The Shear Response of a Thin Aluminum Layer

V. L. Tagarielli

N. A. Fleck[1]
e-mail: naf1@eng.cam.ac.uk

Department of Engineering,
Cambridge University,
Trumpington Street,
Cambridge, CB2 1PZ, UK

Aluminum layers, 10–50 μm thick, have been diffusion bonded to alumina blocks and subjected to simple shear in order to determine the sensitivity of shear stress versus strain response to layer thickness. No significant thickness effect on strength is observed and reversed loading tests indicate isotropic hardening. Final failure in shear is by microvoid coalescence within the sandwich layer with a void spacing comparable to the layer thickness. The significance of the results for strain gradient plasticity theory is discussed. [DOI: 10.1115/1.4002210]

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1 Introduction

There is increasing experimental evidence for size effects in plasticity when macroscopically imposed strain gradients are present, for example, beams in bending [1] and wires in torsion [2]. The underlying concept is that plastic strain gradients are associated with geometrically necessary dislocations and these lead to enhanced strengthening. In other circumstances, plastic strain gradients may or may not arise, depending on the boundary conditions. Examples include dislocation blockage at grain boundaries or at interfaces.

There have been extensive predictions of size effects in the plastic deformation of metals within the micron range, see for example Ref. [3]. These include the prediction of a thickness effect on the shear strength (and rate of strain hardening) for a thin layer sandwiched between elastic adherends. It is commonly argued that the blocking of dislocations by a fully bonded interface leads to dislocation pile-ups and to elastic back stresses, promoting kinematic hardening and a Bauschinger effect. Additionally, gradients of plastic strain near the interface can lead to the storage of geometrically necessary dislocations, thereby, strengthening the layer by forest hardening and leading in turn to macroscopic isotropic hardening. Unfortunately, few measurements have been made in order to explore the magnitude of size effect for a sandwiched thin layer. The aim of the present study is to develop a test technique for shearing thin layers and to assess the magnitude of the size effect for a constrained aluminum layer. The test method builds on that developed by Evans and co-workers for the interfacial fracture of metallic layers [4].

2 Experimental Investigation

2.1 Materials and Sample Preparation. Sandwich specimens were prepared by adhering thin aluminum foil disks of diameter 0.8 mm and thickness of 10–50 μm to alumina plates in a sandwich configuration via diffusion bonding. High-purity (99.999%) aluminum was obtained in the form of rolled sheets[2] of thickness 10 μm, 25 μm, and 50 μm. The three values of thickness were confirmed via an optical microscope. A punching system was used to cut circular samples from the three aluminum foils; the system comprised a flat-bottomed steel rod of diameter 0.8 mm and a mating aluminum die with a circular hole.

The aluminum disks were washed in acetone in order to remove organic contamination and then were placed in an acidic aqueous solution (HF 1%, HNO_3 10%, and HCl 20% by volume) for about 1 min in order to remove any surface impurities. They were rinsed with distilled water and dried in air. Three nominally identical disks of aluminum were diffusion bonded between a pair of alumina plates, as shown in Fig. 1(*a*). The disks were placed at the corners of an equilateral triangle of side length 7 mm.

Alumina was chosen for the adherends due to its high Young's modulus and high adhesion to aluminum. The alumina plates were transparent single crystals of sapphire, of random orientation,[3] and were of plan dimension 10×10 mm^2 and thickness 2 mm. They were optically flat (only three or four interference fringes were visible on placing two plates on top of each other and observing in white light) and had a roughness of 20 nm. The fabrication technique involved the following steps.

(1) The as-received alumina plates were washed with acetone and dried in air. Then, they were held at a temperature of 1373 K in an air-furnace for 2 h, in order to remove hydroxides from the surface. After slow cooling to room temperature, they were cleaned with an air blow duster.
(2) Three aluminum foil disks were then placed in a triangular arrangement on the top face of an alumina plate, see Fig. 1(*a*). A mating alumina plate was placed on top of the foil disks and the sandwich assembly was diffusion bonded in a high-vacuum furnace at 928 K for 5.5 h. Recall that pure aluminum has a melting point of 933 K, and so the bonding operation was performed very close to the melting temperature. Bonding was assisted by the application of a dead weight in the furnace. The dead weight was chosen to give nominal pressures on the aluminum foil disks of 4 MPa, 8 MPa, and 12 MPa for the 50 μm, 25 μm, and 10 μm foil specimens, respectively (these pressure levels were chosen in order to ensure adequate bonding and were obtained by a preliminary series of experiments). After the diffusion bonding operation, the samples were furnace-cooled to room temperature over 5 h. Measurement of the diameter of the disks subsequent to bonding revealed negligible radial deformation and all samples had a final diameter of approximately 0.8 mm. It was deduced that the foil thickness did not change during the diffusion bonding cycle. The grain size of the aluminum layers could be measured by microscopy through the sapphire adherends; in all samples, the in-plane grain size was approximately 50 μm and each grain straddled the height of the layer.

