

Mechanisms of large strain, high strain rate plastic flow in the explosively driven collapse of Ni-Al laminate cylinders

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Abstract. Ni-Al laminates have shown promise as reactive materials due to their high energy release through intermetallic reaction. In addition to the traditional ignition methods, the reaction may be initiated in hot spots that can be created during mechanical loading. The explosively driven thick walled cylinder (TWC) technique was performed on two Ni-Al laminates composed of thin foil layers with different mesostructures: concentric and corrugated. These experiments were conducted to examine how these materials accommodate large plastic strain under high strain rates. Finite element simulations of these specimens with mesostructures digitized from the experimental samples were conducted to provide insight into the mesoscale mechanisms of plastic flow. The dependence of dynamic behaviour on mesostructure may be used to tailor the hot spot formation and therefore the reactivity of the material system.

1. Introduction

Ni-Al multilayered laminates have been identified as potential material systems for use as reactive materials due to their ability to undergo a self-sustaining exothermic intermetallic reaction with significant energy release [1]. In addition to the traditional ignition methods (e.g. spark ignition [2]), it is possible to induce a reaction via mechanical loading due to elevated temperatures that may arise as a result of high amplitude shock loading [3-5] or, at smaller shock pressures, due to the shear localization accompanying large strain plastic flow [6-8]. These shear localized areas act as a mechanism of hot spot generation promoting the initiation of reaction. The spacing between these hot spots determines the ability of the entire material system to react, i.e. many bulk distributed hot spots interacting with each other will cause a bulk reaction while a single or just few ignition points will result in a locally quenched reaction. For applications where the rapid release of energy is desired, it is advantageous to create as many hot spots as possible. It may be possible to tailor the mesostructure of the multilayer laminate to tune the number and spacing of the hot spots to control the rate at which the energy is released during mechanical loading.



The Thick Walled Cylinder (TWC) method [9] was developed to examine the material instabilities that develop during the large strain, high strain rate plastic flow of materials under plane strain controlled conditions including post critical stage of material flow. The TWC method creates conditions (high strain rates, large strains) that are similar to operational conditions of mechanically activated reactive material systems. In the laminate sample there are at least two spatial scales in the laminate material, the layer thickness and the sample thickness. It is not clear which of these spatial scales will provide the dominant mode of large plastic strain accommodation; the buckling of the individual layers, a geometric instability at the layer thickness spatial scale, or the development of patterns of shear bands, a material instability at sample thickness spatial scale. Furthermore, it is not clear if these instabilities will provide conditions where reaction can take place in the laminate materials. As such, two Ni-Al laminate cylindrical samples with differing mesostructures (concentric and corrugated) were assembled by different processing routines and tested using TWC method to examine their mechanism of high strain, strain rate plastic flow. Finite element simulations were conducted to investigate the mechanisms involved in the accommodation of plastic strain in the laminate materials.

2. Thick walled cylinder experiments

The Ni-Al laminates consist of alternating layers of Ni and Al foils. The concentric samples were constructed by alternating the individual layers of Ni and Al foils inside a copper tube. The details of this procedure are presented in reference [10]. The corrugated laminate was constructed by placing the alternating layers of Ni and Al foils into a stack and then placing the stack into a tubular jacket. This assembly was then swaged by using mating tapered dies such that the assembly was compressed from all sides. Details of this procedure can be found in reference [11]. Once swaging was completed, a hole was cut through the center of the rod using electrical discharge machining such that a corrugated Ni-Al laminate tube was created with an inner diameter of 12.1 mm. The mesostructures of the concentric and corrugated laminates are presented in figure 1. Once these laminates are prepared, the samples are placed in a TWC assembly depicted in figure 2.

