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ABSTRACT

Optics damage growth modeling and analysis at the National Ignition Facility (NIF) has been performed on fused silica. We will show the results of single shot growth comparisons, damage site lifetime comparisons as well as growth metrics for each individual NIF beamline. These results help validate the consistency of the damage growth models and allow us to have confidence in our strategic planning in regards to projected optic usage.

Keywords: Laser-induced optics damage, optics lifetime

1. INTRODUCTION

NIF is the world's most energetic laser, delivering up to 2.0 MJ at 351 nm with its 192 beamlines. NIF uses some of the best damage-resistant optics in the world along with an optics loop to manage laser-induced damage in optics [1-4]. The length or duration of an optic's lifetime depends on both damage initiation and growth. In the past, we have shown how we analyzed and benchmarked damage initiations on fused silica optics[5, 6]. In this study, we will turn our attention to the analysis and benchmark of damage growth on fused silica final optics such as the wedged focused lens (WFL) and grating debris shield (GDS)[1].

Our damage growth model is based on extensive offline experimental results over the years [7-18] and although we have done analysis to validate the offline results[18, 19], there are many important factors that exist on the online facility that we cannot simply duplicate on an offline facility – such as large numbers of unique pulse shape designs for science campaigns, the irregularity of the shot sequence and the large area of optics surface survey. In addition, although NIF uses an online optics inspection system called Final Optics Damage Inspection (FODI) [20, 21] to measure damage in-situ, these inspections are not taken after every shot and analysis of damage data must account for the sensitivity of the instrument which can be prone to false positives.

2. THEORY

Our growth model has been published previously [17-19] for exit surface damage sites on fused silica optics, it can be described as

$$D_n = D_{n-1} \cdot e^{\eta \cdot \alpha}, \tag{1}$$

Where D_{n-1}, D_n is the effective circular diameter before and after the nth shot and the growth coefficient η and α are random variables describing the probability of growth and growth rate, respectively. Both of these random variables are dependent on laser parameters such as fluence, pulse shape, etc. as well as the damage site information such as size and morphology[18]. Furthermore, we model the probability of growth as a binomial distribution and growth rate as a Weibull distribution and use the Monte-Carlo simulation to calculate the expectation of damage growth and associated risks.

3. ANALYSIS RESULTS

There are a number of ways to examine online growth and benchmark to our growth model. In this work, we will look at three different analyses that aim at answering these questions:

1. Can the damage model predict single-shot growth accurately?
2. Can the damage model predict the growth trajectory of a large damage site over its lifetime?
3. Can the damage model predict the optics exchanges across all 192 NIF beams over years of operation?

Table 1. Four single-shot growth data surveyed from 2014 with associated participating beams and mean fluence as well as number of damage sites on the fused silica final optics.

Shot ID	**Campaign**	**Beams**	$\phi_{3\omega}$ (J/cm^2)	**Sites**
N140922-003	H_Hyd_Shktub_Reshk	140	~3	~20,000
N140923-002	H_Hyd_Shktub_Reshk	140	~4	~25,000
N141028-003	H_Cval_2DConA_3ShAs	192	~8	~33,000
N141106-002	H_Cval_DT_TShell	192	~7.5	~23,000

The most accurate online growth data consists of when optics are inspected before and immediately after a shot. These instances are rare and sporadic but, gives the most direct feedback regarding the accuracy of the damage model. A series of single shot growth data was surveyed (see Table 1). The simplest analysis is to examine whether the average predicted growth rate agrees with the actual measured online. Figure 1a plots the measured average GDS growth rate (α) across the NIF beamlines for shot N141028-003 for damage sites >100 μm vs. the predicted growth rate given the beamline's measured fluence and pulse shape. The plot shows that the measured growth rate is widely distributed from 0 to 0.5 while the predicted growth rate centers around 0.22 with much less variance. If we plot the difference between the measured and predicted average growth rate (see Figure 1b), it shows a fairly normal distribution. The range of the variation is an ensemble of the average growth of each beamline and it reflects the random nature of the growth rate. Since our growth model fully characterizes the growth rate (as a Weibull distribution), its distribution should cover a similar range as the prediction error of the whole ensemble. Overlying, the Weibull distribution of a typical beamline shows that it does indeed cover the range of variations (see Figure 1b). It should be noted, that only 119 out of the 192 beamlines were plotted because some of the beamlines lack enough data points for this analysis. This however, does not completely validate that the measured growth rate obeys the Weibull distribution.

