Available online at www.sciencedirect.com

SciVerse ScienceDirect

Acta Materialia 60 (2012) 3929–3942

Acta MATERIALIA

www.elsevier.com/locate/actamat

Response of Ni/Al laminates to laser-driven compression

C.T. Wei [a], V.F. Nesterenko [a], T.P. Weihs [b], B.A. Remington [c], H.-S. Park [c], M.A. Meyers [a,*]

[a] University of California, San Diego, La Jolla, CA, USA
[b] Johns Hopkins University, Baltimore, MD 21218, USA
[c] Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

Received 15 March 2012; accepted 18 March 2012
Available online 1 May 2012

Abstract

Ni/Al laminates with bilayer thicknesses in the micrometer (~5 μm) and nanometer (~50 nm) range were subjected to exothermic reactions induced by laser-driven compression. The initial shockless compression steepened into shock in the microscaled laminates generating a pressure pulse duration of several tens of nanoseconds, which induced strain rates varying from 10^7 to 10^8 s^{-1}. The laser energies applied, 650, 875, and 1305 J, generated peak compression stresses of 30, 75, and 118 GPa, respectively, at the plasma stagnated Al surface. Large differences in flow stresses and bulk compression moduli of Ni and Al introduced shear localization in the Ni/Al interfaces. The nanoscale Ni/Al laminates were fully reacted, producing NiAl with grain sizes less than 500 nm. The NiAl intermetallic phases, B2 (β) phase (fcc) and martensitic phase (bcc), coexist in the NiAl nanograins. It was confirmed that the intermetallic reaction in the Ni/Al microlaminate cannot self-sustain for the short duration, laser-driven compressive loading. The intermetallics NiAl (equiaxed grains) and $NiAl_3$ (dendrites) were identified on the plasma stagnated surface of Ni/Al microlaminates. The distribution of intermetallic phases varied according to the incident laser energies.

Keywords: Laser; Nickel; Aluminum; Shock-induced reactions; Intermetallic phases

1. Introduction

Micro- and nanoscale Ni/Al reactive laminates have been used in a variety of different applications, for example the soldering of materials [1–3] by means of localized heating. Potential military applications utilizing the heat of exothermic reactions to enhance blast effects (http://www.wired. com/science/discoveries/news/2002/12/56695, http://www. onr,navy.mil/Media-Center/Press-Releases/2002/Better-Warheads-Through-Plastics.aspx) are also being considered. They have tailorable microstructures and remarkable mechanical and chemical properties: good corrosion resistance, high melting temperatures, low densities and high strengths of the intermetallic phases [3,4].

Reactions in Ni/Al reactive laminates release large amounts of exothermic heat for their intermetallic phases: -150.6 kJ mol^{-1} for $NiAl_3$ and -118.4 kJ mol^{-1} for NiAl [5]. These reactions can be easily ignited by laser heating [6], an electric current [7], or a thermal stimulus [8,9]. In past decades many approaches have been utilized to investigate these exothermic chemical reactions under extreme loading conditions. The intermetallic reactions induced by high pressure shock waves are classified as shock-induced and shock-assisted reactions according to the role of the shock wave in reaction initiation and propagation [10]. The shock wave-induced chemical reactions have extremely fast reaction velocities, 10^7 times faster than normal thermal reactions [11,12]. However, these two reaction mechanisms usually occur concurrently, thus increasing the uncertainty of defining the primary initiating mechanism of the intermetallic reaction under shock loading.

* Corresponding author. Tel.: +1 619 534 5698.
E-mail address: mameyers@ucsd.edu (M.A. Meyers).

1359-6454/$36.00 © 2012 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.actamat.2012.03.028

Laser-driven shock waves have been used to investigate the dynamic behavior of materials [13–28]: aluminum [17,18], copper [19,20], tantalum [21,22], vanadium [23,24], iron [25,26], nickel [27], nickel aluminide [28,29], and nickel–aluminum laminates [13]. The laser beam, of high intensity $I_L > 10^{13}$ W cm^{-2}, generates strong ionization and thermal deposition on the irradiated surface, creating melting pools and craters [13]. Laser-driven shock waves in solid materials are generated by the rapid formation and expansion of a hot, dense plasma on the surface layer caused by direct irradiation by focused laser beams [14–16]. This method of generating shock waves using lasers is significantly affected by three factors: different laser absorption rates of the materials [16]; an inhomogeneous (Gaussian) laser intensity distribution caused by the focal spot of the laser beam [16]; a rapid decrease in the shock pressure in solids [13]. These phenomena have restricted the application of laser-driven shock compression. Direct laser-driven shock compression cannot maintain ultrahigh strain rate ($>10^6$ s^{-1}) conditions in Ni/Al laminates for more than ~10 ns and introduces extended thermal damage on the irradiated surface, which renders the post-shock analysis complicated.

