General Discussion: Miniaturized Disk Bend Test

This general discussion on the miniaturized disk bend test (MDBT) refers back to the four papers immediately preceding; that is, those by Hamilton and Huang, Manahan et al, Harling et al, and Klueh and Braski. The discussion is divided into two parts: (1) the responses of O. K. Harling and G. Kohse, and of M. P. Manahan, to specific questions on the MDBT, and (2) general comments on the technique by O. K. Harling and G. Kohse, R. L. Klueh and D. N. Braski, and M. P. Manahan.

Specific Questions and Responses

1. How critical is the centering of the disk in its die? What measures are used to assure its centering?

O. K. Harling and G. Kohse—The most critical alignment in disk bend testing, using the MIT punch-die geometry, is that of punch axis to die cavity axis, but specimen alignment is also important. Measurements indicate that specimen misalignments up to approximately 0.025 mm result in load/deflection variations of less than 2.5%. In current MIT MDBT practice, this tolerance is maintained by the precision of machining of the die, positioning washer, and specimen diameter. Punch-die alignment is verified to be within these limits by optical comparator measurements of the punch contact point on a polished specimen. Load/deflection curves for standardized specimens are run frequently to monitor possible misalignments or other equipment irregularities. The maximum width of the reproducibility band for such measurements over long periods is typically 5% of the mean up to the onset of fracture. See our paper for details.

M. P. Manahan—Centering of the disk as well as punch and die alignment is very important since the disk stiffness increases with eccentricity of loading and axisymmetry is assumed in the finite element model. It is, of course, possible to perform a three-dimensional analysis and account for misalignment. However, this approach is not cost-effective and we were able to demonstrate with two-dimensional finite element analyses that accurate results are obtainable, provided the total eccentricity of loading is less than approximately 0.0178 mm.

There are three basic contributions to total eccentricity that must be considered: (1) punch axis of symmetry not coincident with die axis of symmetry, (2) specimen not centered in apparatus, and (3) machining tolerances for punch, die, positioning washer, upper disk support structure, and specimen. The first eccentricity has been reduced by using a precision alignment fixture, the third by careful experimentation and by accurate machining of key components. The total eccentricity of loading was measured and found to be approximately 0.0178 mm for all the data presented in the paper. This measurement was made by placing a polished specimen in the die after alignment, applying a small load on the specimen, and subsequently measuring the location of the plastic indentations on both specimen surfaces in an optical comparator. For this eccentricity, the central load-deflection curves for ten tests fell within a band that is only 2.4% of the mean along the entire curve to the point of fracture initiation. An earlier reproducibility investigation with a total eccentricity of approximately 0.0635 mm yielded a reproducibility band that was within 4.0% of the mean along the entire curve to the point of fracture initiation. The results of a small deflection elastic analytical solution indicated negligible errors in the central displacement of the disk for eccentricities of loading as high as 0.1 mm; measurements verified that this prediction was indeed correct. However, the error in the central load-deflection response for the specimen with 0.0635 mm eccentricity becomes quite significant after relatively large portions of the plate have yielded. Also, data spread is reduced for the case where the alignment is improved.

2. How are the departures from linearity in the force-displacement record interpreted? Are they ambiguous?

O. K. Harling and G. Kohse—Departure from linearity of the load/displacement curve is associated with the onset of large-scale yielding in the disk. Although small volumes of the specimen experience plastic deformation before the departure from linearity, load/unload testing has been used to demonstrate that this does not contribute significantly to overall disk response. Ambiguity may arise in the case of materials with low yield stress, where the departure from linearity due to general yielding is obscured by nonlinear contact behavior which is observed at very low loads. In such a case, the transition from plastic bending to membrane stretching might be misinterpreted as the onset of large-scale yielding. This transition will normally involve stiffening of the load/deflection response, however, and this misinterpretation is therefore unlikely. Load/unload testing is in any case a useful tool for resolving potential ambiguities. See our paper for further discussion.

M. P. Manahan—Referring to Region 1 of Fig. 17 in our paper, there is an initial linear portion of the load-deflection curve for the MDBT. Also, at very small punch deflections, there can be an initial nonlinear region associated with the plastic indentation under the punch and around the support. The extent of this deformation depends on the material being tested. This portion of the load-deflection curve is not seen in Fig. 17 because of the scale chosen.

During the deformation on Region 1, yielding occurs first under the punch prior to any bulk plate deflection. Yielding occurs next on the bottom surface of the plate near the center because of bending. The yield surfaces propagate through the thickness near the center of the plate and then radially outward.

Strains on the order of a few percent are not uncommon before reaching the point of departure from linearity on the load-deflection curve. The departure from linearity is due to continued propagation of the yield surfaces radially outward but over much larger portions of the plate. The Region 1 behavior is governed by Young's modulus, the yield stress, and the initial hardening rate. Therefore, it is not, in general, possible to derive any stress or strain information directly from the MDBT load-deflection curve as is done in conventional uniaxial tests. It is recommended that finite element analysis be performed to convert the experimental data into stress and strain data.

