Article

Explosive welding of thin metal plate onto a base plate using regulated underwater shock wave
—As application for surface modification of various materials—

Kazuyuki Hokamoto*, Yasuhiro Ujimoto**,
Shojiro Ohama***, and Mashiro Fujita****

A novel explosive welding technique using regulated underwater shock wave is developed and the possibility for the application is discussed. The assembly is used to accelerate a thin metal plate uniformly at a high velocity to satisfy the condition of explosive welding systems. In the present investigation, a high explosive SEP, (detonation velocity = 7.0 km/s), is employed. Consequently, an inclined set-up angle of the explosive packing is required to decrease the horizontal collision point velocity. Since the reliability and bonding strength for the explosively welded joint are very high, the present method can be effectively used to modify the surface of various materials. Thin plates are welded successfully and multi-layered explosive welding is also suggested. For the explosive welding of metal plates, wavy interface, a characteristic feature, is observed at the bonded interface. Nonetheless, the sizes of the waves vary from the detonation location towards the farther end of the plates. This is caused due to the decrease in the shock pressure applied to the flyer plate. The success of the explosive welding process is highly sensitive to the welding ambience and hence the parameters should be carefully selected. Explosive welding of difficult-to-weld materials is also reported.

1. Introduction

Explosive welding is well known as one of the techniques for bonding metal plates, and various explosively-welded clads have been industrialized widely due to the high bonding strength at the welded interface [1]. As a purpose of increasing the applications of the explosive welding technique, a new method utilizing underwater shock wave [2,3] to accelerate a thin metal plate is proposed. In the present method, a high explosive is employed to accelerate a flyer plate with a short stand-off distance between plates. Hence, the inclined set up becomes mandatory to regulate the collision point velocity, but then, the control of the process parameters for uniform and successful bonding becomes increasingly difficult.

Underwater shock wave explosive welding technique is very useful in welding various difficult-to-weld materials such as metal with ceramic [2] and with other brittle materials. The present investigation deals with the basic characteristics of the assembly based on the results obtained for the welding of metal plates. Various possibilities for the application of the new explosive-welding technique are demonstrated. Since the present technique has an advantage of welding thin plates onto a base plate, the possibilities for surface modification of various materials are suggested.

2. Experimental procedure

The schematic illustration of the assembly is

Received : May 17, 2002
Accepted : December 12, 2002

*Shock Wave and Condensed Matter Research Center, Kumamoto University,
Kumamoto 860-8555, JAPAN
TEL. +81-96-342-3740 FAX.+81-96-342-3729
e-mail hokamoto@mech.kumamoto-u.ac.jp
**Asahi Kasei Corp., Chikushino Plant,
Chikushino, Fukuoka, JAPAN
***Graduate School of Science and Technology,
Kumamoto University
****Dept.of Mech.Eng., Sojo University, Kumamoto
860-0082, JAPAN

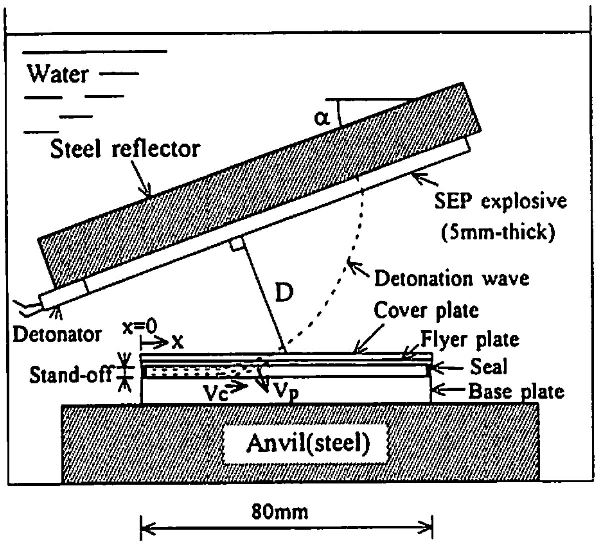

Fig. 1 Assembly used for the investigation.

shown in Fig. 1. To satisfy the condition of explosive welding system, the explosive was set at a specified inclined angle α. In the present investigation, SEP explosive produced by Asahi-Kasei Corp., whose detonation velocity is 7.0 km/s, was employed. Varying the distance between explosive and the center position of a flyer plate (D) controls the pressure applied to the plates. The horizontal collision point velocity, *Vc* (Fig. 1), should be lower than the sonic velocity of the materials so as to generate metal jet ahead of the collision point [1].

