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The Peculiarities of Wave Formation at Explosive Welding Via thin Interlayer

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Abstract

During the experiments on explosive welding of low-plasticity steels with thin interlayer of ductile metal between them, it was found that the size of the waves generated in the bonding area can be different, even if the collision conditions and colliding materials are the same. However, the wavelength λ lies in the range between $\lambda_{\max}$ and $\lambda_{\min}$ determined by contact point velocity v_c, collision angle γ, hardness (HV_1, HV_2) and densities (ρ_1, ρ_2) of colliding plates. The formulas for calculation of the allowed range of values for wave lengths and amplitudes are proposed.

Keywords

Explosive welding; interlayer; wave formation; Landau model; wavelength; wave amplitude.

Introduction

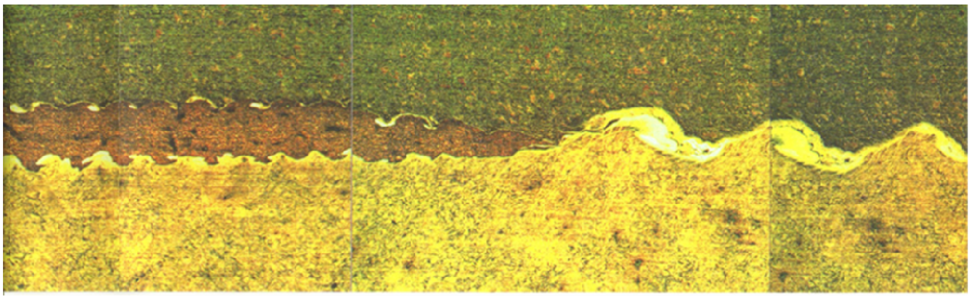
Explosive welding is the process in which the high speed flying plate (flyer plate) collides with the resting plate (parent plate) at a certain angle, at that the flyer plate is accelerated by explosion. The wave formation phenomenon related to explosive welding (**EW**) is well known and there are more than a dozen of models devoted to its description [1]. However, there is yet no satisfactory theory for prediction of wave size considering the strength and physical properties of colliding materials, while experiments show that their hardness and density affect the length and amplitude of generated wave [2]. Evidently, the control of wave formation is very important in welding of low-plasticity metals and alloys, when the problem of cracking arises. Experiments show that it is possible to reduce the wave size, when a flyer plate is in advance clad with a thin copper layer [2, 3]. This is an effective way to get bonding without cracking. The experiments have shown the existence of two types of waves (small and large) occurring in the bond zone and differing in wavelength and wave amplitude [3]. The possible existence of two types of waves has previously been discussed in [4], but experimentally proved for the first time in [3].The present paper describes the last research results on the topic of wave formation at EW via thin interlayers.

Experimental. Materials and methods

Prior experiments showed that strength and density of colliding materials significantly affect the wave size [2, 5]. For example, when the hardness of materials differs by more than 10 times, the boundary is waveless [5]. The same was observed when the densities differed by more than 3 times [2]. To study the wave formation in the presence and absence of the interlayer, a series of experiments on EW of hardened steels was carried out using thin interlayers of different ductile materials. Fig. 1 shows the polished section of the weld zone that has appeared in result of EW performed in two steps. First, the 3 mm thick steel plate with a hardness of 460 HV was clad with the 0.3 mm thick copper band with the hardness of 78 HV. Then, the copper layer was removed from the part of the surface of bimetal by milling, and the obtained plate was welded onto a steel plate with a hardness of 320 HV.

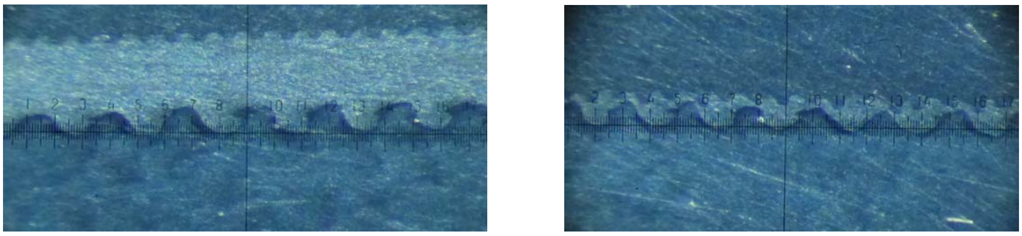
The described method enables obtaining two bonding areas in one experiment: steel-steel area, and steel-interlayer-steel one. The same approach was employed in further experiments on EW of hardened steel plates using copper, aluminum, titanium and mild steel interlayer. Fig. 2 shows wavy interfaces got by EW of two steel plates using the mild steel interlayer. The flyer plate (3.5 mm thick) and parent plate (25 mm thick) were made of hardened 30HGSA steel with a hardness of 334 HV. Interlayer (0.5 mm thick) is made of low-carbon steel with a hardness of 131 HV.

