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Citation: Journal of Applied Physics 121, 215901 (2017); doi: 10.1063/1.4984753
View online: http://dx.doi.org/10.1063/1.4984753
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Published by the American Institute of Physics

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Performance characterization of a miniaturized exploding foil initiator via modified VISAR interferometer and shock wave analysis

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(Received 28 October 2016; accepted 18 May 2017; published online 1 June 2017)

A pyrotechnic device that consists of a donor/acceptor pair separated by a gap or a bulkhead relies on the shock attenuation characteristics of the gap material and the shock sensitivity of the donor and acceptor explosives. In this study, a miniaturized exploding foil initiator, based on high pulsed electrical power generator, was designed to launch a micro Kapton flyer for impact initiation of a high explosive in order to understand its performance characteristics. Here, the explosive substance was replaced with a witness plate because the flyer poses various flight motions of rotation, bend, and fragmentation due to its extreme thinness. By using a Velocity Interferometer System for Any Reflector and ANSYS Explicit Dynamics, the averaged velocity of a flyer is measured, which then allows for the calculation of the shock pressure and the duration imparted to the explosive for an initiation. Subsequently, the relationship between the flyer velocity, the amplitude, and the width of impact loading can be used to assess the performance of the designed exploding foil initiator of a micro pyro-mechanical device. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). [http://dx.doi.org/10.1063/1.4984753]

I. INTRODUCTION

A detonator is a primary initiator unit that ensures reliable triggering of an explosive train of which the sequence of events culminates in the detonation of sensitive high explosives in a variety of applications.1 Traditionally, the explosive train requires a physical barrier or misalignment between the primary and secondary explosives to avoid the inherent hazard of accidental discharging during handling and transport.2 However, an exploding foil initiator (EFI), also known as a slapper detonator, simplifies the design of the explosive train by eliminating the mechanical assemblies usually used for safety when using explosives, because it can directly initiate secondary explosives by the impact of a flyer at a desired velocity.3 Since the EFI development from the mid 1970s,4 the performance map of the EFI detonator and the burst current density have been investigated in order to optimize the explosive system.5 Furthermore, studies on explosive initiation by a micro EFI and optical detonator have been continuously performed to devise micro energetic actuators.6,6–8

An increasing demand for miniaturized and reliable pyrotechnic devices has resulted in an investigation of the shock initiation performance of a micro flyer designed for a miniaturized EFI detonator.1 The shock pressure resulting from the impact velocity and flight characteristics of a flyer, of which the thickness and diameter are two and three orders of micrometers, respectively, must be fully understood. Therefore, in this study, an EFI is used to initiate an insensitive high explosive (HNS) from the impact of a Kapton flyer of which the thickness is 12.5 μm, and velocity reaches up to 5 km/s. Velocity Interferometer System for Any Reflector (VISAR)9 measurement was conducted to obtain the impact velocity of a flyer; the impact velocity is in principle the most significant parameter of EFI performance. In comparison to the existing EFI, the present micro EFI offers additional challenges associated with obtaining precise measurements of flyer velocity. The VISAR measurement can only be taken for a planar flying surface, and the flyer poses various flight motions of rotation, bend, and fragmentation due to its extreme thinness.10 A VISAR system cannot measure the exact center velocity within the focal spot, nor can it receive the deflected Doppler-shifted light which is out of the acceptable angle of the VISAR probe due to a sharp deformation on the very small and local area of the target surface.11 Therefore, as an alternative to using flyer velocity, a 304 stainless steel witness plate is placed in the flight path to measure the free surface velocity of the plate instead of the flyer. Consequently, the averaged impact velocity of a flyer and the following impact pressure are obtained by using the impedance matching technique.12,13 The lens configuration of a VISAR probe is designed to receive more accurate and longer velocity data without failure of data acquisition. The experiments are not completely free from the multiple reverberations of shock waves and large deformation of the thin targets. In order to overcome this difficulty, numerical analysis based on the finite element method is also performed in an inverse approach to determine the initial pressure at zero thickness of a target. By varying the thickness of a target, the attenuation pattern of shock waves is determined in terms of the distance of wave propagation for numerical validation. Therefore, the impact velocity of a
small-scale flyer and the ensuing shock pressure are investigated to determine the performance of the current EFI system.

