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Ablation suppression of titanium optimizing the delay time by two-color femtosecond double-pulse laser

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Abstract

Two-color femtosecond double-pulse laser beam has been used to discuss the suppression of ablation rates on titanium (Ti) surface in the delay time (Δt) from 0 to 700 ps. The double pulse beam consisted of 800 nm with 150 fs pulse and 400 nm with > 150 fs pulse in cross polarization. The ablation rate was clearly suppressed at the delay time of Δt ~ 80 ps. For first pulse of 400 nm case, the ablation rate was suppressed at the delay time of Δt ~ 150 ps. The suppressed delay time was approximately three times difference for both irradiation case. The difference of the suppression time might be suggested that the ablation rate was effectively suppressed when the expanding surface plasma produced by first laser pulse should be close to the critical density for the second laser pulse.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

The material processing with femtosecond double-pulse laser has been demonstrated since 1990. Recently several interesting features such as the ablation suppression, plasma emission enhancement, 2D fine structuring have been reported in the delay time from 0 to few ns for using with double pulse beam. However, the mechanism of laser ablation with double pulse beam is still open question due to two pulses consist of same laser wavelength. It is difficult to distinguish between the effect of the first pulse and the effect of the second pulse. To discuss the suppression of ablation rates, two-color femtosecond double-pulse laser beam has been used for titanium (Ti) surface in the delay time (Δt) from 0 to 700 ps. The double pulse beam consisted of 800 nm with 150 fs pulse (fundamental-pulse) and 400 nm with > 150 fs pulse (second harmonic pulse) in cross polarization. The first pulse fluence F_1 was kept above ablation threshold while the

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second pulse fluence F_2 was kept below the ablation threshold. The delay time was defined as a time interval between arrival first pulse and second pulse. The first pulse can produce the plasma on titanium surface and the plasma expand the sound speed before the second pulse irradiated. The delay time between two pulses might be characterized the plasma density produced by first pulse. The second pulse could be interacted with an interface between the titanium surface and the plasma in certain time delay in which an electron density of plasma close to the critical density for the second pulse. If the interface is important role to ablation suppression, the time delay might depend on the wavelength of the second pulse because the critical density is related to the laser wavelength. In this experiment we have confirmed this effect by using two-color femtosecond double-pulse laser beam.

2. Experimental method

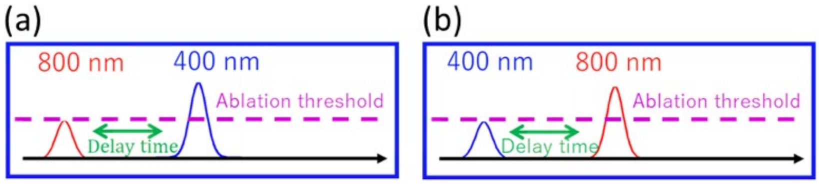


Fig.1. The suppression experiment with two-color femtosecond double-pulse laser beam.

In the experiment, a femtosecond laser was employed Ti:sapphire laser (Cyber Laser, IFRIT) which had wavelength of 800 nm, repetition rate of 1 kHz, and pulse width of 150 fs. Here how to prepare the two-color femtosecond double-pulse laser beam is briefly described. The emitted laser pulse was led by dielectric coating mirrors and made the direction of linear polarization by two polarizers. The laser pulse was separated to two pulses by a beam splitter. One laser pulse was converted to wavelength of 400 nm in a BBO crystal for generating its second harmonic. Finally, two pulses in which wavelength of 800 nm and 400 nm were coaxially aligned and focused on titanium surface by a quartz lens with a focal length of 100mm. The polarization direction of 800nm pulse was parallel to an optical table and 400nm polarization direction was 90 degrees to the table. Thus the polarization directions of two pulses were set to be orthogonal. To control the delay time between two pulses, an optical path length for 800nm pulse was adjusted by a translational stage. At the focal position, the spatial profile of the laser was observed by a CCD camera equipped with an objective lens. The special profile was Gaussian shaped and its diameter was adjusted to be 25 μm (full width at 1/e Maximum) for both pulses. The irradiated fluence of the laser pulse was adjusting by an energy attenuator consisted of a pair of polarizer and a half wave plate. We performed the suppression experiment by transposing the wavelength of the first pulse and the second pulse in two-color femtosecond double-pulse laser beam (Fig.1). The first pulse fluence F_1 was set to be 1.6 times of the ablation threshold while the second pulse fluence F_2 was set 0.8 times of the ablation threshold. The first pulse can contribute to produce the plasma on titanium surface. The plasma expands isotopically with the sound speed before the second pulse irradiated. The delay time between the first pulse and the second pulse might be related to the plasma density produced by first pulse. In the experiment the delay time of two pulses was changed in the range of 0 to 700 ps. The titanium surface was ablated by irradiating two color double-pulse laser beam. The ablation depth was measured using a scanning laser microscope (VK-X250/260, Keyence). The surface of titanium (99.5% purity) was mechanically polished and its roughness was less than 2nm in root mean square. The dimension of titanium plate was 1.5cm square and 1mm thickness. The ablation depth was defined as the distance between the deepest part of the crater and the substrate surface. The ablation depth per unit pulse of the laser (a pair of pulse for double pulse beam irradiation) was defined as an ablation rate. The ablation rate can be expressed by following well known equation;