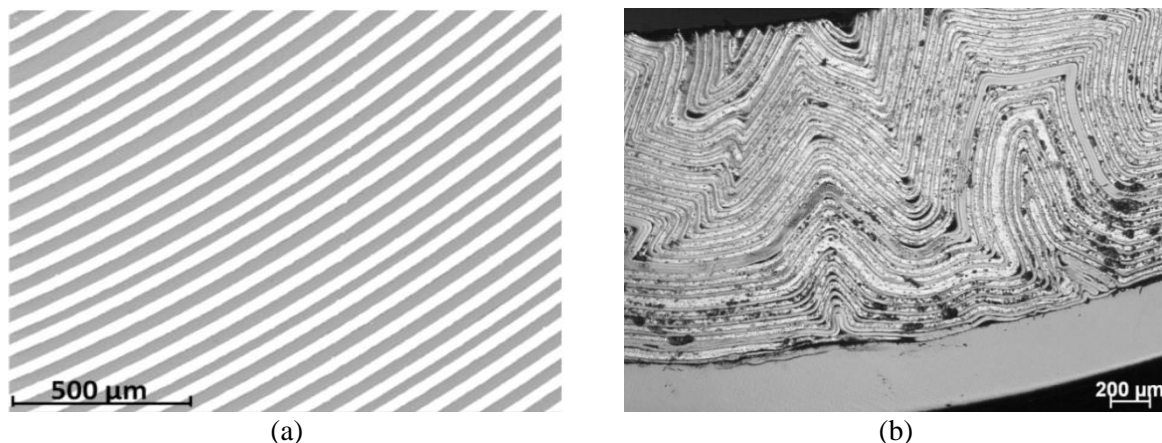


Figure 1. The (a) concentric and (b) corrugated mesostructures of the Ni-Al laminates tested in the TWC experiments. In the concentric sample, the nominal layer thicknesses were Al = 38 microns, Ni = 25 microns. For the corrugated sample, the nominal layer thicknesses were Al = 30 microns, Ni = 20 microns.

Gelled nitromethane (96% nitromethane, 4% PMMA) diluted 5% by mass with glass microballoons was used as the explosive driver (density = 0.82 g/cc, detonation velocity = 4.8 mm/μs). It allowed the fine tuning of the dynamic loading. Grooves in the steel plugs allowed the *in situ* sealing of the TWC assembly during the experiment ensuring a complete recovery of the test specimen. After sectioning the sample, Scanning Electron Microscopy (SEM) was utilized to examine the

mesostructure of the collapsed Ni-Al laminate cylinders. Images of the post experimental mesostructures can be seen in figure 3. For both mesostructures, a complete collapse was observed corresponding to maximum strains of 0.5-0.6 where the range in strains is due to the radial size variations of the interior interface.

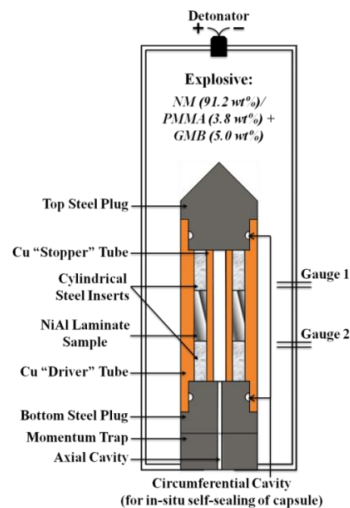


Figure 2. Thick walled cylinder experimental set-up [10].

In the concentric laminate, buckling occurred and generated 148 apices, where one apex is defined at either a peak or a trough of a buckle. Each apex in neighbouring layers was radially aligned suggesting that this buckling was cooperative and initiated at the inner layers. Localized reaction between the Ni and Al was observed in numerous apex regions such as the apex shown in figure 3 (c).

The examination of the post experimental mesostructure of the corrugated laminate (see figure 3 (b)) showed two main mechanisms of strain accommodation: extrusion of the interior facing wedge shaped regions, and trans-layer shear banding in some of the exterior facing wedge shaped regions. The high strain plastic flow of corrugated laminates is analogous to the plastic flow of monocrystals [12, 13]. In both cases planes of easy slip are activated first (e.g., Al layers at an angle to the radius serve as boundaries of the extruded wedges) controlling the overall flow of the material.

This extrusion of interior facing wedges created a wavy interface between the Ni-Al laminate and the inner copper stopper tube with an amplitude range of 150-250 μm . The local trans-layer shear bands were observed only in the exterior facing wedge regions that are in the interior of the cylinder. In a few of the extruded wedges, reaction was observed (see figure 3 (d)).

