SUBSTRUCTURE OF BONDING ZONE IN AN EXPLOSIVE CLADDED TITANIUM-MILD STEEL SYSTEM①

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ABSTRACT

The explosive-cladding TA2/A3 interface bonding zone has been investigated by means of TEM technique. The results showed that the "metallurgical bond" of the explosive cladding was achieved by localized melting and diffusion at the contacted surface. There were microcrystals and amorphous in the molten region due to the rapid cooling, there were diffusion across the interface layer. The residual structure around the explosive cladding TA2/A3 interface bonding zone consists of the interface layer (varied in 0.1μm width), the thermal influence zone and the deformation zone (within the distance of ~50μm from the interface layer) on the A3 side, and the adiabatic structure and ASB, on the TA2 side. Farther away from the interface layer in mild steel (A3) and pure titanium (TA2), the deformation mechanism was reflected in the twins. The twin density in A3 is much lower than that in TA2.

Key words: explosive-cladding interface layer amorphous adiabatic shearing diffusion twinning

1 INTRODUCTION

The explosive welding technique has been increasingly employed to produce composite metals. Since the restrictions to bonding are not those encountered with conventional methods, it becomes possible to clad pairs of metals having widely different mechanical properties that are immiscible or form brittle intermetallic compounds. Such composite metals have excellent properties and low cost, so they become more and more widely used in industrial engineering. Explosive cladding TA2/A3 material having been found many applications in the fields of corrosion protection as well as numerous other fields. Using TA2/A3 composite will largely reduce costs compared with using pure titanium, so th economic benefit is very obvious.

The explosive cladding TA2/A3 interface bonding layer is very thin, so it's difficult for optical metallograph (OM), scanning electron microscopy (SEM) and replica technique to resolve its detail. Although many material science workers having been worked on the investigation of explosive cladding interface layer in the past decade, fewer workers studied it or only restricted to the same metals interface[1-4] by means of transmission electron microscopy (TEM). OM, SEM or replica technique are usually used to investigate the different metal interfaces which often lead to lopsided conclusion due to the limitation of the instrument's resolution. No articles on the investigations of explosive cladding TA2/A3 interface layer by means of TEM have been reported, which is related to the difficulty of preparing its TEM sample. It has important theoretical and practical meaning to investigate the explosive cladding TA2/A3 interface layer

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by means of TEM for correct realizing the bonding mechanism and the deformation mechanism near the interface layer.

2 EXPERIMENTAL PROCEDURE

The materials used in this study were pure titanium TA2 and mild steel A3, their composition were all up to the national standard GB3620 — 83 and GB700 — 88. Cladding was carried out with the constand stand-off explosive cladding technique. Specimens for TEM were cut from the central portion of the sheets in a plane parallel to the direction of propagation of the jet and normal to the plane of the cladding interface by spark erossion. The specimens were prepared by mechanically polishing on progressively finer emery papers and milled to perforate with dual ion beam of Gatan Model 600. Examinaton was performed with JEM — 1000FX analytical electron microscope equiped with a LINK AN10000 EDS system and an EELS system at an operating voltage of 200 kV.

3 RESULTS

Fig. 1 shows a panoramic view of the characteristic wave pattern along the jetting directon. It is seen that approximately 1 mm from the cladding interface the steel recovers its original microstructure while up to a maximum of 50 μm the ferrite grains present an elongated form. On the side of TA2, there are many adiabatic shear bands(ASBs) which are developing from the interface layer and disappering in the TA2 matrix.

Fig. 2 is the bright field image of the explosive cladding TA2/A3 interface layer and the interface was ascertained by EDAX. Fig. 3 shows there are molten and unmolten regions at the cladding interface layer. Within the molten region (on the left of Fig. 2 (a)) the grains are ultrafine, the maximum grain size is not exceeded 20 nm and the grains size are varied in the order of nanometer range.

Fig. 3 is the dark-field TEM image taken from the molten region. The EDAX analysis result demonstrates that the molten region consist of ~56 at.-% Ti and ~43 at.-% Fe. The EELS analysis result indicates that there are carbon elements in the molten region. The electron diffration pattern of the molten region is shown in Fig. 4. This pattern is characterized by several concentric circles which are a little scattered. The pattern has the characteristics of *bcc* structure and indexed according to the *bcc* metal FeTi(a = 29 976 Å). The indexed results show that the (200)reflecton ring disappeared and the distances of crystal planes (110), (112) and(220) all varied a little. Molten region was formed by the high oblique collision between flyer plate and base plate. The temperature rising and cooling rate in this region were very rapid. This process is highly favor to form amorphous in the molten region. It can be concluded from the electron diffraction pattern, forming condition of molten region and the related references that there are Fe-Ti amorphous in the molten region. The molten region consists of FeTi micrograins and Fe-Ti amorphous.

