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WELDING WINDOWS FOR ALUMINUM-MAGNESIUM AND TITANIUM-STEEL EXPLOSIVE CLADDING

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ABSTRACT

This study analytically estimated the welding domain for explosive cladding of aluminium-magnesium and titanium-steel combinations. Welding window, an analytical estimation, can ascertain whether the interface is wave-like or straight. The welding window's lower, upper, left, and right boundaries were constructed using empirical relations suggested by peer researchers. The soundness of the dissimilar clad is primarily positioned near the lower boundary of the welding window. The ideal process parametric condition for an undulating interface is also laid out.

Keywords: *Explosive cladding. Dissimilar metals, welding window, microstructure*

1. Introduction

Hybrid composite materials are employed in various engineering applications due to their adaptable characteristics, such as their lightweight, high strength-to-weight ratio, low cost, and ease of structure creation. Due to their superior mechanical characteristics, hybrid composites are found in the automotive industry's numerous interior and exterior applications [1]. To manufacture hybrid composite plates, various techniques such as laser welding [2], Friction stir welding [3], diffusion bonding [4] and explosive cladding [5] are attempted. Of the above techniques, explosive cladding is superior because of its ability to join multi-layers of similar or dissimilar metals and alloys that cannot be bonded through any other traditional manufacturing method [6]. Fig.1 illustrates the two configurations attempted viz., inclined and parallel. In this joining technique, controlled detonation of chemical explosives promotes metallurgical bonding attributed to significant localized plastic deformation at the bonding interface [7].

