Basic Characteristics of the Explosive Welding Technique Using Underwater Shock Wave and Its Possibilities*

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A novel explosive welding technique which uses underwater shock waves to weld thin sheets and the technical advantages of this technique are reported. Using this technique, a thin metal plate is uniformly accelerated by underwater shock waves. The initial angle of inclination of the explosive pack is determinant in high-explosive welding systems, with respect to decreasing the horizontal collision velocity. Any change in the welding conditions along the cladding plates influences the weld strength and, therefore, the parameters should be judiciously selected so as to lie within the weldability boundary. The size of the waves generated at the welded interface is discussed based on the angle of collision. Future applications for multilayered explosive welding are also suggested.

1. Introduction

It is widely known that the explosive welding technique has established a reputation with respect to the jointing of metal plates due to the high reliability of the obtained bond strength.[1] Generally, explosive welding is performed to set plates with a fixed stand-off distance, and the welding is achieved by a high-velocity collision. The metal jet, formed ahead of the collision point, is vital for obtaining a sound bonding because the jet cleans and activates the metal surfaces ahead of the welding.[1,2] Further, the hydrodynamic behavior of metals under extremely high-strain-rate and high pressure results in a wavy structure at the welded interface.

A new method of explosive welding utilizing underwater shock waves has been proposed, and the possibility of welding thin plate(s) and multilayered plates including amorphous films[3] is suggested. The underwater shock waves, generated by the explosive pack, should be controlled well so as to satisfy the conditions for explosive welding, and the details of this are discussed. An inclined setup of the explosive pack is essential to decrease the horizontal collision point velocity, which, in turn, decreases the underwater shock pressure or vertical collision velocity toward the end farthest from the detonation side. As the detonation progresses, the welding condition changes with the position, and therefore, the relationships among various experimental conditions should be established. The present investigation reports the change in the wavelength at the welded interface under various welding conditions with different geometrical arrangements.

2. Experimental Technique of Explosive Welding using Underwater Shock Waves

Figure 1 shows a schematic illustration of the explosive welding technique using underwater shock waves. In this
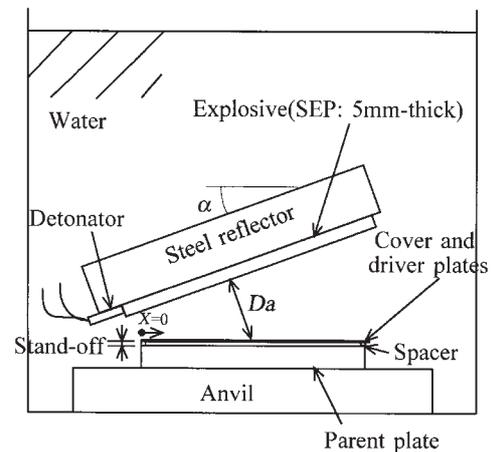

Fig. 1 Schematic illustration of explosive welding method using underwater shock waves.

case, an inclined explosive pack was detonated using an electric detonator, and the underwater shock waves, derived from the detonation, uniformly accelerate the thin metal plate. It is known that the collision angle β and the horizontal collision point velocity Vc should be controlled. The former one is almost proportional to the vertical velocity of the flying plate Vp.[2] In the present investigation, an explosive named SEP, produced by Asahi-Kasei Chemicals Corp., which has a very stable detonation velocity, was employed. The detonation velocity is approximately 7 km/s and the density is 1.3 kg/m³. The explosive with a fixed thickness of 5 mm was attached onto a mild-steel reflector block. The high explosive accelerates the metal plate easily, but the detonation velocity is too high in comparison with that of the explosives generally used for explosive welding. Therefore, an inclined setup of the explosive is essential to decrease the horizontal collision point velocity Vc. Since Vc should be lower than the elastic-wave velocity, the initial inclined angle should be higher than $10°$.[2] The experimental conditions are listed in Table 1. In these cases, a thin plate to be welded was stacked

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Table 1 Experimental conditions for explosive welding using underwater shock waves.

