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Velocity-dependent wave forms of piezoelectric elements undergoing collisions with iron particles having velocities ranging from 5 to 63 km/s

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A response from piezoelectric lead-zirconate-titanate elements was investigated by bombarding them with hypervelocity iron particles. The observed signal form was clearly dependent on the particle velocity during collisions. The signal form exhibited oscillations for particle velocities less than 6 km/s, whereas it changed drastically into a solitary pulse above 20 km/s. This behavior was exclusively classified based on the velocity. The rise time of the solitary pulse in the output form had a good correlation with the velocity at impact. The change in the form was discussed in terms of elastic and plastic states by regarding Young's modulus as a criterion between both states. It is proposed that a single piezoelectric element has the potential to detect the velocity of particles in space. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1929882]

Previous studies[1–3] have reported the collision of hypervelocity microparticles with piezoelectric lead-zirconate-titanate (PZT) elements in the velocity range 2–6 km/s. In these studies, the sensitivity of the element was found to be thickness dependent. On the other hand, it was found to be thickness independent,[4,5] by considering a part of the output signal form immediately after the collision. For convenience, this region was specified as the first one cycle (FOC). Thus, the signal in the FOC is essential for investigating hypervelocity collisions with the PZT element. In order to discuss the dependence of the wave form on velocity, it was necessary to perform the measurements in the FOC with a wider range of velocity.

This work aims at observing the change in the wave form of the PZT element by extending the velocity range to 63 km/s. It was found that the wave form was clearly dependent on the velocity during collisions.

This Letter is concerned with the velocity-dependent nature of the wave form on the velocity during collisions and a possible mechanism based on stress at impact.

The experimental principle[1–5] is outlined as follows. A piezoelectric PZT element was fabricated in the shape of a disk, with a diameter of 20 mm, and a thickness of 2 mm. The element was polarized in the direction of the thickness. It was sandwiched by a pair of several-μm-thick silver electrodes. The output signal was measured with a digital scope.

The hypervelocity iron particles were supplied by the van de Graaff accelerator from the Max-Planck-Institut für Kernphysik, Heidelberg. The particle velocity v was tagged by a preselector.[6] The particle mass m was obtained as $m = 2qU_a/v^2$, where q and U_a represent the particle charge and the acceleration voltage, respectively. Consequently, the particles were sampled in the velocity and mass ranges from 5 to 63 km/s and from 3 fg to 30 pg, respectively.

The tentative signal forms shown in Fig. 1 are arranged according to their corresponding particle velocities from Figs. 1(a)–1(d). The observed forms can be classified into

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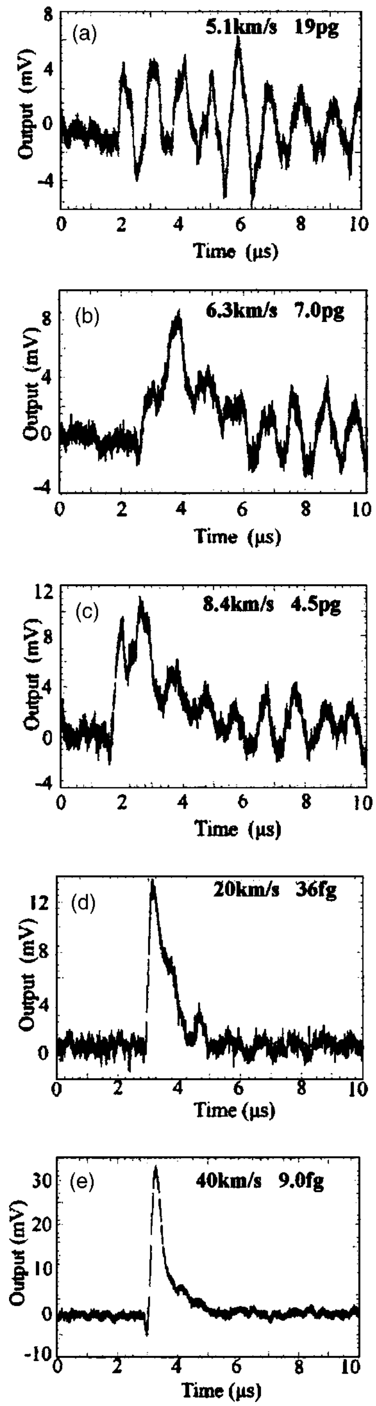

FIG. 1. Typical output forms are arranged in the order of velocity from (a) to (d). The velocity and mass at impact are indicated in each figure. The wave form in (e) was observed with a 4-mm-thick element.

