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THE DEVELOPMENT OF A MINIATURIZED DISK BEND TEST FOR THE DETERMINATION OF POSTIRRADIATION MECHANICAL PROPERTIES

M.P. Manahan, A.S. Argon and O.K. Harling

Department of Nuclear Engineering, Department of Mechanical Engineering, and Nuclear Reactor Laboratory
M.I.T., Cambridge, Massachusetts 02139, USA

A Miniaturized Disk Bend Test capable of extracting postirradiation mechanical behavior information from disk-shaped specimens no larger than those used for Transmission Electron Microscopy is currently being developed. Finite element analysis is performed to convert the experimentally measured load-deflection data into useful engineering information. Since neutron irradiation costs scale with specimen volume, successful development of miniaturized mechanical property tests could provide significant savings in irradiation testing costs for nuclear materials used in fusion and other nuclear technologies. In addition, it may be possible to provide mechanical behavior information which is not ordinarily obtainable due to space limitations in irradiation experiments.

1. INTRODUCTION

There exist many promising advanced alloy systems for possible Controlled Thermonuclear Reactor applications (i.e., austenitic and ferritic steels, refractories, etc.), and of course within each system myriads of thermomechanical treatments and processing conditions. The mechanical behavior of prime candidates from each of these alloy systems needs to be readily determined in the postirradiated state in a timely and cost effective fashion. To this end, a Miniaturized Disk Bend Test (MDBT) is being developed, which is potentially capable of determining biaxial stress/strain response, biaxial ductility, stress relaxation behavior, biaxial creep response and biaxial creep ductility using disk-shaped specimens no larger than those used for Transmission Electron Microscopy (TEM). Additional information on cyclic behavior could then be obtained by use of the standard low cycle fatigue formalisms. Thus, the MDBT could potentially provide most of the mechanical property information desired to screen many alloy systems in the postirradiated state. There are two principal conceptual innovations present in the MDBT. The first innovation is to use bending to extract mechanical behavior information from a very small sample as opposed to the more standard approach of using uniaxial tensile loading requiring gripping extensions. The second innovation is the use of the finite element method to extract useful engineering information from the experimental data. While the former innovation has been suggested and used also by others [1-3,5] with analytical modeling, the latter was first proposed by Manahan and Argon [4] and derives its motivation from the impression creep and impression fatigue tests described by Li and coworkers [6-8].

The determination of a stress/strain curve, using analytical expressions, from a pure bending test was first reported by Herbert [1] for cast iron bars. More recently, Crocker [2] has obtained stress/strain information for large deflections and plastic strains using a three point rotary bend best. He uses the same analytical expressions as Herbert and implements a progressive reconstruction technique to transfer the moment-angle measurements into a stress/strain relationship. Stelson _et al._ [3] have used an adaptive controller to measure force and displacement during brakeforming to estimate workpiece parameters with a microcomputer, which are then used in an analytical elastic-plastic material model to predict correct final punch position. Although these earlier developments have been useful, particularly in the metals-forming industry, they are not readily adaptable to postirradiation mechanical behavior testing because of large size and awkward loading configuration. For this application we have proposed earlier [4] a simply supported miniaturized disk of the size of TEM specimens, which we have now developed much further. We are aware that a similar specimen and loading configuration to provide for ductility screening has also been under development at the Hanford Engineering Development Laboratory (HEDL), using small strain analytical expressions [5]. The advantage of the finite element method for data inversion that we are developing is that it permits the extraction of both plastic resistance and creep resistance from the raw data in addition to the information on ductility from irradiated samples exhibiting moderate to large levels of strain to fracture and with a minimum of material.

This paper primarily addresses the task of generating biaxial stress/strain response and biaxial ductility information using the MDBT. In order to achieve this, it is necessary first to design and implement a test system that reproducibly generates central load-deflection curves at temperatures up to the creep range, and second to implement the finite element method in order to convert the experimental central load-deflection curves into stress/strain information. This paper reviews the current status of this research.