Number	Driver plate (Thickness)	Cover plate (Thickness)	Parent plate (Thickness)	Stand-off	α	Da
CS1	Cu (0.1 mm)	SUS304 (0.1 mm)	SS400 (15 mm)	0.5 mm	20°	40 mm
CS2	Cu (0.1 mm)	SUS304 (0.1 mm)	SS400 (15 mm)	0.5 mm	15°	40 mm
CS3	Cu (0.1 mm)	SUS304 (0.1 mm)	SS400 (15 mm)	0.5 mm	25°	40 mm
CS4	Cu (0.1 mm)	SUS304 (0.1 mm)	SS400 (15 mm)	0.5 mm	30°	40 mm
CM1	Cu × 5 (0.1 mm)	SUS304 (0.1 mm)	Cu (10 mm)	1.0 mm	15°	45 mm

with a cover plate, and the flying plate was accelerated within the gaps of 0.5 mm and 1 mm size made by using spacers to maintain constant stand-off distances. The welding area, 40 mm in width and 60 mm in length, was sealed against water. The average distance between the explosive and the center position of the welded parent plate in the longitudinal direction was defined as Da. Experiments were performed which involved welding a thin copper plate onto a mild-steel (JIS-SS400) parent plate, with changing the initial inclined angle of the explosive, and the possibility of multilayered explosive welding was also examined.

3. Evaluation of Underwater Shock Waves and the Conditions of Explosive Welding

While using an inclined setup as shown in Fig. 1, the distance between the explosive and the plates varies, from one end to the other, horizontally, and therefore, the underwater shock pressure also varies from one end to the other, thus introducing a pressure gradient among the various positions of the to-be-welded plates. To clarify this pressure variation, the pressure profile with time was measured using a semiconductor gauge bonded onto an elastic bar, and the measured results are shown in Fig. 2. The history of pressure
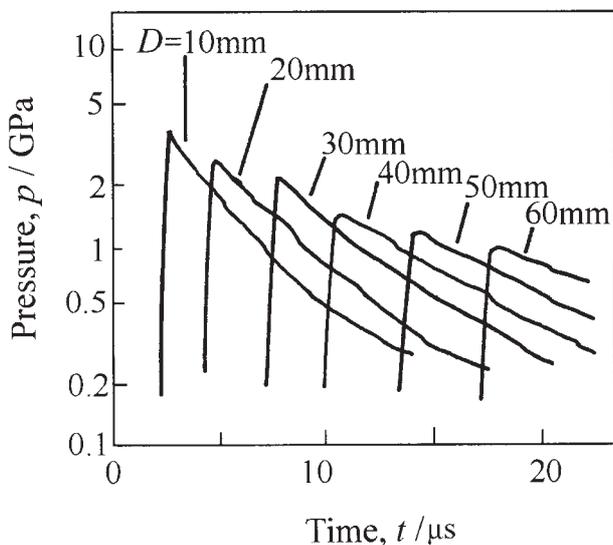

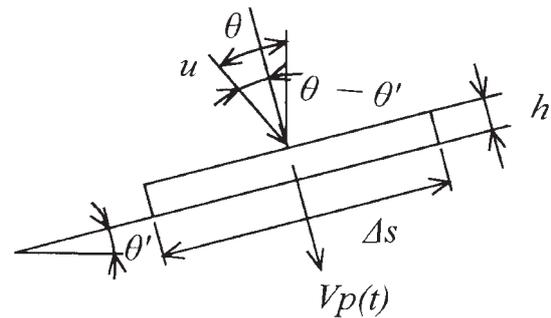Fig. 2 Measured pressure profile with time at distance D from explosive in water.

Fig. 3 Deformation process of flying plate.

(P: in Pa) with time (t: in s) for different distances in water from the explosive (D: in mm) is expressed by the following exponential equation based on these measured results. In this case, the rising time is ignored and a peak pressure will be achieved at the time $t = 0$;

$$P = 10^8 \exp(A_0 t + A_1) \qquad (1)$$
$$A_0 = B_0 \exp(B_1 D), \quad A_1 = C_0 \exp(C_1 D),$$