To validate that the measured data actually agrees with predicted Weibull distribution, we performed hypothesis test to the measured data of each beamline. The hypothesis test consists of two steps:

1. Test whether each beamline growth data could have come from the predicted Weibull distribution using the Anderson-Darling test [22]
2. Test whether each beamline growth data that passes the Anderson-Darling test matches the mean and variance of the predicted distribution using the Chi-Square goodness of fit [22]

Our results for this set of data shows that of the beamlines that have sufficient growth data to test, 94% of the beamlines accept the hypothesis that the data is consistent with the predicted Weibull distribution with specific mean and variance. This is a powerful result since it not only validates our ability to predict the mean growth of a given shot but it also validates our ability to predict the full descriptive statistic.

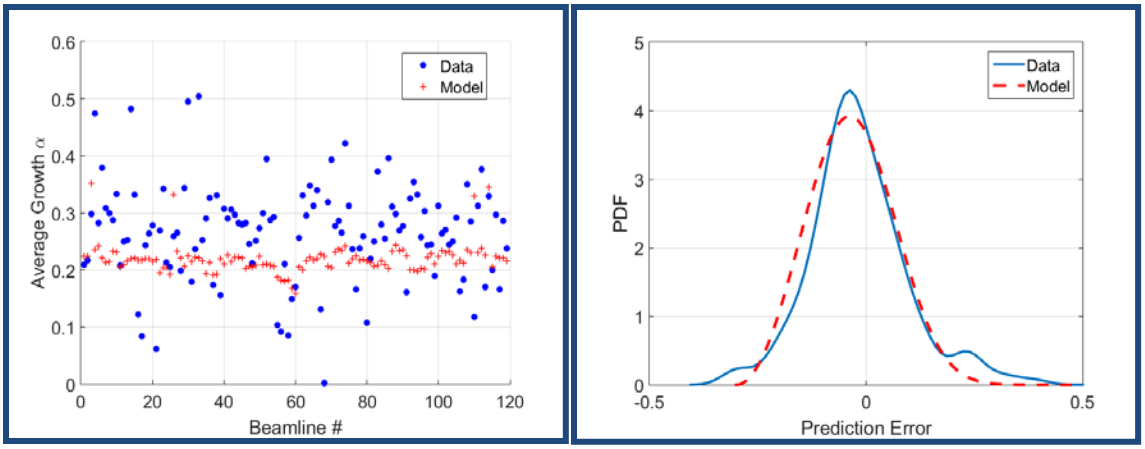

Figure 1a (left side). Measured (•) and predicted (+) mean damage growth (α) is plotted vs. the beamline for shot N141028-003. Figure 1b (right side). Probability density function (PDF) of prediction error (measured-predicted, -) across the beamlines along with the predicted Weibull distribution (--) for a typical beamline (right). Noted not all beamlines are present because some of them lack sufficient data.

A potential problem that the single-shot growth analysis does not catch is, if there is a persistency in regards to the growth trajectory of a damage site or an optic or an entire beamline. In that case, there will be persistent outlier damage sites, optics or beamlines that will be inconsistent with prediction results. In order, to validate that the growth model is independent and identically distributed, we did a set of surveys of the largest growing damage sites and tracked their trajectory. For each damage site, we compare the growth trajectory as recorded by online inspection system (FODI [20]) to the prediction given by the initial size of the damage sites and the all the recorded laser shots.

Figure 2 shows examples of damage site that agree with the prediction, damage site that grows slower than the prediction and damage sites that grow faster than the prediction. It should be noted that a damage site that grows "faster" than the model prediction does not necessarily invalidate the growth model since the model is based on a sequence of random events. Its prediction shown is merely the expected results; there is a whole range of possible results. As a matter of fact, we can precisely calculate based on our Monte-Carlo model results what the probability is that the faster growth trajectory observed and see if it is consistent with the population of data involved. The faster growing site on Figure 2 (right) is calculate to occur at CDF of 99.999% which means that there is 1:1000 chance of this occurring. This is plausible since we have hundreds of thousands of damage sites generated online. Of the ten large damage sites surveyed, 1 was found to be slower, 3 were found to be faster, while the rest were consistent with the model predictions. Furthermore, it was noted afterwards that the three faster growing sites had evidence of upstream intensification[23], meaning that the fluence damage site could have been substantially higher than the calculated beam average fluence. Nevertheless, we will need to survey more of these damage sites in order to get a better statistics.