2. EXPERIMENTAL APPROACH AND PRELIMINARY TEST RESULTS

In the MDBT the simply supported disk is centrally loaded. The specimen disk, which has dimentions 3.0 mm x 0.25 mm, rests in a cylindrical die and the alumina punch presses the disk into the cavity as shown schematically in Figure 1.

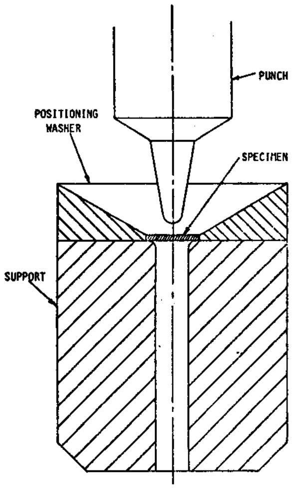

Fig. 1: Schematic of Miniaturized Disk Bend Test showing simply supported central loading.

Prior to designing and fabricating the first test apparatus, simple bench experiments were performed to identify key design parameter ranges and any nonreproducible anomalies associated with simply supported concentric loading to rupture (e.g., plate bucklings, etc.). No such anomalies were discovered and the deflection and load ranges for 316 stainless steel (SS) were on the order of 0-1 mm and 0-650 N respectively. The aspect ratio of the specimen falls in the range where plate buckling does not occur. This was verified by observing the deformation under a stereo microscope all the way to fracture.

The actual test apparatus has been adapted to an Instron 1331 servohydraulic machine with environmental chamber and induction furnace as shown schematically in Figure 2. During the test, either the applied load of the punch vs time under constant impression velocity, or the punch displacement vs time under constant applied load are measured. Deflections are

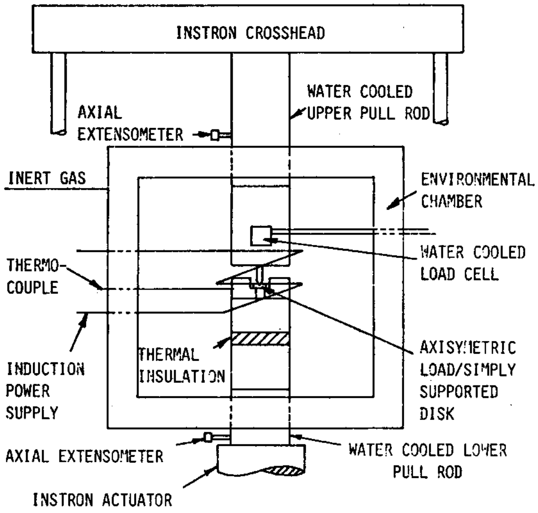

Fig. 2: Miniaturized Disk Bend Test experimental configuration.

measured external to the environmental chamber with MTS axial extensometers (Type 632.12). The maximum error in deflection measurement over the entire calibrated range is 0.00254 mm. A water cooled load cell using semi-conductor strain gauges provides accurate load measurement. The maximum error in load measurement over the entire calibrated range is 6.67 N. The water cooling eliminates any apparent strain effects due to temperature drifts. The load cell is placed in the environmental chamber to eliminate effects due to frictional forces at the upper bellows seal.

The testing apparatus is shown in Figure 3 in exploded view. Most interfaces in the load train are prestressed to minimize nonlinear contact forces. High density alumina was chosen for the punch and die material because of the large compressive strength, good wear resistance and low thermal conductivity of this material compared with the steel specimens. Invar was chosen for the load train material because its low thermal expansion coefficient matches that of the strain gauges and thus essentially eliminates apparent strain effects from temperature variations. The positioning washer and upper disk support structure were fabricated from 304SS to provide some thermal expansion and thus maintain simply supported conditions at elevated temperatures. Since the compression rods are water cooled, heat loss via conduction through them is reduced by using ceramic washers in the load train. A suction operated handling system has been designed to facilitate radioactive specimen handling and positioning.

