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Stationary self-propagation combustion with variations in the total layer thickness of compression-bonded Ni-sputtered Al foil multilayers

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ABSTRACT

Mechanically bonded Al/Ni multilayers have numerous applications such as high temperature bonding and local heat sources if their stable self-propagation high temperature synthesis is controllable. In this study, stationary self-propagating reactions in Al/Ni multilayers are obtained through controlling the total layer thickness using micrometer-scale bilayer thicknesses. While stationary self-propagation is not obtained in multilayers with total layer thicknesses of 180–360 μm, it is consistently observed in multilayers with total layer thicknesses of 630–810 μm. The total layer thickness influenced the consistency of the propagation velocity of the combustion reactions in the compression-bonded Ni-sputtered Al foil multilayers. The minimum total layer thickness for a stationary propagation is identified as between 540 and 630 μm in the Al/Ni multilayers.

1. Introduction

Mechanically bonded reactive Al/Ni multilayers have various advantages, including process simplicity, low cost, and less time consumption [1,2]. Moreover, these multilayers are applicable to high temperature bonding without thermal damage for electronic assembly, emergency bonding for aerospace applications, local heat sources for munitions, propellant ignition, and as igniters to initiate secondary reactions at low temperature slow heating [3–5]. However, the self-propagating high-temperature synthesis (SHS) reactions of mechanically bonded multilayers are not stationary due to the formation of irregular and discontinuous bilayers after the mechanical bonding [6]. Non-stationary SHS results in the formation of a reaction band that is perpendicular to the gross propagation direction [6]. Thus far, stationary SHS reactions have only been obtained in sputtered Al/Ni multilayers with nanometer-scale bilayers [7,8].

Previous researchers have demonstrated that the stationary reaction is governed by the heat loss of the multilayers [6,9,10]. Their research indicated that the effect of the radiant heat loss was increased in systems that self-propagate slowly. This indicates that the effect of the radiant heat loss is an important issue for mechanically bonded multilayers. Because the bilayer thicknesses of the multilayers in mechanically bonded multilayers are a few tens of micrometers, the reported velocities are approximately 0.1 m/s, which is approximately 100 times smaller than those of sputtered Al/Ni multilayers. However, the stationary combustion behavior that depends on the heat loss effect of the multilayers has not been investigated due to the extremely high reaction velocity of the sputtered multilayers and the disuniform and discontinuous multilayers of the mechanically bonded multilayers. Moreover, combustion synthesis for micrometer-scale mechanically bonded multilayers has not yet been reported to generate stationary SHS. Therefore, the effects of the total layer thickness in micrometer-scale bilayers on the stationary propagation of the SHS of Al/Ni multilayers need to be investigated. Stationary SHS is defined as the absence of reaction band nucleation, which is the localized reaction perpendicular to the gross propagation direction [6,11].

In this study, compression-bonded Al/Ni multilayers were used for their uniform and continuous bilayers with sizes of several micrometers in thickness [13]. The bilayer thickness of the Al/Ni multilayers was fixed at 9 μm, which is the minimum bilayer thickness required in order to obtain mechanically bonded multilayers in the compression-bonded Al/Ni multilayer system. The SHS reactions of Al/Ni multilayers with a wide range of total layer thicknesses were tested in order to determine the minimum total layer thickness required for stationary SHS generation.

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2. Experimental

Ni (purity 99.99 wt.%) was deposited on Al sheets (purity 99.5 wt.%) using a DC magnetron sputtering system. The average thickness of the Ni layers was approximately 3.9 μm, and the average thickness of the Al sheets was 5.8 μm. The targeted Al/Ni atomic ratio was fixed at 50:50 in order to generate the maximum temperatures and reaction heats. Each Al sheet was cleaned and surface-treated twice using RF argon plasma, before depositing the Ni and after sputtering the Ni. The deposition vacuum level was less than 2×10^{-6} torr (2.7×10^{-4} Pa) and an Ar atmosphere of 5×10^{-3} torr (0.7 Pa) was maintained during sputtering. The Ni-sputtered Al foils were punched with a diameter of 10 mm and stacked with 20, 30, 40, 50, 60, 70, 80, and 90 disks in order to achieve various total layer thicknesses. Each disk was composed of a single Al/Ni bilayer. The stacked disks were compression-bonded using an Instron 4400R (Instron Corp., USA). The compressive stress was set to 875 MPa in order to obtain continuous and uniform bilayers and to avoid potential separations of bilayers during the SHS.

The self-propagating combustion was generated via continuous wave fiber lasers with a wavelength of 1.03 μm in order to ignite the Al/Ni multilayer. The laser was irradiated at approximately 2 mm inside the outer edge of the samples; the laser power was 80 W and the laser diameter was 500 μm. Three dots of ceramic insulator supported the specimens in an air atmosphere. The propagation velocities were measured using a high-speed camera with the assumption that the front of the flame corresponded to the front of the reaction. The propagation velocity was measured in the middle of the multilayers with more than ten points per specimen. Moreover, all propagation velocities were analyzed over a distance of more than 300 μm from the start to the end point of the reaction region.