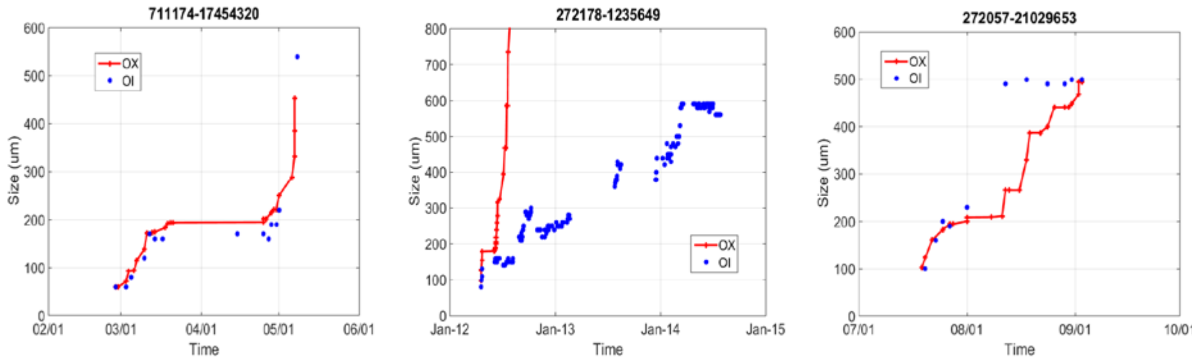

Figure 2. Comparison of the measured damage site size (OI •) and predicted damage size (OX +) vs. time for damage sites that grows consistently with model (left), grows slower than model (center), and grows faster than model (right).

As evident from the previous two analysis, our model does a good job in predicting the average behavior but, the lifetime of these optics will be driven by the tails of the growth distributions, i.e. abnormally large growth persistently over time. If the behaviors are truly independent and identically distributed, we would hope that it will average out over time. However, if they are persistent outliers or if external factors such as the upstream intensification[23] was dominant, it could deviate from the Monte-Carlo model prediction and drive the whole entire optics exchange. In order to test this, we look into evaluating the optics lifetime across the entire NIF 192 beamlines from 2014-2015. First, we would like to introduce a simple metric that can be used to track growth performance of an optic in terms of its lifetime. One possible metric is simply the number of shots and if the optic was able to survive online. However, since there are large variations of shot types (i.e. fluence, pulse shape etc.), not every shot produces the same amount of growth. This is evident from our simulation (see Figure 3) where we simulate an actual NIF beamline from 2014 using our growth model to see how many shots a typical optic survives to. The horizontal axis is the number of damage sites (normalized to the number of blockers) that is seeded in the beginning of the simulation. An optic is pulled when the number of blockers is exhausted and the damage sites exceed 300 μm. The vertical axis shows the percentage of shots that are greater than 4 J/cm^2. Figure 3a shows a contour plot of the number of shots an optic can survive given the number of damage sites and the percentage of high fluence shots; it shows that that the lifetime of an optic as measured by number of shots that can change greatly with the high fluence shot percentage. Figure 3b is the same simulation result but, measures the lifetime of an optic by the sum of its growth rate ($\sum\alpha$) instead because it accounts for growth better. The contour in Figure 3b is more invariant with respect to the percentage of high fluence shot.