The present aim of the detailed analysis of the system is the development and optimization of an EFI towards miniaturization of the pyrotechnic device. In Sec. II, the analytical methods such as flyer impact and the impedance matching techniques are introduced. Sec. III provides the information on the experimental setup that includes shock generator, velocity measurement, and experimental limit. The numerical analysis that is based on the finite element method using an explicit time integrator for highly transient and nonlinear dynamics is described in Sec. IV. Section V deals with both experimental and simulation results, and the flyer velocity is determined via the shock analysis.

II. ANALYTICAL APPROACH

Figure 1 illustrates the impedance matching technique in which the impact velocity, pressure, and pulse duration are determined from the analysis of P-u and x-t diagrams. Since the same impact pressure is loaded on both sides of the target and flyer from the momentum conservation, the flyer velocity can be obtained from a mirror image of a flyer Hugoniot intersecting with a target Hugoniot at the impact pressure, which is measured by VISAR in an ideally planar condition without any edge effects. Here, \( v_f, u_p, \) and \( l \) represent the impact velocity, particle velocity, and thickness of a flyer, respectively. \( P_i \) is the pressure imparted to a target material when a flyer impacts at velocity \( v_f \). The \( t \) is the pulse duration of the pressure loading, which is similar to the double transit time of the shock wave within a flyer. This is because the shock impedance of a flyer is lower than that of the target material. Therefore, a single rectangular pulse applied to a target is easy to control if planar conditions remain until the rarefaction wave on the shock front catches up.

When a flyer collides with a target material, two equal impinging pressures incur on both sides of the target due to pressure continuity. The relationship between impact velocity and pressure is derived by combining the momentum conservation and linear shock relation as follows:

\[
P_i = \rho_{0,T}(c_{0,T} + s_{T}u_{p,T})u_{p,T} \\
= \rho_{0,F}(c_{0,F} + s_{F}(v_f - u_{p,T}))(v_f - u_{p,T}), \tag{1} \\
u_{p,T} + u_{p,T} = v_f. \tag{2}
\]

The impact velocity can be summarized in terms of the particle velocity of a target and material properties as

\[
v_f - u_{p,T} = \frac{-\rho_{0,F}c_{0,F} + \sqrt{(\rho_{0,F}c_{0,F})^2 + 4s_{F}\rho_{0,F}(\rho_{0,T}(c_{0,T} + s_{T}u_{p,T})u_{p,T})}}{2s_{F}\rho_{0,F}} \tag{3}
\]

or

\[
u_{p,T} = \frac{\rho_{0,T}c_{0,T} + \rho_{0,F}c_{0,F} + 2\rho_{0,F}s_{F}v_f}{2(p_{0,F}s_{F} - \rho_{0,T}s_{T})} + \frac{\sqrt{(-\rho_{0,T}c_{0,T} - \rho_{0,F}c_{0,F} - 2\rho_{0,F}s_{F}v_f)^2 - 4(p_{0,F}s_{F} - \rho_{0,T}s_{T})(\rho_{0,F}c_{0,F}u_f + \rho_{0,F}s_{F}v_f^2)}}{2(p_{0,F}s_{F} - \rho_{0,T}s_{T})}, \tag{4}
\]

where \( P_i \) and \( v_f \) are the impact pressure and velocity at the impact surface, respectively. Subscripts T and F represent the properties for the target and flyer, respectively. The impact velocity of a flyer is calculated by using VISAR measurement and the shock Hugoniot data of the materials.

The resulting shock pressure versus velocity curve for a 304 stainless steel target and a flyer of polyimide is presented.
Shock pressure at the impact surface increases proportionally to the impact velocity, but the amount of velocity increase gradually decreases, because shock pressure has a quadratic term of particle velocity due to the linear relation between the shock and particle velocity. Finally, the impact velocity of the flyer is successfully obtained.

