Laser-induced damage and defect analysis of calcium fluoride window caused by the high pulse repetition rate of ArF excimer laser radiation

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ABSTRACT

The lifetime of optics, especially windows, has grown to reach 100 Bpls, and its evaluation lasts for several years at least. In elementary testing (short term), focusing on each damage phenomenon must be established. The degradation of calcium fluoride windows used as laser chamber windows in ArF excimer lasers (193-nm wavelength, 30-ns pulse width, 10-mJ output energy, ~80-mJ/cm2, 6-kHz and several dozen billion pulses) is analyzed. The results of analysis such as TEM-EDX, Nomarski-type differential interference contrast (DIC) microscope, AFM, etc. is shown. The damage mechanism can be estimated from these results. Comprehensive durability evaluation becomes more efficient by creating accelerated element tests (short term).

Keywords: calcium fluorides, ArF excimer laser, degraded, surface damage

1. INTRODUCTION

With the miniaturization and high integration of semiconductor integrated circuits, improvement of resolving power is required for semiconductor exposure equipment. For this reason, the wavelength of the light output from the light source for exposure has been shortened, starting with a mercury lamp, and now KrF and ArF excimer laser devices that output ultraviolet rays with wavelengths of 248 nm and 193 nm respectively are used. This is because the current exposure technology, consisting of liquid immersion exposure for shortening the apparent wavelength of the light source for exposure by filling the space between a projection lens on the side of the exposure apparatus and wafer spacing with liquid and changing the refractive index at the interval, has become practical. In addition, in conjunction with the advancements in recent multi-patterning technology, the laser light source demands increased higher output such as the increase of output energy and the repetition rate, as well as the improvement of the degree of polarization and stability capacity so as to prevent the deterioration of contrast due to higher NA exposure. Although the optical elements in the excimer laser have been drastically improved from the 1990’s to the 2000’s when the excimer laser was introduced to the market, the problem has not been completely solved so as to respond to the performance improvement request as described above and therefore, it is necessary for advancing higher tolerance. Advancement in higher tolerances are required. Various analyses and improvements have been implemented regarding the deterioration of optical elements up to this point. The lifespan of optical elements, especially windows, has been growing to reach 100 Bpls, and its evaluation takes a very long time. Therefore, by repeating element tests (short term tests) for each instance of deterioration, the improvement of overall element tolerance has been achieved. Now, we focus on surface damage, analyze in detail the deterioration, postulate damage production mechanisms inferred therefrom, and then create element tests (short term tests).

Surface damage is one type of element degradation phenomena, and can be observed as scattering from visual observation of the optical element surface as shown in Figure 1. The phenomenon is easy to produce on no-coat CaF2 substrates and the production of damage is not dependent on the number of shots experienced. This is a motive for considering the possibility of creating element tests (short term tests). Surface damage increases element scattering and reduces the laser system efficiency due to laser light absorption.

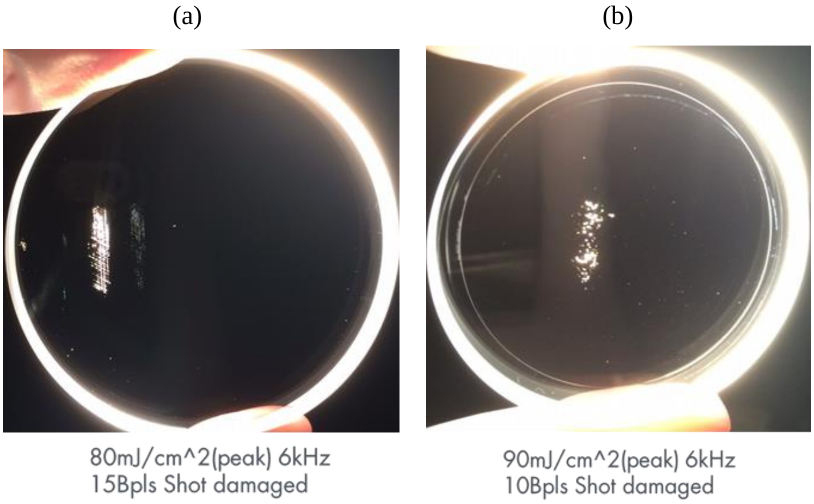


Figure 1. Surface damage morphology pictures. Sample had surface damage at 80mJ/cm2 15Bpls (a), and another sample was damaged at 90mJ/cm2 10Bpls (b)