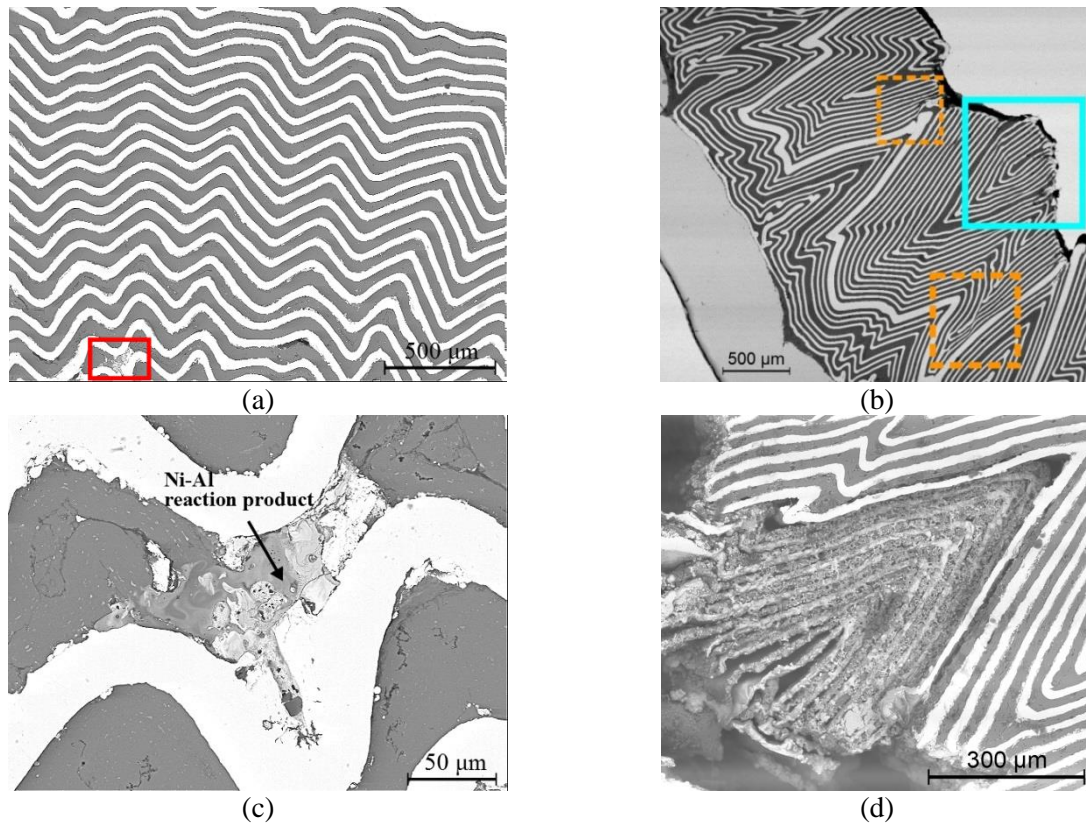


Figure 3. A detail view of the (a) concentric and (b) corrugated laminates after the TWC experiment. The red box in (a) shows a localized reaction spot. The blue box in (b) shows an extruded wedge shaped region, the orange dashed box shows trans-layer shear bands in the exterior facing wedge shaped region. The reaction at the apex regions of the concentric mesostructure are shown in (c) and a reacted wedge of the corrugated mesostructure is shown in (d).

3. Numerical modelling

Finite element simulations were conducted to elucidate the development of the large strain, high strain rate deformation of the laminate during the TWC experiment. These simulations were conducted in LS-DYNA, a general finite element software. The dimensions of the initial TWC assembly were used to define the geometry in the simulations. The mesostructure of the concentric laminates is represented by alternating concentric layers with sizes equal to the nominal layer thicknesses in the experimental sample (Ni = 25.4 μm, Al = 38.1 μm).

The corrugated laminate mesostructure was constructed by digitizing the mesostructure in figure 2 (b). Both of the initial mesostructures used in numerical calculations are presented in figure 4, and the deformed mesostructure at the time of the simulated collapse is presented in figure 5. Mesh convergence studies were conducted and showed that an element resolution with ~5-7 elements across the thickness of the layer was adequate.

The Al, Ni, Cu and the thin stainless steel jacket left on the exterior of the corrugated sample after swaging were modeled using the Johnson-Cook [14] constitutive model in conjunction with the Grüneisen equation of state. The material parameters were taken from the literature [15-17]. The explosive driver was modeled using the Jones-Wilkins-Lee (JWL) equation of state of the form:

$$P = A \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

where $A = 78.69$ GPa, $B = 1.92$ GPa, $\omega = 0.36$, $R_1 = 4.61$, and $R_2 = 1.06$ are constants obtained from calculations using CHEETAH [18].

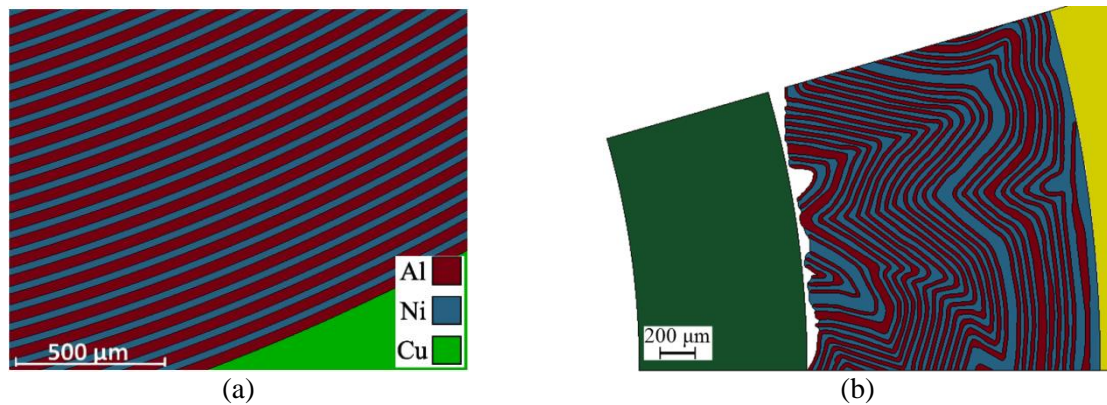


Figure 4. The initial mesostructures used in the finite element simulations for the (a) concentric case and (b) the corrugated case. The mesostructure in (b) was extracted from the mesostructure shown in figure 1 (b). For both (a) and (b), the Ni is shown in blue, the Al in red, and the Cu in green. The stainless steel jacket in (b) is colored yellow.