In the unmolten region (on the right of Fig. 2 (b)) the bonding interface is characterized by a continuous ribbon-like transition from TA2 to A3 with a varied width(varied within the order of 0.1 μm) instead of a very sharp or continuous line transition from one metal to the other which are the conclusions that Lucien, F Trueb[5] etc gave out from electron probe microanalysis and replica technique results. The EDAX analysis of composition along the perpendicular line to the interface layer in

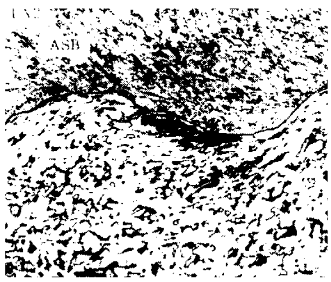

Fig. 1 Microstructrue of explosive cladding TA2/A3 interface layer

Fig. 2 Bonding interface layer in TA2/A3 explosive joint
(a)--molten region; (b) unmolten region

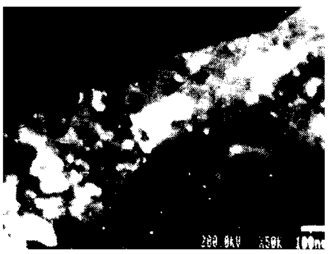

Fig. 3 Dark field image of the microcrystals in the molten region

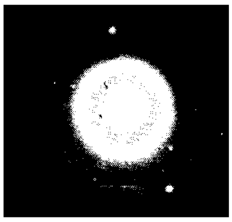

Fig. 4 Diffraction pattern from the molten region given in Fig. 2(a)

the unmolten region also confirmed that there are diffusion.

Fig. 5 shows that the equiaxed grains and abnormal growth grain on the side of mild steel near the interface layer. Recrystallization have happened in this area. Recovered structure is adjacent to the recrystallized region. It can be seen that there are heat affected region near the explosive cladding interface layer instead of the conclusions that there are no heat affected region near the explosive cladding interface layer gave out by Linse, V D[6]. Fig. 6 shows the deformation microbands which were next to the recovered grains and characterized by ribbon-shape elongated subgrains, heigh deslocation density as well as poorly defined cell-like substructure. The microstructure farther away from the interface in A3 are deformation twins , see Fig. 7 .

Away from the interface layer in TA2, the microstructure characteristics are reflected in the sequence of adiabatic structure (which are the ASB along the interface layer)and the ASB at about an angle of 45° to the interface layer(see Fig. 1), and many deformation twins (see Fig. 8). These features are different from those of cubic metals and alloys as Cu/Cu[1], Cu/ Cu- 2Be[2] systems and those of the A3 side in TA2/A3 system. There are heat affected region and severe plastic deformation in cubic metals around the explosive cladding interface layer. This may be related to the difference of deformation mechanism in cubic and hexagonal close-packed (*hcp*)structures and the low thermal conductivity of titanium. From the above results, it can be seen that the residual deformation structure around the TA2/A3 explosive cladding interface layer consists of the interface layer (varied in 0. 1 μm width), the heat affected zone and the deformaton zone (wthin the distance of ~ 50 μm from the interface layer) on the A3 side, the adiabatic structure and ASB, on the TA2 side. The

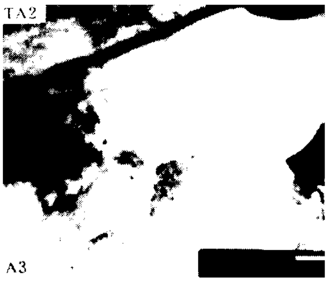

Fig. 5 Bright field image of the equiaxial grains and the "abnormal growth" grain

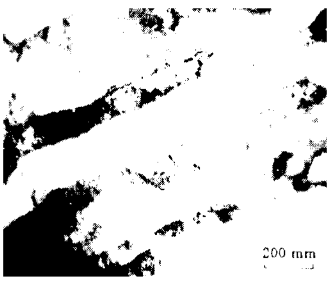

Fig. 6 Deformation microbands in the deformed layer of mild steel(A3)

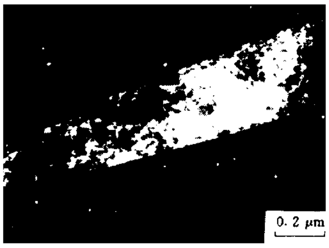

Fig. 7 Bright field image of the twins away from the interface layer in A3

Fig. 8 Twins away from the interface layer in TA2

schematic of the structures within the "bond zone" across both sides of the interface layer shown in Fig. 9.

4 DISCUSSION

Explosive cladding process from the mechanical collision to the import of thermo-mechanics energy is finished in the order of nanoseconds. Although explosive cladding technique has been widely used in industrial engineering, its bonding mechanism is not very clear.

Lucien, F Trucb[6] gave out the conclusion that are diffusionless across the explosive cladding interface by means of electron prob analysis and replica technique which is a lopwided conclusion resulted from the limitation of the instruments resolution. Hammerschmidt[2] and Ganin[4] considered that a thin melting layer along the interface is the basic bonding mechanism of explosive cladding. They are based on the follow facts that randomly oriented equiaxial grains formed and the untrafine grains center zone with no precipitates in the interface layer and new grains formed by severe deformation and recrystallization always show a very sharp texture with prefered orientation.

