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Roshdy George S. Barsoum, PhD, PE
One Liberty Center, 875 N. Randolph St., Suite 1425, ONR 334
Arlington, VA 22203-1995

on

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Characterization of Deformation and Failure of Stainless Steel Welds

by

Rodney J. Clifton, Principal Investigator
Professor of Engineering; Rush C. Hawkins University Professor
Division of Engineering, Brown University
182 Hope St., Providence, RI 02912
Phone: (401) 863-2855
Fax: (401) 863-9025
Email: clifton@engin.brown.edu

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Division of Engineering
Providence, Rhode Island 02912

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14. ABSTRACT
Kolsky bar experiments have been used to determine the high-strain-rate response of AL6XN welds — including the base material, the heat-affected zone, and the weld. A finite element model for analyzing ductile fracture near the weld has been developed and implemented as a material routine VUMAT in ABAQUS/Explicit. The FE model involves a Gurson-type constitutive description for porous materials, combined with a microstructural length scale and an upper bound approach for modeling the onset and evolution of void coalescence. This model appears to provide a promising description of dynamic failure of butt-welded stainless steel plates. In a second investigation, pressure-shear plate impact experiments have been used to determine the shearing resistance of an epoxy and two vinyl esters at strain rates of 100,000/sec. This shearing resistance has been shown to increase significantly with increasing pressure.

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Abstract

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Problem Statement

The navy has considered the possibility of building ships with stainless steel hulls. The advantages of such ships are apparent. However, questions arise regarding the strength of welded joints in these ships. In particular, large scale tests suggest that failure of components subjected to dynamic loading tends to occur along welds. This grant was motivated originally by the need to develop a deeper understanding of the conditions for failure along butt-welds of stainless steel plates. Inititially the interest was in both Nitronic 50 and AL6XN stainless steels; however, early in this effort there was a request to focus on AL6XN butt-welded plates provided by the Carderock Division of the Naval Research Laboratory. A combined experimental and computational investigation was indicated so that computational approaches suitable for design would be developed in the sense that these approaches would be well substantiated by comparisons with experiments.

Objectives

The initial objective of this research was to provide a mechanistic understanding of the failure of stainless steel welds subjected to dynamic loading. This understanding is to guide computer modeling of the response of stainless steel welded structures to blast loading. Initially, a second objective was to understand the frictional resistance of interfaces between composite materials and stainless steel. However, at ONR's request, the second objective was changed to determining the high strain rate response of an epoxy and of vinyl esters used as matrix materials in fiber reinforced composites.

Technical Approach

Quasi-static tests in an Instron and dynamic fracture tests conducted in a Kolsky Bar have revealed that the fracture process in AL6XN stainless steel originates at or near a weak HAZ/Weld interface. In order to facilitate a mechanistic understanding of the micro-structural events leading up to fracture, a combined computational and experimental investigation of the AL6XN Weld/HAZ interface has been conducted. The experimental investigation has involved Kolsky Bar compression experiments to determine the dynamic stress-strain response of the base metal, the HAZ (Heat Affected Zone), and the weld. It has also included Kolsky Bar tension experiments to determine the fracture behavior of these same materials. Failure surfaces were studied by means of SEM micrographs. Composition of the AL6XN/Inconel-625 alloy interface was obtained using X-ray EDS. X-ray Computed Microtomography (XCMT) of AL6XN-IN625 tensile specimens, conducted at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory, was used to obtain a three-dimensional map of the voids in a tensile specimen at a pre-fracture level of load.

The computational investigation involved the development of a model for ductile fracture based on void nucleation, growth, and coalescence. The model is for the finite deformation and fracture of a porous, elastic-viscoplastic material. The effects of strain hardening, rate sensitivity, material inertia, and adiabatic heating are included. For simulating the high-strain-rate tensile response, a Gurson-type constitutive relation is used for void growth – along with a criterion for the onset of void coalescence based on upper-bound velocity fields. The viscoplasticity model incorporates the effects of athermal hardening, thermally activated motion of dislocations past short-range barriers, and viscous-drag at very high strain rates and high temperatures. This computational model was implemented in ABAQUS/Explicit, using 8-noded C3D8R elements and a material routine VUMAT. The validity of the computations was examined by performing mesh sensitivity studies. Quasi-static experiments on notched cylindrical tensile specimens used for the XCMT studies were simulated to gain insight into the failure mechanism at the root of the notch. To account for the dual-size population of voids, two types of elements were included – those with primary nucleation sites for the large voids and those with secondary nucleation sites for the small voids. Dispersion of elastic waves in the incident and transmitter bars was accounted for in the simulation of the Kolsky Bar experiments.