The quality of the diffusion bond was monitored by visual inspection of the interface using an optical microscope, as viewed though the transparent alumina plates. Specimens that displayed a defective bonding were discarded.

2.2 Shear Test Technique. The sandwich specimens were loaded in simple shear by bonding the outer faces of the alumina plates to aluminum grips using cyanoacrylate adhesive, as indicated in Fig. 1(*b*). The grips were loaded quasistatically in tension by a screw-driven testing machine and the load was measured by a 500 N load cell in series with the aluminum grips and the test specimen. The relative displacement between the steel grips was

[1]Corresponding author.

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[2]Supplied by Goodfellow Cambridge Ltd., Huntingdon PE29 6WR, UK.
[3]Obtained from Crystran Ltd., Dorset BH12 4PA, UK.

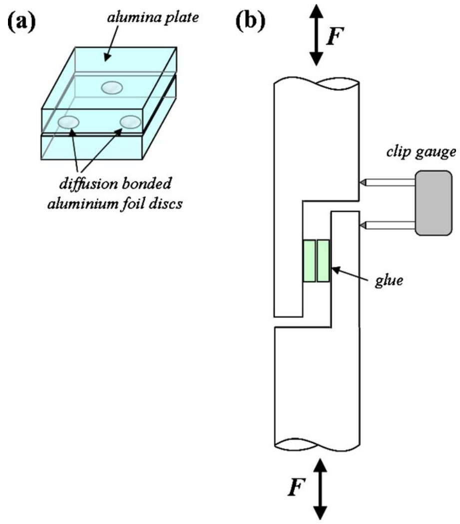

Fig. 1 (*a*) Test specimen, comprising three aluminum foil disks sandwiched between two alumina plates and (*b*) setup for the monotonic and reversed shear testing of the aluminum thin films

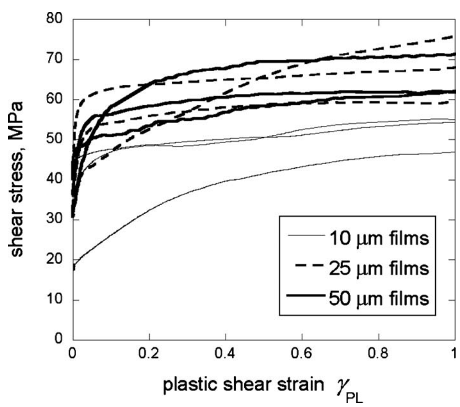

Fig. 2 Shear stress versus plastic shear strain response for aluminum foil samples

measured by a clip-gauge.

First, the compliance of the loading system was measured. A reference test specimen was prepared by gluing two alumina plates together with cyanoacrylate, absent the aluminum disks, over the $10\times10\ \text{mm}^2$ faces of the plates. The outer faces of this sample were then bonded to the test rig and the specimen was loaded in tension. An elastic, linear response of the system was observed up to a load of 350 N with a stiffness of approximately $30\ \text{kN mm}^{-1}$. The compliance of the loading system was subtracted from the measured force versus relative displacement response of the specimens in order to deduce the shear stress versus plastic shear strain response.[4]

2.3 Monotonic Shear Tests. Three repeated tests were performed for each foil thickness and the measured shear stress versus plastic strain responses are presented in Fig. 2 at an imposed plastic strain rate of $10^{-2}\ \text{s}^{-1}$. Although some specimens exhibited premature shear failure by spallation of the diffusion bonded interface, most samples did not fracture until a nominal plastic shear strain of 3–4 was reached. Fracture surfaces were observed in a scanning electron microscope (SEM). SEM observations, not reported here for the sake of brevity, revealed that failure was by microvoid growth and coalescence in shear.