2. ANALYSIS OF SURFACE DAMAGE

We analyzed in detail one surface damage sample named sample A, using various measurement devices and methods. Surface damage was observed at 193-nm wavelength, 30-ns pulse width, 15mJ output energy, ~89mJ/cm, 6-kHz and 7.3 Billion pulses. We experienced irradiation with over 50Bpls without damage with the same configuration. Damage can be explained without relation to the shot number.

The methods used for analysis are “dark field image, “Nomarski-type differential interference contrast (DIC) microscope,” “AFM,” “Slice & View,” and TEM-EDX). Analysis results will be introduced for each.

2.1 Dark field image

The dark field image of Sample A is shown in Figure 2. We will introduce the positions of damage with the analysis methods that come afterward using these photographs. The damage size is about 6 x 12 [mm]; it is almost the same size as the footprint of the laser beam. The intensity of the surface damage varies for each framed area – red and blue. The part framed in red indicates “extreme damage”, and the part framed in blue indicates comparatively “slight damage.” We can judge the damage intensity by the intensity of light scattering.

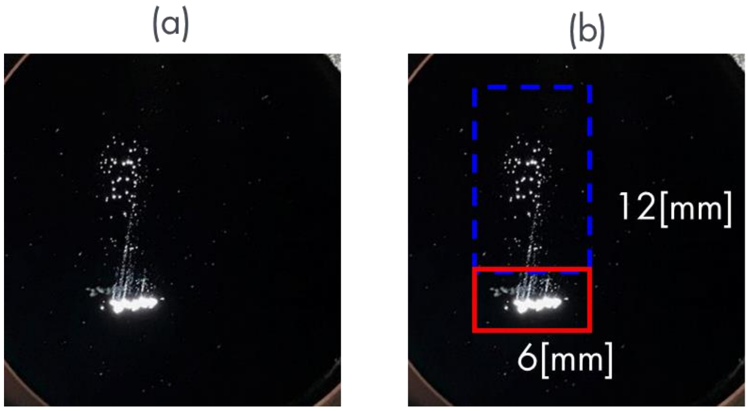


Figure 2. Observation results of surface damage image in dark field (a). An image divided by a color frame for each intensity of damage (b).

2.2 Nomarski-type differential interference contrast (DIC) microscope

In the Nomarski-type DIC microscope, it is impossible to judge whether the sample surface is concave or convex, but because the concavo-convex shape can be emphasized intensely, the shape can be measured and it is extremely suitable for surface analysis. The red frame and the blue frame in Figure 3-(a) indicate the same areas as the red frame and blue frame of the dark field image (Figure 2). In addition, Figure 3-(b) shows an enlarged image of the slight damage and Figure 3-(c) shows an enlarged image of the extremely heavily damaged portion respectively.

When looking at the "slight damage" in the blue frame area, one can see the damage in the shape of linear scratches. Further, the heavily damaged portion is in the shape of a bird's foot. Also, linear scratches are seen at the edge of damage the same as the blue frame. Therefore, "heavy damage" can be assumed to be advanced deterioration caused by combining many scratches of "slight damage". The orientation of surface damage "linear scratches" might be related to crystal orientation and laser resonance direction, etc.

