DYNAMIC EXPANSION AND FRACTURE OF STAINLESS STEEL CYLINDRICAL SHELLS

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SUMMARY

Cylindrical shells of stainless steel were expanded at strain rates between 10^2 and 10^4 s^{-1} in order to determine fracture strength at high strain rates. The shells were expanded with magnetic pressure pulses from a capacitor discharge and the simultaneous detonation of high explosives with a mesh of copper bridgewires. Response of the cylinders was monitored with a high speed framing camera and pulsed x-rays.

The fracture strength of 301, 304 and Armco Nitronic 33 stainless steel cylinders was determined by expanding a series of each material at high rates of strain with magnetic pressure pulses. All cylinders had a length of 3.0 in. and thickness 0.02 in.; the outer diameter for the 301 and 304 materials was 5.5 in. and the outer diameter for the Nitronic 33 material was 6.5 in. Axial lines were drawn on the outside surface of the cylinders and were initially 1.0 in. apart. Expansion strains and strain rates were obtained from photographs taken with a Cordin Model 114 framing camera by measuring the frame by frame elongation between the lines on the surface of the cylinder. Initial strain rates are proportional to the initial radial wall velocities which were always nearly constant and compared closely with that calculated from the integration of the magnetic pressure over time. Final strains are plotted versus initial strain rates and the initial strain rate required to produce fracture is bracketed. For these cylinder geometries the cylinders reached 35, 23 and 19 percent strain prior to fracture for the 301, 304 and Nitronic 33 materials, respectively.

Scaled model tests were also performed on four 304 stainless steel cylinders which were expanded with PETN high explosive detonated with mesh-initiated copper bridge wires. These cylinders had a length of 7.5 in., outer diameter of 5.7 in. and wall thickness of 0.20 in. The thin layer of PETN was uniform and extended over the length 5.5 in.; a length of 1.0 in. on either end of the cylinder was not loaded. Framing camera data indicated that the initial strain rates were $\sim 2700\,s^{-1}$ for the four tests. Two cylinders expanded to 35 and 45 percent strain without fracturing and the other two cylinders failed in a complete single axial fracture. The final strains for the fractured cylinders were 45 and 50 percent.

Work in progress is being conducted to examine the strain rate sensitivity of 304 stainless steel. A stress-strain-strain rate law will be fitted to data obtained from tension machine experiments for strain rates up to 10 s^{-1}. The accuracy of this material law for strain rates up to $10^4\,s^{-1}$ will be examined by comparing predictions using this material law and strain measurements from a series of expanding ring experiments.

1. Introduction

Development programs concerned with magnetic flux compression generators [1], the simulation of impulse loads produced by radiation-induced materials blowoff [2] and the containment of high explosives [3] have created a need for new experimental methods which examine the response of structures under high rates of strain. We have developed several methods for loading the surfaces of structures with short-duration magnetic pressure pulses [4] and the simultaneous detonation of explosives with mesh-initiated copper bridgewires [5]. Much of our recent work has been concerned with experimental-analytical studies designed to verify nonlinear dynamic stress-strain laws and computer programs. Examples of these studies are published in [6,7,8] where 6061-T6 aluminum and 1018 steel rings and beams were driven through the elastic and into the plastic regime with short-duration magnetic pressure pulses. Responses were monitored with streak or framing cameras and strain gages, and these measurements were compared with predictions.

The magnetic pressure loading technique used to expand the stainless steel cylinders described in this paper is reported in [9]. In [9], the radial expansion and subsequent fracture into segments of thin-walled 6061-T6 aluminum cylindrical shells at strain rates up to 10^4 s^{-1} were studied analytically and experimentally. The theory of probability along with a description of relief wave propagation away from each fracture was used to formulate a theory which predicts the number of fractures and the distribution of fragment lengths. Good agreement is shown between predictions and the results from eleven experiments.

This paper will describe the loading and measurement techniques used to determine the fracture strength of 301, 304 and Armco Nitronic 33 stainless steel at high strain rates. A program currently in progress designed to obtain a stress-strain-strain rate law for 304 stainless steel at high strain rates is also described.

2. Experiments with Magnetic Pressure Loading

2.1 Loading Technique

The loading technique for radially expanding cylindrical shells is illustrated in [6,9]. Briefly, the apparatus consists of a fast discharge capacitor bank and a loading fixture which fits snuggly into the inner diameter of the cylindrical test specimen. The fixture contains two concentric current carrying conductors; the primary conductor is part of the capacitor bank circuit and the secondary conductor receives current through magnetic induction. These oppositely directed currents produce a short duration (~10 μs) magnetic pressure pulse between the conductors and the secondary conductor pushes on and expands the cylindrical test specimen.

2.2 Measurements

Expansion strains and strain rates were obtained from photographs taken with a Cordin Model 114 Framing Camera. A frame was recorded every 11 μs and a total of 25 frames were obtained. Figure 1 shows a photograph of an Armco Nitronic 33 cylinder prior to expansion. As shown in Figure 1, axial lines were drawn one inch apart on the outer surface of the cylinders. Figure 2 shows the cylinder expansion at 198 μs. To obtain strain and strain rate the frame by frame elongation between the lines on the surface of the cylinder were measured.