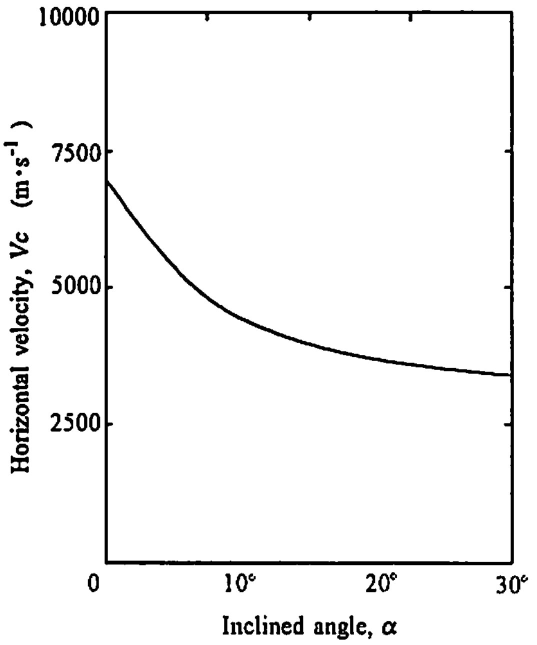

Fig. 2 Change of collision point velocity Vc with inclined angle of explosive α [2].

Figure 2 shows the variation of collision point velocity (*Vc*) with inclined angle of explosive α [2]. As α = 20° in these experiments Vc is approximately 3.8 km/s based on Fig. 2, and this condition favors the formation of metal jet for most engineering materials. For conventional explosive welding systems using parallel plate set-up, ammonium-nitrate based explosive (detonation velocity = 1.6 to 2.5 km/s) is employed [1], and it is much easier to generate metal jet to achieve an intensive flow of materials to be welded which results in a formation of large waves. Though the high Vc in the present assembly renders the formation of the metal jet or wave formation difficult, it also enables the welding of thin plate onto a base plate easy due to the formation of finer waves. So far, a few researches have been reported using conventional parallel set-up for the explosive welding of a thin plate onto a base plate using a thick flyer plate originally bonded with a thin plate by adhesive [5][6], but it is very difficult to control the parameters in this process due to the following reasons. (1) Unstable detonation velocity of the ammonium-nitrate base explosive [1], and (2) the formation of large waves whose amplitude exceeds the thickness of a thin plate employed [5].

The experimental conditions are listed in Table 1. In some experiments, a thin copper plate was welded onto a mild steel plate to establish the effect of the inclination of the explosive. Also, the possibility of multi-layered explosive welding was demonstrated using stacked thin-plates at a fixed stand-off distance at 0.5mm. Welding of a metal plate onto a partially stabilized zirconia ceramic and other non-ductile materials was also attempted in other experiments.

3. Results and discussion

The explosive welding of a thin metal plate onto a metal base is easy for a certain welding condition and the wavy interface typically found in explosively-welded clad is observed as shown in Fig. 3. Due to the use of inclined explosive set-up, the underwater shock pressure applied to the flyer plate is changed with horizontal distance *x*. The water pressure and a flyer plate velocity Vp is decreased with increasing horizontal distance *x*. The

Table 1 Experimental conditions.

Number	Flyer plate (Thickness)	Cover plate (Thickness)	Base plate (Length x thickness)	Stand-off	D
CM	Copper (0.1mm)	Stainless steel (0.1mm)	Mild steel (80mm x5mm)	0.5mm	40mm
CC	Copper (0.1mmx5)	Stainless steel (0.1mm)	Copper (80mmx5mm)	0.5mm	45mm
MM	Molybdenum (0.05mm)	Copper (0.3mm)	Mild steel (80mmx5mm)	0.3mm	50mm
AZ	Aluminum (0.1mm)	Aluminum (0.3mm)	Zirconia (40mmx40mm)	0.5mm	45mm
ATS	Aluminum (0.1mm)	Stainless steel (0.1mm)	JIS SKD11 (50mmx30mm)	0.5mm	40mm
TTS	Titanium (0.1mm)	Stainless steel (0.1mm)	JIS SKD11 (50mmx30mm)	0.5mm	40mm
CTS	Copper (0.1mm)	Stainless steel (0.1mm)	JIS SKD11 (50mmx30mm)	0.5mm	40mm