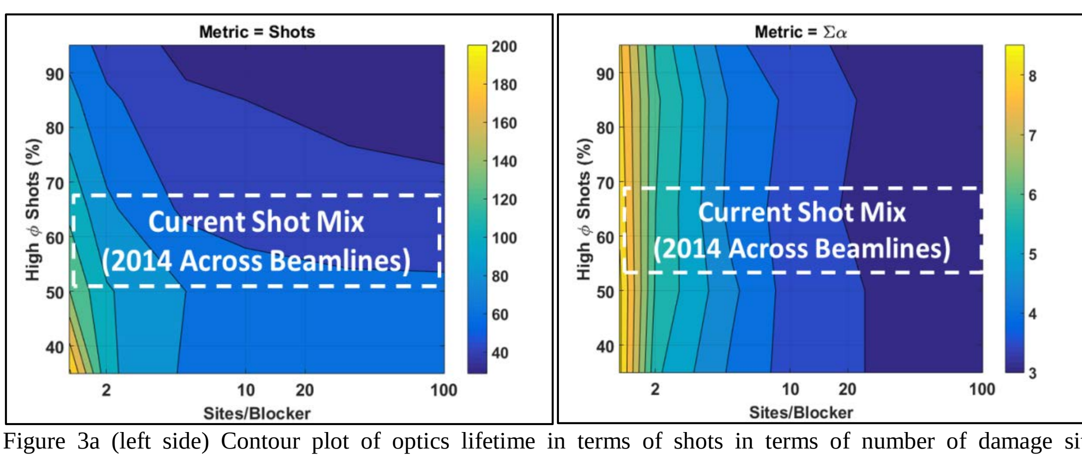

Figure 3a (left side) Contour plot of optics lifetime in terms of shots in terms of number of damage sites (normalized blockers) and percentage of high fluence shots. Figure 3b (right side) Contour plot of optics lifetime in terms of sum of growth rates ($\sum\alpha$).

The measured optic lifetime can be calculated simply by dividing the sum of all calculated growth rate (α) for each beamline by the number of actual optics (WFL and GDS) exchanges for that beamline. For each of the 192 beamlines in the past two years, the distribution of this metric is shown in Figure 4a. The mean of the distribution for accumulated growth rate/optic (∑α/optic) is ~3. Using this simple metric, we can predict within 3% accuracy of the 2329 actual optics exchanges just by simply adding up all of the growth rates for all of the shots for 2 years and dividing it by the average lifetime metric. This is very powerful metric that has been used for operation and planning, especially when dealing with a potentially long lead time for procurement and processing. However, this result does not accurately pinpoint the exact number of exchange each beamline requires because if we plot the difference of optics exchanges (see Figure 4b), it shows large variation vs. different beamlines. Once again, this highlights the power and limitations of our growth model which does an excellent job predicting the average behavior for an ensemble but are not as accurate when dealing with the specifics (i.e. which damage sites causes an optic to pull, which beamline needs to be pull at what time, etc.). We believe some of the variation comes from quad-based operation of the NIF beams and the timing of initial exchanges but overall, this does not affect the effectiveness of the model in planning and operations.

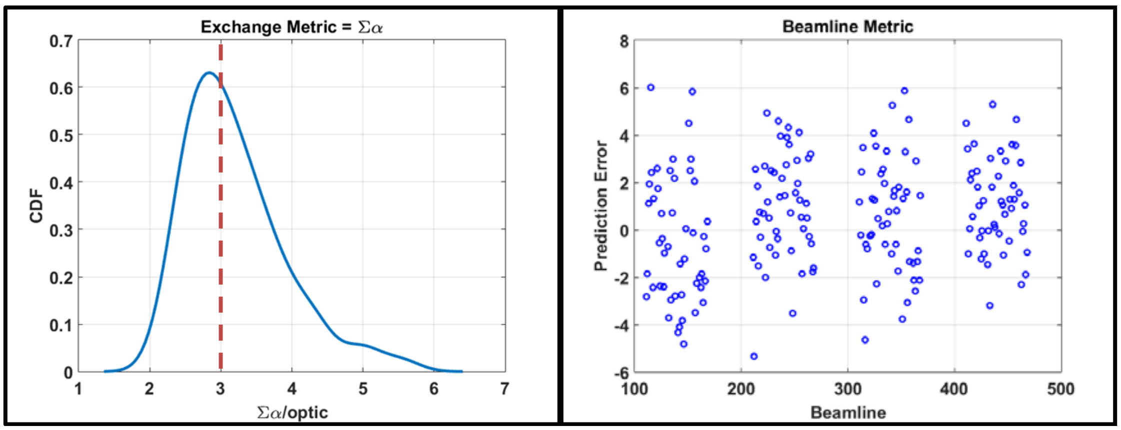

Figure 4a (left side) Measured cumulative density function (CDF) of the lifetime metric of all fused silica in for two years (∑α/optic) with the mean ~ 3 (with red dash line). Figure 4b (right side) Prediction error (measured exchanges – predicted exchanges) plot vs. NIF beamlines.

4. CONCLUSION

We have demonstrated that our offline-derived growth model is able to validate online growth in terms of single-shot growth, growth trajectory of large damage sites, as well as beamline based growth in terms of optics exchange. We also show that the use of growth parameter (∑a) is a powerful metric in predicting optics exchange. It is able to predict 97% of the optics exchanges over a 2 year period (>65,000 shots). Future work will to implement automatic statistical tracking of damage metric (single shot, single site, beamline etc.) and examine the difference between different optics.

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