3. What are the limits of buckling of the disk?

O. K. Harling and G. Kohse—Experimentation has demonstrated plastic instability in disks with a diameter-to-thickness ratio of 118, and no instabilities were observed for ratios of 60 or less (i.e., disk thickness $\lesssim$0.05 mm). No evidence of such instability has been observed in any materials tested with our standard diameter-to-thickness ratio of 12. An extensive theoretical analysis of this issue has not been performed.

M. P. Manahan—The aspect ratio (AR) of the specimen, which is defined as the diameter-to-thickness ratio, was varied by holding the diameter constant and changing the thickness. All other experimental variables were held constant.

Figure 8 of our paper presents the results for 302 stainless steel specimens with ARs varying from 11.8 to 118.0. A plastic instability was discovered for an AR of 118.0 as evidenced by the rapid load drop for Curve 1. Figure 9 shows the radial wave that developed at the point of instability. Another specimen with an AR of 118.0 was loaded to a level short of the buckling load as shown in Curve 7 of Fig. 8. There was permanent set in the specimen but no radial waves present. Further evidence that the observed phenomenon is a plastic instability was obtained by testing a specimen with an AR of 59.0 at 600°C. No instability phenomena were observed. Therefore it was concluded that the MDBT procedure is applicable for specimens with ARs of less than about 60.0 for stainless steel. Further work is necessary to more precisely define the buckling limits. The work reported to date was undertaken to assure that the 3 by 0.25 mm disk was adequate for testing stainless steel over the temperature range of 20 to 600°C.

4. To what limits of strain is the disk bend technique useful? What defines those limits?

O. K. Harling and G. Kohse—It is not yet clear to what strains disk bend test data are useful. In the MIT MDBT methodology, we can measure the load/deflection response of a disk to fracture, demonstrated for materials with greater than 50% total uniaxial elongation. Ductility information can be extracted using a simple analytical approach for brittle material (i.e., ductilities $\lesssim 5\%$). Useful qualitative comparisons can be made between material with higher ductilities. Ultimate tensile strength and ductility calculations at higher strain to fracture are contingent on improved finite element analysis.

M. P. Manahan—The limit of strain for the MDBT is determined by the limit of strain for which the finite element method is accurate. Finite strain theory has been benchmarked to very high strain levels. Therefore, for most materials of interest, there is no strain limit for the MDBT. This is why the finite element approach was originally pursued. Unfortunately, finite strain theory was not available in ABAQUS when the work reported herein was performed and the small strain theory was used.

Rodal (Ref *12* of our paper) showed that there can be significant differences between the results of finite and small-strain theories for strains greater than about 5% in thin structures. In the MDBT, we noted large force balance errors for strains in excess of about 25%. Up to this strain level, the calculated load-deflection curve fell within the uncertainty band for the measured data.

In general, the force balance tolerance and comparison of the model prediction with experimental data (model benchmarking) can be used to define strain limits for finite element formulations.

5. How accurately do the results of the disk bend tests predict bulk- or macro-behavior? What types of bench marking are necessary?

O. K. Harling and G. Kohse—In any miniature test the applicability to predicting bulk behavior is strongly dependent on homogeneity with respect to relevant specimen dimensions. The advantage of a disk bending method is that the contributions from material across almost the entire disk *diameter* are measured. Demonstration of relevance to bulk behavior for yield stress and small ductilities have already been made (see our paper). Bench marking of the test against uniaxially measured material properties for any new class of materials is strongly recommended.

M. P. Manahan—The goal of the first phase of research on the MDBT has been to show that the methodology is *capable* of delivering uniaxial stress-strain information with approximately the same level of accuracy as that obtained using large uniaxial specimens. In these experiments, the methodology was implemented in reverse order (i.e., the flow curve determined using conventional specimens was input to the finite element code, and the calculated and measured load-deflection curves were compared). A detailed discussion is presented in Refs *1* and *4* of our paper. The next logical step in this Phase I research is to use the finite strain theory as discussed in our response to Question 4 above.

However, the Phase I research answers only part of the question. The second phase of research is currently addressing the question of overall data inversion accuracy. The test would, of course, normally be used to determine unknown mechanical response. In this case, some additional uncertainty will be introduced by the data inversion scheme. The approach that is being pursued is to write an interpolation code to pick the actual solution which lies between two finite element solutions. It is cost-effective to develop this type of software since, for a given base alloy, it would be possible to decouple from the finite element analysis when a large enough data base has been developed. We plan to benchmark the method and assess the overall data inversion accuracy by testing an alloy using the MDBT technique for which the flow curve is not known beforehand and later comparing the results with measured uniaxial data.

6. What is the usefulness of current finite element models of the disk? How accurate are they? How can they be verified?

O. K. Harling and G. Kohse—Finite element modeling has been shown to be useful for calculating yield stresses from MDBT load/deflection curves. Verification by comparison to experimental results for materials of known properties has shown the current version to be accurate (within a few percent) up to a point beyond the deviation from linearity of the load/deflection curve.

