Materials Science and Engineering A 404 (2005) 291–300

MATERIALS SCIENCE & ENGINEERING A

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On the failure of NiAl bicrystals during laser-induced shock compression

Eric Loomis [a], Damian Swift [b], Pedro Peralta [a,*], Ken McClellan [c]

[a] *Arizona State University, Department of Mechanical and Aerospace Engineering, Tempe, AZ 85287-6106, USA*
[b] *Los Alamos National Laboratory, Physics Division, Los Alamos, NM 87545, USA*
[c] *Los Alamos National Laboratory, Materials Science and Technology Division, Los Alamos, NM 87545, USA*

Received in revised form 20 May 2005; accepted 26 May 2005

Abstract

Thin NiAl bicrystals 5 mm in diameter and 150–350 μm thick were tested under laser-induced shock compression to evaluate the material behavior and the effect of localized strain at the grain boundary on the failure of these specimens. Circular NiAl bicrystal samples with random misorientation were grown using a modified Czochralski technique and samples were prepared for shock compression at moderate pressures (<10 GPa). The observed crack patterns on the drive surface as well as the free surface were examined using optical microscopy. Transmission electron microscopy (TEM) of the drive surface as well as in the bulk of one grain was performed on recovered specimens following shock compression. This revealed that a nanocrystalline region with a grain size of 15–20 nm formed on a thin layer at the drive surface following the plasma expansion phase of the laser-induced shock. TEM in the bulk of one grain showed that plastic deformation occurred in a periodic fashion through propagation of dislocation clusters. Cracking on the free surface of the samples revealed a clear grain boundary affected zone (GBAZ) due to scattering of the shock wave and variations in wave speed across the inclined boundary. Damage tended to accumulate in the grain into which the elastic wave refracted. This damage accumulation corresponds well to the regions in which the transmitted waves impinged on the free surface as predicted by elastic scattering models.

Keywords: Laser-shock; Compression; Nickel–aluminide; Bicrystals; Elastic wave; Grain boundary

1. Introduction

The reliability of a material is decreased by the existence of defects from processing as well as intrinsic defects such as grain boundaries and dislocation clusters. Under dynamic loading conditions, a compression wave passing through regions containing these defects may produce asymmetric deformation as well as strain and energy localization causing early failure of the material. The presence of elastic precursor waves during shock deformation has the effect of conditioning the material ahead of the plastic wave. Therefore, it is important to examine the influence the elastic wave has on the deformation and eventual failure of the material. The current research is concerned with studying elastic effects, particularly at grain boundaries accompanied by small scale plastic yielding of anisotropic materials subjected to nanosecond laser pulses. Nickel–aluminide (NiAl) is the material being used in this research due to its high strength and hardness, well-characterized slip behavior [1–4], moderate anisotropy factor ($A = 3.3$) [2,4], and relative ease of growth in single and bicrystal form.

NiAl is a structural intermetallic and the focus of research for high strength and high temperature applications by authors such as Miracle [1,2] and Noebe [4]. Maloy et al. [3] have studied high strain rate effects on NiAl subjected to compression at strain rates up to $2000\,s^{-1}$ at various temperatures finding that single crystals of NiAl possess rate-sensitive properties such as increases in yield strength. Laser-induced shocks of NiAl single crystals have been performed by McClellan et al. [5] to evaluate the dynamic material properties of NiAl in the high pressure and strain rate regimes.

The low ductility at room temperature of NiAl makes it readily susceptible to cracking as a stress relieving mecha-

* Corresponding author at: Arizona State University, Department of Mechanical and Aerospace Engineering, P.O. Box 876106, Tempe, AZ 85287-6106, USA. Tel.: +1 480 965 2849; fax: +1 480 965 1384.
E-mail address: pperalta@asu.edu (P. Peralta).

0921-5093/$ – see front matter
doi:10.1016/j.msea.2005.05.074

nism making it possible to better understand the stress state in fractured specimens. Cracking typically occurs in NiAl by cleavage on {1 1 0} planes with low Schmid factors as reported by Miracle [2] as well as Noebe [4]. By studying crack patterns in shocked specimens, the cause of failure can be deduced more accurately.