where $B_0 = -4.130 \times 10^5$, $B_1 = -24.14$, $C_0 = 3.900$ and $C_1 = -9.355$. On the basis of the pressure profile, the velocity of the flying plate is calculated with time t. As schematically shown in Fig. 3, a small element of a flying plate (area; Δs, thickness; h, inclined angle θ') is accelerated at time t under pressure P, and moves at $Vp(t)$ under P'. When the time increment and the particle velocity of water are defined as Δt and u (incidence angle θ), respectively, the change in the momentum of water should be equal to the impulse of the flying plate as follows,

$$\rho_0 \cdot Us \Delta s \Delta t \{u \cdot \cos(\theta - \theta') - Vp(t)\} = (P' - P)\Delta s \Delta t, \quad (2)$$

where ρ_0 is the density of water in ambient atmosphere and Us is the propagating velocity of the underwater shock waves. In this investigation, Us was calculated based on the underwater shock pressure P using the Mie-Grueneisen equation of water and Rankine-Hugoniot's eq.[4] Also, θ was derived from the detonation velocity of the explosive, Us and the initial inclined angle of explosive α, and u was derived from the relation $P = \rho_0 u Us$.[5] P' is derived from eq. (2), where the velocity increment ΔV is given by the equation of motion of the flying plate expressed as eq. (3). Based on the equation for the velocity with time $Vp(t)(= Vp(t - \Delta t) + \Delta V)$, P' is expressed as eq. (4),
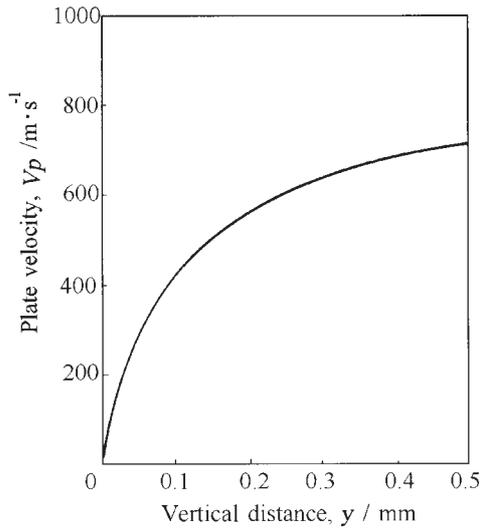
Fig. 4 Calculated plate velocity Vp with vertical distance y for experiment #CS1.

Fig. 5 Microstructure of thin copper plate explosively welded onto mild steel (#CS1).

$$\Delta V = P' \Delta t / (\rho_c \cdot h), \qquad (3)$$

where ρ_c is the density and h is the thickness of the flying plate.

$$P' = \frac{\rho_c \cdot h[P\{1 + \cos(\theta - \theta')\} - \rho_0 Us Vp(t - \Delta t)]}{\rho_c \cdot h + \rho_0 Us \Delta t} \qquad (4)$$

Figure 4 shows the estimated velocity Vp. The figure shows the change in the flying plate velocity in the vertical direction y at the center of the plate ($x = 30$ mm). The calculated result in the figure corresponds to the experimental condition #CS1 as shown in Table 1. In this case, the initial inclined angle of the explosive α was 20°. As suggested in Fig. 4, the plate is immediately accelerated to several hundreds m/s within a very small stand-off (less than 1 mm). It has been reported that the lower limit of the collision velocity for the explosive welding of metals is 200–300 m/s[2]); therefore, the collision velocity is sufficiently high to achieve the welding of metals using the present method.

The other vital condition to be satisfied is the horizontal collision point velocity Vc, as mentioned earlier. When the initial setup angle of explosive α is 20°, the velocity Vc for the SEP explosive is estimated to be about 3.5 km/s, which is lower than the elastic wave velocity of common materials.[6] The initial setup angle α should in general be higher than 10° for common materials.

