Effects of Target Position on Direct Initiation of Detonation using Laser Ablation

Hidefumi KATAOKA,1) Hiroyuki KATO,2) Keitaro SUZUKI,2) Sakiko ISHIHARA,2) Kazuhiro ISHII2) and Daisuke SEGAWA1)

1)Department of Mechanical Engineering, Osaka Prefecture University, Osaka 599–8531, Japan
2)Department of Mechanical Engineering, Yokohama National University, Kanagawa 240–8501, Japan

Laser ablation is expected to achieve the direct initiation of detonation with a smaller amount of energy compared to laser breakdown. In the present work, the critical energy for direct initiation was experimentally studied with an acetylene/oxygen mixture varying the distances between the focal point of the laser beam and the target surface. The observed plasma formation in the laser ablation is divided into three modes: (a) the plasma generated by laser ablation is attached to the target surface; (b) the breakdown plasma partly overlaps with the ablation plasma; and (c) the breakdown plasma is formed separately from the ablation plasma. The dependence of the critical energy for the laser ablation on the distance between the target surface and the focal point is explained by interaction between the breakdown and the ablation plasma. The present results demonstrate that it is possible to initiate detonation directly using laser ablation with much smaller laser energy compared to laser breakdown.

Key Words: Detonation, Direct Initiation, Laser Ablation

Nomenclature

\( d_f \): focal spot diameter
\( d_i \): initial beam diameter
\( d_s \): beam spot diameter
\( D_{CJ} \): Chapman-Jouguet velocity
\( E_0 \): laser energy
\( E_{CR} \): critical energy for direct initiation
\( E_{CRab} \): critical energy in laser ablation
\( E_{CRRb} \): critical energy in breakdown
\( f \): focal length
\( H \): target height
\( L \): distance between focal point and target surface
\( M^2 \): beam quality factor
\( p \): initial pressure
\( p_{iso} \): combustion pressure at constant volume
\( p_{CJ} \): Chapman-Jouguet pressure
\( W \): cell width
\( z \): length from focal point
\( \phi \): equivalence ratio
\( \lambda \): wavelength
\( \rho \): density

1. Introduction

Propulsion systems using detonation have been studied intensively because of their simple structure and high thermal efficiency.1–3) It is necessary to initiate detonation in a short time interval to realize these propulsion systems. Initiation processes of detonation can be classified into two groups. One is deflagration to detonation transition (DDT),4) which occurs in a confined tube. The other is direct initiation,5–14) which refers to instantaneous formation of detonation without the flame acceleration stage. Direct initiation is expected to downsize the combustor of detonation engines, although it requires a relatively large amount of energy to generate a strong blast wave that causes detonation.

There are various energy sources for direct initiation such as laser sparks,6–8) exploding wires,8–10) electrical sparks,8,11–13) and condensed explosives.11,14) Among them, laser is a probable candidate for the energy source of direct initiation, since it can provide high energy density in a very short time without perturbing a flow field. There are two typical methods to generate the blast wave in combustible mixtures using a laser; laser breakdown and laser ablation.7) In the former, the blast wave is generated by plasma induced by focusing an intense laser pulse into a gas. In the latter, the plasma plume, which is ejected from a solid surface of target materials irradiated with a laser pulse, generates the blast wave.15) Once a sufficiently strong blast wave is generated in combustible mixtures, chemical reactions are induced. The chemical reactions are coupled to the blast wave, and a detonation wave is generated.16)

From the fact that the critical laser energy required for usual ignition using laser ablation was lower than using laser breakdown,17) laser ablation is expected to achieve direct initiation using a smaller amount of energy compared to laser breakdown. It should be noted that the ignition characteristics using laser ablation are affected by the relative position between the target surface and the focal point of the laser beam.17,18)

In the present work, laser ablation was applied for direct
initiation of detonation, and the effects of the target position relative to the focal point of the laser beam were examined. The effects of the target position on the characteristics of direct initiation were discussed using emission images of plasma formed by laser ablation recorded on an Intensified Charge Coupled Device (ICCD) camera. The critical energy, with which detonation was directly initiated, was compared with the calculated value based on the surface energy theory.5)

