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Effects of indentation depth on micro hardness and scratch behavior of thin composite laminate

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ABSTRACT

The effects of indentation depth on micro hardness and scratch behavior of an 80 μm thick copper/aluminum composite laminate were discussed. When the indentation depth exceeded the thickness of the plate layer (C1100 copper, 10 μm), the measured hardness gradually decreased as the indentation depth increased. When the indentation depth increased to a relatively large value, the Vickers hardness manifested as a slight decrease, and the micro morphology of the scratch zone of the substrate layer was relative smooth and flat compared with the plate layer. The main reasons of the variation of micro hardness and scratch behavior were that the plate layer and interfacial adhesion have restrained the pile-up behaviors and plastic flow of the substrate layer.

1. Introduction

Based on composite technologies and metallurgical technologies on the metal interface, multilayer metal composite materials could effectively improve the mechanical properties of single metal material. Due to the good formability, specific strength, low-cost and thermal conductivity, the applications of metal composite materials gradually increased [1–5]. With regard to the bilayer metal composite laminates, the mechanical behaviors depend on the comprehensive mechanical behaviors of the interlamination, plate layer and substrate layer [5,6]. Especially, the bonding force between the layers and peeling mechanism are extremely focused [4,6–8]. Such as L.Y. Sheng et al. [4] adopted scanning electron microscope, transmission electron microscopy and peeling test to study the bond strength of a copper/aluminum/copper sandwich clad sheet, which was fabricated by means of cold rolling process and heat treated with different temperature and time, and Y. Miyajima et al. [9] carried out the tensile shear tests in order to investigate the effects of rolling reduction and strength of composed layers on bond strength of pure copper and aluminum clad sheets.

Meanwhile, by using Vickers micro hardness test and scratch test, the Vickers hardness, scratch hardness and friction coefficient could be quantitatively tested [10–22]. However, the indentation depth might influence the measured parameters because the contact zone of the indenter may not be a single metal layer. Based on abundant experimental data and theoretical analysis, the studies on hardness, indentation and scratch behaviors of multi-layer composite materials were gradually deepened. P. Kurkcu et al. [16] stated that incorporation of hard fillers could enhance the scratch hardness of polymers but leads to an increase in scratch visibility due to a change in scratch deformation mode from ductile ploughing to a brittle failure. H. Chakraborty et al. [17] used nanoindentation and nanoscratch tests to determine the dynamic viscoelastic properties of titania reinforced poly nanocomposites. However, for thin bilayer composite material, when the indenter penetrated the interlamination, the contact zones of the indenter were both the plate layer and substrate layer, and the micro hardness and scratch behavior of the composite material would gradually change as the indentation depth increased. Up to now, the related researches were seldom mentioned.

In this paper, with the aid of an 80 μm thick copper/aluminum composite laminate and a commercial Vickers micro hardness tester, the influence rules of indentation depth on micro hardness and scratch behavior were discussed experimentally, and the inhibition effects of plate layer and interfacial adhesion on the plastic flow of the substrate layer were explained.

2. Instrument and material

The adopted commercial Vickers micro hardness tester (HX-

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1000TM, Shanghai Optical Instrument Factory) presented a series of loading functions with loading range from 0.245 N to 19.6 N. As shown in Fig. 1, the diagonal length of the standard rectangular pyramid diamond indenter was 400 μm, and the angle between the couple of opposed planes of the Vickers indenter was 136° [14]. With the aid of a three-dimensional optical microscope (DXS-500, Olympus) with large depth of field, the radius of 2 μm of the Vickers indenter's tip was confirmed. Optical lens with different magnifications were integrated with the micro hardness tester in order to locate the initial indentation zone [13]. By using the standard Vickers indenter combining with the horizontal mobile platform, the scratch test could also be carried out on basis of various initial indentation loads.

To carry out the hardness and scratch behavior tests of thin composite material, an 80 μm thick copper/aluminum composite laminate specimen was prepared. By rolling the two metals together followed by a sintering heat treatment, the bond strength of the Cu/Al laminate was enhanced. The laminate was firstly heated to 300 then kept thermal insulation for 30 min. To obtain thin plate layer and substrate layer, the Cu/Al laminate was mechanically polished via abrasive papers with various roughness and Al_2O_3 grinding pastes with particle size of 0.5 μm. The cross-section optical image of the polished Cu/Al specimen is shown in Fig. 2, the materials of the plate layer and substrate layer were C11000 copper and 1060 aluminum respectively. Olympus microscope (DSX500) was adopted to observe the micro morphology, the thicknesses of the plate layer and substrate layer were respectively measured as 10 μm and 70 μm, the Cu/Al interlamination of specimen was clearly visible. Also, seen from Fig. 2, by using energy disperse spectroscopy (Inca X-Max, Oxford Instruments), the elementary composition of the substrate layer was confirmed, the compositions of aluminum and oxygen were 81.64% and 16.35% respectively, which indicated that the surface of substrate layer was oxidized. However, when the indenter penetrated the interlamination, considering that the substrate layer was covered by the plate layer, and the contact zone of the Vickers indenter's tip was not oxidized, under this circumstance, the hardness and scratch behavior tests could reflect the mechanical properties of the composite material itself rather than the oxide.