4. Results and Discussion

The micrograph of the interface in an explosively welded sample is shown in Fig. 5 (Experiment #CS1). The interface exhibits a typical wavy structure normally found in the explosively welded cladding. Therefore, it is confirmed that welding has been achieved by means of the mechanism of explosive welding. The change in the wavelength with horizontal distance x is shown in Fig. 6. In this case, an initial inclined angle of explosive α at 20° was employed. This introduces the change in the wavelength from the detonator
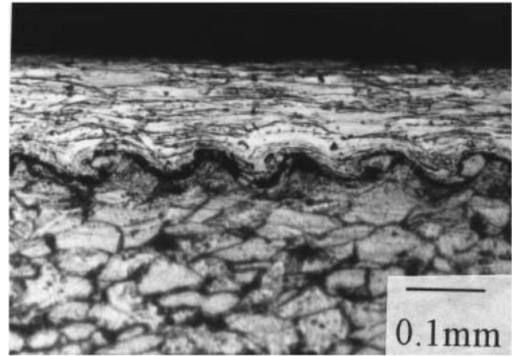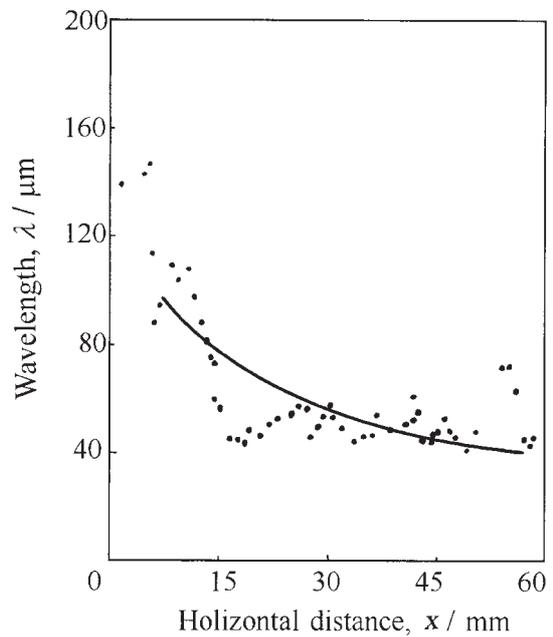

Fig. 6 Measured wavelength with horizontal distance x for experiment #CS1.

side to the farthest end. The result is better explained with respect to the change in the underwater shock pressure, which decreases to the farthest end as a result of increasing the stand-off distance between the explosive pack and the plates to be welded, as explained earlier. Figure 7 shows the change in the vertical plate velocity with distance x, and the calculated result suggests that there is a decrease in Vp with increasing x. As shown in Fig. 6, the measured wavelength shows a deviation from the averaged line. It is considered that the result is attributable to the effect of the propagation of reflected waves.

Figure 8 shows the change in the measured wavelength for various different angles of inclination, α, of the explosive pack. As expected, the change in the wavelength increased with increasing α. Though this result can be explained by the change in the underwater shock pressure or the collision velocity in the vertical direction, a more precise explanation can be made on the basis of the postulations made by Gupta and Kainth.[7] Their explanation is based on a consideration of
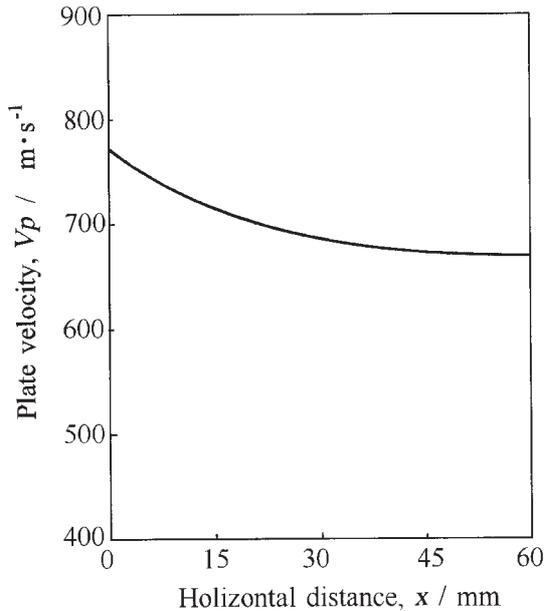
Fig. 7 Calculated plate velocity with horizontal distance x for experiment #CS1.
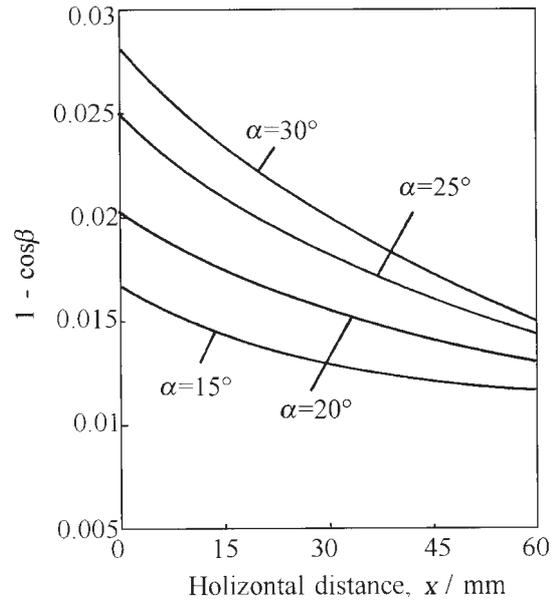