2. Experimental Apparatus

The optical arrangement for laser ablation is shown schematically in Fig. 1. The laser used in the present work was a pulsed Q-switched Nd:YAG laser (LOTIS TII, LS2137U/2), operating at a wavelength of 532 nm, with a pulse duration of 8 ns and a beam diameter of 8 mm. The laser energy $E_0$ was varied using a combination of a 1/2 wave plate and a polarizing beam splitter, and was monitored by a laser power detector (OPHIR, PE50BB). The laser beam was focused by a converging lens with a focal length of 60 mm, inside the combustion chamber shown in Fig. 2. It had an inner height of 40 mm and was 30 mm in diameter. The target was a stainless steel (SUS304) rod of 10 mm in diameter mounted on a cover disk opposed to the optical window for laser irradiation. A pressure transducer (PCB, 113A22) was installed on one end wall to record pressure histories in the combustion chamber. Direct initiation was determined from the measured pressure histories. The other end wall was coated with soot for recording the detonation cellular structure. To observe plasma formed by laser ablation, this end wall was replaced by a glass window and the emission image of the plasma was recorded on an ICCD camera (Hamamatsu, C7972-03). The trigger signal to the ICCD camera was supplied from a delay generator (Stanford Research System, DG535) synchronized with laser irradiation.

The distance between the focal point of the laser beam and the target surface, $L$, ranged from $-6$ mm to $6$ mm as shown in Fig. 3. The value of $L$ becomes negative when the focal point is located inside the target. In the present work, $L$ was varied by varying the target height $H$, without any change in the optical arrangement. As a test gas, a C$_2$H$_2$/O$_2$ (equivalence ratio $\phi = 1$) mixture was introduced into the combustion chamber at an initial pressure, $p$, of 50 kPa and at room temperature.

3. Results and Discussion

3.1. Erosion of target surface

The surface condition of the target after several tests is shown in Fig. 4. Erosion caused by laser ablation17–20) can be found in all cases. The position of the beam spot was changed after each shot so that a fresh target surface was irradiated with the laser beam, and several erosion marks appeared.

3.2. Emission image of plasma

Figure 5 shows emission images of the plasma 25–30 ns after laser irradiation for the laser energy $E_0$ of 60 mJ. The neutral density filter (optical density = 2.0) was used, and the exposure time was very short (5 ns). The emission images are not assumed to include any emission from combustion-
related chemical reactions. For $L \leq -1 \text{ mm}$, the plasma was formed in the vicinity of the target surface that is, the plasma was generated only by laser ablation. The shape of the plasma was stretched in the direction of the beam axis for $0 \text{ mm} \leq L \leq 2 \text{ mm}$. The plasma was divided into two parts with larger $L$: one was formed near the target surface, and the other had an extended shape, which was formed away from the target surface. From similarity to the plasma for $L \leq -1 \text{ mm}$, it is assumed that the former is due to laser ablation. The latter was formed just ahead of (and behind) the focal point of the laser beam, indicating that the latter is generated by laser breakdown.\textsuperscript{21,22} This is supported by the observation that the incident side of the plasma revealed always higher brightness as shown in Fig. 5.

Plasma formation in the present study can be classified into three modes,\textsuperscript{15} which are sketched in Fig. 6: (a) the plasma is generated by laser ablation in that vicinity of the target surface; (b) the breakdown plasma partly overlaps with the ablation plasma; and (c) the breakdown plasma is formed separately from the ablation plasma. The effects of these plasma formation modes on direct initiation of detonation are discussed later.

### 3.3. Pressure histories and smoked records

Figure 7 shows typical pressure histories for $L = 0 \text{ mm}$ and two conditions of the laser energy. The dashed lines of $p_{\text{CJ}}$ and $p_{\text{iso}}$ denote the CJ pressure and combustion pressure at constant volume calculated by AISTJAN,\textsuperscript{23} respectively. For $E_0 = 57 \text{ mJ}$, the pressure increased well above the CJ pressure at the beginning, indicating success in direct initiation of detonation. Subsequently, several pressure peaks were due to shock reflections at the chamber wall, and finally
the pressure showed \( p_{\text{iso}} \). For the lower laser energy, \( E_0 = 39 \) mJ, no rapid pressure rise was observed. The pressure gradually increased to \( p_{\text{iso}} \). In this case, no direct initiation occurred, resulting in usual flame propagation. The delay time from direct initiation to detection by the pressure transducer is assumed from the distance between the location(s) of plasma formation and the pressure transducer, and from the CJ velocity. The assumed delay time is less than 10 \( \mu \text{s} \), which is determined to be the threshold between direct initiation and DDT. Direct initiation is assumed to occur when there are no apparent pressure increases during the threshold delay time before the rapid pressure rise in the pressure records.