III. EXPERIMENT
A. Shock generator

Utilizing the impact of a flyer is a useful technique to generate a reproducible pressure pulse in a target material. The impact pressure and duration of the pressure pulse can be easily controlled by changing the impact velocity and the thickness of the flyer, respectively, by tuning the initial energy that moves the flyer.

Therefore, in this experiment, an EFI is used to generate the input shock loading on the explosive. The operation sequence and schematic of an EFI detonator is presented in Fig. 3(a). Figure 3(b) shows the case when the electric current pulse of a capacitor, which is charged up to several thousand volts, is discharged onto a thin metal bridge foil configured as a bridge structure having a narrow channel. The 165 \( \mu \)m long copper bridge undergoes an explosive phase change to a plasma state, as the electrical resistance is at maximum in the narrow channel. During the capacitor discharge, a tamper, which is an insulator under the metal foil layer, directs the plasma towards the flyer to enhance the acceleration performance.\(^{15}\) The expansion of high-density plasma rapidly accelerates the 12.5 \( \mu \)m thin Kapton flyer to the desired velocity by varying the charging voltage of the capacitor.

Subsequently, an explosive block is initiated from a shock wave generated by the flyer impact. The heat penetration depth \( l \), is given by \( \sim \sqrt{D\tau} \), where \( D \) and \( \tau \) are the thermal diffusivity of a material and the pulse duration of the capacitor discharge, respectively. The heat penetration depth of \( \sim 115 \) nm is obtained from the Kapton thermal diffusivity of \( 1.31 \times 10^{-6} \) m\(^2\)/s\(^s\) (Refs. 16 and 17) and the discharging current of approximately 100 ns. Therefore, sublimation of the Kapton is neglected because the heat penetration depth is too small compared to the thickness of a flyer.

B. Velocity measurement

VISAR measurement was conducted to obtain the impact velocity of a flyer for characterizing EFI. The measurement of the flyer velocity is particularly challenging as the system is developed for a miniaturized pyro-mechanical system, requiring additional precision in the measurement.

First, while the VISAR measurement is intended for a planar surface, the actual flyer exhibits various flight motions such as rotation, bending, and fragmentation due to its extreme thinness. Therefore, as an alternative to measuring flyer velocity, a witness plate of varying thickness is placed in the flight path to measure the bulging velocity, as depicted in Fig. 4. Then, the average impact velocity of a flyer is obtained using the impedance matching technique. Stainless steel of 304 type is used as a witness plate, the thickness of which varies from 50 to 300 \( \mu \)m to obtain the shock attenuation data according to the distance of wave propagation. Kapton used as a flyer is a dielectric insulation film which increases the plasma pressure by limiting the extent of heat transfer until the flyer is torn away.\(^{18}\) Here, the thickness and width of the flyer are 12.5 \( \mu \)m and 165 \( \mu \)m, respectively. An alignment guide ring, which has a small hole at the center, is utilized in the target assembly. Since the VISAR signal disappears when the center of the VISAR probe beam exceeds the inner circle of the guide ring, the beam center is moved up, down, left, and right to find the

FIG. 3. (a) Operation sequence and schematic of an exploding foil initiator and (b) metal foil layer configured as a bridge structure having a narrow channel.
boundary of the inner circle and to place the focal spot at the center of the target.

Generally, the shock pressure is obtained from the peak value of the velocity profile, which is measured by a velocity interferometer under an ideally planar wave condition where the shock front has not been caught-up by the rarefaction wave of the unloading and edge effects coming from the impacted surface. However, when the double transit time of shock waves within a target plate is less than the pulse duration of the shock load, multiple reverberations of shock and release waves rapidly accelerate the target without obvious fluctuation of velocity. It is difficult to distinguish the peak value from the velocity profile when shock waves arrive at the free surface. Therefore, numerical simulation is adopted to overcome the experimental limitation and to predict the initial pressure at the zero thickness by comparing with the measured time history of the free surface velocity of the target at various thicknesses.