Fig. 9 Change in $(1 - \cos \beta)$ with horizontal distance x for various initial setup angles of explosive α, based on calculations.
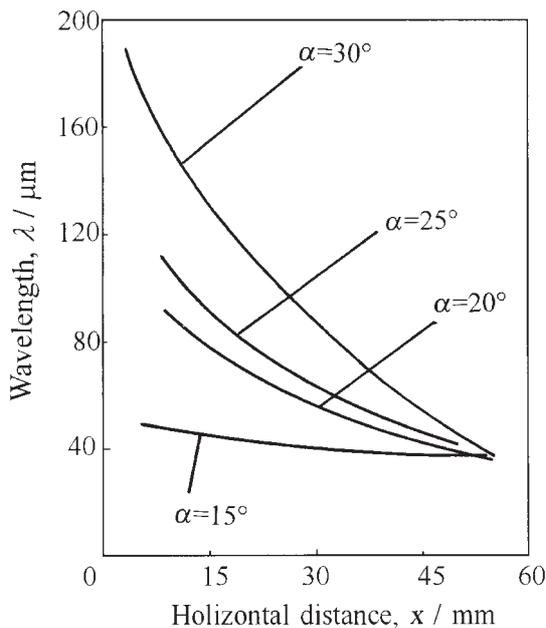

Fig. 8 Measured wavelength with horizontal distance x for various experiments, with changing the initial setup angle of explosive α.

the hydrodynamic flow of materials at an extremely high-strain-rate in the welded interface, and the fluidized height of the waves is expressed as follows, where h_0 is the thickness of the flying plate.

$$h = h_0(1 - \cos \beta) \qquad (5)$$

Here, β is calculated by using Vp and Vc based on the geometrical relationship.[2] Figure 9 shows the change in $1 - \cos \beta$, and the result corresponds to the experimental result shown in Fig. 8. Some of the authors have reported the relationship between the kinetic energy loss by collision and

the wavelength,[8] but this relationship is only valid for parallel plate setup.

With the use of an explosive of low detonation velocity, it is difficult to obtain a high-velocity acceleration to the bonding plates within shorter stand-off distances. Therefore, the initial inclination angle α of the explosive while using a high explosive becomes mandatory to satisfy the condition for horizontal collision point velocity. Hence, large samples are more difficult to weld explosively than smaller ones, as are difficult-to-weld materials whose region of weldability is limited.

Multilayered explosive welding is also possible by the present method. Figure 10 shows the microstructure of the welded multilayered plates under a fixed stand-off of 1 mm (#CM1). As shown in the photograph, each interface is welded well with waves. In the welding of thin plates, the wave size is similar in each layer as the collision angle remains almost unchanged throughout; however, large interfacial waves are introduced at the welded interface between the final layer and the previous one due to the large variation in the collision angle. The variation of the wave-length with distance x is shown in Fig. 11. It is noted that there is a decrease in the wavelength with increasing horizontal distance x. It is apparent that the welding of multilayered plates is feasible, and the authors are now investigating the future applications of multilayered thin amorphous films.

