DUCTILE TO BRITTLE TRANSITION OF INTER PURE AL SHEET CONSTRAINED BY PARALLEL BI-INTERFACE WITH HIGH STRENGTH AL ALLOY

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ABSTRACT

The ductile to brittle transition (DBT) in constrained Al sheet was investigated by experimental and numerical methods with its decreasing thickness, h, sandwiched by 2024 Al alloy through explosive cladding. The results clearly show that this transition has taken place characterized by different load deflection curves and decreasing fracture toughness, i.e. critical J integral. Correspondingly, fracture surface morphology develops from typical dimple type to brittle cleavage patterns appearing. And brittle cleavage patterns, mainly belong to {100} facets besides a very few {110}. Finite element calculations shows that during the loading process there is always a yield zone in Al interlayer constrained by neighboring elastic substrates. It is this growing region that results in increasingly high triaxial tensile stress and makes materials more brittle. The thickness scale in inter Al layer plays a key role in determining peak stress triaxiality. TEM analysis shows that Al interlayer has an obvious {100}<110> preferred orientation due to cold rolling process, the grains band width reaches about $1\mu m$. This texture has an obvious effect on local cleavage fracture features. In micro mechanisms dislocations pile-up against grain boundaries around crack tip is remarkably enhanced as h decreasing, while it is little in bulk metal, which is assumed to be the root source resulting in ductile to brittle transition.

1 INTRODUCTION

As an intrinsic ductile metal of a face center cubic (FCC) lattice, pure aluminum has an excellent ability to deform plastically, without any possibility for a brittle failure, even though in low temperature and high loading rate. However, Varias [1~3] showed that a metal layer, bonded between elastic blocks like ceramics, shows obvious plastic constraint that results in high triaxial tensile stress during the loading. It is analytically and numerically believed that metal sheets constrained as such could exhibit unusual failure modes from that of bulk metal in which the high triaxial stress will result in brittleness even in the intrinsic ductile metal as FCC pure Al, see Hsia [4~10]. Unfortunately, up till now, there is not any experimental evidence to the unusual phenomenon.

In present work the DBT phenomenon, in pure Al interlayer, was investigated in details by experimental and numerical methods and some useful conclusions can be drawn.

2 EXPERIMENTAL

Pure Al sheet (99.97% purity), with various thicknesses (0.2~3mm), and commercial 2024 aluminum alloy with higher strength were explosively bonded together. A fatigue pre-crack was carefully introduced into the side-grooved center plane of Al interlayer parallel to the bonding interfaces. Symmetric Four point bending (FPB) test was conducted to determine whether the DBT would occur or not. A bulk Al specimen was also done for comparison. SEM observation and EDXS analysis on fracture surfaces were done to determine the crack path and etch pits were used to determine the cleavage facets. In addition in situ TEM tensile test was conducted to investigate dislocations pile-up against grain boundaries.

3 NUMERICAL ANALYSIS

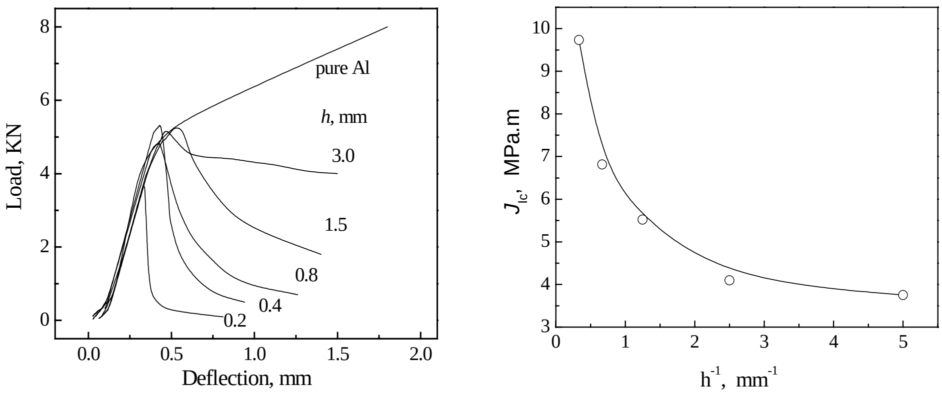
An elastic-plastic large deformation finite element analysis was conducted through ANSYS software on FPB specimens under conditions of plane strain, small scale yield (SSY) and mode I loading. Both materials are assumed as isotropic with the same Poisson's ratio of 0.33 and simulated by multi-lines method from actual uniaxial stress-strain curves. Six-node triangle elements were used to support large strain at vicinity of crack tip. Blunted crack model with $4.6\mu m$ width is adopted with a symmetric and orthogonal crack tip.