Although some scatter is observed in the shear experiments, it is possible to conclude that the shear response of the aluminum films is insensitive to layer height, in the range of 10–50 μm. Figure 3 summarizes the 1% offset yield strength and the flow strength (at a plastic shear strain of 0.5) as a function of layer height; to within material scatter; there is no effect of height on the flow stress.

2.4 Reversed Shear Tests. Additional tests were performed in order to determine the response of 50 μm thick aluminum foil to cyclic plastic straining in shear at a strain rate of $10^{-2}\ \text{s}^{-1}$. First, the testing rig was loaded in tension, until a maximum plastic strain $\gamma_{pl}\approx 0.35$ was attained in the aluminum specimens; then, the testing rig was loaded in compression up to a plastic strain of 0.35 in the opposite direction. Subsequently, an additional strain cycle was imposed, of amplitude $\gamma_{pl}\approx 0.7$. The cyclic response is shown in Fig. 4 along with an example of monotonic loading in shear to reveal the degree of material scatter from test to test. Upon load reversal at $\gamma_{pl}\approx 0.35$ and at the shear stress τ_1, the sample displays an elastic response followed by yielding at a stress level only slightly less than τ_1; the Bauschinger effect is negligible. Strain hardening continues with decreasing plastic strain until the loading direction is inverted again at a strain of $\gamma_{pl}\approx -0.35$ and stress $-\tau_2$. Again, load reversal causes the mate-

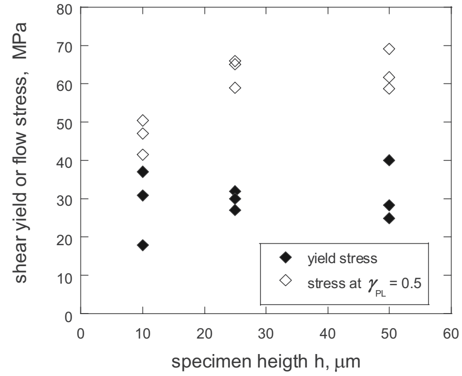

Fig. 3 Measured shear yield stress and shear flow stress at a plastic shear strain of 0.5, as a function of the height of the aluminum thin film specimens

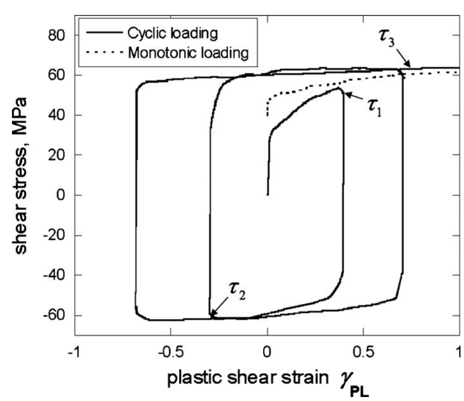

Fig. 4 Typical shear stress versus plastic shear strain for a 50 μm thick aluminum thin film specimen subject to reversed plastic straining. The response of a nominally identical specimen to monotonic shearing is included for the purpose of comparison.

[4]The elastic shear stiffness of the aluminum specimens much exceeds the stiffness of the loading system.

rial to yield at a stress somewhat below τ_2 with a minor Bauschinger effect. With continued forward plastic loading, the stress attains a saturated value τ_3.

In the subsequent cycle of reversed shear straining, the material displays a similar response to that described above with the exception that the material shows less strain hardening at these higher plastic strains. The absence of a strong Bauschinger effect on load reversal and the essentially symmetric stress-strain response indicate an isotropic hardening response.

3 Concluding Remarks

The present experimental results are surprising in the sense that no thickness effect on strength is detected and no strong Bauschinger effect is noted. It appears that the interface between aluminum layer and the sapphire substrates is able to absorb dislocations without generating long range back stresses and an associated Bauschinger effect. Strain gradient theories of plasticity and discrete dislocation calculations are consistent with this observation provided plastic slip is allowed to each of the interfaces. It is known from the experiments and analysis of Borg and Fleck [5] that grain boundaries in aluminum can allow for slip transmission with only a minor resistance to plastic strain. Danas et al. [6] developed the theoretical analysis of the layer problem presented herein. They showed that the size effect in shear was sensitive to the assumed constitutive description of the interface. Discrete dislocation simulations were performed with the interface modeled as a thin, compliant layer that could absorb dislocations with only small back stresses.

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