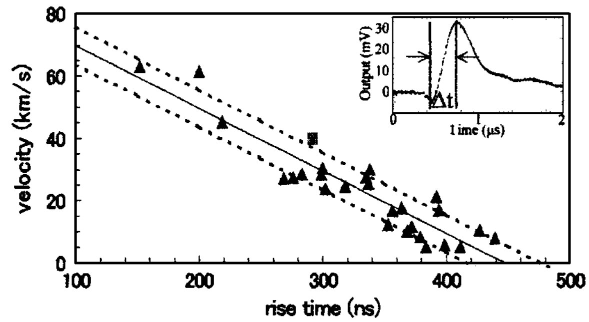

FIG. 2. A correlation between the rise time and the velocity is shown using data by the 2-mm-thick element (triangle) and the 4-mm-thick element (square). The solid line is drawn by Eq. (1) and the dotted lines indicate a $1-\sigma$ level. The rise time is defined by an interval Δt as in the inset.

three categories, corresponding to their particle velocities: category I [Fig. 1(a)], category II [Figs. 1(b) and 1(c)], and category III [Fig. 1(d)].

For comparison, a solitary signal[5] resulting from the collision of a 9-pg particle with a 4-mm-thick element at 40 km/s is shown in Fig. 1(e).

The oscillatory form in category I essentially exhibits a similar behavior as that observed with silver particles,[1–4] with an overlapping velocity region.

The wave form changes drastically in category III. The form in Fig. 1(d) consists of a single peak accompanying a small sinusoidal wave. Since the latter part is considered as a standing wave inherent in piezoelectricity, only the former signal is taken into account. Moreover, it is emphasized that the solitary wave is free from the reflections at the boundaries of the element.

As shown in Fig. 1(e), the contribution from the sinusoidal part is minor and asymptotically negligible.

Regarding the output form belonging to category II, the wave form is considered to be a superposition of regularly oscillating pulses and a bump. At a relatively low velocity, its behavior resembles that in category I, whereas, with an increase in the velocity, the bump grows relatively dominant. The entire structure is finally reduced to the form in category III.

It is interesting to demonstrate the relation between the velocity v at impact and the rise time Δt of the solitary signal, as defined in the inset of Fig. 2. The correlation between Δt and v is plotted in Fig. 2 by selecting the samples with uniquely identified rise times. By assuming a linear relation, the velocity is empirically expressed by Δt as

$$v(\mathrm{km/s}) = 91 - 0.20\Delta t(\mathrm{ns}), \tag{1}$$

with an ambiguity of approximately 6 km/s. Accordingly, the velocity can be determined with an accuracy of 6 km/s by a single PZT element. This result confirms the fact[4] that the output form is independent of the thickness.

At present, no reliable theories exist that explain the behaviors displayed in Fig. 1. Moreover, the hypervelocity reaction is too complicated to exclusively determine the individual final states. It is also evident that the wave form is independent of the particle mass. Therefore, the final states should be treated in an averaged manner based on the velocity.

According to a production and propagation mechanism[7] in solids, the observed signal is mediated with a shock wave. The wave is presumed to be elastic in category I and plastic in category III. This change of states is considered to cause the drastic change in the wave form.

In this case, a yield point is an important parameter. Contrary to the yield point, Young's modulus is unambiguously estimated by two variables; v_s and ρ_{P}, the sound velocity in PZT and the density of PZT, respectively. Hence, it is postulated that Young's modulus E is instrumental in distinguishing the two states, because its value is estimated as $E=\rho_{\mathrm{P}} v_s^2$. For $v_s \approx 4$ km/s (Ref. 4) and $\rho_{\mathrm{P}} \approx 7.5$ g/cm^3, then $E \approx 1.2 \times 10^{11}$ Pa.