For the second objective, pressure-shear plate impact experiments were conducted on thin samples of an expoxy (Hysol® EA9394) and two vinyl esters (8084 and 411-350) that were sandwiched between two hard stainless steel plates. The samples were cured *in situ* to promote bonding with the steel plates so that shear stress could be transmitted through the sample even after unloading longitudinal waves arrive and remove the compressive stresses on the sample. Experiments were conducted at room temperature. Sample thicknesses varied from $10\ \mu m$ to $75\ \mu m$. Strain rates were of the order of $10^5\ s^{-1}$. Velocity-time profiles at the rear surface of the target assembly were monitored by means of laser interferometry. Elastic wave propagation analysis was used to infer the stress and nominal strain rate in the sample from the measured free surface velocities. Each experiment provided a dynamic stress-strain in shear, under pressure, followed by a stress-strain curve of shorter duration at zero pressure.

Technical Activities Performed

Samples taken from stainless steel butt-welded plates, obtained from the Carderock Division of the Naval Surface Warfare Center, were tested in an extensive series of Kolsky bar experiments. These experiments involved tests in both compression and tension. The base materials in these tests were AL6XN and Nitronic 50. Tests were done on the base material, the weld material, and the heat-affected zone. For the tension experiments, SEM micrographs were obtained of the fracture surfaces. Composition of the base material and the weld material was obtained across the interface by means of X-ray Energy Dispersive Spectroscopy (EDS). X-ray Computed Microtomography (XCMT) was used to study the fracture process in AL6XN weldments by providing insight into void growth in partially voided, pre-fractured, tensile specimens. Extensive computational simulations were performed to interpret the Kolsky bar experiments and the void formation observed by XCMT. For the Kolsky bar experiments in tension, these simulations established a suitable specimen design to successfully minimize end effects. For all Kolsky bar experiments these simulations made it possible to take account of radial inertia effects.

A major computational effort was directed toward understanding the observed ductile fracture on the basis of void nucleation, growth and coalescence. This effort required the development of a VUMAT material model for implementation in ABAQUS. This model provides a description of void growth of an ellipsoidal void in a unit cell of the material. It provides a plastic limit-load criterion for the onset of void coalescence. It also provides a description of the post-coalescence deformation. Three dimensional simulations of tensile tests on notched cylindrical specimens were performed to enable comparisons of predicted void distributions with those obtained by XCMT.

Pressure-shear plate impact experiments were conducted on thin samples of an expoxy (Hysol® EA9394) and two vinyl esters (8084 and 411-350) cast between two hard stainless steel plates. The thicknesses of the front and rear plates of the target assembly were chosen such that the shearing resistance of the sample could be measured both under pressure and, subsequently, at zero pressure. Elastic wave propagation analysis was used to obtain dynamic stress-strain curves, in shear, from the rear surface velocity-time profiles measured in the experiments.

Results and Discussions

The principal results of the research on stainless steel butt-welded plates are described in the enclosed Ph.D. thesis of Vasanth Kothnur. From the Kolsky bar tests in compression it was determined that the weld zone is undermatched by approximately 10% in comparison to the base material and that the HAZ is overmatched by approximately 5% compared to the base material. From the Kolsky bar tests in tension it was determined that the HAZ was significantly less ductile than either the base material or the weld.

The computational material model for ductile fracture has been implemented as a user material routine VUMAT in ABAQUS/Explicit. The response of the material at macroscopic length scales has been related to the microstructural response through a set of internal state variables: matrix effective stress, ligament ratio, void spacing ratio, void aspect ratio and void shape factor. The evolution of the macroscopic material response and of the internal state variables has been derived for two distinct flow regimes: pre-coalescence and post-coalescence. The post-coalescence behavior has been shown to be influenced strongly by the small-scale void nucleation and growth. Because ultimate failure is strongly connected to small-scale void processes, the predicted results are relatively insensitive to mesh size for mesh sizes small enough that elements with secondary nucleation sites for small voids surround elements with primary nucleation sites for large voids. These conditions are met for element sizes less than or equal to the $66\ \mu m$ size used for the reported simulations. Predicted load-displacement response is in good agreement with experimental observations. The finite element simulations were also generally accurate in modeling the onset of void coalescence and rapid unloading in the post-coalescence regime. The locations of voided zones predicted by the FE simulations are in approximate agreement with experimental observations using XCMT. Differences between simulated and observed void-volume fraction are believed to be associated with difficulties in modeling ductile fracture at low stress triaxialities. Overall, these FE simulations indicate that Gurson-type constitutive models for porous materials, combined with a microstructural length scale and an upper-bound approach for modeling the onset and evolution of void coalescence, is a useful tool for modeling the dynamic failure of heterogeneous weldments.

