JOURNAL OF MATERIALS SCIENCE 22 (1987) 3143–3147

Effect of base plate thickness on wave size and wave morphology in explosively welded couples

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The influence of plate thickness on the wave morphology generated in explosive welding is analysed by the use of mild steel base plates machined into steps of different thicknesses and a constant-thickness mild steel flyer plate, to ensure similar impacting conditions. It is found that wave shape, at the same distance from the collision point, remains unchanged for the different thicknesses. However, wavelength and wave amplitude are observed to decrease for thinner base plates, while the incubation distance for stable wave generation is observed to increase with decreasing base plate thickness. Previously suggested mechanism for explosive wave generation are analysed in terms of the present experiments. It is apparent that most of the theories proposed to date for wave formation are in one way or another incomplete.

1. Introduction

It is a well-known fact that the thickness of the thinner of the two plates involved in a weld influences the wave size, as well as the length of the incubation period preceding a steady state, in explosively welded interfaces. However, the studies conducted to derive these correlations experimentally have only utilized thickness differences in the flyer plate, creating with this change in one or more of the parameters involved in explosive welding. Under these conditions, though, flyer plate kinetics become very difficult to maintain unaltered. Changes in the flyer plate velocity or kinetic energy should be expected when the ratio of mass of explosive to mass of flyer plate is altered. The collision angle could also be influenced since the elastic–plastic behaviour of a thick flyer plate must be different from that of one which is very thin [1]. Thus, the picture of the role played by the thickness of either plate, on wave size and wave morphology, has not been clarified yet.

In some early studies [2–6], the use of a constant value of the collision angle β, for all the flyer plate thicknesses, required that the kinetic energy input be a variable. This was accomplished by the use of the same explosive and the same flyer plate velocity. Alternatively, if different explosive loads were used, changes in detonation velocity were introduced when the explosive was thickness-sensitive. Points of concern in such studies have omitted the fact that if the flyer plate velocity is different, the pressure at the interface is also rendered different. Likewise, when flyer plate velocity is the same, for plates with different thicknesses, the kinetic energy generated by them will be different. Therefore, the number of variables introduced is increased and studies of wave generation mechanism or wave size and shape have, through these experiments, become quite complicated. The study presented uses a very straightforward approach to characterize this effect.

2. Experimental procedure

The mild steel flyer plates used in the explosive welding studies were maintained at a single thickness (3.0 mm) and were accelerated by the same amount of the same explosive, ensuring with this the same values for flyer plate velocity V_p, detonation velocity of explosive V_D, critical welding angle β, and the kinetic energy generated at the interface. The mild steel base plates were machined into steps with different thicknesses. Several conditions for base plate to flyer plate ratio (t_b/t_f) were then satisfied. The geometry of the base plates relative to the detonation direction are shown in Figs 1a and b.

The explosive used in these experiments was ANFO 1800 m sec^{-1}. The desired flyer plate velocity was calculated according to plots of this explosive, as reported by Crossland [7].

No anvil was used in these experiments to avoid possible alteration of the rarefaction waves. The bottom part of the base plate was levelled off with a rubber buffer, approximately one inch (25 mm) thickness. These plates were suspended in air by a constraint-free arrangement.

3. Results

Samples cut along the specimen and parallel to the detonation direction were analysed with an optical microscope. Examples of the waves developed for the different thickness combinations are illustrated in Fig. 2. Wave amplitudes and wavelengths were measured at 400 × in a Unitron TMS 6967 optical microscope equipped with a micrometer, with a resolution of 2.5 μm. The wavelength and wave amplitude measurements are given in Fig. 3. These figures indicate that wave amplitude and wavelength both increase with increasing t_b/t_f ratio. However, the incubation distance for wave formation is seen to increase with decreasing t_b/t_f. No change in wave morphology was evident; this is shown in Fig. 2 and also exhibited in