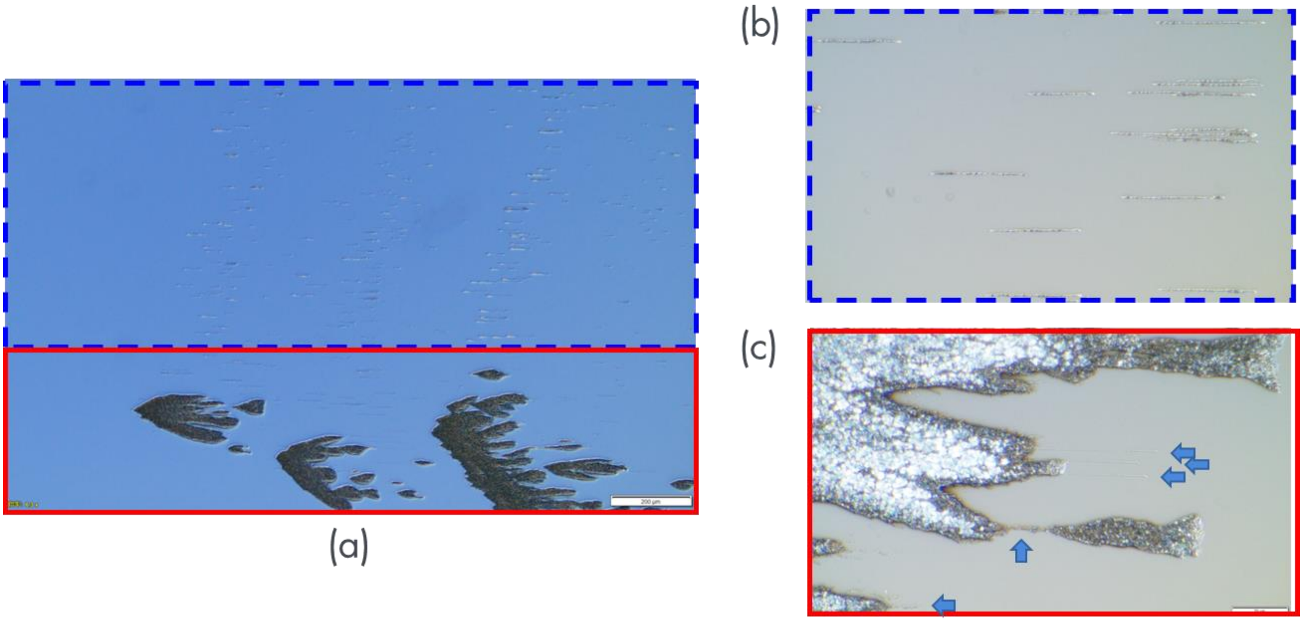


Figure 3. Morphology of surface damage using Nomarski-type DIC microscope. Result of damage analysis at wide [1.5 x 2.0[mm]] range (a). (b) shows the enlarged blue frame of (a). (c) shows the enlarged red frame of (a). Both ranges are [0.15 x 0.2 [mm]].

2.3 AFM (Atomic Force Microscopy)

AFM (Atomic Force Microscopy) is a method to scan the uneven condition of the surface of a sample with an extremely fine probe and three-dimensionally measure the nano-scale irregular shape. In AFM, information on height direction was added for damage analyzed with a Nomarski type differential interference microscope. For an area of 80 μm square, the area including the damaged portion and the undamaged portion was observed, and a detailed analysis of 1.0 μm square was conducted for each part without damage and the parts with high damage.

Compared with the color scale, we can see that almost all the damaged area has a convex shape with regard to the substrate from Figure 4-(a). Further, in Figure 4-(b), the vertical axis shows the height of blue line in the center of Figure 4-(a). In the blue line, the right area has damage and left area is stable CaF_2, so we can see that the damaged area is above the stable surface. When it is compared with the measurement results of Nomarski, scratch-like convex shaped damage like a small part of damage occurs on the surface of the element, and as the scratches are joined and the region expands, we can see that the region grows due to large damage, including deep valleys, rather than the substrate, due to the increasing intensity of the unevenness. In the area where the damage was large, the damage was about ± 2 μm. This is similar in shape to a protrusion called a nanohillock in reference [4].

As shown in Figure 4-(c), when the undamaged part was enlarged, the unevenness of the polished surface was several nm or less, and it was observed that there was no damage, as expected. Figure 4-(d) is a further enlarged diagram of the damaged part, the undulations observed at 80 µm square were observed as large waviness, and aggregates of fine clusters (grains) of several tens of nm were confirmed. As this has not been observed in the undamaged area, we did not analyze further, but some shape deformation of CaF2 is presumed.

