EFFECTS OF STRENGTH AND COMPRESSIBILITY OF MATERIALS ON WAVE FORMATION AT INTERFACE IN EXPLOSIVE WELDING

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INTRODUCTION

Waves are often observed at the interface of two metal sheets in explosive welding. A number of theories were proposed by early investigators to explain wave formation. But up to now none of them appears to be completely satisfactory. Therefore the mechanism of wave formation is still an open problem.

In the past years a series of works on the wave formation mechanism has been done[1, 2,3] at the Institute of Mechanics,CAS.Recently,based on a model of hydro-elasto-plasto-dynamics, a new wave formation mechanism has been proposed[4]. At same time, in order to explore the role of material strength and compressibility,a series of experiments have been carried out, using different metals.These experiments further confirm the mechanism of wave formation in explosive welding proposed in[4].

Some of our recent experimental results are presented in this paper, and explicit formula for λ/H (wavelength/plate thickness) based on hydro-elasto-plasto-dynamics and the Karman-Tsien approximation is given.

EXPERIMENTAL RESULTS

Results of a series of experiments for symmetric explosive welding of mild steel are given in Fig.1. The relation between non-dimensional wavelength ($\bar{\lambda}=\lambda/H$)and pressure $\bar{p}(=\rho\cdot U_0^2/2\sigma_b)$ is shown in the curves 1,2 and 3 for different impact angle β of 13°,11° and

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COMPARISON BETWEEN THE RESULTS OF CALCULATION AND EXPERIMENTS

The calculated $(\overline{\lambda}/K \cdot \sin^2(\beta/2)) \sim \overline{p}$ relations for the various compressible materials are given in Fig.5, where curves 2,3,4 and 5 correspond respectively to Al, Cu, mild steel and stainless steel, according to equation (5), but curve 1 is from (3). In the above calculation, the material constants ρ_o, σ_b, a_o chosen are lised in Table 1. In Fig.5 curves 2′, 3′, 4′ and 5' are based on experimental data for the four metals. The results of experiment and calculation agree well except near the right end of the curves. It should be pointed out that the Karman-Tsien approximation is not valid close to M_o=1.For mild steel the difference seems larger than those for the other metals. One possible reason could be that the static ultimate strength and a_o used in the calculation is inadequate. Better agreement between experimental result and equation (5) can be achieved if we set a_o to 3570m/s which is the sound speed for iron.

Table 1

material	ρ_o g/cm^3	σ_b kg/mm^2	a_o m/s
aluminum	2.7	10 - 11	5300
copper	8.9	32 - 34	3970
stainless steel	7.8	55 - 68	4550
mild steel	7.8	39 - 42	4800
iron	7.8	30 - 32	3570

CONCLUSIONS

Experimental results given in this paper show that the study of mechanism of wave formation at the interface in explosive welding falls within the general subject of hydro-elasto-plasto-dynamics, and the effects of material strength and compressibility on interfacial wave formation need be considered. They are in agreement with the model proposed in [4]. The formula developed in this paper should be applicable to other materials.

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Experiments were carried out in the blast chamber in the

We first note that around point O the velocity and pressure fields are highly non-uniform, especially on the reentrant jet side. The corresponding strain rate in that part is also very large. Then, we have reason to assume that an adiabatic shear band will lead to the formation of a thin layer at the surface of the reentrant jet and sliding may occur between the fluid and this layer. (Fig.4). Secondly we note that the fluid region is limited approximately by the curve $P/\sigma_b=C$, where C is a constant of the order 10. Outside of this region the material may be regarded as rigid. Based on these observations, the follow formula for $\bar{\lambda}$ was given by [4]

$$\bar{\lambda}= K \sin^2(\beta/2)\cdot(U_c/U_o) \qquad (2)$$

where K is a non-dimensional constant independent of material properties and of the order 10^2, U_c is the velocity at y=0 and $P/\sigma_b=C$, where the transition from fluid-like to solid-like behavior takes place. Now we show that the effect of material property is contained in U_c/U_o.

(1) The effect of strength.

From Bernoulli Equation in ideal incompressible hydrodynamic theory, we have

$$U_c/U_o =\sqrt{1-C/\bar{P}} \qquad (3)$$

It shows that U_c/U_o increases with $\bar{P}$ and approaches 1 when $\bar{P}$ is sufficiently large.

(2) The effect of compressiblity.