3. Results and discussion

3.1. Stationary propagation

Fig. 1 presents a schematic of the front of the combustion flame, which circularly progressed from the laser dot ignition. The multilayers had continuous and uniform bilayers as seen in the cross sectional SEM images in Fig. 2(a). In the microstructure presented in Fig. 2(b), the reaction products of the Al/Ni multilayer specimens were homogeneous AlNi intermetallic compounds. While the thermal annealing of the Al/Ni multilayers resulted in the formation of heterogeneous intermetallic compounds (IMCs) [13], the self-propagating combustion reactions of the Al/Ni multilayers induced homogeneous IMCs due to the molten Al and Ni during the SHS.

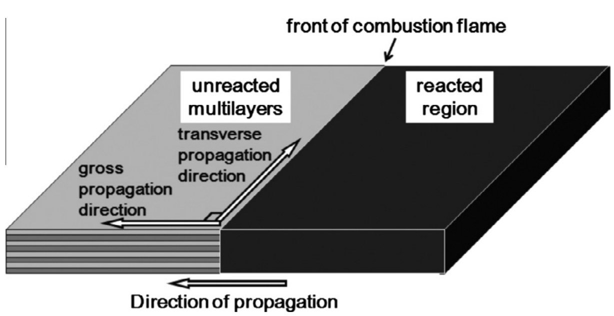

Fig. 1. Schematic of the front of the combustion flame.

The reaction behavior was investigated using a high-speed camera (Fig. 3). The combustion flame progressed with nucleating bands in the multilayers with a total layer thickness of 360 μm, as seen in Fig. 3(a). However, the combustion flame for the multilayers with a total layer thickness of 630 μm was smooth and stationary, as seen in Fig. 3(b). The stationary propagation of the multilayers was quantified through measuring the time and distance for the stationary self-propagation reactions, as seen in Fig. 4. Both the time and distance for the stationary self-propagation increased with increases in the total layer thickness from 450 to 630 μm, while stationary self-propagation was not obtained in the multilayers with total layer thicknesses from 180 to 360 μm. The stationarity of the self-propagation was not significantly altered with increases in the total layer thickness from 630 to 810 μm. The minimum total layer thickness for the stationary SHS was more than 630 μm. Meanwhile, it was found that the multilayers were separated by combustion when they were compressed with a pressure of less than 625 MPa. Furthermore, the stationary SHS was not observed for the multilayers compressed with a pressure of more than 1125 MPa.

In order to investigate the stationary behavior of the self-propagation reaction with the total layer thickness, only the radiant heat fluxes of quasi-freestanding multilayers were investigated. The effect of the heat conduction was not considered because the multilayers were maintained in a quasi-freestanding condition during combustion. However, in the future, the effects of the conductive heat must be investigated for bonding and joining

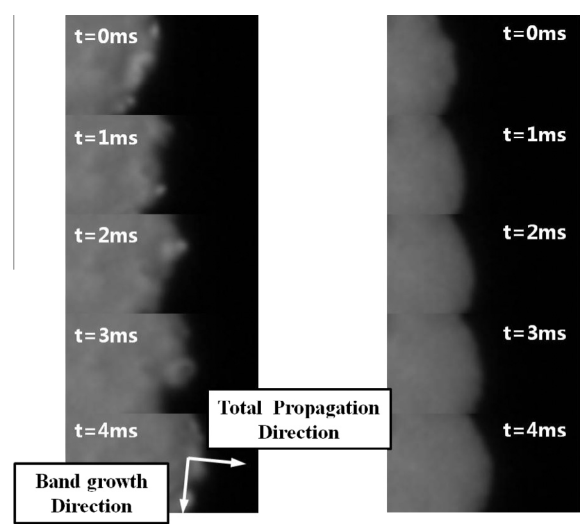

Fig. 3. Front of the combustion flame in multilayers with total layer thicknesses of (a) 360 μm and (b) 720 μm using dynamic images from the high-speed camera.

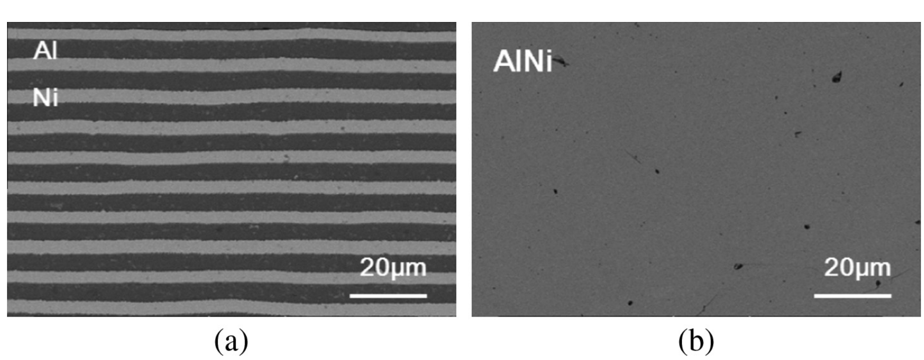

Fig. 2. Cross sectional SEM images of (a) the compression-bonded Al/Ni multilayers and (b) after the SHS.