All welded samples were cut and microsections were made from them to measure the size of emerging waves. The welding parameters (v_c, γ) and the measured wave lengths λ and amplitudes a are given in Table 1.



a) *b*)

Fig. 1. Small (*a*) and large (*b*) waves in the bond zone of steel plates welded via copper interlayer (*a*) and directly (*b*) in one experiment at collision point velocity v_c = 2.5 km/s and collision angle $\gamma \approx 10°$



a) *b*)

Fig. 2. Welding two plates of hardened steel:
a – bonding through the interlayer of mild steel, *b* – direct bonding

Table 1

Collision parameters and wave sizes

No.	Flyer plate	Interlayer	Parent plate	$D = v_c$, km/s	γ, °	λ, mm	*a*, mm
1	2	3	4	5	6	7	8
1	30HGSA, δ = 1.5 mm, 35HRC (334HV)	Cu, δ^* = 0.5 mm, 60HB (78HV)	30HGSA, δ_1 = 25 mm, 35HRC (334HV)	2.20	12	0.381	0.056–0.085
2	30HGSA, δ = 3.0 mm, 35HRC (334HV)	Cu, δ^* = 0.5 mm, 60HB (78HV)	30HGSA, δ_1 = 25 mm, 35HRC (334HV)	2.25	12	0.449	
3	30HGSA, δ = 4.5 mm, 35HRC (334HV)	Cu, δ^* = 0.5 mm, 60HB (78HV)	30HGSA, δ_1 = 25mm, 35HRC (334HV)	2.63	12	0.538	0.035–0.070
4	60G2A, δ = 3 mm, 45HRC (460HV)	Cu, δ^* = 0.3 mm, 60HB (78HV)	30HGSA, δ_1 = 25mm, 32–33HRC (320HV)	2.50	9.6	0.24	0.05
	60G2A, δ = 3 mm, 45HRC (460HV)	Cu layer is removed	30HGSA, δ_1 = 25mm, 32–33HRC (320HV)		10.5	0.56	0.1

Continuation of Table 1

1	2	3	4	5	6	7	8
5	St20, $\delta = 4$ mm, 120HB (120HV)	Al, $\delta^* = 1$ mm, 30HB (40HV)	St20, $\delta_1 = 20$mm, 120HB (120HV)	2.72	11.2	Can't be measured	
	St20, $\delta = 4$ mm, 120HB (120HV)	Al layer is removed	St20, $\delta_1 = 20$ mm, 120HB (120HV)		12.0	0.64	0.135
6	30HGSA, $\delta = 3.5$ mm, 35HRC (334HV)	VT1-0, $\delta^* = 0.5$ mm, 131–163HB (131–162HV)	30HGSA, $\delta_1 = 25$ mm, 35HRC (334HV)	2.58	14.0	0.43	Very small
	30HGSA, $\delta = 3.5$ mm, 35HRC (334HV)	VT1-0 layer is removed	30HGSA, $\delta_1 = 25$ mm, 35HRC (334HV)		14.8	0.81	0.15
7	30HGSA, $\delta = 3.5$ mm, 35HRC (334HV)	St3, $\delta^* = 0.5$ mm, 131HB (131HV)	30HGSA, $\delta_1 = 25$ mm, 35HRC (334HV)	2.48	12.8	0.46	0.085
	30HGSA, $\delta = 3.5$ mm, 35HRC (334HV)	St3 layer is removed	30HGSA, $\delta_1 = 25$ mm, 35HRC (334HV)		14.2	0.35	0.075

Notes: 30HGSA (0.28–0.34 C, 0.9–1.2 Si, 0.8–1.1 Mn, 0.8–1.1 Cr, 96 % Fe) is an alloy structural steel; 60G2A (0.57–0.65 C, 0.17–0.37 Si, 0.7–1.0 Mn, 97 % Fe) is a spring structural steel; St20 (0.17–0.24 C, 0.17–0.37 Si, 0.35–0.65 Mn, 98 % Fe) is a structural high quality carbon steel; St3 (0.14–0.22 C, 0.15–0.3 Si, 0.4–0.65 Mn, 97 % Fe) is a mild structural steel of an ordinary quality; VT1-0 (98,61– 99,7 % Ti) is a technical titanium; Cu and Al are the metals of technical purity; δ is the flyer plate thickness, δ^* is the interlayer thickness, δ_1 is the parent plate thickness.

Results and discussion

For the theoretical interpretation of the wave formation phenomenon let's use the approach proposed in [6] and based on Landau model of instability of a stationary flow of a viscous liquid [7]. According to this model, a non-stationary flow in a viscous liquid is characterized by two dimensionless parameters – Reynolds number $R = \rho ul/\eta$ and Strouhal number $S = u\tau/l$, where ρ and η are respectively the density and viscosity of liquid; l – characteristic dimension; u – characteristic velocity and τ – characteristic time of the considered problem.