The magnitude[7] of stress σ at impact is estimated by the product of particle velocity u and wave velocity U. On the

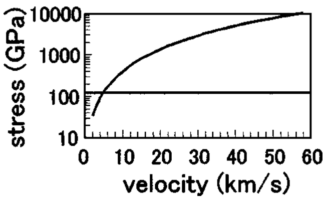

FIG. 3. Estimated stress as a function of the collision velocity. Young's modulus is indicated by a horizontal line, which corresponds to approximately 6 km/s. This is instrumental in distinguishing the elastic states and plastic states in the PZT element.

basis of the impedance match method, the particle velocity u is given by $u=v/2$, since the density of iron ρ_F is almost equal to ρ_P. The wave velocity is given by $U=au+b$, where a and b are the parameters to be experimentally determined. Thus, the stress σ is calculated by $\sigma=\rho_P uU$. The constants a and b are replaced with $a=(1+\Gamma)/2$, using the Grüneisen coefficient Γ, and $b=u_0$, which is the bulk sound speed. By substituting $\rho_P=7.5\times10^3$ kg/m^3, $\Gamma=2$ (Ref. 8), and $u_0=3$ km/s, the stress σ is estimated as in Fig. 3. Hence, the stress on impact exceeds the magnitude of Young's modulus at $v\approx5$ km/s. Consequently, in the region of category III, the shock wave is plastic dominant and its form is different from that in category I. Therefore, it may be concluded that the compressive waves on impact are elastic in the region $\sigma<E$, while the plastic states dominate with increasing values of σ for $\sigma>E$.

In the present scheme, the criterion is discussed based on E, not on Y. Kelly[9] discussed a connecting factor k between Y and E, $Y=kE$. For the time being, the factor is regarded as $k\approx1$.

Based on the Fourier analysis, the frequency spectra for Figs. 1(d) and 1(e) are shown in Figs. 4(a) and 4(b) respectively. The frequency distributions below approximately 0.5 MHz are identical. On the other hand, the higher components over 0.5–3 MHz are slightly different. This fact suggests that the rising part is velocity dependent as in Fig. 2, whereas the falling part is velocity independent.

A dip at approximately 1 MHz in Fig. 4(a) is representative of the sinusoidal wave.

As shown in Fig. 1, the response from the piezoelectric PZT element is sensitive to the particle velocity. In particular, in the solitary form, the velocity at impact can be determined within an ambiguity of approximately several km/s. The scope of the PZT element can be extended by referring to the experimental data accumulated by on-ground experiments. Therefore, the PZT element is a promising candidate as a real-time dust detector in space. In fact, a dust detector based on the piezoelectric PZT element is to be on board the BepiColombo mission.[10]

In summary, the response of the PZT element to hypervelocity microparticles was discussed. The behavior of the PZT output form is confirmed to be well distinguished by the particle velocities. The following criteria are postulated: elastic dominant in the region $\sigma<E$ and plastic dominant in $\sigma>E$. This classification is consistent with the category of the wave forms in three states; elastic properties are dominant in category I and plastic properties are dominant in category III. Category II is a transition region, in which both states coexist. The velocity can be obtained by the empirical formula in Eq. (1) when the signal resembles a solitary wave. It should

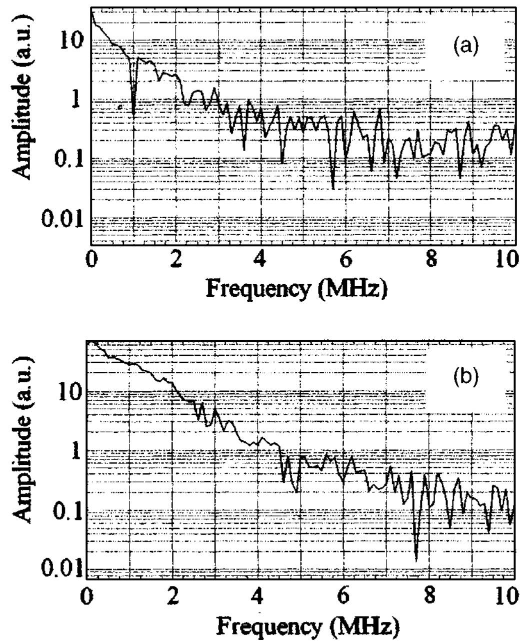

FIG. 4. Frequency distributions. The distribution in (a) results from Fig. 1(d) and that in (b) results from Fig. 1(e). A slight difference between (a) and (b) is found over 0.5–3 MHz. A dip in (a) is representative of the sinusoidal wave in Fig. 1(d).

be noted that the empirical formula is independent of the mass of the particles.

A single PZT element can be used as a real-time detector of hypervelocity particles, by referring to the empirical formulas that are established by on-ground experiments.

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