4. Comparison of the experiments and the simulations

The mesostructures of the laminates generated in the simulations are presented in figure 5. They show good qualitative agreement with the mesostructures observed in the post TWC samples (figure 3). The concentric sample demonstrates that radially aligned apices developed due to cooperative buckling where the characteristic wavelength of the buckling was determined by the innermost layers during the initial collapse of the cylinder. This characteristic wavelength then spread outward causing all the layers to have the same number of buckles. No additional buckles were generated as the cylinder continued to collapse; instead, the amplitude of the original buckles grew to accommodate the reduction in circumference. In the sample with the corrugated mesostructure, three main mechanisms of plastic strain accommodation were observed: (1) the extrusion of an interior facing wedges, (2) the development of trans-layer shear bands, and (3) the cooperative buckling on the exterior concentric layers.

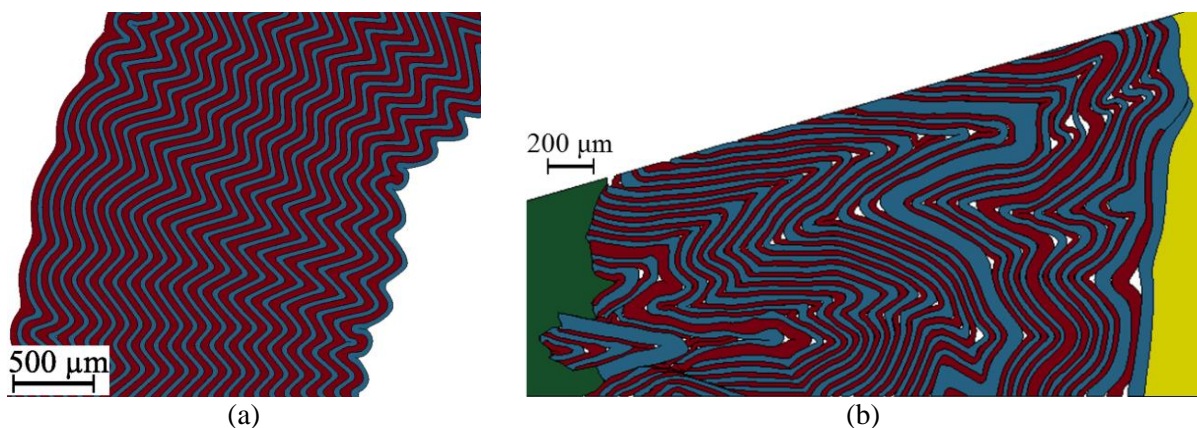


Figure 5. The final mesostructure of the (a) concentric and (b) corrugated laminates after the simulated TWC experiment. The interior of the cylinder in (a) is on the right hand side. For both (a) and (b), the Ni is shown in blue, Al in red, and Cu in green. The stainless steel jacket in (b) is colored yellow.

5. Conclusions

Thick walled cylinder experiments were conducted with two Ni-Al laminates with different mesostructures, concentric and corrugated, and similar thicknesses of the layers. Finite element simulations of these experiments were performed and showed good qualitative agreement with the experiments.

The mechanisms of accommodation of high strain, high strain rate plastic flow was dramatically different in the concentric and the corrugated samples. The experiments and simulations showed that mechanism of plastic flow accommodation in the concentric laminate sample was the cooperative buckling of the Ni and Al layers. The buckling originated in the interior layers and propagated outward to the exterior layers. No shear localization bands were detected.

The deformation of the corrugated mesostructure demonstrated three main mechanisms of plastic strain accommodation – (1) the extrusion of interior facing wedge shaped regions, (2) trans-layer shear bands in some of the initially outward facing wedge shaped regions, and (3) the cooperative buckling of Ni and Al layers that were initially concentrically aligned.

In the concentric laminate, intermetallic reaction was observed in many of the apices. In the corrugated laminate, reaction was observed in a few of the extruded wedges adjacent to the interior interface with inner copper stopper tube. The mesostructure of the laminate materials dramatically changed the dominant mechanisms of plastic strain accommodation. This suggests that using the mesostructure may be an effective way to tailor the reactivity in these material systems undergoing mechanical deformation.

Acknowledgements

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