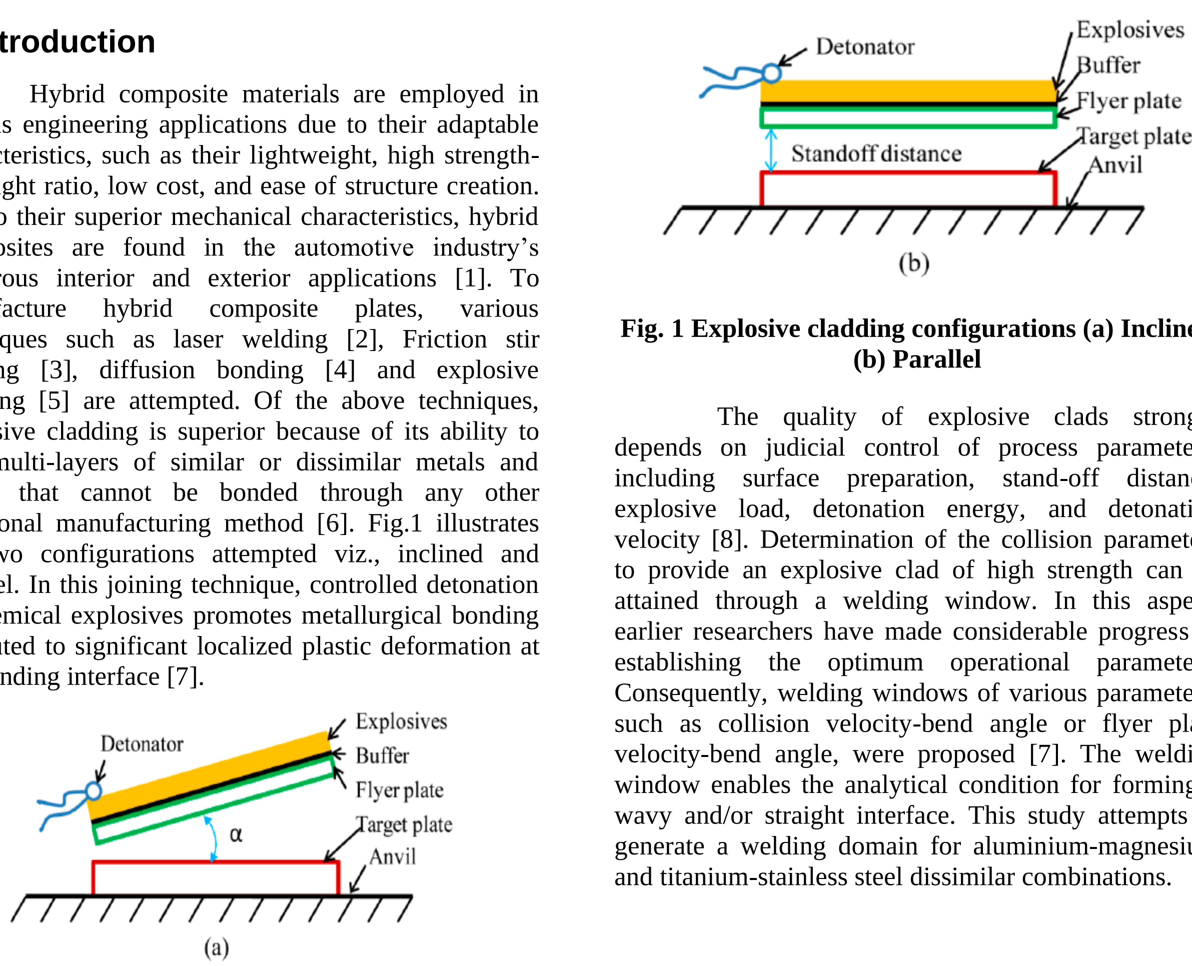

Fig. 1 Explosive cladding configurations (a) Inclined (b) Parallel

The quality of explosive clads strongly depends on judicial control of process parameters, including surface preparation, stand-off distance, explosive load, detonation energy, and detonation velocity [8]. Determination of the collision parameters to provide an explosive clad of high strength can be attained through a welding window. In this aspect, earlier researchers have made considerable progress in establishing the optimum operational parameters. Consequently, welding windows of various parameters, such as collision velocity-bend angle or flyer plate velocity-bend angle, were proposed [7]. The welding window enables the analytical condition for forming a wavy and/or straight interface. This study attempts to generate a welding domain for aluminium-magnesium and titanium-stainless steel dissimilar combinations.

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2. Theoretical

When an explosive detonation occurs, the pressure wave accelerates the flyer plate instantly to a rapid rate before impacting the base plate to form a clad. The flyer plate loses a portion of its kinetic energy during a collision, which leads to plastic deformation at the point of impact. The following expression yields the plate velocity, Vp and dynamic bend angle, β [9]

$$V_p = 2V_d \sin\left(\frac{\beta}{2}\right). \quad (1)$$

$$\beta = \left(\sqrt{\frac{k+1}{k-1}} - 1\right) \cdot \frac{\Pi}{2} \cdot \frac{r}{r + 2.71 + 0.184 t_e / s}. \quad (2)$$

The collision velocity can be calculated using [7]

$$V_c = V_P \cdot \frac{\cos\left(\frac{\beta - \alpha}{2}\right)}{\sin \beta}. \quad (3)$$

3. Welding window

The bottom, upper, right, and left boundaries, transition, minimum and maximum bend angles, and critical jetting angles are straight and curved boundaries that make up the welding window, drawn between two parameters. Wittmann et al. [10] and Deribas et al. [11] created an explosive welding window where collision velocity Vc is plotted in abscissa and bend angle, and β is plotted in ordinates. The left boundary is particularly relevant because it provides minimal impact velocity. The transition (V_f) from laminar to turbulent flow was defined by Cowan [11] using the fluid hypothesis as follows:

$$R = \frac{(\rho_F + \rho_P) V_F^{\,2}}{2(H_F + H_P)}. \quad (4)$$

At the point of transition, the Reynolds number is 10.6. The sonic velocity of the flyer plate, or 120% of bulk sound velocity, is the right boundary [12]. However, it is visible from the literature that an experimental condition closer to the upper boundary restricts the choice of process parameters. Bahrani and Crossland [13] conducted experiments to identify the lower and upper limits of the dynamic angle and proposed a lower value of 2-3^o and a maximum of 31^o. The maximum and minimum initial angle in an inclined configuration is recommended between 18° and 3°, respectively. The equation below was proposed by Deribas et al. [11] as the lower boundary.

