Predictive modelling of laser heating in low thermal expansion glass to laser assist plasma surface figuring

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Abstract

The fast figure correction of optics using atmospheric plasma has been modified to create a hybrid laser/plasma process in order to increase figure correction tunability, improve material removal rates and counteract edge effects. Characterisation of the laser thermal interaction with optical substrates was needed to understand the removal footprint, as the temperature on the surface determines the local removal rate.

The thermal footprint of a CO_2 laser operating with a wavelength of 10.6 µm incident on Corning ultra-low expansion glass (ULE®) was examined. An analytical model was developed to predict the laser-induced temperature distribution. The surface temperature was measured using pyrometers and resistance temperature detectors (RTDs) for validation of the model. The results show model correlation in the centre of the process parameter window to within the prediction uncertainty of ± 9.3 % for the RTD measurements. Predictions of pyrometer measurements could be improved by greater understanding of the material-specific cooling rate.

1. Introduction

Over recent years the demand for large optics has risen to fulfill the needs of projects like the European Extremely Large Telescope [1], exposing a deficit in manufacturing capability. Reactive Atom Plasma (RAP) technology was developed to address this problem. RAP processing, an atmospheric plasma etching tool, can be used to figure correct a metre-scale optic in under ten hours [2]. A hybrid process based on RAP technology has been developed using a laser as an auxiliary heat source to increase etch rate locally and provide a tunable etch footprint. In this work, to predict the temperature distribution from an incident laser, an analytical model has been developed and the predictions have been investigated experimentally.

2. Model

Analytical solutions for modelling of laser heat transfer are well established and a model has been adapted from that proposed by Cline and Anthony [3]:

$$T = \frac{P}{C_p} \times \int_0^{\infty} \frac{e^{[-\{[(x+vt')^2 + y^2](2R^2+4Dt')^{-1} + (z^2)(4Dt')^{-1}\}]}}{(\pi^3 Dt')^{\frac{1}{2}}(2R^2+4Dt')} dt'$$

where T is the temperature rise, P is the incident total laser power, C_p is the specific heat capacity of the substrate material, x, y and z are the two surface and one depth axes relative to the beam spot centre, v is the spot travel velocity relative to the substrate in x, R is the spot radius, D is the substrate thermal diffusivity, and the integrated time of processing is represented by t'.

This model has been adapted for use with a custom beam delivery system used for laser assisted plasma processing, which projects a circular beam on the substrate surface from a 65° incidence angle. Reflectivity is accounted for, as is a conversion factor between mathematical (σ) and practical ($1/e^2$) descriptions of Gaussian beams. The implementation in Matlab allows for a discrete region of a semi-infinite substrate to be examined on a point-by-point basis.

3. Experimental work

To conduct temperature measurements, RTD sensors and pyrometers were used giving both contact and non-contact values. Each instrument has a characteristic measurement region, pyrometers measuring a large circular area temperature and RTDs measure localised temperature.

During RAP processing with a laser, the variable parameters are laser power and feed

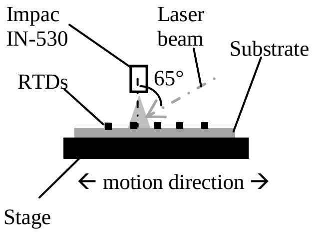

Figure 1. Experimental setup. Note: the pyrometer and the laser were positioned off the RTDs.

speed, and were investigated to observe their effect on the laser-induced temperature footprint. A laser spot with diameter of 2.0 mm ± 0.1 mm from a continuous wave CO_2 was set coincident with a pyrometer and moved relative to a substrate with attached RTDs as seen in figure 1. The RTDs were positioned 4 mm ± 0.5 mm away from the spot centre. Laser powers of 20 W and 40 W were investigated, and the feed speeds were 3, 4 and 5 m/minute respectively: typical RAP processing speeds.

4. Results

The predicted results were plotted against those experimentally obtained for a specific time during trials, giving a known time and location relative to the laser beam. The correlation is shown in figure 2. The main error contributor is the alignment and positioning of the laser relative to the sensors. The lowest and highest energy trials (5 m/minute at 10W and 3 m/minute at 20W respectively) lie outside process window for model use as the error exceeds the model uncertainty of ± 9.3 % for these points.

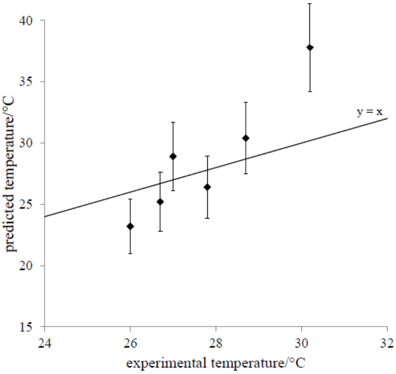

Figure 2. Predicted temperature against experimental temperature for a set of RTD measurements. The trendline indicates a theoretical perfect model, and the deviation of each data point from that line is the error in the prediction.

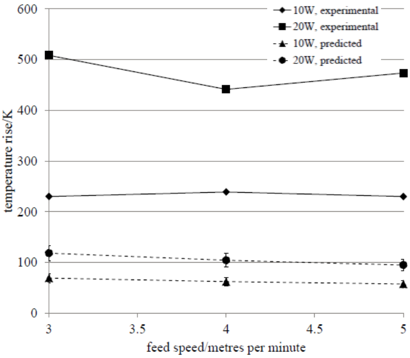

Figure 3. Predicted and experimental (pyrometer) temperature measurements showing the influence of feed speed and power. While the effect of speed is small, doubling laser power results in approximately double temperature rise.

Figure 3 shows the experimentally measured temperature rise using a pyrometer and the corresponding predictions from the model. The experimental results are significantly higher than the predictions in this case, and thus the model diverges from measured data at high temperature; this limits the scope of its use without further refinement. However, it can be seen that both the experimental data and model show a doubling of temperature with doubling of laser power. With further experimental validation, the extent of this seemingly linear relationship can be explored. Also shown in figure 3 is that the most influential parameter to vary in laser assisted plasma processing is the laser power, and the feed speed has a relatively weak effect on the laser-induced temperature. If the speed dependence is weak, the speed can be varied to control plasma-induced temperature in a figuring scenario, while the laser power can determine the laser-induced etch component which gives improves tunability.

5. Conclusions

The analytical model shows some correlation to the experimental data in a key area of the process parameter window for low temperatures, implying that this may be a valid tool for some temperature predictions. This could be used for predicting the local etch rate during laser assisted RAP processing. However, the results show that at higher temperatures the model fails to predict the temperature with enough accuracy for precision surface figuring use. The model may be improved to match a larger process envelope by introducing a cooling factor to better predict thermal gradients.

The model agrees with the trend of doubling laser power doubles temperature, and further experimental work may verify the extent of this relationship. Despite the limitations, the model has helped to increase understanding of laser heating for a laser assisted plasma application, which will enable improved control of the process. The laser can be varied in power with minimal effect from the change in feed speed required to control the plasma-induced temperature, thus improving the figuring capabilities, enabling technology to meet the industrial demand.

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