5. Conclusions

The present investigation reports the development of a new experimental technique for explosive welding using under-water shock waves, and the change in the wavelength with the change in the collision conditions is discussed. In the present experiments, an inclined setup of an explosive with a high detonation velocity is employed to accelerate a plate,
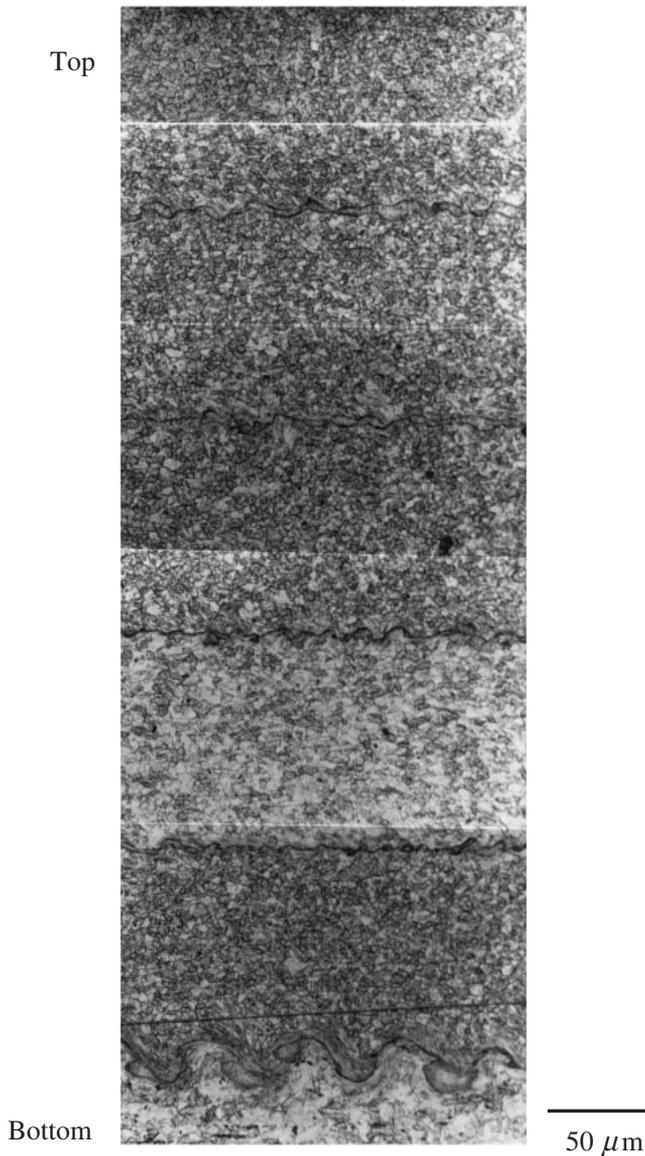
Top

Bottom

50 μm

Fig. 10 Microstructure of explosively welded multilayered copper plates (#CM1).

Fig. 11 Measured wavelength with horizontal distance x for multilayered explosive welding (#CM1).

and this induces the change in underwater shock pressure or vertical velocity. In addition, the present investigation suggests the possibility of multilayered welding. Considering the high reliability of conventional explosively welded joints, the state of bonding in the materials obtained by the present method should be sufficiently high in comparison with that of conventional surface coating methods. Further experiments are being considered to investigate the applications and the technical limitations of the present method.
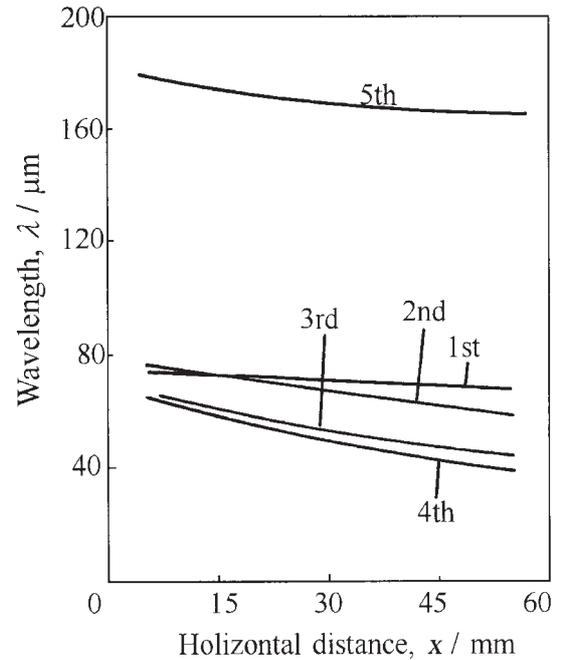
Acknowledgements

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