$$\beta = K \sqrt{\frac{H_V}{\rho V_C^2}}. \quad (5)$$

. Deribas [11] proposed a relationship for finding the upper boundary of welding beyond which the flyer gets damaged and is given by

$$\sin\frac{\beta}{2} = \frac{K_3}{\left(t^{0.25} . V_C^{\;1.25}\right)}. \quad (6)$$

Where $k_3 = C_f/2$, $C_f = \sqrt{K/\rho}$, K= E/3(1-2γ),

4. Results and discussion

4.1 Formulation of welding window

The welding windows for aluminium-magnesium and titanium-steel dissimilar combinations are shown in Figures 1 and 2, respectively. Since numerous assumptions and constants are associated with the derivation of the window, it becomes difficult to establish the precise boundaries of the window. For aluminium-magnesium and titanium-steel explosive cladding, flyer plate characteristics exert a more significant impact with regard to how the welding window emerges. The details of experimental conditions for the attempted combinations were reported elsewhere [14, 15]. The experimental conditions (shown by bullets) prevailing inside the window would mean successful cladding with a wavy interface characteristic of a strong weld. However, a straight interface can also produce a sound joint [16].

Furthermore, circumstances closer to the lower boundary are preferred because they produce smaller waves and lower plate velocities due to the lower collision angle, which reduces the generation of intermetallic compounds and defects. This phenomenon is similar to the reports of Inao et al. [17]. As the interfacial microstructures described in more detail in the following section, the experimental conditions associated with the points lying within the window lead to a wavy interface. It is inferred from Figures 2 and 3 that a successful explosive clad is obtained when the bend angle is between 15^o to 25^0 and a collision velocity of 2500-3500 m/s, depending on the nature and detonation velocity of the chemical explosive employed.