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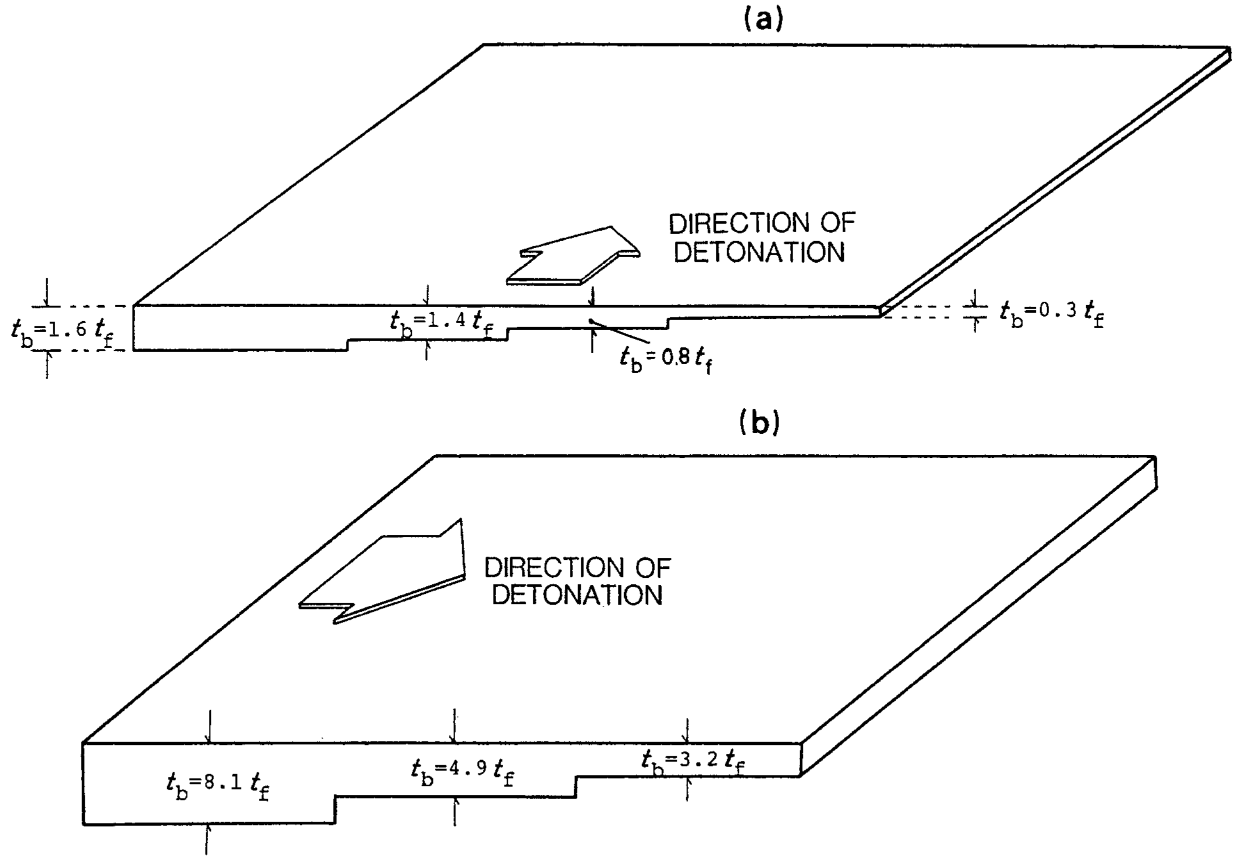

Figure 1 Configuration of the base plates used to measure the influence of thickness on wave morphology. (a)t_b/t_f < 1.6, (b) t_b/t_f > 3.2.

the fact that the wave amplitude to wavelength ratio is almost constant along the specimen when the point is located at the same distance from the collision point.

The measured wavelength was plotted against the t_b/t_f ratio in Fig. 4. This figure shows that, for values of t_b/t_f less than 1.6, wavelength increases with t_b/t_f ratio. However, for values of t_b/t_f above 3.2 no effect on the wave size is evident. The expected value for the wavelength, calculated according to the equations of Godunov *et al.* [8] in which the thinner of the plates involved is considered, is also plotted in this figure. This plot is defined by an equation of a straight line passing through the origin. For $t_b/t_f \geqslant 1$ this equation will predict a horizontal line with the wavelength corresponding to the flyer plate thickness and, even if the