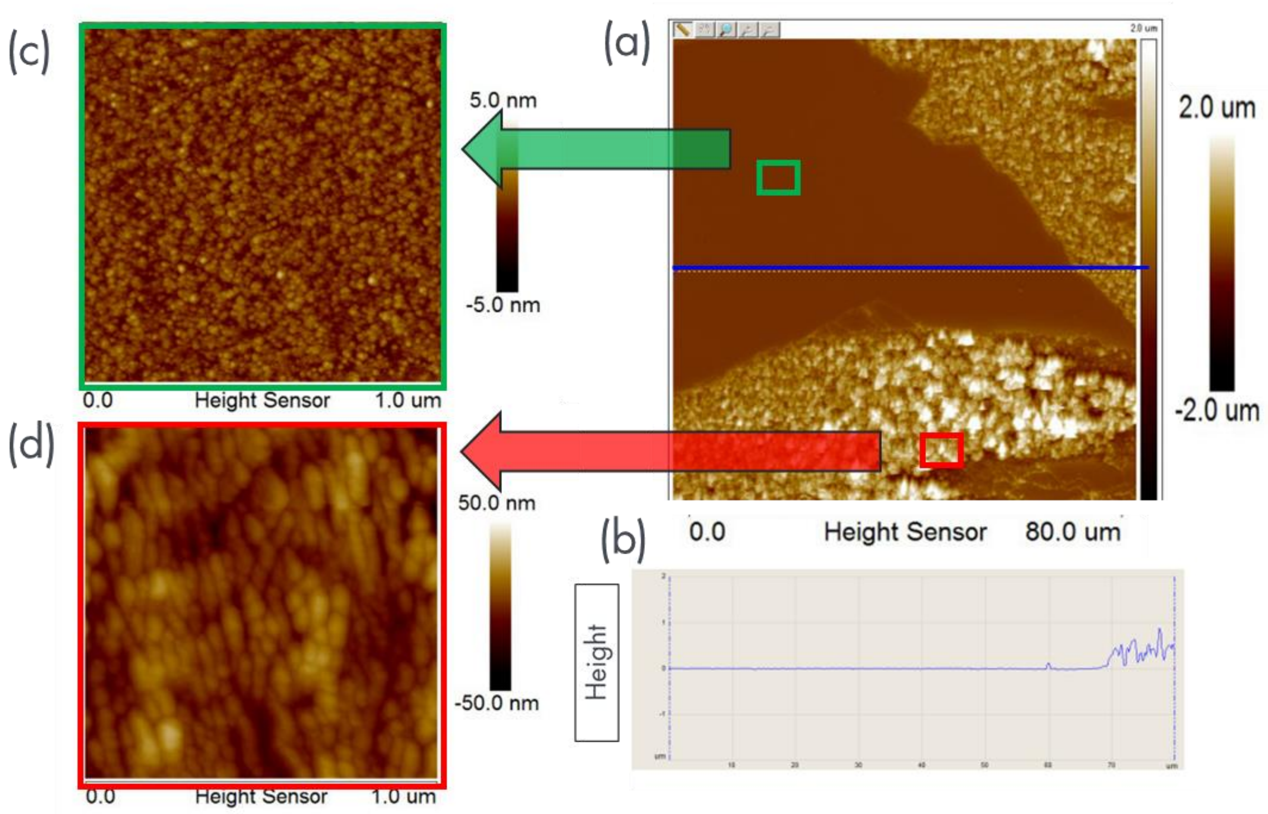


Figure 4. Morphology of surface damage using AFM (Atomic Force Microscopy). Result of damage analysis at wide [80µm square] range (a). (b) shows the height of the blue line in (a). (c) shows the enlarged stable CaF2 in (a). And (d) shows the enlarged damaged area. Both ranges are [1.0µm square].

2.4 Slice & View

Slice & View is one method of destructive inspection. Samples are measured by slicing, using SEM. By forming slices for each regular interval using FIB, it is a method where internal sample information can be captured three-dimensionally. In order to easily view the diagram, we have drawn a red dotted line representing the top surface in some images (1, 2, 4 view). The white part is the protective film (platinum) applied before processing to reduce damage due to FIB treatment, and in these analysis results, the air gap between CaF2 and protective coat is not related to damage. Further, the sample has a silver sputtered layer on it and has a thickness of several nm at the interface between the sample and the film. These portions contain C, O, Ga and other components.