An innovative laser-driven shockless compression method was recently developed [17,18]. It enables an essentially smoother compression pulse propagating through the entire sample, which is similar to the "z-pinch" technique developed by Asay et al. [30]. This new approach generates compression by soft stagnation of the expanding plasma across a vacuum gap from a reservoir of polymer against the sample surface instead of direct laser irradiation of the exposed surface. Edwards et al. [17] and Lorenz et al. [18] conducted these laser-driven shockless compression experiments on aluminum samples in the Omega laser facility and proved that this approach induced quasi-isentropic compression stresses with amplitudes of 100–200 GPa within a 20–40 μm depth. This shockless compression was much less influenced by thermal heating than direct laser illumination of the sample. There are advantages to the study of the mechanical properties and phase transformations of bulk materials in a high stress, high strain rate and lower temperature regime. This laser-driven shockless compression has not previously been applied to study the chemical and mechanical response of reactive Ni/Al laminates. This is the primary objective of the research reported here.

2. Experimental methods

Ni/Al reactive laminates were subjected to laser-driven shockless compression using the Omega glass laser in the Laboratory for Laser Energetics at the University of Rochester. In order to investigate the behavior of the Ni/Al reactive laminates under the aforementioned loading conditions the 351 nm wavelength laser [31] with energies of 1305, 875 and 650 J was used to produce an expanding dense plasma which generated laser-driven shockless compression in the laminates. The laser pulse duration was 3.7 ns and the intensity varied from $\sim 3.8 \times 10^{12}$ to $\sim 7.6 \times 10^{12}$ W cm^{-2}. The shockless compression produced by stagnation of the high density plasma was applied to the Ni/Al laminates having a nanoscale Ni/Al laminate structure (bilayer thickness 54 nm) sandwiched between two microscale laminates (bilayer thickness 5 μm). Samples were enclosed in a hollow tube with a 6 mm inner diameter and a length of 3 cm which was filled with aero-gel, as shown in Fig. 1a. A removable cap with a centered 4 mm hole was used to clamp and fix the sample at the front end of the tube (Fig. 1a).

There are three stages in generating shockless compression using an expanding plasma. First, the incident laser energy flux is converted in the ablator–reservoir to a low density plasma [17]. In the second stage, after plasma generation, it expands across the vacuum gap. In the third and final stage the plasma stagnates and piles up against the front surface of the laminate, producing a monotonically rising pressure. The amplitude of the pressure wave propagating into the laminates gradually increases and steepens to form a shock wave. This three-step approach to loading the sample isolates the sample from laser heating effects.

The micro- and nanolaminates were prepared by accumulative roll bonding [32] and magnetron sputter deposition [1–3], respectively. Two microscale laminates which had a total thickness ~0.85 mm were machined into 5 mm disks with three ~0.3 mm well-aligned screw holes used to sandwich a nanoscale laminate of 54 nm bilayer thickness, giving a total thickness of 8.5 μm, as shown in Fig. 1b. The sandwich structure was assembled and fixed to a 300 μm thick tungsten washer (which formed the gap required for this shockless loading technique) with an outer diameter of 10 mm and inner diameter of 2 mm. A 3 mm diameter and 20 μm thick polycarbonate ablator ($C_{16}H_{16}O_4$), density 1.2 g cm^{-3}, and a 180 μm thick brominated polystyrene reservoir ($C_{50}H_{48}Br_2$), density 1.23 g cm^{-3}, were placed on the laser irradiated front surface of the tungsten washer (Fig. 1b). The tungsten washer, with a machined radial groove for the vacuum pump (dashed line in Fig. 1b), was clamped between the cap and the front end of the tube. The radial groove was designed to allow the creation of a vacuum between the ablator–reservoir and the front surface of the sandwich laminates.

The as-produced and recovered samples were characterized and analyzed using a scanning electron microscope (Philips XL30 ESEM), scanning/transmission electron microscope (EFI Titan 80-300 kV S/TEM) and the energy-dispersive X-ray spectroscopy (EDX). The dynamic response of the laminates and the shock-wave propagation in this bulk material were estimated using the one-dimensional radiation hydrodynamics code HYADES.

3. Results and discussion

3.1. Initial structure of micro- and nanolaminates

Cross-sections of the Ni/Al micro- and nanolaminates before being shock loaded are presented in Fig. 2. The