MECHANICS OF EXPLOSIVE WELDING

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1. INTRODUCTION

This paper is a summary of work done in recent years at the Institute of Mechanics, Chinese Academy of Sciences, on several problems of theoretical interest in explosive welding from the point of view of hydro-elasto-plastic dynamics, where the medium or media have to be regarded as exhibiting both fluid-like and solid-like properties. Explosive welding provides a unique case in which phenomena such as interfacial waves, thermo-plastic shear bands, grain distortion, twinning, recrystalization, melting spots, cast structure, shrinkage voids, etc., peculiar to this type of material behavior are especially rich and can be examined in considerable detail both experimentally and theoretically. Fig.1 is a flash X-ray radiograph showing a symmetric configuration of two identical flat plates. This is the case we shall address in this paper. We note that when a steady state collision is achieved, the only parameters are the dynamic angle of collision α and the incoming jet velocity U as shown schematically in Fig.4.

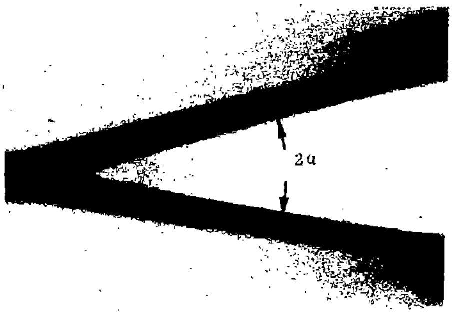

Fig.1 X-ray radiograph

Fig.2 Raidiograph showing shock wave and air-explosion product interface

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2. FLYER PLATE MOTION

2.1 Determination of the effective γ for the detonation product

From X-ray radiographs it is possible to determine experimentally the initial inclination of the air shock wave and that of the air-explosion product interface, Fig.2. Given the detonation velocity it is then possible to compute, according to the theory of oblique waves and the Prandtl-Meyer expansion, both the detonation pressure and the polytropic index γ. Following this consideration, Shao et al[1](1981) obtained the so-called effective polytropic index for a number of commonly used explosives.

2.2 Motion of Flyer plate

The difficulty of calculating the motion of flyer plate lies in the accurate solution of gas dynamic equations of the detonation product. To overcome this difficulty Shao et al[2](1985) simplified the problem by taking the Prandtl-Meyer expansion as the basic solution and regarding the effect of the flyer plate as a small perturbation superposed to the basic flow in accordance with the Lighthill piston theory. This method turns out to be quite effective as shown in Fig.3.

3. MECHANISM OF INTERFACIAL WAVE FORMATION

3.1 Basic model

The mechanism of formation of interfacial waves is of both practical and scientific interest. In the previous literature several me-

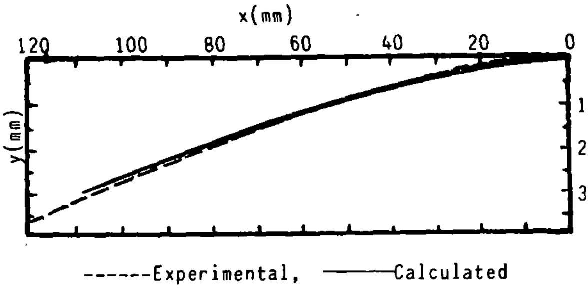

Fig.3 Motion of Flyer Plate

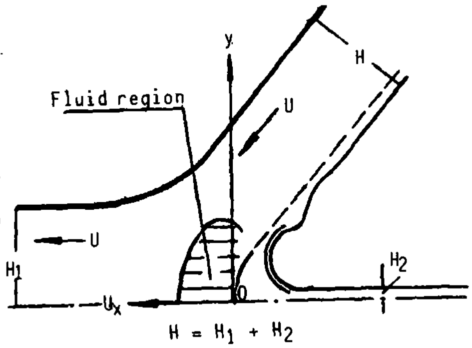

Fig.4

chanisms have been proposed. Short descriptions of these can be found in Crossland's recent book[3](1982). Our own experiments show that these theories, if not inapplicable, are at least inadequate, and a new theory was proposed (Cheng and Tan, 1984)[4].

This new thoery is based on the following assumptions. The basic flow field is thought to be adequately described by the classical hydrodynamic theory of jet collision (see, for example, Milne-Thomson, 1949)[5] with two important modifications,namely(Fig.4),

(1) As the two incoming jets meet, due to the solid behavior of the metal, a thin layer of thickness h is peeled off, presumably as a result of thermo-plastic shear on the reentry jet side. Thus, to a higher order of approximation the rest of the jet adjacent to this layer may move at a different velocity streamwise.

(2) At a certain distance downstream of the stagnation point on the salient jet side, disturbances become frozen because of the solid behavior of the material.