Under explosive-cladding condition, there are extremely high velocity gradient, high strain rate as $10^5 \sim 10^7$/s and high pressure region near the collision point in very short time. So the recrystallization and plastic deformation behaviours of metals under these extreme conditions will differ from those of metal under normal state.

From the exprimental results of our study, it indicates that there are microcrystals and amorphous in the molten region due to the rapid cooling. EDAX composition analysis in the unmolten region proved that there is diffusion across the interface and the diffusion layer is very narrow due to the extremely short heating time. The interface layer varied in 0.1 μm width. It demonstrates that the "metallurgical bond" of the explosive cladding is achieved by the actions of localized melting together with diffusion across the interface.

The cooling rate is extremely rapid in the molten region at the cladding interface layer. According to the relationship of titanium rapid solidefication[7], $L = (AT^{-n})$. (L- grain size, T- cooling rate; A and n are constant $A \approx 3 \times 10^6$ μm(K/s)^n $n = 0.97$ the cooling rate in the molten region estimated to be $10^8 \sim 10^9$ K/s. Such high cooling rate is highly favor amorphous to be formed in this region. In addition, A3 is the *bcc* alloy while TA2 is the *hcp* structure metal. Carbon atoms mixed in this region, which formed a certain concentration of Fe, Ti, C existed together in the molten region. Hence the crystal structure, technique and composition conditions stablized the conditions for amorphous to be formed and resulted in the formation of Fe-Ti amorphous.

The high velocity oblique collision will produce high pressure near the collision point under the explosive cladding condition. Accumulation of thermal energy contributed to a temperature rise, which will lead to the occuring of the adiabatic shearing near this region. According to the law of

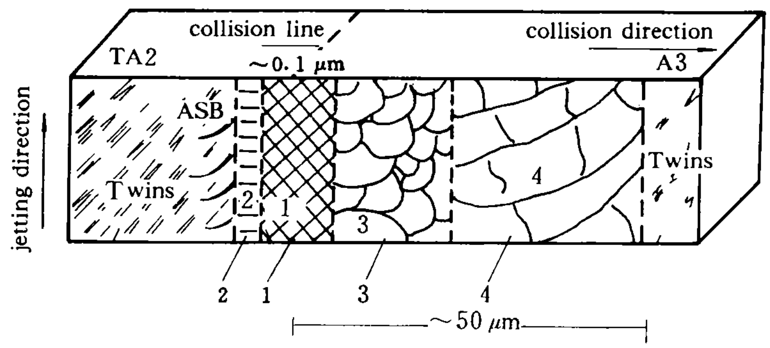

Fig. 9 Schmatic presentation of the structures within the "bond zone" across both sides of the interface layer

1—interface layer; 2—adiabatic structure; 3—heat affected zone; 4—deformation zone conservation of energy, the growth rate of thermal internal energy in this areas is

$$p_0 C_V \frac{\partial T}{\partial t} = \tau_{ij}\dot{\gamma}_{ij} - k\frac{\partial^2 T}{\partial x^2} \quad (1)$$

where $\tau_{ij}\dot{\gamma}_{ij}$ is the plastic shearing deformation power. $k\frac{\partial^2 T}{\partial x^2}$ is the energy lossing rate due to the thermal conduction. C_V, ρ_0, T *and* k are the specific heat per unit volume and density, temperature, thermal conductivity; τ_{ij} the equivalent shear stress, which is dependent not only on the strain and temperature but also on the strain rate. Under high strain rate($\dot{r}_{ij} > 10^2/s$), the constitutive relation of the material had the form[12]

$$\tau_{ij} = \tau_0(1 + \alpha\gamma_{ij})\exp[-\beta(T - T_0)] + \mu\dot{\gamma}_{ij} \quad (2)$$

Where α and β the material constant; μ is the viscosity factor. In the TA2/A3 system, the thermal conductivity of Ti is only twenty percent of that of Fe. As to TA2 the energy-lossing rate caused by thermal conduction is less than the energy-increasing rate due to the plastic deformation, and the energy accumulation led to a temperature rise near the collision point. Relation equations(2) indicated that the temperature rise will produce the flow stress decrease exponentially, which will cause the plastic deformation intensified and in reverse result in a temperature rise, therefore adiabatiic shearing occured and ASB formed on the side of TA2 with two directions, one is always along the interface layer (i. e. the adiabatic structure along the interface layer on the TA2 side), the other is at an angle of about 45° to the interface layer and disappear in the TA2 matrix(see Fig. 2.) In the case of A3 side, the values of $\tau_{ij} \cdot \dot{\gamma}_{ij}$ and $k\frac{\partial^2 T}{\partial x^2}$ are about the same due to the large k value, hence there are no ASB formed on the A3 side under the TA2/A3 explosive cladding condition.

Farther away from the interface in A3 and TA2 the deformation mechanism is reflected in the twins (see Fig. 9) Twinning is a highly favored deformation mechanism under explosive shock loading and stacking-fault energy(SFE) is an important internal factor to affect twinning deformation of shock loaded metals. The twin density in A3 is much lower than that in TA2 under the same shock loading condition, which is closely related to the differences of their SFE and their crystal structures.

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