The impact of a micro flyer induces relatively large deformation on a small and local area of the target surface. However, since a VISAR system generally has a laser beam focal spot ranging from 0.1 to 1 mm, it is difficult to measure the exact velocity at a specific point when a flyer is smaller than the spot size, especially when the probed object is moving out of the focal position. Furthermore, it is easy to lose the light signal of a reflected beam because of the relatively large deformation at a very small spot.

For this reason, the optical configuration of a VISAR probe is designed to receive more accurate and longer velocity data as shown in Fig. 5. The laser beam passes through an optical fiber, and a collimator is emitted towards the aperture, which is used for central alignment with the optical axis of the collimated beam. The width of the collimated beam is increased through a beam expander for a high numerical aperture, and the beam is then focused on the free surface of the target. All these components are assembled at 5-axis optical mounts, which have an XYZ translation as well as horizontal and vertical tilting in order to precisely control the alignment between the probe beam and the target surface.

![FIG. 4. Target assembly of the test EFI.](image1)

![FIG. 5. Assembly configuration of the improved VISAR probe.](image2)
a result, the advantages include the reduction in both time and cost by minimizing the failure of data acquisition.

In order to determine an appropriate lens configuration for each experimental condition, the Gaussian beam propagation needs to be understood.\(^\text{19}\)

Equation (5) represents the diameter of the focused spot in terms of the input beam and focusing lens parameters, as presented in Fig. 6.

\[
d_0 = \left(\frac{4\lambda}{\pi f_D}\right) \left(\frac{f}{D}\right).
\]  

(5)

Here, \(d_0\) is the Gaussian beam diameter, which is defined by the \(1/e^2\) contour of the maximum intensity; \(f\) is the focal length of a convex lens; \(\lambda\) and \(D\) represent the wavelength and diameter of the incident beam, respectively. The total angle of light that can enter or exit the lens is determined by using

\[
\theta \approx \frac{D}{f} = \frac{1}{N} \approx 2NA,
\]  

(6)

where \(N\) and \(NA\) are the photographic f-number and numerical aperture of the lens, respectively. Therefore, we apply a beam expander and a lens of short focal length to increase the numerical aperture and precision of the focal point of the VISAR probe. Consequently, the spot diameter of 5 \(\mu m\) and the numerical aperture of 0.19 radius are obtained from an incident beam size of 15.5 mm, focal length of 40 mm, and laser wavelength of 1550 nm. In this experimental condition, the free surface velocity by shock loading ranges from 2 to 3 orders of \(m/s\) and the duration of surface movement considering multiple shock reverberation is several hundred nanoseconds. Consequently, the displacement by shock wave is several tens of \(\mu m\) and then the focal spot increases by several \(\mu m\).

As shown in Fig. 7, the overall experimental setup consists of an assembly of a target and a VISAR probe, a capacitor, two oscilloscopes, and a computer. When a capacitor is discharged, a current pulse flows out to the EFI detonator and then propels the Kapton flyer. The VISAR is connected to an oscilloscope (digital oscilloscope with 4 channels, bandwidth of 300 MHz, and sampling rate of 2 GS/s) to measure the intensity history of photodetectors (InGaAS photodiode with bandwidth of 10 GHz, rise/fall time of less than 30 ps, and spectral range of 950–1650 nm), which varies with the change of flyer velocity. The principle and details of the VISAR used in our system were explained in the authors’ earlier work.\(^\text{18}\) A semiconductor diode laser, operating at 1550 nm, less than 20 kHz of line width, and up to 5 mW of power, was used. The intensities of interference signals are measured by the fiber coupled photodetectors with a bandwidth of 10 GHz. The fringe constant of 750 m/s and time resolution of 1 ns are obtained from a delay leg of 200 mm. For capturing the free surface motion of a target when a collision with a flyer occurs, it is necessary to synchronize the release of the transistor-transistor logic (TTL) signal emitting from the capacitor unit with the trigger point of an oscilloscope. After measuring the delay with jitter of less than 75 ns between the release of the TTL signal and start point of intensity fluctuation, the oscilloscope is triggered in 1 \(\mu s\) after firing the capacitor. The profile of the current pulse is also measured using another oscilloscope to validate the bursting current for each shot. The current was converted from the voltage across the current viewing resistor (resistance of 4.874 m\(\Omega\), band pass of 800 MHz, rise time of 0.45 ns, and the maximum energy of 40 J), which is mounted in the circuit path to the EFI detonator.