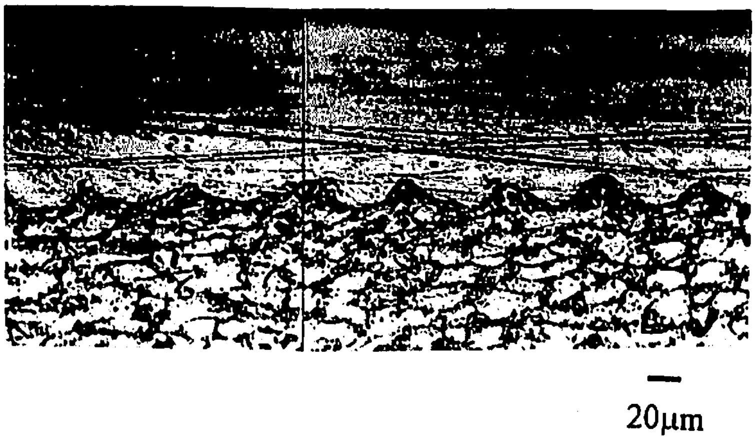

Fig. 3 Wavy structure found in copper/mild steel interface (#CM).

difference in the plate velocity induces the difference in the wavelength with horizontal distance x (Fig. 4) which is measured for a sample #CM. The measured wavelength shows deviation with a certain interval from a solid average line, and it is considered that the deviation is generated due to the reflected waves propagated in the plates.

The explosive welding of multi-layered plates was attempted by stacking some plates at a fixed stand-off distance. Five layers of copper plates were successfully welded, with post-weld interfacial waves (Fig. 5). Final interface in Fig. 5 shows large wave size due to the variation in the initial experimental conditions [7].

Figure 6 shows an illustration of the weldability window based on the previous investigations [1] [5]. Other than the condition for making metal jet, which is strongly related with Vc, upper and lower welding limits exist as shown in the figure. Excessive energy results in excessive melting to cause degradation of the bonding characteristics, and lower energy results in non-bonding due to the lack of energy for an intensive deformation. Close to the lower limit is a weldability region showing planar interface [5]. In our experiments the whole area is within the favorable conditions of explosive welding.

In case of the explosive welding of molybdenum and mild steel, the welding is slightly difficult which shows partially bonding (#MM). The microstructure of the region very close to detonator shows bonding with waves as shown in Fig. 7 (a), but the region far away from the detonator (end side) is separated (Fig. 7 (b)). Since the harder

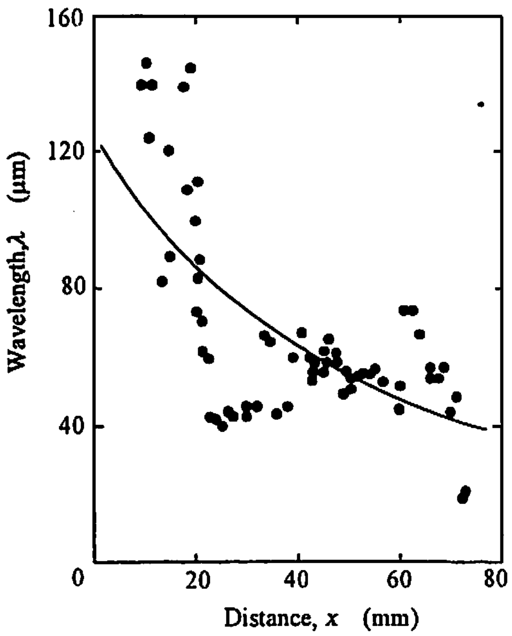

Fig. 4 Change in wavelength with horizontal position for sample #CM.