The analysis results in figure 5 indicate the results of slicing into eight parts for each 200 nm of a protrusion observed in the analysis up to now. It can be seen the protruding part has many defects and is sparse with respect to the normal CaF2. In other words, there are many voids inside the protrusion, and it seems that the outermost surface is bulging. (3,4,5th view).

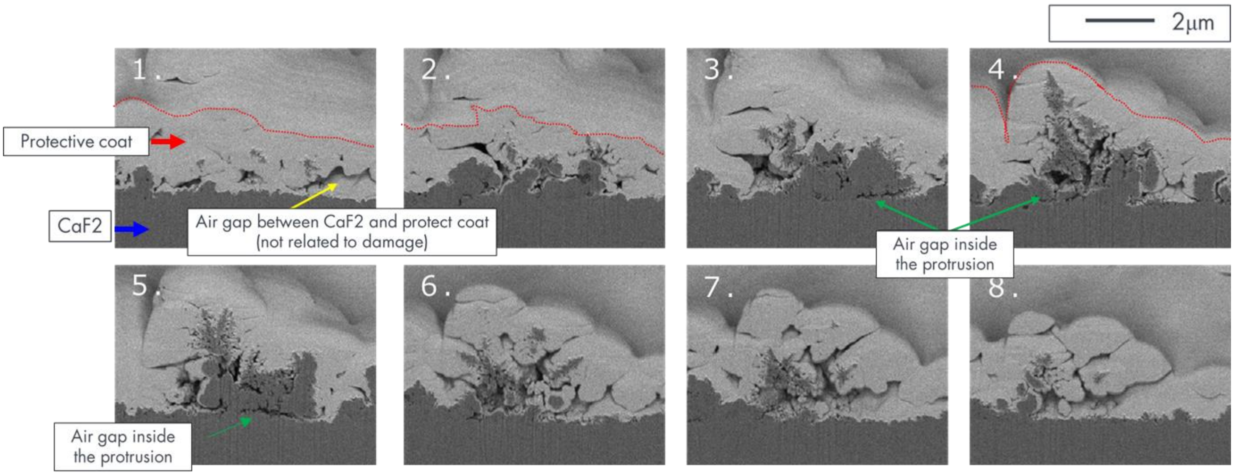


Figure 5. 3D image of surface damage using Slice and View.

2.5 TEM-EDX

TEM - EDX is the last analysis method to be introduced at this time. It is a method that identifies material by irradiating electron beams onto thinned samples, and by combining electrons transmitted through the sample and scattered electrons. TEM images vary mainly in density (element weight), but also in atomic density, crystallinity and directionality. It can be a factor in changing contrast.

When looking at the analysis results in Figure 6, as indicated by the blue arrows in the TEM image, regardless of the visibility of a difference in intensity in the protrusion and substrate portion, no intensity was observed in the Ca or F in the EDX image. This suggests that the element crystallinity has deteriorated. These phenomena can also be observed in the element subsurface. Further, when the results of component analysis are discontinued, there is a part where the fluorine is missing in a part of the normal substrate and the components of that part can read that the fluorine atoms were substituted with oxygen atoms.