IV. NUMERICAL SIMULATION

In the present work, numerical analysis was conducted by using ANSYS Explicit Dynamics, which is based on the finite element method with explicit time integrator that handles the highly transitional and nonlinear dynamics subjected to a very short and severe loading condition. In the solution process, the Lagrangian formulation is used to solve the governing partial differential equations for conservation of mass, momentum, and energy along with constitutive equations as well as initial and boundary conditions. The Lagrange-Lagrange
interaction specified for the projectile/target contact and three-dimensional (3-D) structures is applied to determine the influence of geometry on longitudinal stress and particle velocity according to the wave propagation.

A. Setup

As shown in Fig. 8, a 304 stainless steel target of 700 μm diameter and 400 μm thickness and a Kapton flyer of 165 μm diameter and 12.5 μm thickness are defined for a two-dimensional (2-D) axisymmetric flyer impact. Quadrilateral dominant meshes are generated and then inflated toward the edge of the flyer and widened toward the fixed edge to ensure optimal computation time and accuracy. Here, the quadrilateral elements of a size of 2 μm are used to construct the mesh with a reasonable aspect ratio and computation time. Gauges are placed at intervals of 10 μm along the central axis to record the shock signals along the wave propagation. The impact velocity of a flyer and the fixed line at the outer radius of target are given as initial and boundary conditions, respectively.

B. Material model

The material model is comprised of (i) an equation of state representing the relation between density, pressure, and internal energy and (ii) strength model describing the constitutive relation. For the impact phenomenon between solid materials, the Mie-Gruneisen form of equation of state is used to properly describe the state of a shock compressed solid by representing the relation between volume and pressure

\[ p = \rho v \left( e - e_0 \right), \]

where \( v, p, \) and \( e \) are the volume, pressure, and internal energy, respectively. \( \Gamma \) is the Gruneisen parameter which represents the thermal pressure induced by the vibration of atoms. \( p_0 \) and \( e_0 \) are the pressure and internal energy, respectively, at a reference state that is generally at a temperature of 0 K or at the Hugoniot state when they are not available.

The Rankine-Hugoniot jump condition represents the relation between states on both sides of shock waves in uniaxial compression. The conservation of mass, momentum, and energy for the Rankine-Hugoniot condition are

\[ \rho_0 u_s = \rho(u_s - u_p), \]
\[ p_H - p_0 = \rho_0 u_t u_p, \]
\[ p_H u_p = \rho_0 u_t \left( \frac{u_s^2}{2} + e_H - e_0 \right). \]

Here, \( \rho_0 \) and \( \rho \) are the densities at the reference and current states, respectively. \( p_H \) and \( e_H \) represent the pressure and internal energy on the Hugoniot, respectively, and \( u_s \) and \( u_p \) are the velocities of shock wave and particle, respectively.