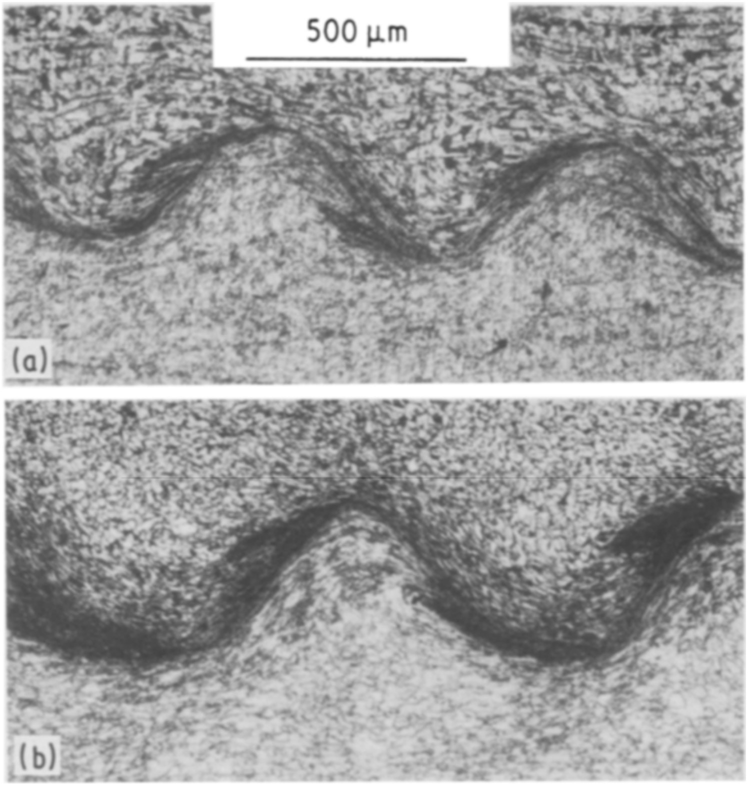

Figure 2 Wave morphology observed for different t_b/t_f ratios: (a) > 3.2, (b) 1.6, (c) 1.4, (d) 0.8, (e) 0.3.

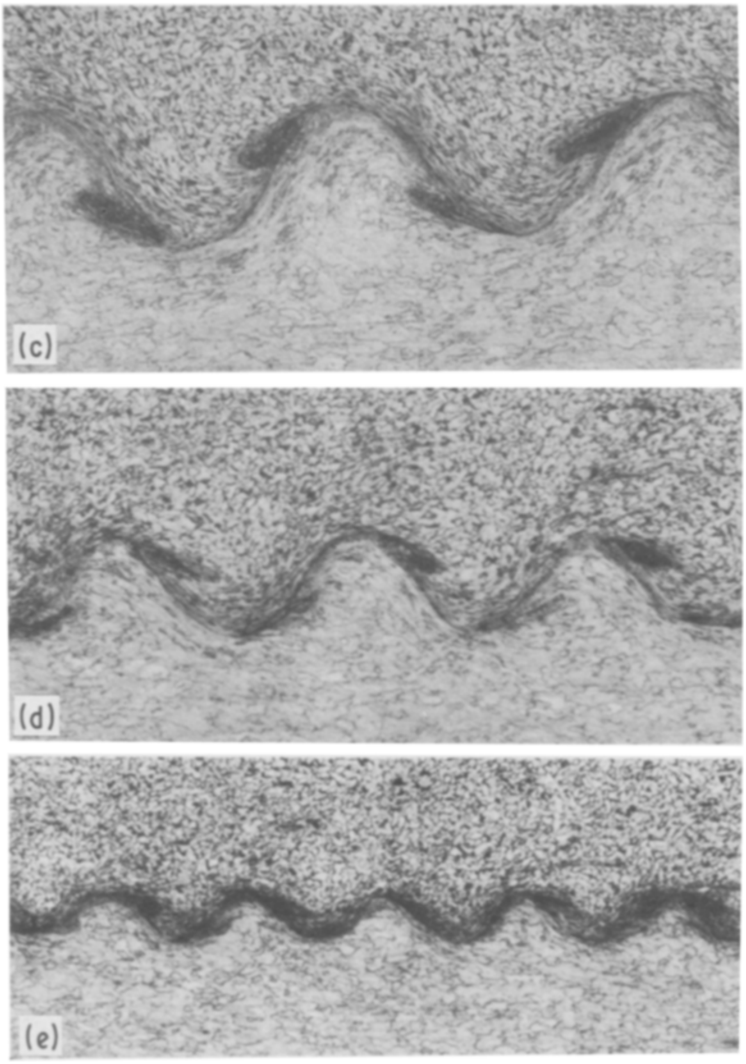

Figure 2 Continued.

flyer and base plate have the same size, no difference in wave size is predicted.