4 RESULTS ANALYSIS

4.1 Ductile to brittle transition behavior

In Figure 1 (a) the FPB load-deflection curve for bulk pure Al continues to increase. However for layered specimens there is always a peak load in existence and it dropped more rapidly as h decreasing. The critical J integral shown in Figure 1 (b), corresponding to peak loads, decreases remarkably. Correspondingly, brittle cleavage patterns on fracture surfaces, shown in Figure 2 (a), begin to appear when h equal to 0.4mm and become dominant for 0.2mm. These results clearly show that ductile to brittle transition in Al interlayer has occurred as h decreasing. Cleavage facets primarily belong to {100} characterized by the cube shape and a very few {110} characterized by symmetrical V-notch shape, as shown in Figure 2 (b, c).

It should be noted that crack propagation is fully limited in Al interlayer through carefully searching for the second particles containing Cu element, of course not found, as well as EDXS analysis on two counterparts of fracture surfaces.



(a) (b)

Figure1: Load-deflection curves (a) and critical integral (b) with interlayer thickness, h

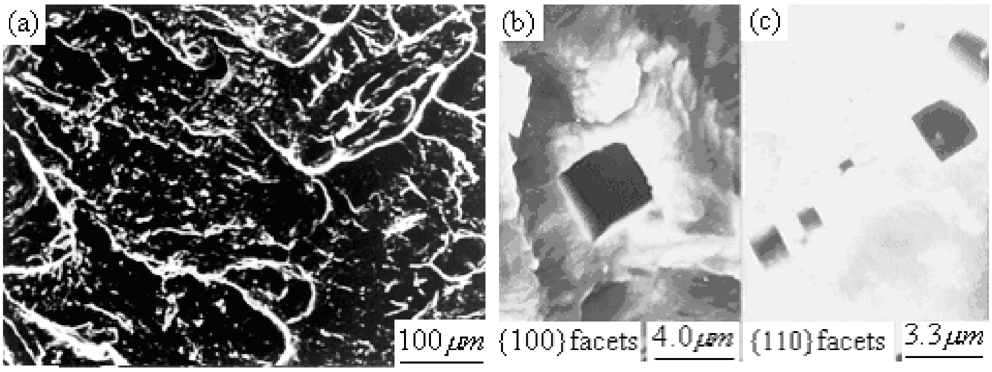
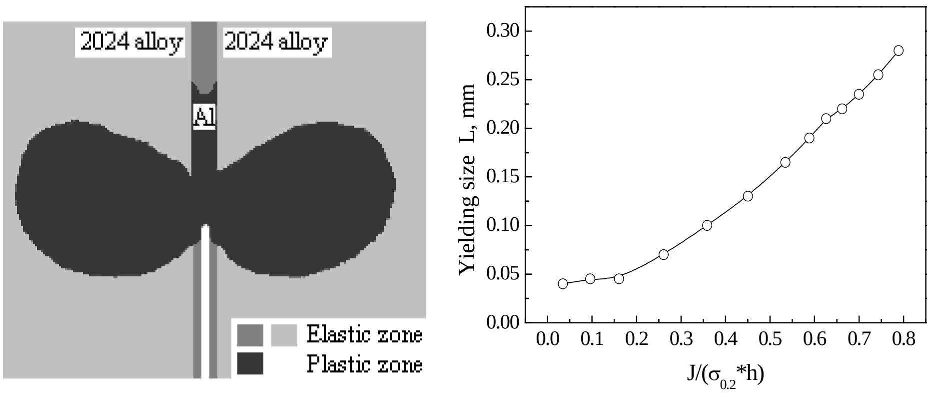