For most solids and many liquids, an empirical linear relationship between particle and shock velocities has been found over a wide range of pressures

\[ u_s = c_0 + su_p, \]

where \( c_0 \) and \( s \) represent the velocities of bulk sound wave and characteristic material constant, respectively. Therefore, the Mie-Gruneisen form of equation of state with the shock Hugoniot as the reference state is expressed as follows:

\[ \begin{align*}
  p &= p_H + \Gamma \rho (e - e_H) \\
  p_H &= \frac{\rho_0 c_0 \mu (1 + \mu)}{1 - (s - 1) \mu^2} \\
  e_H &= \frac{p_H}{2 \rho_0} \left( \frac{1}{1 + \mu} \right).
\end{align*} \]

Here, \( \mu = \rho / \rho_0 - 1 \) and the assumption of \( \Gamma \rho = \Gamma \rho_0 \), which is indicated by experimental and theoretical works, are applied. In using this form of equation of state, it is necessary to recognize the allowable range of impact velocity, because

FIG. 8. Geometry and mesh of finite element model for 2-D axisymmetric flyer impact.
it is not suitable for any material change, such as melting or vaporization. The shock Hugoniot data of the flyer and the target material are presented in Table I.\textsuperscript{20,21}

At a high velocity impact, the yield strength increases as the plastic strain increases. This phenomenon is known as work hardening and plays an important role in determining the profile of shock waves at a stress order of GPa. Although the yield strength also increases with the increase in strain rate, the strain-rate-dependent effect rapidly decreases when it generally exceeds a stress of 10 GPa or $10^5 \text{ s}^{-1}$ of strain rate. This is because an increase in the dynamic stress causes a high temperature at which the strain rate dependence of the yield strength is no longer valid. Therefore, the Steinberg-Guinan model, which can reproduce experimentally measured shock-induced stress and free surface velocity profiles at a high strain rate, is used in the present impact simulation. The constitutive relation of the shear modulus $G$ and the yield strength $Y$ are represented as functions of effective plastic strain, density, pressure, and temperature (or internal energy)

$$G = G_0 \left\{ 1 + \left( \frac{G_p}{G_0} \right) \frac{p}{\eta^{1/3}} + \left( \frac{G_p}{G_0} \right) \left( T - 300 \right) \right\}, \quad (13)$$

$$Y = Y_0 \left\{ 1 + \left( \frac{Y_p}{Y_0} \right) \frac{p}{\eta^{1/3}} + \left( \frac{G_p}{G_0} \right) \left( T - 300 \right) \right\} \left( 1 + \beta \varepsilon \right)^n. \quad (14)$$

These equations are subject to the limitation that $Y_0 \left( 1 + \beta \varepsilon \right)^n \leq Y_{\text{max}}$. Here, $\varepsilon$, $T$, $Y_{\text{max}}$, and $\eta (= \rho / \rho_0)$ represent effective plastic strain, temperature, maximum yield stress, and compression, respectively. $\beta$ and $n$ are the hardening constant and hardening exponent, respectively. The subscript zero indicates values at the reference state ($T = 300 \text{ K}$, $p = 0$, and $\varepsilon = 0$). Parameters with a prime and subscript also refer to derivatives of the parameter with respect to each subscript variable at the reference state. The parameters of the Steinberg-Guinan strength model for a 304 stainless steel target are presented in Table II.\textsuperscript{22}

Erosion is permitted to ensure that the time step is kept large enough to ensure calculation to a specified termination time at reasonable stability. When a Lagrangian element is removed, the element changes into a free node of which the mass can be neglected or transferred to the adjacent nodes of the elements. If the inertia of the resulting free node is retained, the mass and momentum of the free node are maintained and are involved in the following calculation step. Otherwise, all free nodes are automatically eliminated from the calculation. Here, the erosion is based on the strain with the threshold of 1.5, which is generally recommended for simulating high velocity impact phenomena.

V. RESULTS AND DISCUSSION

The free surface velocity for various thicknesses was measured by VISAR to determine the decay of shock waves according to the distance of the wave propagation. Figure 9 presents the temporal profile of the free surface velocity measured by VISAR for a 304 stainless steel target of 100 $\mu$m thickness at the capacitor charging voltage of 1 kV.

The free surface starts to move approximately 1.39 $\mu$s after triggering the firing circuit, which means that such amount of time is necessary for the overall process including the plasma generation, flight time, and shock propagation to the free surface.