3. Results and discussions

During the micro hardness test, the holding time was set as 60 s. With minor indentation loads of 0.49 N (0.05 kgf) and 0.98 N (0.1 kgf) respectively applied on the surface of substrate layer, corresponding Vickers hardness of 23.3 Hv and 23.6 Hv were calculated. For the plate layer, Fig. 3 shows the two-dimensional (a) and three-dimensional (b) morphologies of the micro-indentation

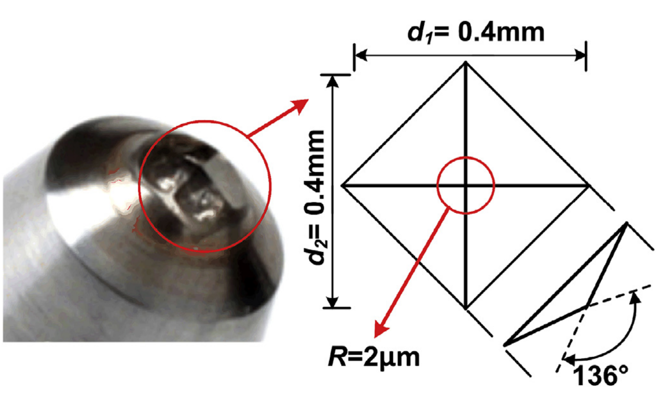

Fig. 1. Specific dimensions of the standard Vickers indenter adopted for the indentation and scratch tests.

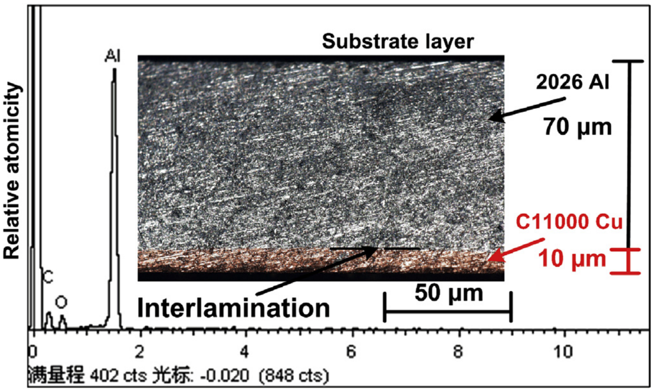

Fig. 2. Cross-section optical image of Cu/Al specimen and the energy spectrum analysis results of the substrate layer.

under different indentation loads with range from 0.49 N to 9.8 N. When the initial indentation load was also 0.49 N, the diagonal length $d_{0.49}$ and the indentation depth $h_{0.49}$ of the indentation were 38.1 μm and 7.7 μm respectively, which were measured by the commercial Olympus software. The indentation depth $h_{0.49}$ was less than the thickness of the plate layer and the Vickers hardness was calculated as 65.4 Hv. When the indentation load increased to 0.98 N, the corresponding indentation depth $h_{0.98}$ of the indentation and Vickers hardness were measured as 11.1 μm and 63.4 Hv respectively, the Vickers hardness presented a slight decreasing trend. Under this circumstance, $h_{0.98}$ has exceeded the thickness of the plate layer and the contact zone of the indenter's tip was the substrate layer. Moreover, based on the incremental indentation loads of 4.9 N, 9.8 N and 19.6 N, the measured indentation depths of $h_{4.9}$ (26.1 μm), $h_{9.8}$ (40.7 μm) and $h_{19.6}$ (49.2 μm) were accordingly measured. Defined the ratio of the substrate layer's indentation depth to the thickness of plate layer as the depth ratio R_d. Corresponding to the various indentation loads above mentioned, R_d presented an increasing trend with relevant values of 0, 0.11, 1.61, 3.07 and 4.92.

Fig. 4 shows the variation trend of Vickers hardness as the indentation depth or R_d increased. Theoretically, as R_d increased, the comprehensive Vickers hardness would be more inclined to the substrate layer's hardness. Under the condition of relatively small R_d, the Vickers hardness indeed decreased sharply. However, when R_d increased to a relatively large value, the Vickers hardness manifested as a slight decrease. Specifically, corresponding to R_d of 3.07 and 4.92, the obtained Vickers hardnesses were 46.6 Hv and 42.1 Hv respectively. Based on the increment of substrate layer's indentation depth of 18.5 μm, the reduction rate of hardness was only 9.66%, which was far below the reduction rate based on relatively small R_d. On the other hand, with R_d of 4.92, in consideration that the substrate layer's indentation depth (49.2 μm) already approached the thickness of the substrate layer (70 μm), the measured hardness (42.1 Hv) was still much larger than the hardness of substrate material (23.3 Hv). The main reason that caused this phenomenon was the existences of the plate layer and interfacial adhesion have restrained the plastic flow and pile-up behaviors [6] of the substrate layer.

With regard to the effects of indentation depth on the scratch behavior, the initial scratch speed and indentation load were set as 50 μm/s and 9.8 N respectively. Similar to the hardness test, the initial contact location was also the plate layer's surface. The two/three-dimensional morphologies of the scratch captured by the Olympus microscope are shown in Fig. 5. Along the scratch direction, the morphology of the scratch profile was approximately symmetrical, which indicated that the projection of the indenter's