Figure 2: Typical river patterns (a), {100} cube-shaped etch pits (b) and {110} symmetrical V-notch shaped etch pits (c)

4.2 Constrained plastic deformation and stress triaxiality evolution

It is obvious that the DBT is associated with high triaxial tensile stress resulting from confined plastic deformation. Therefore, it is necessary to investigate the constrained plastic deformation and stress triaxiality in Al interlayer. FE simulation shows that there is always a part of yield region in Al interlayer constrained by neighboring elastic substrates and it grows gradually in the direction of ligament as applied load increases, as shown in Figure 3 and this constraint is similar to that from ceramics blocks.



(a) (b)

Figure 3: Plastic zone in Al interlayer, $h = 50\mu m$, constrained by neighboring elastic substrates (a) and its size growing in the direction of interfaces (b)

Figure 4 presents the evolution of peak stress triaxiality ahead of crack tip, $(\sigma_m/\sigma_e)_{\max}$ where σ_m and σ_e represent triaxial tensile stress and Von mises stress respectively, with applied load characterized by J integral for different h and normalized J integral, $J_n = J/(\sigma_{0.2} * h)$ where $\sigma_{0.2}$ is the yield stress of substrates. For a given applied load the peak stress triaxiality increases as h decreasing and there is a specific relation between peak stress triaxiality and J_n which is the primary parameter affecting triaxial constraint and can be easily reached by fitting method as shown in eqn (1).

$$(\sigma_m/\sigma_e)_{\max} = 5.0 - 74.15/(1 + \exp((J_n + 1.18)/0.34)) \qquad (1)$$

4.3 Dislocation pile-up against grain boundaries

The banded grains in Al interlayer have an obvious {100}<110> preferred orientation, as shown in Figure 5, due to cold rolling process and the band width is about $1\mu m$. Dislocations pile-up in bulk Al is little and they can easily continue to slip across grain boundaries, while the pile-up is enhanced remarkably in laminates. When h reaches 0.4mm considerable pile-up forms against grain boundaries around crack tip, as shown in Fig.8, before a sudden crack.

5 DISCUSSION

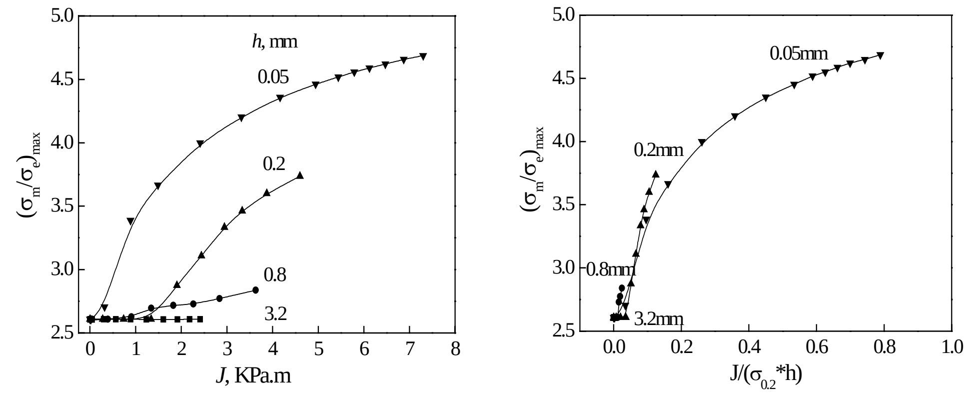
5.1 Effect of stress triaxiality on DBT behaviors