The first peak and consecutive peaks represent the first arrival of the shock waves at the free surface and its reverberations in a target. The value of the first peak was considered to determine the strength of the shock front. Based upon the Rankine-Hugoniot jump condition and the elastoplastic behavior of the material, the longitudinal stress of shock waves is calculated with the velocity of the first peak as follows:

$$\sigma_x = \begin{cases} \rho_0 c_{el} u_p & (\text{HEL}) \\ \rho_0 u_p u_f + \frac{2}{3} Y_0 & (\text{HEL}) \end{cases} \quad \text{where} \quad u_f \simeq 2 u_p. \quad (15)$$

Here, the Hugoniot elastic limit (HEL) is the transition point at which the material behavior changes from purely elastic to elastoplastic. $c_{el}$ and $Y_0$ represent the velocity of elastic wave

| Material       | $\rho_0$ (kg/m$^3$) | $c_0$ (m/s) | $S$  | $\Gamma_0$ |
|----------------|---------------------|-------------|------|-------------|
| 304 SS         | 7900                | 4570        | 1.49 | 1.93        |
| Kapton         | 1414                | 2741        | 1.41 | 0.76        |

TABLE II. Parameters of Steinberg-Guinan strength model for 304 stainless steel.\textsuperscript{22}

| $Y_0$            | $Y_{\text{max}}$ | $\beta$ | $n$   | $G_0$     | $G_p$     | $G_T$     | $Y_p$       |
|------------------|------------------|--------|------|-----------|-----------|-----------|-------------|
| $6.7 \times 10^8$ Pa | $2.5 \times 10^8$ Pa | 43     | 0.35 | $7.7 \times 10^{10}$ Pa | 1.74      | $-3,504 \times 10^7$ Pa/°C | $7.684 \times 10^{-3}$ |
and yield strength of the material, respectively. The particle velocity is approximated from the free surface condition in which the free surface velocity $u_f$ is two times faster than the particle velocity. Since spall fracture appears as pullback and reloading signals in the velocity profile of a free surface, the tensile stress just before the spalling is approximated by the Novikov approach. The spall strength $\sigma^*$ of 2.515 GPa is obtained, and it is consistent with the literature data, 2.1 and 2.69 GPa (Ref. 23 and 24)

$$\sigma^* = \frac{1}{2} \rho_0 c_0 \Delta u_f,$$  \hspace{1cm} (16)

where $\Delta u_f$ and $c_0$ are the velocity pullback of a spall and bulk sound wave, respectively.

It is difficult to distinguish the first peak of a single shock for thin stainless steel below its thickness limit, where the release shock wave reflected at the free surface overlaps with the input shock loading at the impact surface. Therefore, the numerical simulation was conducted to obtain the pattern of shock attenuation for various impact velocities. The pattern was then compared with that of the experimental results to determine the matching value.

Figure 10 presents the particle velocity generated by the shock front according to the distance wave propagation within a 304 stainless steel target. The dots and lines represent the results obtained from experiment and numerical simulation, respectively. It is shown that the shock front is caught-up by the unloading rarefaction wave coming from the flyer and then starts the hydrodynamic decay after running 50 $\mu$m in the SS304 target. Based on the VISAR measurement, the impact velocity of a flyer was inferred by selecting a numerical case that most closely resembles the tendency of the experimental data. While the gauges in the simulation recording the time history of the shock properties are placed along the exact central axis, the focal point of the VISAR probe beam can be aligned slightly off the center from the experimental setup. Since the hole of the guide ring for center alignment has a tolerance of 50 $\mu$m, the focal spot could be misaligned up to 25 $\mu$m. Therefore, it is necessary to recognize that the experimental measurement is susceptible to deviations from the effect of the beam being off-center.

In the present system, shock waves rapidly decay within a very short distance due to the very short duration of pressure loading. As shown in Fig. 11, a rectangular pulse of about 5–6 ns is generated by a flyer with thickness of 12.5 $\mu$m at various impact velocities. The solid line and dashed-dotted line represent the analytical and numerical results, respectively. Both calculations show slightly different pulse durations due to the rising and falling time, while peak pressures are quite similar. Hence, the pressure and duration of an input pulse loading can be predicted by analytical means. The pressure pulse falls off sharply as the shock impedance of the flyer is lower than that of the target material. Therefore, the pressure attenuation can be manipulated by controlling the thickness of the target and varying the impact velocity.