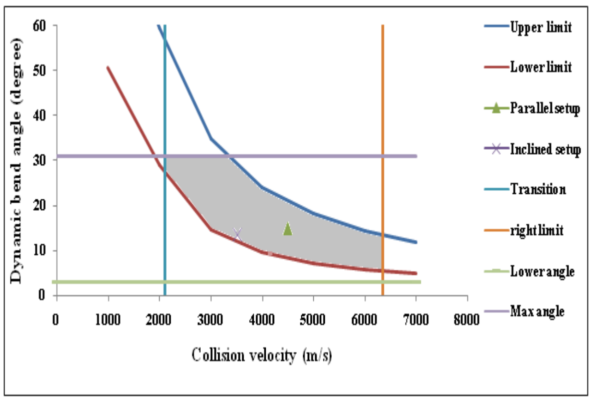

Fig. 2 Welding window for aluminium-magnesium explosive cladding

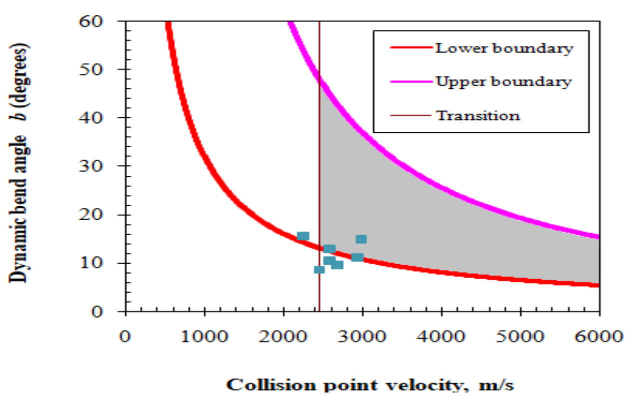

Fig. 3 Welding window for titanium-steel explosive cladding

4.2 Microstructure

As detailed in the previous section, the microstructure obtained from aluminium-magnesium and titanium-steel explosive cladding shows a wavy morphology (Fig. 4 and 5). The formation of wavy interfaces is consistent with the earlier studies [18, 19]. The interfacial waves are uniform and appear sinusoidal. There are no visible defects such as a molten layer, intermetallic layer or cracks in the interface microstructure. The interfacial grains are elongated in the direction of detonation. 'Trapped jet' is seen at the vortex of the Ti-steel clads. It is attributed to the generated jet not escaping during high-velocity impact; then, it is partially or completely trapped in the single vortex formed before and after each undulation. The formation of jet trapping is consistent with the reports of Parchuri et al. [20]. It is concluded that welding window is an effective method to predict the nature of interface in dissimilar explosive clads.

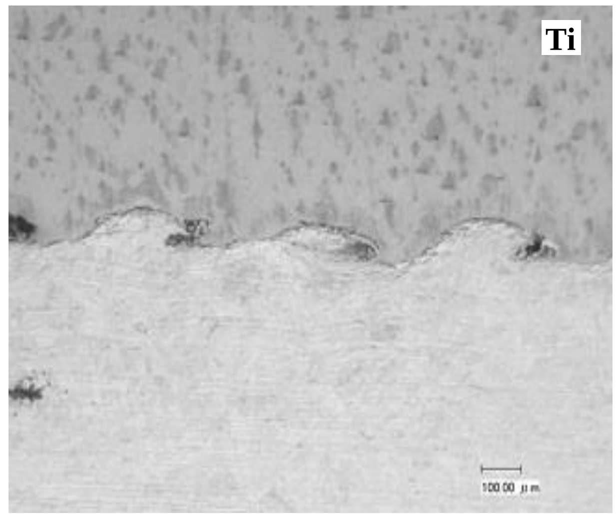

Fig. 4 Microstructure of Ti-Steel explosive clad

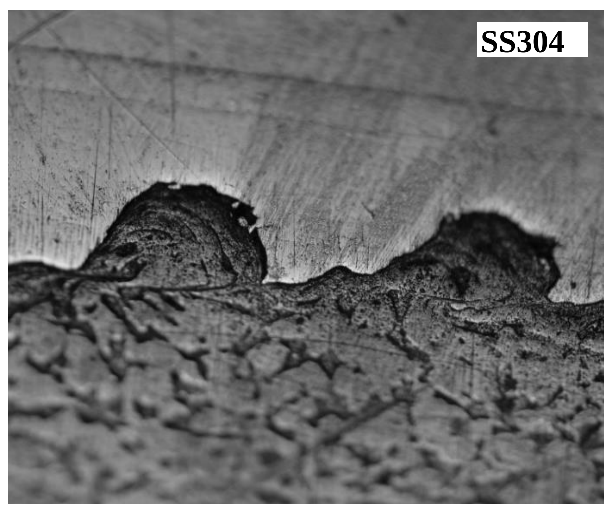

Fig. 5 Microstructure of Al-Mg explosive clad

5. Conclusion

The following conclusions were drawn from this study.

i. Aluminium-magnesium and titanium-steel explosive clad with a wavy interface emerges for a dynamic bend angle range of 15° to 25^0 and collision velocity between 2500-3500 m/s
ii. Experimental conditions closer to the lower boundary of the welding window are recommended for experimentation.
iii. Microstructure reveals an interface free from molten layers or defects.

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Nomenclature

β	dynamic bend angle
r	loading ratio
s	stand-off distance
α	initial angle
F	flyer plate
C_f	Compressive wave velocity
V_c	collision point velocity
E	young's modulus
V_p	plate velocity
t_e	thickness of explosive
K	constant
H	Vickers hardness
B	base plate
ρ	density
k	bulk modulus