To count for the effect of compressibility we apply the Karman-Tsien approximate method and obtain

$$U_c/U_o=(W_c/W_o)[\sqrt{1-M_o^2(1-(U_c/U_o)^2)}+ \sqrt{1-M_o^2}]/[1+ \sqrt{1-M_o^2}] \qquad (4)$$

where W_c/W_o equals the U_c/U_o given by (3) for incompressible flow,and $M_o=U_o^2/a_o^2=\bar{P}\sigma^*$. Equation (4) then reduces to

$$U_c/U_o = 2\sqrt{1-\bar{P}\cdot\sigma^*} (1+\sqrt{1-\bar{P}\cdot\sigma^*}) \sqrt{1-C/\bar{P}} /[(1+\sqrt{1-\bar{P}\cdot\sigma^*}) - \sigma^*\cdot(\bar{P}-C)] \qquad (5)$$

9°, where ρ is the density, U_0 is the impact velocity and σ_b is the ultimate static strength of the material. Fig.1 can be divided into four regions. In region I welding does not take place. In region II there is no wave at the bonding surface. At the boundary between the regions II and III regular waves start to form at the welding interface. In region III $\bar{\lambda}$ increases with $\bar{p}$, and for a given impact angle β the wave structure also varies with $\bar{p}$. At a certain $\bar{p}$ vortex-like struture and molten pockets begin to appear in succession. However, $d\bar{\lambda}/d\bar{p}$ decreases as $\bar{p}$ continues to increase with U_0 until it reaches a maximum $\bar{\lambda}_{max}$ where $\bar{p}=\bar{p}_n$ and $d\bar{\lambda}/d\bar{p}=0$. Here we can see that material strength plays a major role on wave formation in region III. At region IV, $\bar{p}>\bar{p}_n$, as $\bar{p}$ increases, $\bar{\lambda}$ decreases. This phenomenon can not be explained by incompressible and inviscid hydrodynamics because according to that theory $\bar{\lambda}$ will approach a constant value and the decrease of $\bar{\lambda}$ is impossible. In order to study the effect of compressibility, a set of experiments using copper, aluminium and stainless steel at $\beta=13^{\circ}$ was carried out. These materials are different in sound speed and compressibility, i.e. $\bar{p}$ varies with V/V_0, where V_0 is initial specific volume ($V_0=1/\rho_0$), V is specific volume at the stagnation point where the static pressure is approximatly equal to $\rho_0 \cdot U_0^2/2$. The $V/V_0 \sim \bar{p}$ relations of these materials are shown in Fig.2.

It is seen from Fig.3 that at the same $\bar{p}$, $\bar{\lambda}$ varies from material to material. The $\bar{\lambda}_{max}$'s in these curves are also different. The

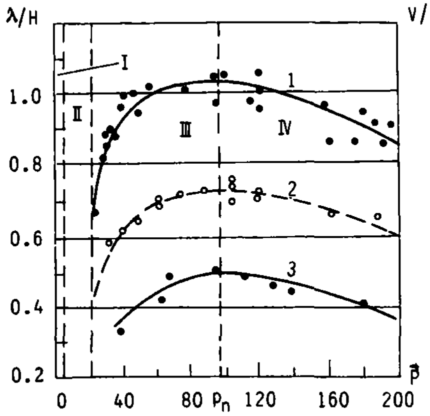

Fig.1

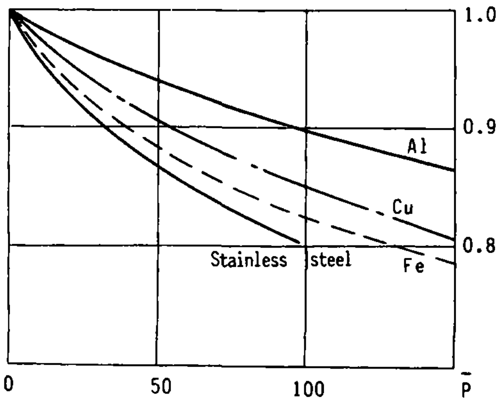

Fig.2

$\bar{\lambda}_{max}$'s of Al and Cu are higher than those of mild and stainless steels. In addition, the corresponding $\bar{p}$ at $\bar{\lambda}_{max}$ also differs from material to material. Thus, the characteristics of these curves depend upon material properties. Aside from wavelength, wave structures are also different. Comparing Fig.2 and Fig.3 we find that the order of $\bar{\lambda}\sim\bar{p}$ curves for the different metals is identical to that of the $V/V_0\sim\bar{p}$ curves. Thus it is seen that the compressibility of material is another factor that influences the wave formation.