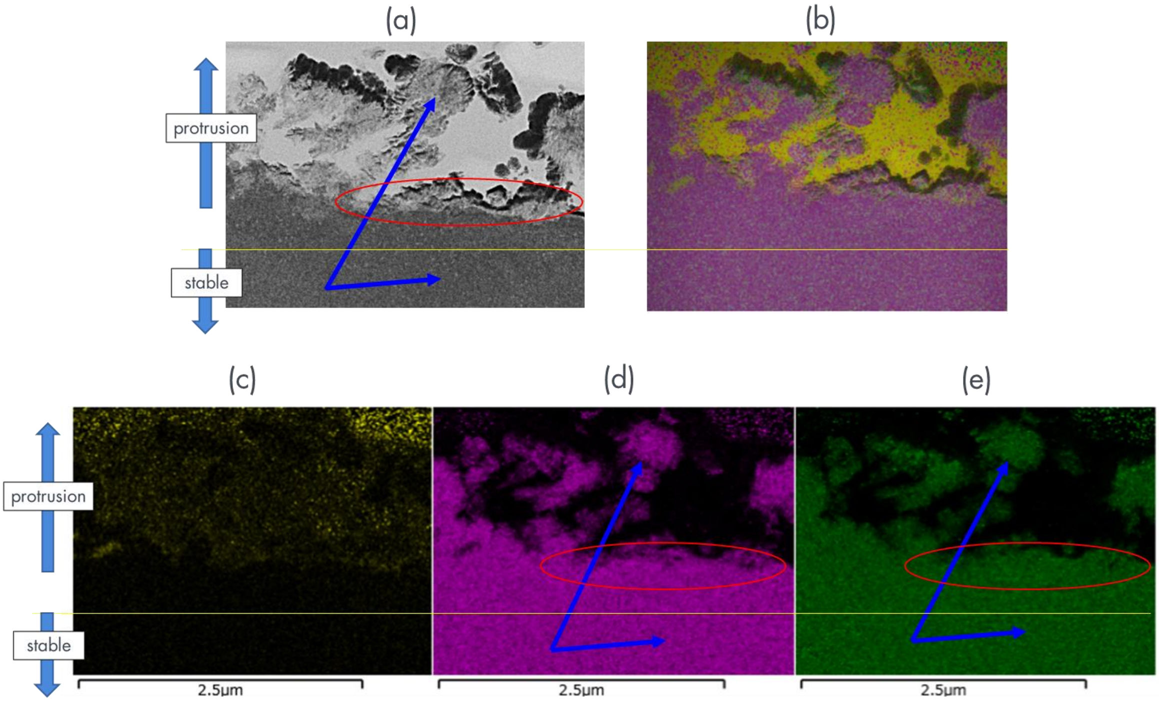


Figure 6. Morphology of surface damage (one of protrusion) using TEM-EDX. (a) shows a TEM image, and (b) shows a TEM-EDX superimposed image. (c)-(d) is an image map of component analysis by EDX, "oxygen" shows in (c), "fluorine" shows in (d), and "calcium" atoms show in (e).

2.6 Summary of analysis results

To summarize the analysis results performed by various measurement methods, the shape of the damage was confirmed from the Nomarski type differential interference microscope, AFM, and Slice & View analysis. The shape of the damage grows in the form of scratches with protrusions (convex shape). It gradually joins or deteriorates and seems to spread the range of damage gradually. Although the degree of damage also increased, unevenness of ± 2 μm or more in height was not observed. That is, damage does not proceed deeply, spreading the surface area. The interior of the convex portion has a hollow void. When the results of component analysis are put together, it can be seen that the crystallinity of CaF2 is deteriorated in the convex portion, the volume expands and the density decreases, thereby expanding the volume.

3. CAUSE OF SURFACE DAMAGE

3.1 Estimation of Surface damage

We assume a mechanism whereby surface damage will progress gradually. The crystallinity deteriorates in about 100 nm of the crystal surface [step 1]. From an extremely shallow depth, this deterioration might start from scratch and sub-surface damage at polishing. Decrease in density produces the expansion of volume, due to the deterioration of crystallinity. This creates protrusions on the surface and due to the increase in scattering, the protrusion absorbs laser light and it can easily be assumed that this further accelerates crystallization deterioration [step 2]. The protrusions grow while being affected by crystal orientation and laser resonance direction. The protrusions are deformed by scratches, repeatedly combine, expand and form larger protrusions including big air gaps, and grow into surface damage that includes the above. Ultimately, the scattered light can be visually distinguished easily.

3.2 Assumption

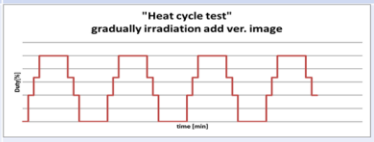
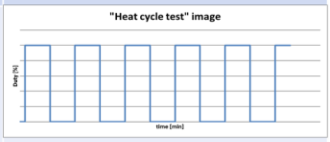
We focused on step 1 and made an assumption. When irradiation starts, the defects and scratch/SSD absorb laser-light and increase the temperature. The locally produced temperature distribution disconnects the crystal bonds and ionizes the optical surfaces. (It cuts the CaF2 bonds and decreases the density.) From experience, as the temperature distribution quickly stabilizes and because it disappears, the surface damage has no direct correlation with the number of irradiations. The assumption derived from the above is that “surface damage” is produced in the process until the temperature stabilizes by laser irradiation.