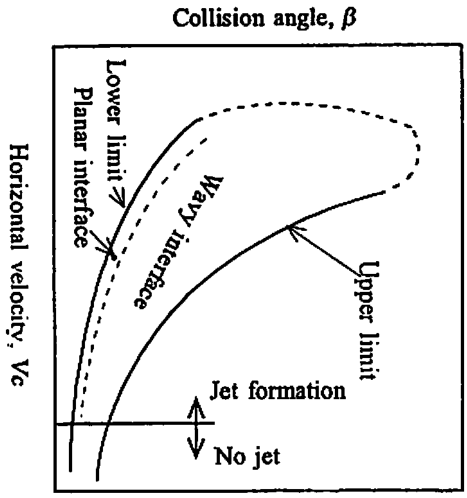

Fig. 5 Schematic illustration of weldability window.

component molybdenum does not favor the formation of metal jet, the welding is not achieved for the whole area. For successful welding of the complete area, it is recommended to judiciously select the welding parameters to be within the upper and lower limits shown in Fig. 6.

The explosive welding of thin metal plate onto a ceramic base is very difficult. Shaffer et al. [8] reported the spot welding of such combination using very less quantity of explosive of the order of mg. The present method is also applicable to the welding of such combination for larger areas and the

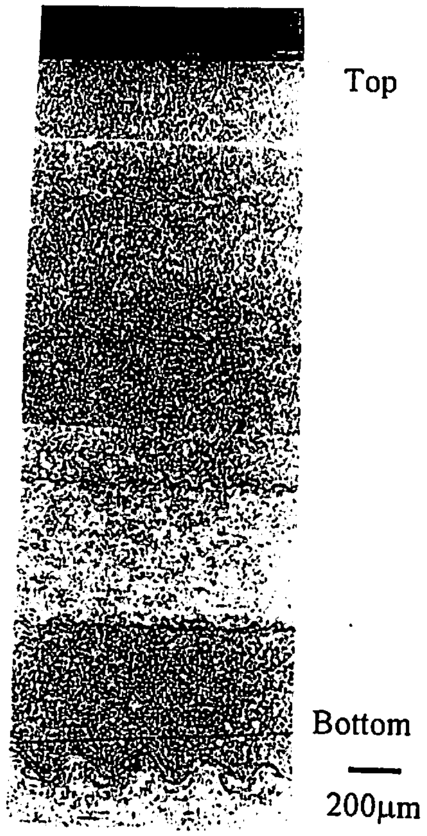

Fig. 6 Cross-section of explosively welded multi-layered copper plates #CC.

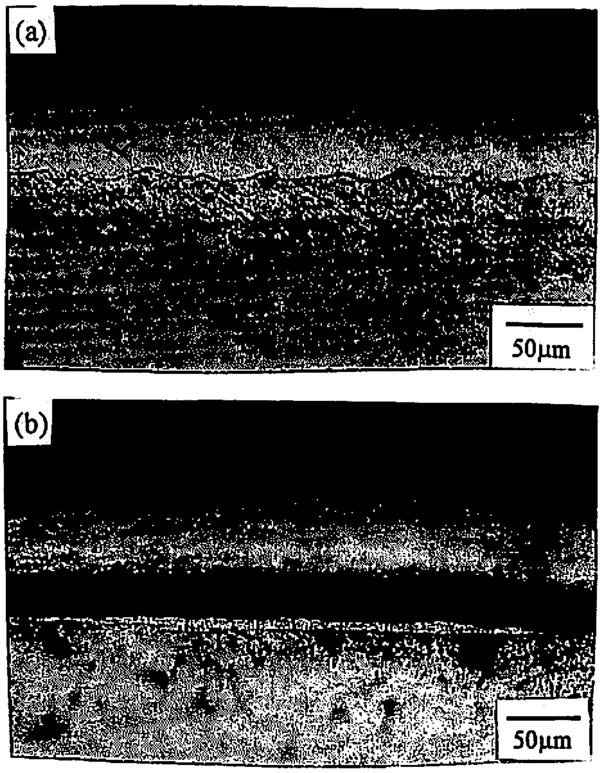

Fig. 7 Microstructure of molybdenum/mild steel interface (#MM) close to detonator and to the farther side.