2.3 Results

Initial strain rates are proportional to the initial radial wall velocities. The initial velocities were always nearly constant and compared closely with that calculated from the integration of the magnetic pressure over time; see [6,9]. In Figure 3 the final strains are plotted versus initial strain rates for the three materials and fracture is bracketed. Cylinder geometries are given in the abstract, and for these geometries the cylinders reached 35, 23 and 19 percent strain prior to fracture for the 301, 304 and Nitronic 33 materials, respectively.

3. Experiments with Explosive Loading

3.1 Loading Technique

Experiments conducted with PETN explosive charges up to 0.6 m^2 in area have been surface initiated with electrically exploded copper mesh patterns. The mesh patterns, constructed by conventional chemical etching techniques, have contained firing point densities ranging from 2.5×10^4 to 6.5×10^5 m^{-2}. The PETN explosive charges may be sprayed, cast or vibrated dry into a cavity between the mesh and test item; see [5,10]. For the present cylindrical system, PETN was vibrated dry into a cavity between the mesh and 304 stainless steel cylinder specimen. The mesh and high explosive covered 5.5 in. of the 7.5 in. overall shell length; a length of 1.0 in. on either end of the cylinder was not loaded. The mesh was then exploded using a capacitor bank discharge which, in turn, initiated the PETN. The test cylinder expanded radially outward with the center portion moving faster than the unloaded ends.

3.2 Measurements

Three pulsed x-rays were taken of the expanding cylinder and a high-speed framing camera recorded the event. An initial velocity and strain rate were determined from early-time measurements of the expanding cylinder from the framing camera film.

3.3 Results

Four experiments were performed at a strain rate of approximately 2700 s^{-1}. Two cylinders expanded to 35 and 45 percent strain without fracturing and the other two cylinders failed in a complete single axial fracture.

The final strains for the fractured cylinders were 45 and 50 percent. Post-test photographs of an expanded and a fractured specimen are shown in Figures 4 and 5.

4. Work in Progress

Work in progress is being conducted to examine the strain rate sensitivity of 304 stainless steel. Some stress-strain data at constant strain rates obtained from tension machine experiments was published by Steichen [10] for rates up to 10^2 s^{-1}. We will also perform experiments at constant strain rates with tension machines. A stress-strain-strain rate law will be curve fitted to these data and this material law will be examined at strain rates up to 10^4 s^{-1} with expanding ring experiments. As discussed in [6], the postulated material law obtained from constant strain rate experiments at lower rates can be verified with this procedure.

5. Acknowledgments

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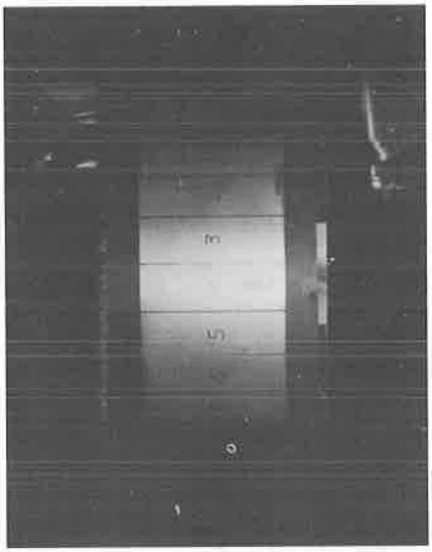

Fig. 1 Armco Nitronic 33 Stainless Steel Cylinder Before Expansion.

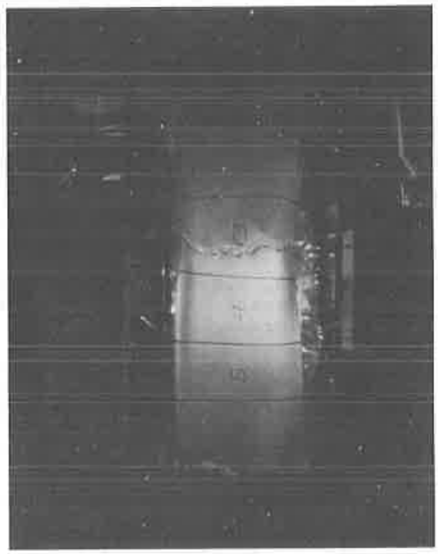

Fig. 2 Armco Nitronic 33 Stainless Steel Cylinder Expanded at 198 μs.

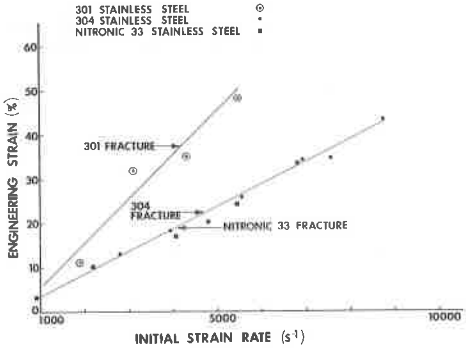

Fig. 3 Final Strains Versus Initial Strain Rates.

Fig. 4 Expanded 304 Stainless Steel Cylinder.

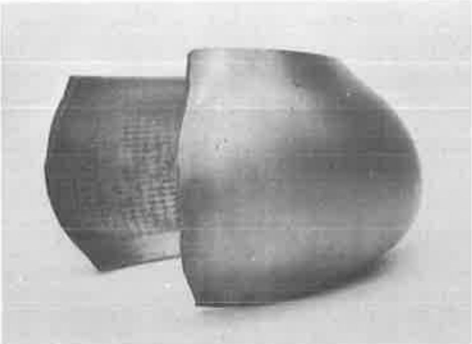

Fig. 5 Fractured 304 Stainless Steel Cylinder.