4. VERIFICATION TEST

4.1 Verification test conditions

We conducted a verification test of our assumption in section 3. Entitling it a “duty cycle test,” it focuses on the extreme temperature changes due to heating because of irradiation of the element and cooling because of not irradiating the light after changing the laser irradiation pattern to a great extent. Testing basically repeats irradiation (5 minutes) and no irradiation (5 minutes). In pattern 1, we assume an irradiation pattern like actual usage in the field. By inserting 30% and 50% irradiation for one minute each, the temperature change occurs moderately. For pattern 2, in contrast, with an irradiation method that forcefully invokes the largest change, 5 minutes of irradiation and 5 minutes of rest are simply repeated. The respective total shot count is 100 Mpls for pattern 1 and 60 Mpls for pattern 2. Actually, with regard to the shot count experienced up to the present, it is an extremely short number of irradiation shots. If our assumption is correct, we can expect that damage will occur only in pattern 2.

Table 1. Duty cycle test condition

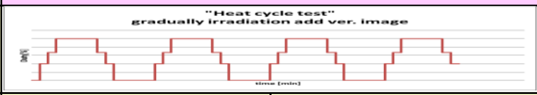
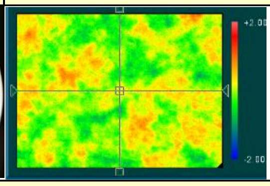
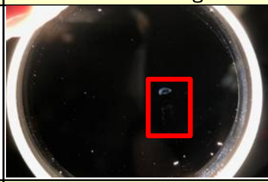
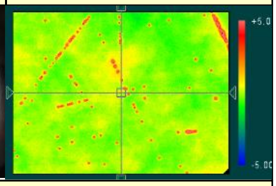
item	Field : Actual usage	Duty cycle test	
		Pattern1	Pattern2
Duty [%]	Average 30% (75% can be available)	0-30-50-75 Gradual irradiation	0-75 Burst irradiation
Total shot	Target : 100Bpls	100 M pls	60 Mpls
Irradiation pattern	No image		

4.2 Verification test results

We used “dark field image,” “Nomarski-type DIC microscope” and “Zygo New View” for the elements after irradiation in each pattern to confirm the presence or absence of damage. We did not observe any change whatsoever from the initial conditions in the elements for pattern 1, whereas in pattern 2 we confirmed a clear change that could be judged visually. We observed forms that closely resembled scratches during polishing in convex form. Continuing laser irradiation into the future, we can assume that the protrusions will grow linearly and further, their area will enlarge

We can verify our assumption from the above. With an extremely short shot number of 60 Mpls we succeeded in reproducing surface damage and further, we were able to confirm that it would be difficult to occur in normal market usage.

Table 2. Verification test results

	Pattern1 : Gradual irradiation		Pattern2 : Burst irradiation	
Irradiation Pattern				
damage check	dark field image	New View7100	dark field image	New View7100
				
	Nomarski DIC microscope		Nomarski DIC microscope	
				
Result	**Non damaged**		**Damaged**	

5. SUMMARY AND CONCLUSION

Due to element development, the extended element life span has grown to reach 100 Bpls. In simple testing it has come to the point where they take extremely long periods such as several years. By establishing specialized element tests (short term tests) for each damage shape, it is expected that these tests will be carried out more efficiently. We have now analyzed surface damage and have observed deterioration of the crystallinity and changes in the surface. For these reasons, we hypothesize that "'surface damage' occurs in the process up until the heat is stabilized by laser irradiation." We succeeded in establishing an element test, called a "duty cycle test" (pattern 2). This test is in keeping with the evaluation of polishing quality and from the test results we can expect that they can contribute to the extension of element life span on into the future.

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