Corresponding smoked records support the success or failure in the direct initiation mentioned above. In Fig. 8(a), much fine structure can be seen on the smoked record, although apparent cellular structure cannot be recognized owing to its small size. The failure case gives no structure or pattern on the smoked record as shown in Fig. 8(b).

### 3.4. Effects of target position on critical energy for direct initiation

Figure 9 shows the effects of the distance between the target surface and focal point on critical laser energy, \( E_{\text{CRab}} \), for direct initiation of detonation. An open circle represents success in direct initiation and a cross symbol represents failure. The dashed lines connect the estimated values of the critical laser energy. The critical laser energy was estimated based on Weibull analysis.\(^{24}\) The distribution function of the energy for direct initiation is assumed as

\[
F = 1 - \exp \left\{ - \left( \frac{E_0 - E_{\text{CR}}}{\alpha} \right)^2 \right\},
\]

where, \( \alpha \) is the scale parameter.

In the range of \( -6 \text{ mm} \leq L \leq -2 \text{ mm} \), the critical laser energy decreased as \( L \) increased. This result is consistent with the usual ignition characteristics using laser ablation.\(^{18}\) For \( -2 \text{ mm} \leq L \leq 4 \text{ mm} \), the critical laser energy increased slightly as \( L \) increased, and much larger laser energy was needed for direct initiation in the range of \( L > 4 \text{ mm} \).

This manner of the critical laser energy can be explained by interaction between the breakdown and ablation plasmas, which is shown in Figs. 5 and 6.

For \( L \leq 0 \text{ mm} \), the power density of the laser beam at the target surface increases with \( L \). Consequently, the strength of the blast wave generated by the plasma plume ejected when using the laser ablation increases, as the focal point of the laser beam approaches the target surface.

![Fig. 8. Photograph of smoked record for \( L = 0 \text{ mm} \).](image)

![Fig. 9. Effects of \( L \) on the critical laser energy.](image)

![Fig. 10. Effects of \( L \) on the critical laser energy density per unit spot area.](image)

\[
E_{\text{CRab}} = \frac{4 \lambda M^2}{\pi d_i},
\]

where, \( d_i, f, \lambda \) and \( M^2 \) are initial laser beam diameter, focal length, wavelength of the laser light and beam quality factor, respectively. The present specifications of the optical components of \( d_i = 8 \text{ mm}, \lambda = 532 \text{ nm}, M^2 = 1 \) and \( f = 62 \text{ mm} \) gives \( d_i \) of 0.0052 mm. Then the beam spot diameter, \( d_z \), can be calculated from the following equation,

\[
d_z = \frac{d_i}{2} \left[ 1 + \left( \frac{z M^2}{\pi (d_i/2)^2} \right)^{1/2} \right],
\]

where, \( z \) is the length from the focal point.

For usual laser ignition by laser ablation, it has been reported that the critical laser energy density per unit area is independent of the spot diameter.\(^{18}\) However, the present
results show that the critical laser energy density depends on $L$, and in particular, rapidly increases with $L$ around $L \approx 0$ mm. This might be related to the occurrence of laser breakdown. The above estimation of the beam spot diameter is made under no assumption of passing through the breakdown plasma. The beam spot diameter at the target surface may be underestimated in the case of breakdown plasma formation.