4. Analysis of the results

The conclusions of the present experiments can be summarized in the following points.

1. Since there are no changes in the flyer plate kinetics, the changes in the amount of plastic deformation, pressure, loss of kinetic energy, impact velocity, stream velocity, welding velocity, or velocity discontinuities could be analysed in terms of the base plate thickness and kinetic energy loss. This assumption is not present in most of the theories on wave formation.
2. There is a considerable influence on wave features of the thickness of both plates involved in the welding couples, for values of t_b/t_f less than 1.6, when the plates are relatively thin (short pulse duration).
3. Above a certain value of t_b/t_f, there is no influence introduced by the thicker plate involved in the welded couple. This fact could be explained by the increase in the inertia that the base plate induced in the flyer plate during the collision process. After a certain thickness, the base plate acts as a rigid body leading to a rigid base-plate welding configuration, with the same amount of kinetic energy loss. However, the presence of a transition stage cannot be explained and defined in a precise manner in this configuration, since values for the t_b/t_f ratio between 1.6 and 3.2 have not been studied.
4. The equation that fits the experimental data up to $t_b/t_f = 1.6$ is

$$\lambda = \lambda_0 + 0.62 t_b/t_f,$$

where λ_0 is equal in this case to 0.27.

5. If the experimental values of wavelength are compared to those determined by use of the equation of Godunov *et al.* [8] for the thinner of the plates involved, the results listed in Table I are obtained. These values indicate that, for ratios of t_b/t_f smaller than 1.6, there is a notable discrepancy between theory and experiment. The fact that Godunov *et al.* [8] consider only the effect of one of the plates involved is possibly responsible for this difference. However,

TABLE I Observed and calculated wavelengths

t_b/t_f	Wavelength (mm)	
	Observed	Calculated
0.287	0.35	0.241
0.794	0.70	0.667
1.42	0.87	0.841
1.64	1.00	0.841
3.20	0.82	0.841
4.90	0.81	0.841
8.10	0.84	0.841

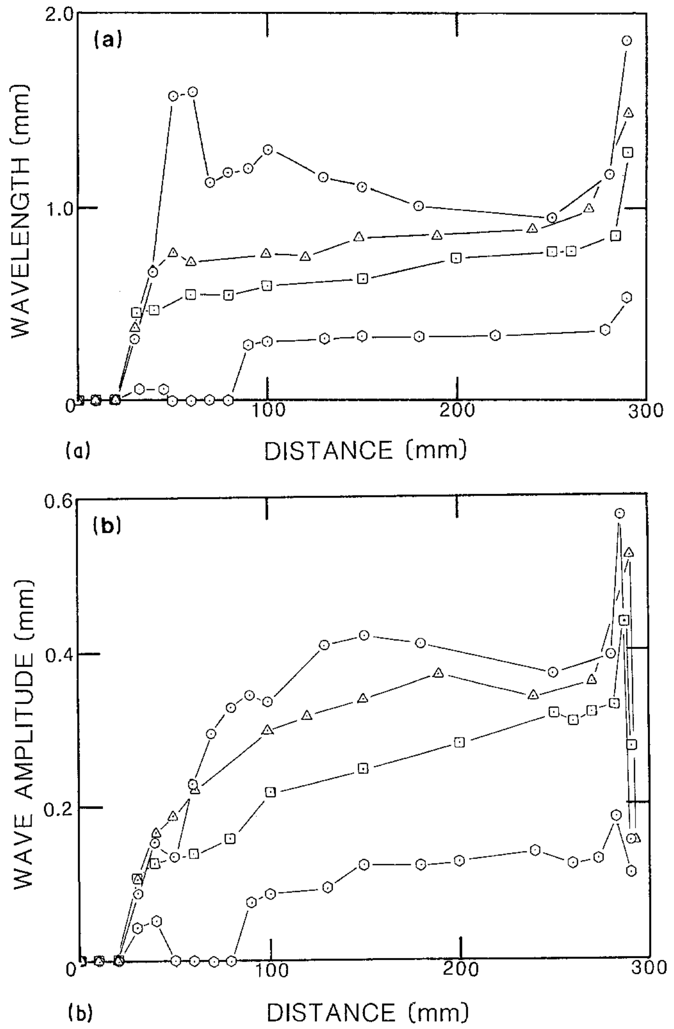

Figure 3 Effect of t_b/t_f ratio on (a) the wavelength and (b) the wave amplitude: (⊙) 1.6, (△) 1.4, (□) 0.8, (○) 0.3.