Since the hydrodynamic attenuation, which is related only to the thermomechanical variables, is the main cause of the large pressure drop, a shock wave starts to decrease when the release wave reaches the shock front, and its attenuation pattern is influenced by the amplitude and temporal profile of the input loading of the flyer impact. Figure 12 shows the longitudinal stress and particle velocity generated by the flyer impact at 1.25 km/s. Gauges placed at intervals of 10 $\mu$m along the central axis are used to record the shock properties on each line along the wave propagation. The shock front is sustained within approximately 50 $\mu$m and then starts to decay until it reaches the amplitude of the elastic precursor. Then, the elastic precursor is almost constant and is accompanied by a very slow decrease. The elastic precursor is visible after 10 ns of propagation time and is about 1.2 GPa in pressure and 25 m/s for the material velocity.

Moreover, geometric attenuation occurs because the one-dimensional (1-D) planar shock waves cannot be sustained along the wave propagation due to the edge effect, where the release waves emitted from the boundary of a flyer cause a decay in the shock waves. Figure 13 presents the
pressure contour in a 400 \( \mu m \) thin stainless steel target 304 subject to the 12.5 \( \mu m \) thin Kapton flyer impact at 1.25 km/s. The consecutive images are captured at time intervals of 5 ns. The 2-D shock front structure diminishes with the radial distance of propagation. Since the input shock duration is rather short, as presented in Fig. 10, the plastic shock wave becomes fully attenuated within 40 ns as the elastic precursor remains. The waves propagating in the radial direction have no influence on the main shock wave since the diameter of the target is too large compared to the distance of the shock propagation. Therefore, a 304 stainless steel target with varying thicknesses from 50 \( \mu m \) to 200 \( \mu m \) is sufficient for determining the performance characteristics of the EFI unit.

Before the attenuation of a shock front, VISAR can be applied to a 304 stainless steel target with \( \sim \)50 \( \mu m \) thickness, and the impact velocity is determined from the impedance matching technique, as illustrated in Fig. 1. Finally, the impact velocity of the flyer is successfully obtained despite the limitation of the experimental technique, as explained earlier. The present miniaturized EFI detonator can accelerate a flyer of approximately 1.5 km/s, which is equivalent to laser accelerated flyer\(^{27} \) at the charging voltage of 1 kV. The obtained pattern of shock attenuation and the obtained shock pressure-velocity curve can be used to assess the performance of the designed exploding foil initiator of a micro pyro-mechanical device.

VI. CONCLUSION

The averaged impact velocity of a Kapton flyer was successfully obtained to understand the performance characteristics of a miniaturized EFI detonator. VISAR measurements and numerical simulation of the shock attenuation within a stainless steel witness plate were carried out. For overcoming the experimental difficulties associated with the microscale system, the impedance matching technique was utilized to predict the average impact velocity of the flyer. The lens configuration of a VISAR probe was specially designed to insure the focal spot reduction and the receiving angle increase. Thus, the exact velocity at the center of a stainless target was measured without any signal loss, despite the relatively large deformation at the local spot. Numerical simulation was also conducted to determine the initial pressure at the zero thickness of a target because it is difficult to distinguish the initial value from experimental results due to the multiple reverberations of shock waves. The obtained attenuation pattern according to the distance of wave propagation is necessary for the precise control of the flyer velocity for shock initiation of the target explosive.
ACKNOWLEDGMENTS

The work was financially supported by the NSL-2014 and Hanwha-ADD PMD Grants contracted through IAAT and IOER at Seoul National University. Additional support was provided by the Advanced Research Center Program (NRF-2013R1A5A1073861) through the National Research Foundation of Korea, contracted through Advanced Space Propulsion Research Center at Seoul National University.

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