NiAl bicrystals have been subjected to laser-induced shocks by Greening et al. [6] to study grain boundary effects in anisotropic materials. They suspected that the difference in acoustic impedance in adjacent grains plays a strong role in the deformation modes at pressures around the dynamic yield strength. For this acoustic impedance mismatch to be present, the wave propagation and particle speeds must vary as a function of orientation in the lattice. NiAl conforms to this anisotropy requirement nicely with the highest longitudinal velocities being along ⟨1 1 1⟩ directions and the lowest being along ⟨0 0 1⟩ directions, which is a plastically "hard" direction for NiAl [1–4].

Bicrystals of NiAl were prepared and subjected to laser-induced shock loading to study crack patterns along with shock-induced microstructural defects. The angles of reflection and refraction of the scattered elastic waves have been found in order to better understand the state of the material ahead of the plastic wave.

2. Experimental

NiAl bicrystals were grown in a random orientation using a modified Czochralski technique originally developed by Garrett et al. [7]. The modified Czochralski technique uses a Tri-arc furnace and crystal puller where crystals are pulled from a button of the growth material lying on the surface of a rotating water-cooled hearth. The NiAl button was melted by dual stingers sitting just above the surface of the button, which were powered by a 500-W arc welding power supply. A sharp-tipped tungsten rod was used as a seed to initiate the growth. This seed was attached at the end of a counter-rotating water-cooled seed rod and dipped into the molten button of NiAl to start the growth. The crystal was then pulled at 25 mm/h. The set-up of the modified Czochralski technique is shown schematically in Fig. 1.

For these bicrystal growths, the sharp tip of the tungsten seed may have acted as the initiation site of a second grain due to the higher surface energy in this region as the seed was submerged into the liquid NiAl. The bicrystal was not allowed to neck in order to maintain both grains in the boule, which was grown until a single grain became dominant.

Thin disks were cut from the grown bicrystal to approximately 500 μm using electro-discharge machining (EDM). The samples were then polished using 600 and 800 SiC paper on one side, which was used as the energy deposition surface during laser-shock compression. The backside of the sample was polished down to 1200 grit size SiC paper and was used as a reflecting surface for velocity measurements during the shock. The final polished samples were about 200 μm thick

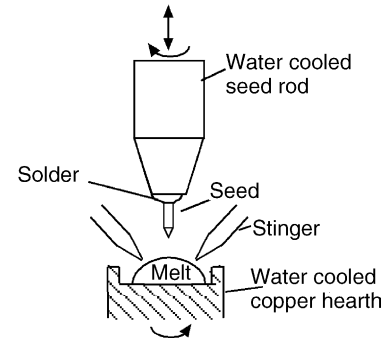

Fig. 1. Schematic of the modified Czochralski technique for growing bicrystals.

to keep an appropriate aspect ratio of 1:10 (thickness to beam diameter) so that two-dimensional loading effects from the interaction of the longitudinal loading and unloading waves with lateral rarefaction waves from the sample edges were minimized [8]. The orientation of each grain in the bicrystal was measured using Laue back-reflection X-ray diffraction, which revealed the loading axes of the bicrystal was [2 2 7] in one grain and within 5° of [0 0 1] in the other. Optical microscopy was then used to measure the inclination of the boundary through the thickness by comparing the position of the boundary on both sides of the polished samples to a reference point. The difference in the distances from the boundary to the reference point was then used along with the specimen thickness to obtain the boundary inclination through simple trigonometric relations assuming a linear grain boundary through the thickness.

The bicrystal specimens were tested at the TRIDENT laser facility at Los Alamos National Laboratory. The direct drive method was used to produce a primarily uniaxial shock wave through the samples [9,10]. One surface of the sample, the "drive surface", was irradiated with a pulse of laser light 527 nm wavelength (green), with sufficient intensity to convert the surface material to plasma. During the laser pulse, the plasma pressure and reaction from the expanding plasma created supported a shock wave that propagated through the specimen [8,11]. This process is shown schematically in Fig. 2.

Two bicrystals were used in this experiment and they were shocked such that in the grain boundary region in sample B1 the incident wave went from the [2 2 7] grain into the [0 0 1] grain. The sample B3 was prepared so that the loading took place in the opposite sense to that of B1. B1 was shocked over a 5 mm diameter area with a total absorbed energy of 9.35 J after 15% of the incident beam was lost due to scattering effects. This translates to a peak initial pressure of 4.5 GPa at the drive surface using Lindl's equation [12,13]:

$$p = 40\left(\frac{I}{\lambda}\right)^{2/3} \quad (1)$$

Here I is the irradiance in 1×10^{15} W/cm^2 and λ is the laser wavelength in microns. (It should be noted that these are