most important is the fact that the experimentally drawn line does not pass through the origin. λ_0 may thus be assumed to be an intrinsic, dynamic, material property; its value should be expected to change when different materials are utilized.

5. Conclusions

The present experiments indicate that most of the mechanisms proposed to data for wave formation are in one way or another incomplete. The hydrodynamic analogy models [3, 4, 9–17], for instance, cannot be accepted since the size of the obstacle, stream velocity, and velocity discontinuities utilized in their derivation are the same for all configurations; a single flyer plate in a single experiment was used and different wave sizes were developed at the interfaces. The stress wave mechanisms [8, 17], on the other hand, use a comparison between the wave amplitude and the oscillation time of the rarefaction wave or the width of the rarefaction wave. Table II demonstrates the fact that wave size cannot be expresed just in terms of linear acoustic approximations [8]; it requires the use of some intrinsic material property under dynamic loading. However, this dynamic parameter could not be the one explained by Al-Hassani and co-workers [5, 6] either, since differences in wave size, with the same

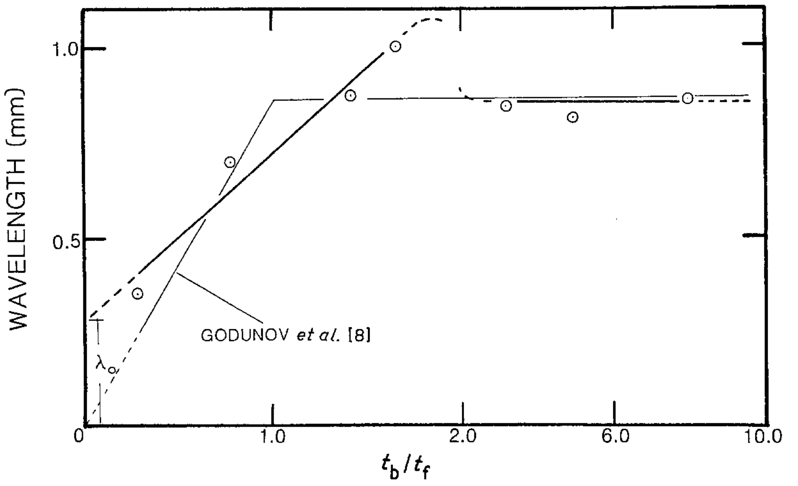

Figure 4 Variation of wavelength with t_b/t_f ratio.

TABLE II Wave parameters

t_b (mm)	t_0 (μsec)*	$\delta \times$ (mm)†	λ (mm)
0.85	0.41	0.073	0.350
2.35	1.12	0.201	0.700
4.25	2.02	0.364	0.870
4.85	2.33	0.419	1.000
3.00‡	1.42	0.254	–
9.70	4.66	0.835	0.820
14.80	7.08	1.269	0.810
24.30	11.63	2.083	0.840

*Pulse duration.
†Width of the rarefaction wave at the moment of arrival at the point of contact.
‡Thickness of the flyer plate.

morphology, are obtained when the same kinetic energy is introduced at the interfaces of similar base plates with different thicknesses.

The above observations seem to suggest the need for the execution of further experiments with different plate thicknesses and different materials to elucidate the role of λ_0, the intrinsic dynamic elastic–plastic parameter. The inclusion of new theories [18], combining both shock-wave physics and the role of the metallurgical features of materials, at high strain rates, seems to be a possible solution to this problem.

Acknowledgements

One of us (D.J.) wishes to thank CONACyT (National Council of Science and Technology of Mexico) and ESIQIE–IPN for support to carry out his graduate studies. Thanks are also due to Professor S. T. S. Al-Hassani (UMIST, UK) for valuable comments.

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Received 13 August 1986
and accepted 11 February 1987