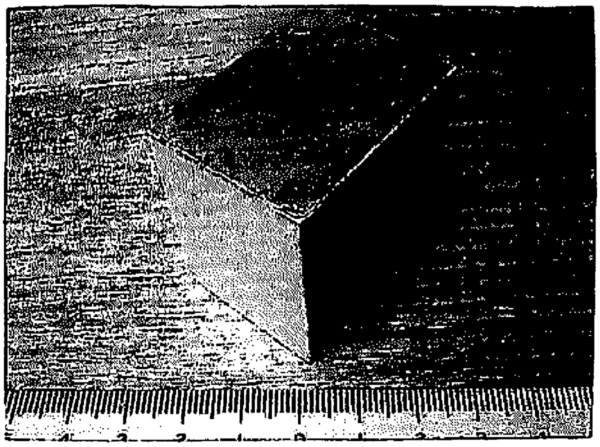

Fig. 8 Appearance of explosively welded aluminum/zirconia (#AZ).

method has been published elsewhere in details [2]. Figure 8 shows the appearance of the aluminum/partially stabilized zirconia welded successfully for 40 mm length and 30 mm width, and such larger area has not been attempted yet using explosive welding technique. As not deformation is anticipated in the ceramic plate a planar interface is produced as reported earlier [2]. Since the formation of undulations at the interface induces cracks in the ceramic plates, the welding parameters should be selected so as to produce a planar interface and the weldability length is limited while using the inclined explosive assembly. The upper limit of explosive welding (Fig.6) is unattanable for the present case because the problems induced by excessive energy are not only brought by the excessive melting as already mentioned in the welding of metal plates. In this case, the formation of cracks in a ceramic block under a high pressure limits the successful welding, and the condition for cracking strongly depends upon the assembly and the materials used. The use of momentum-trap blocks and the thick base plate enables successful welding of the materials without defects [2], but the quantitative analysis of the weld conditions is difficult. Actually, the favorable condition for cracks to develop is often different even for the experiments using the same set-up. Further, the mechanical property of the ceramic block is remarkably changed depending upon the production lot. The quality of the ceramics especially the fracture toughness, should, therefore, be homogenized in future to generate the weldability window for these combinations.

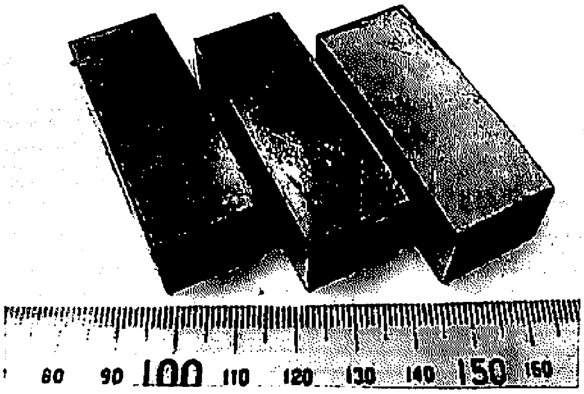

Fig. 9 Appearance of explosively welded (titanium, copper, aluminum)/SKD11 (#TTS, #CTS, #ATS; from left to right, respectively).

The present method has an advantage of welding a thin metal plate onto a brittle base material. An alloyed tool steel, JIS SKD11 (1.4-1.6%C, <0.4%Si, <0.6%Mn, <0.03%P, <0.03%S, 11-13%Cr, 0.8-1.2%Mo, 0.2-0.5%V, bal.-Fe), which has been quenched and tempered, showing the highest hardness, is employed as a base plate. Aluminum, titanium and copper thin plates are successfully welded onto such hardened tool steel as shown in Fig. 9, and the whole area is welded satisfactorily showing clean surface over the thin plates which is the same as the appearance of the plate before welding. Though the ductility of SKD11 is slightly higher than the ceramics, no macroscopic crack has been observed because of the use of a small momentum trap block placed ahead of the main SKD11. The microstructure at the interface of aluminum/SKD11 and copper/SKD11 are shown in Fig. 10 (a) and (b), respectively. Planar interface has been confirmed for aluminum/SKD11, and a wavy structure is confirmed for copper/SKD11. Though the collision velocity is almost the same for these two cases, the difference in microstructure is caused due to the difference in the density and flow strength of the materials used [1] [1]. It is well known that interfacial waves are formed when the densities of the materials are similar [1]. Further, aluminum is much easier to fluidize over the hard base plate. Therefore, planar interface is observed in aluminum/SKD11 weldment. The formation of