In the investigation of the high-strain-rate response of an epoxy and two vinyl esters, the shearing resistance was found to increase significantly with increasing pressure. The shearing resistance increases only weakly with increasing strain rates at the high strain rates of the pressure-shear plate impact experiments. These results are believed to be important in modeling the shearing resistance of composites as well as in modeling the strength of adhesively bonded joints.

Conclusions and Recommendations

Failure of butt-welded stainless steel plates subjected to dynamic loading is likely to occur at the welds. Therefore, design against failure should pay close attention to the stress states at the welds; additionally, rigorous inspection of the welds should be done to ensure their competence in withstanding the anticipated dynamic stresses. For the analysis of the load carrying capacity of welds, the computational methodology developed in this investigation provides a means for analyzing failure based on void nucleation, growth and coalescence. This computational capability, combined with data obtained here on the dynamic stress-strain response of the base material, the weld, and the heat affected zone should be useful in the design of welded, stainless steel structures.

Design of fiber-reinforced composites as structural elements in ships should account for the rate dependence of the mechanical response of the composites. This rate dependence should come primarily from the epoxy or vinyl ester matrix material used in the composite. Thus, the dynamic shearing resistance of these materials, measured as part of this investigation, should be useful in modeling the dynamic response of many of the composites of interest. In view of the observed pressure-dependence of the shearing resistance of the epoxy and vinyl esters examined here, such pressure-dependence should be included in design calculations for dynamical applications in which large pressures are generated.

Technology Transfer:

This project has had close interaction with Drs. Richard Everett, Andrew Geltmacher and Kirth Simmonds of the Naval Research Laboratory, centered on an X-ray tomographic investigation of the AL6XN HAZ/Weld fracture process zone. We have worked with them in the planning and performance of experiments on several different occasions when we were able to get beam time at the National Synchrotron Light Source in Brookhaven National Laboratory. Through this interaction we have helped them to understand the possibilities and limitations of X-ray computed microtomography (XCMT) as a non-destructive technique to spatially re-construct the internal microstructure of the voided material at the tip of a crack.

We have also interacted with Dr. David Kiehl and colleagues at the Carderock Division of the Naval Surface Warfare Center. They have supplied the stainless steel butt-welded plates used in this investigation. We reported to them the dynamic plastic response of the parent material, the heat-affected zone, and the weld material. We also reported the premature failure, along the interface between the weld material and the heat affected zone, when these samples were subjected to tensile loading perpendicular to the weld. When we showed the presence of large inclusions in this region they supplied new welded plates that were used for the reportable part of the experimental investigation.

For the investigation of the high strain rate response of an epoxy and two vinyl esters we interacted with scientists at the Carderock Division in the selection of materials to be studied. Results of this investigation were reported at ONR workshops attended by Carderock personnel.

Attachments

1. Kothnur, Vasanth S., "An experimental and computational investigation of dynamic ductile fracture in stainless steel welds," Ph.D. thesis, Brown University, May, 2002.
2. Clifton, Rodney J., Jearanaisilawong, P., and Jiao, Tong, "High strain rate response of epoxy and vinyl ester," to appear in Proceedings of the Meeting of the APS Topical Group on Shock Waves in Condensed Matter, held in Baltimore, MD, August, 2005.

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Refereed Journal Articles:

Clifton, Rodney J., "Response of materials under dynamic loading," *International Journal of Solids and Structures* **37,** 2000, pp. 105-113.

Clifton, Rodney J., Jearanaisilawong, P., and Jiao, Tong, "High strain rate response of epoxy and vinyl ester," to appear in Proceedings of the Meeting of the APS Topical Group on Shock Waves in Condensed Matter, held in Baltimore, MD, August, 2005.

Books and Chapters: None

Technical Reports:

Kothnur, Vasanth S. , " An experimental and computational investigation of dynamic ductile fracture in stainless steel welds," Ph.D. thesis, Brown University, May, 2002.

Presentations:

R. J. Clifton, "Deformation and Failure of Stainless Steel Welds," ONR 6.1/6.2 Workshops annually, 1998-2002.

Patents: None

Honors/Awards/Prizes:

Rodney J. Clifton, Timoshenko Medal, Applied Mechanics Division of ASME, November, 2000.

Other Sponsored Work:

Plastic Flow of Molybdenum at Very High Strain Rates, ARO

Dislocation Mobility in Ni3Al, NSF MRSEC at Brown

Dynamic Compressive Response of Bulk Amorphous Metal Rods Heavily Reinforced with Refractory Metal Wires, SBIR with Amorphous Technologies Inc.

Carroll, Nancy

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