Yan [11,12] shows that under low stress triaxiality a nucleated micro-crack can be easily blunted into a cavity, which sufficiently reduces this constraint and results in ductile failure like bulk pure Al. However, when this constraint is enhanced to a large extent and difficult to be released through plastic deformation, it will propagate sharply in a brittle manner under the action of principal tensile stress. Take the effect of explosive impact on the thickness scale in Al interlayer into account and the factual minimum thickness is about $50\mu m$ for Al interlayer with $0.2mm$ nominal thickness. According to eqn (1) and FE results the critical stress triaxiality is about 4.5 and the principal tensile stress reaches as high as $550MPa$. Such a high scale could hardly to be reached in bulk Al metal at all.

5.2 Effects of dislocations pile-ups against grain boundaries on mechanic behaviors

Arzt [13] thinks that in metal materials all the strengthening effects are due to obstacles, which block or retard the motion of lattice dislocations**.** Cook [10] shows that, when the metal ductile layer is in microns level, dislocation glide will be impeded by a back stress from interface, which hinders further dislocation emission from tip. It is the back stress that results in an increasingly tensile stress, which results in the brittle fracture even in intrinsically ductile metals such as aluminum and copper.

Here the width of banded grains is about $1\mu m$. When h equal to 0.4mm, the piling-up dislocations can’t cross grain boundary at all. This is probably the nature of cleavage fracture. If we consider the banded grains as strong interface the thickness scale is completely agreed with that deduced analytically mentioned above. And thus the role of grains, especially those parallel to interface, would be the root source resulting in DBT phenomenon.



(a) (b)

Figure 4: Peak stress triaxiality versus load characterized by J integral (a) and normalized J integral (b) respectively

5.3 Effect of texture on cleavage feature

Sun [14] thinks that the preferred orientation produces an obvious anisotropy of cleavage fracture stress and makes the rolling plane more tend to cleavage for providing a continuous cleavage path. Under FPB test condition {100} rolling plane has the maximum principal tensile stress and thus most cleavage facets coincide with {100}<110> preferred orientation.

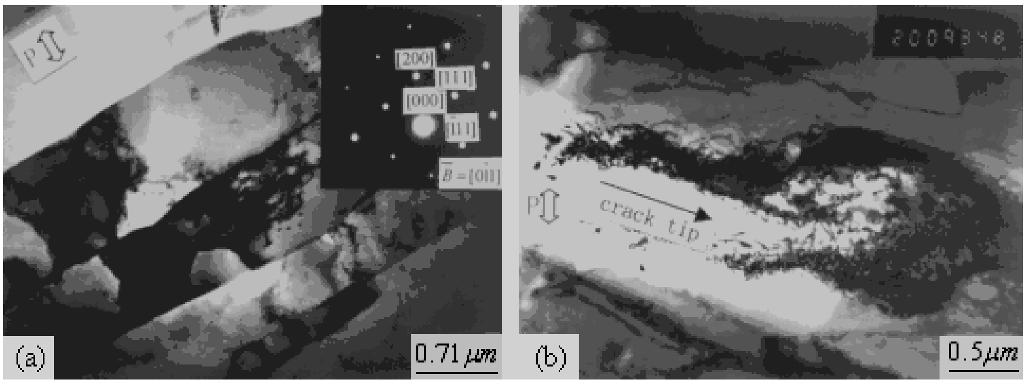


Figure 5: (a) Layered microstructure in Al interlayer and TEM diffraction patterns

(b) Pronounced dislocations piles up against grain boundaries around tip

6 CONCLUSIONS

Pure Al sheet sandwiched by 2024 alloy shows obvious ductile to brittle transition with its decreasing thickness, characterized by dramatic decrease of the critical J integral and fracture surface morphology transition. Corresponding cleavage planes mainly belong to {100} besides a very few {110}, which is consistent with the texture feature of banded grains. The DBT results from high triaxial tensile stress caused by confined plastic deformation in Al interlayer, while the root source is the blocking effect of grain boundaries on dislocation slip.

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