Alignment of the specimen is critical since disk stiffness increases with eccentricity of loading. Therefore, an alignment fixture is

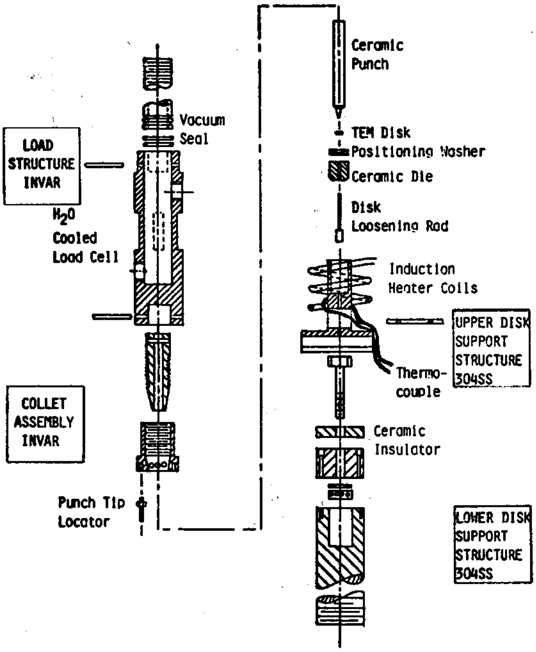

Fig. 3: Minizturized Disk Bend Test apparatus.

used which provides accurate specimen alignment. Preliminary tolerance measurements indicate that the disk is aligned to within 0.0254 mm. This tolerance was measured by placing a polished specimen in the die after alignment, applying a small load on the specimen, and subsequently measuring the location of the indentation center in an optical comparator. An estimate of the error in central displacement due to eccentric loading can be obtained using the small deflection elastic solutions for simply supported point loading [9]. The resulting error curve is shown in Figure 4.

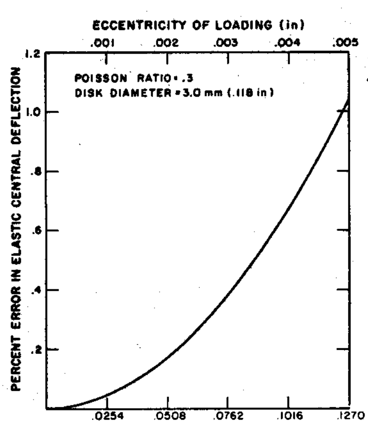

Fig. 4: Estimate of error in elastic central deflection due to eccentric loading.

The preliminary alignment tolerance results in less than approximately 0.1% error in central deflection. The load train compliance was measured and found to be linear over the load range of interest as expected. The load train deflection is 0.0381 mm at 667.2 N.

The MDBT has been designed to operate at elevated temperatures. There are two thermocouples (TC) permanently attached to the upper disk support structure; one for control, and one for recording. For calibration purposes, a small diameter TC was silver soldered to the disk and the temperature calibrated with the permanent control TC, which is located in the upper disk support structure. With the present design of the MDBT apparatus, testing is carried out in an inert gas atmosphere after the environmental chamber has been pumped down and flushed several times. Testing in high vacuum should also be possible after some modifications are made to the apparatus.

Experimental reproducibility is shown in Figure 5.

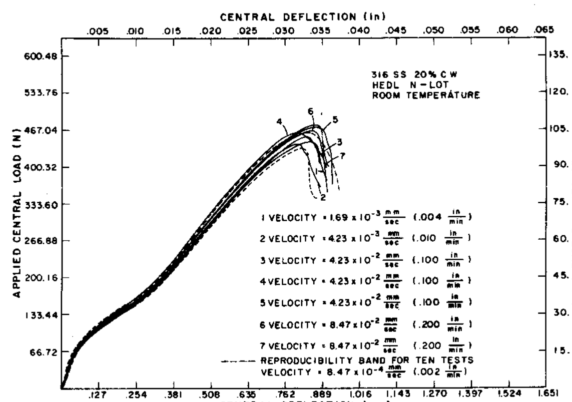

Fig. 5: Miniaturized Disk Bend Test reproducibility and velocity effects curve.