Based on (1) a small sinusoidal perturbation is introduced to the basic classic hydrodynamic flow. It is then shown that sinusoidal disturbances of certain discrete frequences become magnified at the interface more than others. Finally, (2) which amounts to admitting disturbance of a given frequency to enter from the fluid side to the solid side and become frozen there leads to the following expression for the wave length λ at the interface,

$$\lambda/H = \text{const.}\frac{2\pi}{\Omega}\,\frac{Ux}{U}\sin^2\alpha/2 \qquad (1)$$

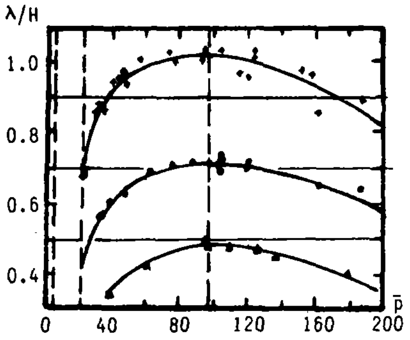

Fig. 5

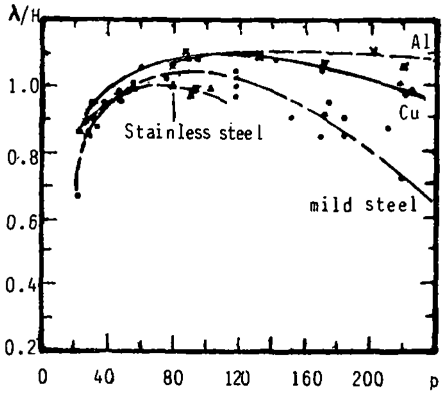

Fig. 6

where H is the thickness of the flyer plate, Ux is the flow velocity given by the classical jet collision theory along the center line and at the point where freezing takes place, Ω is a non-dimensional constant equal approximately to 0.3. The same dependence of λ/H on d without the other factors was pointed out by Utkin (1980)[6] and an explanation was given on the basis of Helmholtz instability of parallel inviscid and incompressible flow. Here it is derived in the spirit of two dimensional hydro-elasto-plastic dynamics. As will be shown below that, unlike all previous theories, this relation allows for corrections of material strength and compressibility.

3.2 Material dependence

Previous experiments in our laboratory showed that λ/H varied with $\bar{p}(=\rho U^2/2\sigma y)$ in a manner shown in Fig.5 for low carbon steel (Zhang et al, 1984)[7] where ρ is the density and σy is the ultimate stress, and little change, if any, was discernable when geometric scale was increased by one order of magnitude, indicating that strain rate effect requires no special consideration in our range of interest.

Recent experiments by Li show that λ/H varies from material to material as shown in Fig.6 for low carbon steel, stainless steel, copper, and an aluminium alloy. Cheng and Li(1985)[8] proposed that the relation presented above remains valid. One, however, has to find a correct experession for Ux/U to count for the strength and compressibility effects of the materials tested. Now, as an incompressible, inviscid fluid, Bernoulli equation along the central streamline gives

$$Ux^2 + 2p/\rho = U^2 \qquad (2)$$

To count for the effect of material strength, we simply assume that the solid-fluid boundary is determined by $p/\sigma y=c$ where c is of the order of 10 this yields

$$Ux/U = (1-c/\bar{p})^{\frac{1}{2}} \qquad (3)$$

To correct for compressibility we assume that the Karman-Tsien approximation applies. It follows then that Ux/U in eq.(1) is a root of the following equation,

$$Ux/U = (1-c/\bar{p})^{\frac{1}{2}}[(1-(U^2/a_o{}^2)(1-Ux^2/U^2))^{\frac{1}{2}} + (1-U^2/a_o^2)^{\frac{1}{2}}]/(1+(1-U^2/a_o^2)^{\frac{1}{2}}) \tag{4}$$

where a_o is the sound speed of the material under consideration. Referring to Fig.6 we note that the corrections proposed here do lead to results in agreement with experiment.

4. TEMPERATURE DISTRIBUTION AND MICROSTRUCTURE

From micrographs of the weld it can be seen that the degree of distortion of grains increases as U increases. This is in accordance with the view that the fluid region defined by $p/\sigma y > c$ expands as U increases. For still greater U the temperature close to the bonding surface becomes so high and the strain so large that upon cooling recrystalization occurs. Eventually melting appears at places where very large plastic deformation takes place.

At the suggestion of author, efforts have been made at the Institute of Mechanics to study the temperature field and correlate it with the microstructure (Zhang,1985)[9][10]. One notes that the heating due to adiabatic compression up to the stagnation pressure $\rho U^2/2$ is relatively small and reversible while the heating by plastic work is much higher and irreversible. Thus it is reasonable to assume that only plastic work contributes to heating.

To the first approximation the temperature field due to plastic deformation may be calculated from the known classical hydrodynamic theory by equating the rate of increase of heat content to $\tau_{ij}\dot{\gamma}_{ij}$ where τ_{ij} is the shear stress tensor and $\dot{\gamma}_{ij}$ the strain rate tensor, and integrating this relation along a streamline, beginning from the point where this streamline first meets the curve $p/\sigma y = c$ and the initial temperature is taken to be equal to the room temperature. The integration terminates when the streamline intersects the same curve again. To effect the integration an appropriate constitutive relation must be provided. In Zhang's calculation, the material is assumed to be ideally plastic-rigid, obeying the Mises Yield condition and the

Prandtl-Reuss flow rule. The flow stress was given by a modified Towle formula suggested by Cheng(1973)[11].

In the solid region there is a redistribution of temperature. This temperature field can be calculated according to a one dimensional model since the temperature gradient is significant only in the direction normal to the plate.

Using the above method Zhang succeeded in counting for the width of the recrystalization zone and in predicting the melting and non-melting of the material at and close to the interface as well as some finer points.

5. CONCLUDING REMARKS

In this paper we outlined the main results of our investigation of some of the interesting features of explosive welding from the point of view of applied mechanics. A new mechanism of the formation of interfacial waves is given which enables us to establish a formula to relate the wave length with material properties as well as geometric and kinematic factors.

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