EXPLICIT FORMULA FOR λ/H

Mechanism of interfacial wave formation has been the subject of investigation by many authors [5,6,7]. Most of the theories are based on hydrodynamic theory. For example, Utkin(1980) gave the following formula for $\bar{\lambda}$, i.e.

$$\bar{\lambda} = 128 \sin^2(\beta/2) \qquad (1)$$

His theory is based on Helmholtz instability of parallel flow of incompressible and inviscid fluid. This formula fails to count for material property and would be the same for all materials. Evidently, this is not consistent with the results of our experiments. Another model was proposed by the first author in [4]. The general idea of that model is as follows:

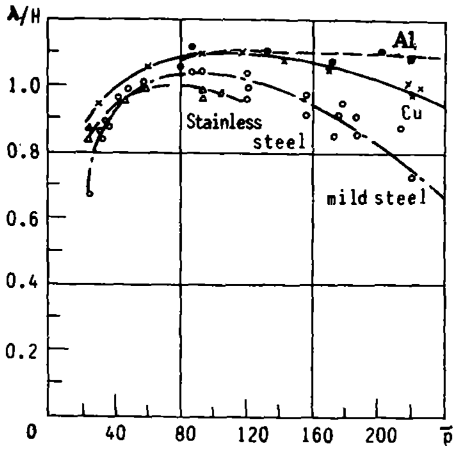

Fig.3

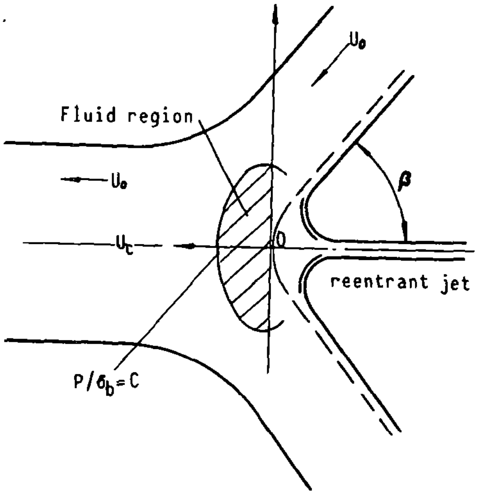

Fig.4

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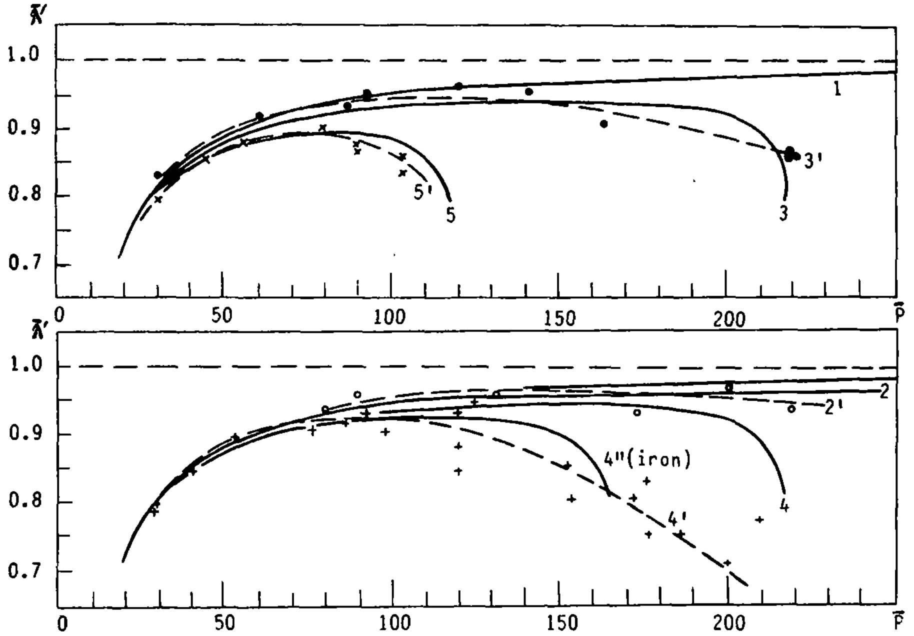

* $\bar{\lambda}' = \bar{\lambda}/K\sin^2(\beta/2)$ Fig.5

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