The dotted lines represent the maximum and minimum central load deflection curves observed in ten separate room temperature tests. The tested material was 316SS with 20% cold work (CW).[1] This material was chosen because the mechanical behavior has been well characterized and should serve as a good validation of the MDBT. The specimens were stamped from rolled sheet to a diameter of 3.0 ± 0.0076 mm and subsequently precision lapped to a thickness of 0.254 ± 0.00254 mm. Punch velocity effects at room temperature were found to be unresolvable for punch speeds ranging from 8.47×10^{-4} mm/s to 8.47×10^{-2} mm/s. A convenient velocity of

4.23×10^{-3} mm/s was chosen for subsequent experiments.

Figure 6 illustrates central load-deflection curves for a variety of materials.

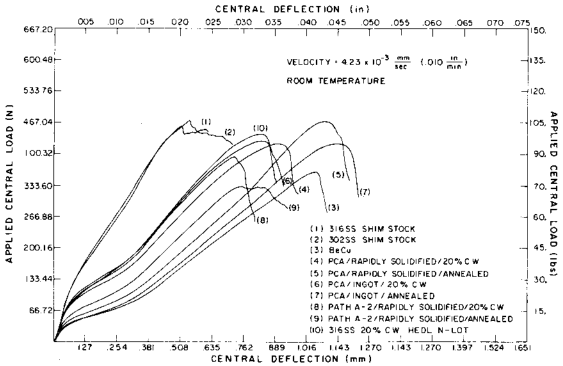

Fig. 6: Miniaturized Disk Bend Test experimental results for various materials.

The BeCu, 302SS and 316SS shim stock specimens were stamped out of rolled sheet 0.254 mm thick. The primary candidate alloys (PCA) and rapidly solidified Path A alloys are described in Ref. 10. Specimens of 0.381 mm thickness were cut from 3.0 mm rod and subsequently precision lapped to 0.254 ± 0.00254 mm thickness. Each material has unique and distinguishable load-deflection curves. The initial linear portion of the load-deflection curve was found to be in the elastic range for the bulk plate response by loading and reloading several times up to the point of departure from linearity. Qualitatively, it has been observed that for the ten materials shown in Figure 6, higher yield strengths correspond to larger elastic central loads. Also, it is observed that as the modulus of elasticity increases, so also does the initial slope of the load-deflection curve. Figure 7 compares room temperature and elevated temperature curves. The loads which correspond to the yield and ultimate tensile strengths respectively of 316SS 20% CW were found to decrease as temperature increases in accordance with previously reported data [11]. Upon completion of the finite element modeling which is currently under development, an attempt will be made to reproduce these curves and thus assess the ability of the MDBT test procedure to determine quantitative mechanical behavior information for a wide range of materials.

3. FINITE ELEMENT MODELING

The analysis of the MDBT data primarily consists in the conversion of the experimentally determined central load-deflection curve to stress/strain information via finite element solutions. In order to accurately analyze this highly

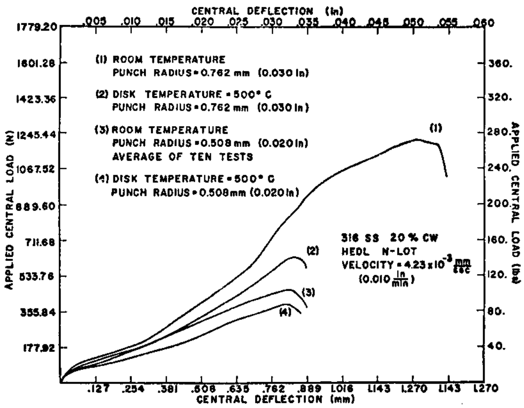

Fig. 7: Miniaturized Disk Bend Test experimental results for elevated temperature.

nonlinear boundary value problem with shifting contacts, a model to reproduce the frictional contact has been developed for the support [12]. Work is currently underway to apply a similar model to the punch. There is experimental evidence which suggests that the specimen may separate from the punch and leave only an annular section in contact for a punch tip radius of 0.508 mm. In all experiments using this size punch, the specimen was stuck on the punch tip after large plastic strains. Also, as shown in Figure 8, fracture has been observed to occur at a radial location of approximately 0.254 mm for 302SS shim stock. This is due to the fact that the punch tip is of finite radius and causes an abrupt change in specimen curvature at this location.