$$AR = \alpha \ln(\frac{F}{F_{th}}) \tag{1}$$

Here, the ablation rate is *AR*, the penetration of light is α, the fluence of the laser is *F*, and the fluence of ablation threshold is F_{th}.

3. Results

Figure 2 shows the ablation rate dependence on the delay time for 400nm first pulse case Fig.2(a) and that for 800nm case Fig.2(b). The irradiation condition are inserted. The dotted lines in the dependecies showed the ablation rate when only the first pulse (single pulse irradiation) was irradiated. The ablation rate for only first pulse irradiation was 6.1nm/pulse ((Fig.1(a)) for 400nm pulse and 7.3nm/pulse((Fig.1(b)) for 800nm pulse. For double pulse beam of 400nm first pulse case, the ablation rate was suppressed in few hundred femtosecond to 600ps. The most suppressed delay time was 150 ps and its ablation rate was about 1.9nm/pair. For double pulse beam of 800nm first pulse case, the dependence of the ablation rate suppression was similar tendency. The most suppressed delay time was 80 ps and its ablation rate was about 3.5nm/pair. Therefore the suppression delay time was decreased as decreasing the wavelength of second laser pulse.

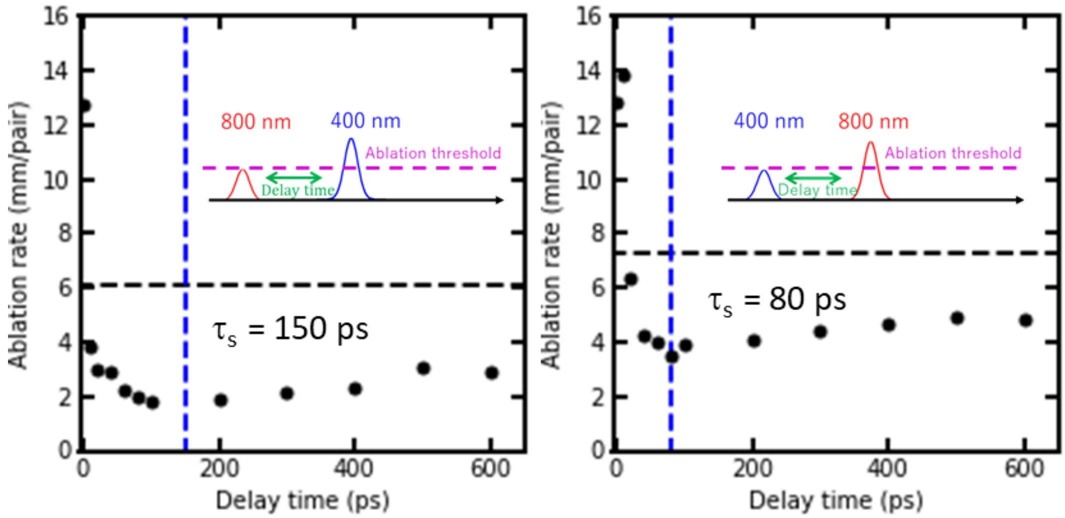


Fig. 2. Graph of delay time and ablation rate when the wavelength of first pulse was 400nm in (a) and when the wavelength of first pulse was 800nm in (b)

