the traditional dielectric option.

Acknowledgements

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References

[1] Gallais and Commandré, "Laser-induced damage thresholds of bulk and coating optical materials at 1030nm, 500 fs", *Applied Optics* **vol. 53**, issue 4, pp. A186-A194 (2014).

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[3] Streeter et al., "Damage testing of reflective coatings in Astra TA2", *Central Laser Facility Annual Report* (2007/08).