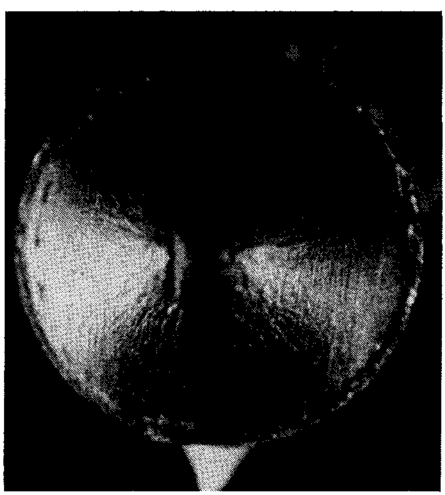

Fig. 8: Fractured 302SS Miniaturized Disk Bend Test specimen at 25 X showing fracture location.

Thus, it is anticipated that the friction-gap model applied at the support and also at the punch will prove essential in accurately predicting the specimen curvature as a function of central deflection and also in predicting the fracture location. Further experimental evidence illustrating the importance of accurately modeling the punch boundary condition is shown in Figure 7, where the punch tip radius is varied while all other experimental variables are held constant.

The ABAQUS [13] computer code was chosen for this modeling application because of its superior nonlinear capabilities and the fact that it already contains a simple two body single node frictional-gap model applicable to Cartesian space. The code uses classical Coulcomb friction with a stiffness in stick method to aid convergence. This simple model can be used as a basic building block to accurately represent multiple node friction contact boundary conditions for essentially any geometry by the introduction of the shadow node concept that helps monitor the region of contact between a rigid support and a deforming structure in contact with it. The details of this finite element development are beyond the scope of this paper and will be presented elsewhere. It will suffice here to state that the multi-point constraint equations due to such sliding contacts have been incorporated into the ABAQUS program as subroutines. A typical finite element mesh, using two dimensional axisymetric continuum elements, giving the detail near the sliding frictional support that has been used in the modeling is shown in Figure 9.

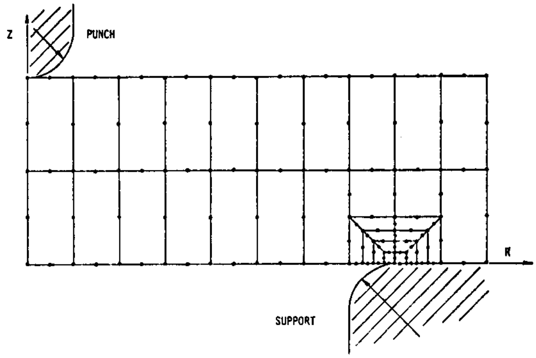

Fig. 9: Minizturized Disk Bend Test finite element mesh.

Parametric sensitivity studies are currently underway to perfect the finite element model. Limit analysis studies showed that the model yields correct results as the coefficient of friction approaches 0 and ∞ respectively. Work has been initiated to apply this model to the punch. This case is slightly more complex because of the additional velocity boundary condition. Although the current computations have been limited to elastic response only, they will be generalized to deal with parabolic hardening or any other piecewise linearizable stress-strain curve which the ABAQUS code can handle over large strains.

4. SUMMARY

1) A new mechanical behavior test using TEM sized disks has been designed, constructed and is being developed for postirradiation mechanical behavior determination. This new test is potentially capable of determining biaxial stress/strain response, biaxial ductility, stress relaxation behavior and biaxial creep response.

2) Initial testing indicates good experimental reproducibility. Central load-deflection curves have been generated for ten materials at room temperature and elevated temperature testing capability has been demonstrated.

3) A friction-gap boundary condition model is being developed to accurately model the MDBT using the finite element method to convert the experimental load-deflection curves into stress/strain information. The friction-gap modeling for the MDBT support has been completed for elastic disk response and the punch friction-gap model is currently being developed.

FOOTNOTES

[1]Material obtained from HEDL in rolled sheet 0.348 mm thick; heat designation 87210; HEDL N-LOT.

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