4. Discussion

With using two-color femtosecond double-pulse laser beam, the ablation rate was clearly suppressed at the delay time of Δt ~ 80 ps for first pulse of 800nm case while the suppressed delay time was Δt ~ 150 ps for the first pulse of 400 nm case. The suppressed delay time was approximately three times difference for both irradiation case. The difference of the suppression time might be suggested that the ablation rate was effectively suppressed when the expanding surface plasma produced by first laser pulse should be close to the critical density for the second laser pulse. Therefore the second pulse interacted with the interface between the the solid surface (titanium surface) and the surface plasma is one of the key issues. When the plasma density is higher than that of critical density for the second laser pulse, the second laser pulse reflected by the surface of high dense plasma. Therefore the second laser pulse is not able to reach the interface of plasma-titanium surface. When the plasma density is below the critical density for the second laser pulse, the second pulse reaches the interface and the interaction occurs. This interaction may be the key to ablation suppression. It is expected that the interaction became small even if the electron density of the plasma is too large or too small. In other words, there is a plasma electron density at which the interaction is maximized, which is a critical density. The plasma density was calculated by following assumptions.

- The plasma produced by first laser pulse is expanded isotopically at sound speed.
- The initial thickness of the plasma is defined as the optical penetration depth of first pulse.
- The initial diameter of the plasma is same as the laser diameter.
- The initial plasma density is the electron density of solid titanium at room temperatures.

From the reference, the expansion velocity of the plasma is assumed to be the sound velocity. Figure 3 shows calculated plasma density as a function of expanding time for 400nm first pulse(red curve) and the density for 800nm first pulse(blue curve). The red dotted line represented the critical density(n_{cr}=7.0×10^{21}cm^{-3}) for 800 nm second pulse, and the green dotted line represented the critical density (n_{cr}=1.7×10^{21}cm^{-3}) for 400 nm second pulse. The intersection of the dotted line and the solid line was the delay time when the plasma density produced by first pulse reached the critical density for second laser pulse. When double pulse beam with 800nm first pulse is irradiated on titanium, the time delay in which the plasma density for 400nm second pulse became the critical density was calculated to be 81 ps. On the other hand, when the double pulse beam with 400nm first pulse is irradiated, the delay time for 800nm second pulse was calculated to be 168 ps. Table 1 summarized the delay time for the suppression experiment and the calculation of critical density. The calculated time is qualitatively good agreement with the delay time obtained by the suppression experiment. The suppression time might be suggested that the ablation rate was effectively suppressed when the expanding surface plasma produced by first laser pulse should be close to the critical density for the second laser pulse.

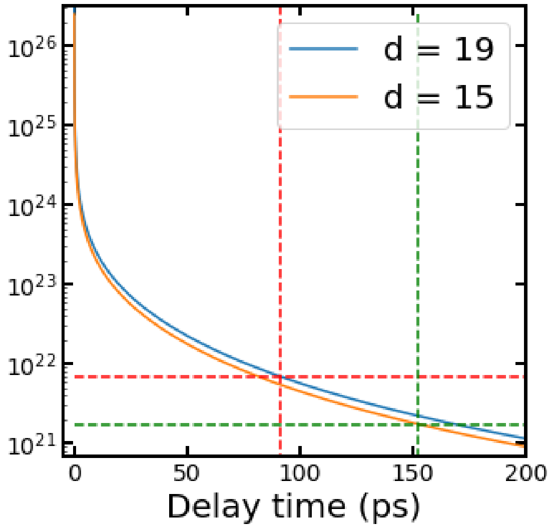
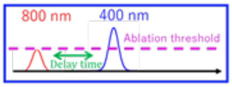
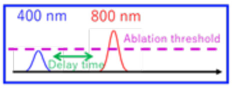


Fig. 3. Plasma density as a function of time. The red curve shows the plasma density produced by first pulse in irradiation of Fig.1(a). The optical penetration depth d= 15nm is used. The blue curve corresponds to the irradiation of Fig.1(b). The d=19nm is used for obtaining the blue curve.

Table 1. A table of experimental values and calculated values.

		
	Δt [ps]	Δt [ps]
Experimental values	150	80
Caculated values	168.38	81.23

Acknowledgements

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