The difference in the dependence of the critical laser energy density might also be attributed to the laser energy needed for ablating the target to form plasma plume, which ranges between laser energies for usual ignition and direct initiation. For the case of usual ignition of hydrogen/oxygen mixtures with laser irradiation, it is reported that the laser energy for ablation is larger than the ignition energy.25) Thus, successful ignition by laser ablation is dominated by the laser energy density, because generation of the plasma plume depends mainly on laser energy density. Consequently, the critical laser energy density for usual ignition by laser ablation is independent of the spot diameter. On the other hand, the laser energy for plasma plume formation by laser ablation is smaller than the critical energy for direct initiation (cross symbol in Fig. 9). The blast wave must be maintained at or above the minimum strength for a certain duration to achieve direct initiation.26) While the blast wave strength is dominated by the laser energy density, the duration for which the blast wave with certain strength is maintained is dependent on the initial volume of the plasma plume, or the spot diameter. It is, therefore, reasonable that a smaller spot diameter requires more laser energy density to cause direct initiation, as shown in Fig. 10.

For $L > 0$ mm, besides the ablation plume, breakdown plasma is formed ahead of the ablation plasma. The breakdown plasma also generates a shock wave, which eventually merges with the shock wave by the ablation plasma. The breakdown plasma has little ability to cause direct initiation by itself and this merger shock wave contributes to direct initiation of detonation. The power density of the laser beam at the target surface decreases because of the energy consumed when generating the breakdown plasma. The strength of the merger shock wave weakens for longer distances between the breakdown and ablation plasmas.

### 3.5 Comparison of laser ablation with laser breakdown

Figure 11 shows a comparison of the critical laser energy to realize direct initiation of detonation between laser ablation and laser breakdown. The experiments for laser breakdown were conducted by replacing the cover disk for the target by a glass window so that the laser beam could be transmitted with less reflection. In Fig. 11, the open circles indicate success in direct initiation, and the cross symbols indicate failure. $L$ was set as $-2$ mm, because this condition provides the minimum critical laser energy. The dashed lines denote the critical laser energy for laser ablation, $E_{CRab}$ of 33 mJ, or the critical laser energy for laser breakdown, $E_{CRbr}$ of 110 mJ. The former is about one-third of the latter; that is, much smaller laser energy is needed for direct initiation of detonation using laser ablation.

![Fig. 11. Comparison of critical laser energy between laser ablation and laser breakdown.](image)

The critical energy for direct initiation, $E_{CR}$ has been estimated by the following equation,

$$E_{CR} = \frac{2197\pi \rho D_{CJ}^2 W^3}{16},$$

where, $\rho$, $I$, $D_{CJ}$, and $W$ are density of the mixture, a numerical constant of 0.432 for ratio of specific heats of 1.4, CJ velocity and cell width, respectively.5,27) The cell width of the stoichiometric acetylene/oxygen mixture at 50 kPa is 0.42 mm from the experimental results by Manzhalei et al.28) On the other hand, an experimental equation, $W = 18.9 \times p^{-0.105}$, has been proposed by Zhang et al.27) Substituting $p = 50$ kPa into the equation, the cell width becomes 0.36 mm. There is a difference of 17% in the cell size, resulting in a difference of about 1.6 times in the critical energy. The CJ velocity is calculated by AISTJAN.23) The critical energy, $E_{CR}$ is calculated to be 41 mJ with the average cell width. This $E_{CR}$ is essentially the energy to generate a spherical blast wave causing detonation. The conversion efficiency for the laser breakdown is calculated to be about 0.37, which is comparable to that for the laser propulsion.29) For laser ablation, a dome-shaped blast wave is formed over the target surface. $E_{CRab}$ is, therefore, can be assumed to be half of the critical energy calculated by Eq. (4). However, $E_{CRab}$ is found to be larger than $0.5E_{CR}$. This excess energy is mainly attributed to loss of the laser energy through reflection and heat losses. In addition, it is possible that the shape of the blast wave is distorted, because the shock wave does not originate from a single point. These effects on direct initiation need to be studied in the future.

### 4. Conclusions

Direct initiation of detonation by laser ablation was experimentally studied for a stoichiometric acetylene/oxygen mixture. The critical laser energy for direct initiation was obtained with various distances between the focal point of the laser beam and the target surface. The following conclusions are drawn from the present study:

1. The critical energy for laser ablation is dependent on the distance between the target surface and focal point, which is due to the interaction between the plasma pockets of breakdown and ablation. Only when the laser ablation plasma is
formed, the critical laser energy decreases with the focal point of the laser beam approaching the target surface.

2. It is possible to initiate detonation directly using laser ablation with much smaller laser energy compared to laser breakdown.

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