When as-waves disturbances in a liquid occur spontaneously (not under the action of external periodic force), then S is a function of R, i.e. $S = f(R)$. If we take the period of oscillations T as a characteristic time τ, the contact point velocity v_c as a characteristic velocity u, and the thickness of a cumulative jet δ_j as a characteristic dimension l, then we have

$$S = v_c T / (\delta \cdot \sin^2(\gamma/2)).$$

Here the thickness of a cumulative jet is calculated by the formula $\delta_j = \delta \cdot \sin^2(\gamma/2)$ derived for the collision of a flyer plate with very thick parent plate [8]. Evidently, for the wave disturbances arising in a stationary flow moving with the velocity v_c, there is the relationship $v_c T = \lambda$, because these disturbances are transferred by a flow. Hence we obtain the formula for the wavelength

$$\frac{\lambda}{\delta} = f(R)\sin^2(\gamma/2). \quad (1)$$

Here δ is the flyer plate thickness, ρ_1 and ρ_2 are the densities of flyer and parent plates correspondingly, v_c – the contact point velocity; γ – the collision angle, HV_1 and HV_2 – Vickers hardness of flyer and parent plate respectively. R designates a Reynolds number as it is accepted among specialists in explosive welding [4, 9]

$$R = \frac{(\rho_1 + \rho_2)v_c^2}{2(\mathrm{HV}_1 + HV_2)}. \quad (2)$$

Processing the experimental data in the Table 1 howed that there were not only two types of waves described in [3]. It was discovered that the experimental values of wavelength λ fall in the interval between the upper $\lambda_{\max}$ and lower $\lambda_{\min}$ bounderies which depend on the collision angle, contact point velocity, strength and density of colliding materials. These bounds are described by empirical equations

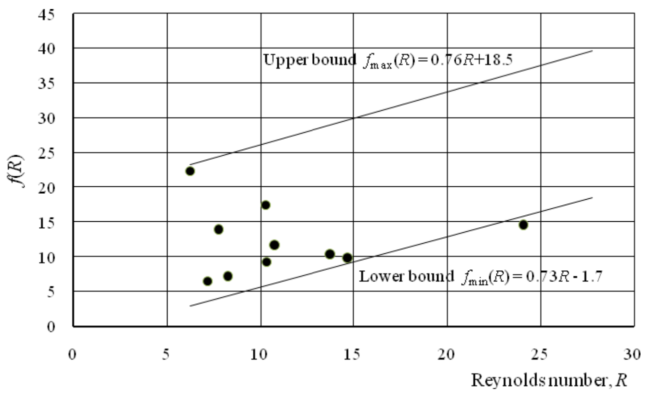


Fig. 3. Dependence of $f(R) = \lambda/(\delta \sin^2(\gamma/2))$ on R

$$\lambda_{\max} = f_{\max}(R)\,\delta\sin^2(\gamma/2) = \\ = (0.76R + 18.5)\delta\sin^2(\gamma/2)\,; \qquad (3)$$

$$\lambda_{\min} = f_{\min}(R)\,\delta\sin^2(\gamma/2) = \\ = (0.73R + 1.70)\delta\sin^2(\gamma/2)\,. \qquad (4)$$

Fig. 3 shows $f(R) - R$ diagram on which experimental points and boundaries of the wavelengths area are marked. Experimental points are based on the data of Table 1, while upper $f_{\max}(R)$ and lower $f_{\min}(R)$ bouderies are built using equations (3), (4).

So, it is impossible to predict exactly the wavelength for a given collision conditions, but a range for λ values can be specified using the equations (2) – (4). As for the wave amplitude, a range of its values has been also found

$$0.14\left(\frac{\rho_{\min}}{\rho_{\max}}\right)^{2.6} \le \frac{a}{\lambda} \le 0.30\left(\frac{\rho_{\min}}{\rho_{\max}}\right). \qquad (5)$$

The uncertainty in the wave size can be associated with the uncertainty in the thickness δ_j of cumulative jet arising between the colliding surfaces because it is not solid, but dispersed at $\gamma < 30°$ [10]. Besides, the wave size can be influenced by other reasons associated with acoustic waves travelling in the collided plates.

Conclusion

1. Instead of given in [4] classic formulas for estimation of wave length λ and amplitude *a*, the new modified equations (2) – (5) considering the strength and density of explosively welded materials are proposed.

2. The use of thin ductile interlayer welded previously onto the flyer plate enables to get waves with minimal values of λ and *a*, close to the lower bound of the wave size diapason. This is important when welding low-plasticity metals and alloys.

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