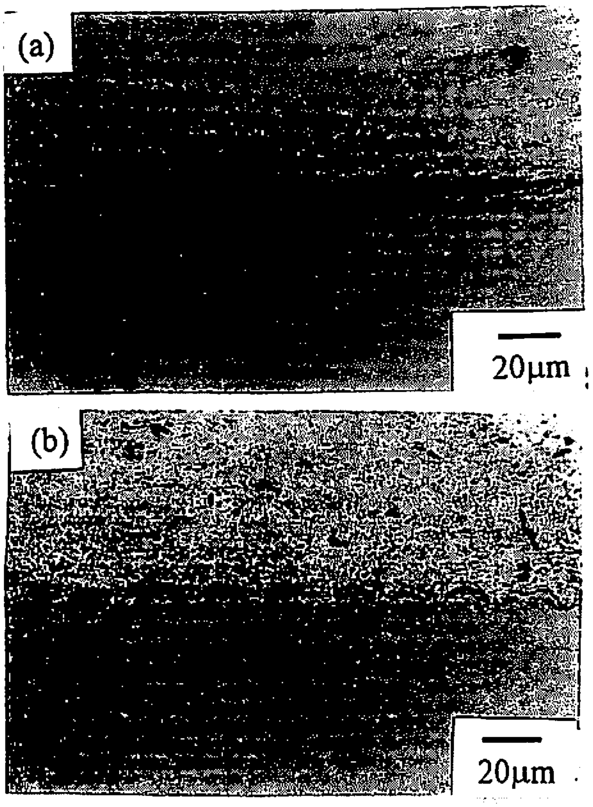

Fig. 10 Welded interface of aluminum/SKD11 (a) and copper/SKD11 (b).

wavy interface in copper/SKD11 joint should also be noticed, because the alloyed tool steel SKD11 has been fully hardened and normally shows no plastic deformation. Since the formation of waves is the evidence of a large plastic deformation, even hardened alloy tool steel shows plastic deformation at an extremely high-strain-rate phenomena under conditions of very high pressure.

4. Conclusions

A new method of explosive welding using underwater shock wave is introduced and the possibility of the welding of a thin metal plate onto various difficult-to-weld materials is suggested. The experimental conditions should be carefully chosen to satisfy the weldability requirements. Some of the experiments demonstrate that the present method enables the welding of a thin metal plate onto ceramics or other materials of low ductility. Since the reliability of the bonding strength for the explosively welded joint is quite high, this technique has good industrial potential, eventhough the range of the thickness of the metal plates is limited at present.

Acknowledgements

The present investigation is partially supported by the Grant-in-Aid for Scientific Research under grant number 11650747. The authors appreciate for the help of the explosion experiments by Mr. Susumu Akimaru, Shock Wave and Condensed Matter Research Center, Kumamoto University.

References

1) B. Crossland, "Explosive Welding and Its Application", (1982) Oxford University Press.
2) K. Hokamoto, M. Fujita, H. Shimokawa and H. Okugawa, J. Mater. Process. Technol., 85, 175 (1999).
3) K. Hokamoto, Y. Ujimoto and M. Fujita, Fundamental Issues and Applications of Shock-Wave and High-Strain-Rate Phenomena, Edited by K.P. Staudhammer, L.E. Murr and M.A. Meyers, pp.601-608 (2000) Elsevier.
4) K. Hokamoto, T. Izuma and M. Fujita, Metall. Trans., 24A, 2289 (1993).
5) D.J. Vigueras, O.T. Inal and A. Szecket, Metallurgical Applications of Shock-Wave and High-Strain-Rate Phenomena, Edited by L.E. Murr, K.P. Staudhammer and M.A. Meyers, pp.927-942 (1986) Dekker.
6) C.F. Cline and R.W. Hopper, Scripta Met., 11, 1137 (1977).
7) K. Hokamoto, A. Chiba, M. Fujita and T. Izuma, Composites Engineering, 5-8, 1069 (1995).
8) J.W. Shaffer, B.W. Cranston and G. Krass, Proc.5th Int. Conf.on High Energy Rate Fabrication, pp.4.12.1-4.12.28 (1975) University of Denver.