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Miyachi, T; Fujii, M; Hasebe, N; Kobayashi, M; Kuraza, G; Nagashima, A; Nakamura, Y; Nogami, K; Iwai, T; Sasaki, S; Muranaga, K; Ohashi, H; Hasegawa, S; Yano, H; Shibata, H; Grun, E; Srama, R; Okada, N; Tou, T

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T. Miyachi, M. Fujii, N. Hasebe, M. N. Kobayashi, G. Kuraza, A. Nagashima, and Y. Nakamura
Advanced Research Institute for Science and Engineering, Waseda University, Shinjuku-ku, Tokyo 169-8555, Japan

K. Nogami
Department of Physics, Dokkyo University School of Medicine, Mibu, Tochigi 321-0293, Japan

T. Iwai
Research Center for Nuclear Science and Technology, University of Tokyo, Tokai, Ibaraki 319-1106, Japan

S. Sasaki
Graduate School of Science, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan

K. Muranaga and H. Ohashi
Faculty of Marine Science, Tokyo University of Marine Science and Technology, Minato-ku, Tokyo 108-8477, Japan

S. Hasegawa and H. Yano
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 229-8510, Japan

H. Shibata
Graduate School of Engineering, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan

E. Grün and R. Srama
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

N. Okada and T. Tou
Honda Electronics Co. LTD., Toyohashi, Aichi 441-3193, Japan

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A response from piezoelectric lead-zirconate-titanate (PZT) 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]
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 arising 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 $\Delta t$ of the solitary signal, as defined in the inset of Fig. 2. The correlation between $\Delta t$ 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 $\Delta t$ as

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

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 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 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 $\rho_p$, 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 $E = \rho_p v_s^2$. For $v_s = 4 \text{ km/s}$ (Ref. 4) and $\rho_p = 7.5 \text{ g/cm}^3$, then $E \approx 1.2 \times 10^{11} \text{ Pa}$.

The magnitude of stress $\sigma$ at impact is estimated by the product of particle velocity $u$ and wave velocity $U$. On the
basis of the impedance match method, the particle velocity \( u \) is given by \( u = v/2 \), since the density of iron \( \rho_p \) is almost equal to \( \rho_p \). The wave velocity is given by \( U = au + b \), where \( a \) and \( b \) are the parameters to be experimentally determined. Thus, the stress \( \sigma \) is calculated by \( \sigma = \rho_p U \). The constants \( a \) and \( b \) are replaced with \( a = (1 + \Gamma)/2 \), using the Grüneisen coefficient \( \Gamma \), and \( b = u_0 \), which is the bulk sound speed. By substituting \( \rho_p = 7.5 \times 10^3 \) kg/m\(^3\), \( \Gamma = 2 \) (Ref. 8), and \( u_0 = 3 \) km/s, the stress \( \sigma \) is estimated as in Fig. 3. Hence, the stress on impact exceeds the magnitude of Young’s modulus at \( u \approx 5 \) 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 \( \sigma - E \).

In the present scheme, the criterion is discussed based on \( E \), not on \( Y \). Kelly discussed a connecting factor \( k \) between \( Y \) and \( E \), \( Y = kE \). For the time being, the factor is regarded as \( k = 1 \).

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.

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 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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