For unirradiated 316 stainless steel we have been able to accurately model the disk bend load/deflection curves to one half the maximum load. Only very limited work has been done to model the entire load/deflection curve, to fracture, with large strain, large rotation finite element codes. It remains to be seen how well this can be accomplished. If it can be achieved, the entire plastic flow behavior can in principle be obtained.

Finite element models can be verified by comparing calculated and measured load/deflection curves for materials with known properties.

M. P. Manahan—A paper entitled, "Applications of a New Finite Element Boundary Condition Model to Reactor Structural Problems," will be presented to the 8th International Conference on Structural Mechanics in Reactor Technology in August 1985. Applications of the finite element model to a variety of structural problems in operating reactors are discussed. One possible application is in the analysis of containment penetrations for loads anticipated during a severe accident. The model enables a more mechanistic treatment of time-dependent penetration seal leakage estimation under various loads. Also, a variety of dynamic problems can be solved accurately using this model, such as pipe whip and missile impact analysis of reactor components. Other future applications include metals forming, automobile crash analysis, and shipping cask design.

The modeling approach may have some practical advantages over other approaches since fewer elements are used in our analyses than in codes using interfacial elements. Also, the boundary supports do not have to be modeled if the deformation response in those regions is not of interest. Further research is needed to quantify these potential advantages.

Finite element models are benchmarked by comparison with experimental data. The model has been benchmarked for the MDBT as described in our paper in this volume. However, benchmark experiments are recommended in the future as the model is expanded to other geometric and loading conditions. As shown in Fig. 12 of our paper, good agreement between the model and experiment was obtained for the MDBT using literature values for the friction coefficient. In future benchmark studies, the friction coefficient parameter can be effectively eliminated by lubricating the punch and die. Also, sensitivity studies on the friction coefficient are planned.

The problem of benchmarking large codes against experimental data is not trivial. It is meaningful to compare the mean and uncertainty in the measurements with the mean and uncertainty in the model predictions. Such an analysis can be very costly, however, since the code input and model assumption uncertainties must usually be treated stochastically and combined in meaningful way to yield the overall model prediction uncertainty. Until sponsorship for such and effort is found, we plan to continue to compare the code prediction obtained using the most representative set of inputs with the measured data to benchmark and define the model accuracy.

General Comments on the Miniaturized Disk Bend Test

O. K. Harling and G. Kohse—Mechanical property testing based on bending of a 3 mm diameter by (typically) 0.25 mm thick disk has been developed to a point where some useful mechanical property information can be extracted. Early work at Hanford developed an approach to ductility screening, using disk bending, for relatively brittle materials. At MIT we have worked on the development of a disk bend test which uses a specimen-punch-die geometry that allows the determination of load/deflection curves, to fracture, even for ductile materials. The MIT approach also includes the use of finite element modeling to attempt to extract the entire flow curve from the measured load/deflection response.

In our judgment the present status of the miniature disk bend test can be summarized as follows:

1. Ductilities of $\leq 5\%$ can be estimated using the HEDL analytical approach from data generated with HEDL or MIT size punches.
2. Yield stress can be extracted with useful accuracy for a range of materials using finite element calculations which model the load/deflection curve up to the point of deviation from linearity.
3. A gratifying level of reproducibility has been achieved in MIT disk bend testing.
4. Future work to extend finite element modeling to higher strains should be undertaken. Other mechanical properties, such as ductile-to-brittle transition temperature and relative fatigue life, may also be obtainable from disk bend testing.

R. L. Klueh and D. N. Braski—The idea of using a miniature disk bend test (MDBT) for determining mechanical properties on very small specimens is appealing, especially for irradiated specimens. However, we feel that much more work is required before this goal can be achieved. The MDBT technique, as originally developed by HEDL, was used qualitatively to determine if an alloy was embrittled by irradiation. As such, the technique has been used successfully by HEDL and ORNL as a screening test for identifying alloys that were embrittled by irradiation. Unfortunately, even under this simple mode of operation, we encountered problems, as pointed out in our paper. Intergranularly embrittled tensile specimens with total elongations of $\leq 1\%$ also failed intergranularly when tested in the MDBT. However, 50% cold-worked stainless steel tensile specimens that failed transgranularly with a total elongation as low as 0.5% survived the MDBT.

The extension of the MDBT technique to obtain quantitative information on tensile behavior requires more work. Certainly, before the technique is used to attempt to determine quantitative creep, fatigue, relaxation, and impact data, as has been proposed, it is first necessary to demonstrate that conventional uniaxial tensile information can be extracted from the MDBT load/deflection curves. We feel that "benchmark validation," as proposed in this symposium, needs to be conducted to prove that the MDBT can be used to quantitatively determine tensile behavior. A benchmark experiment would consist of determining the conventional tensile parameters using large conventional specimens and comparing them with the results obtained from miniature specimens prepared from the same heat of material. Although the need for benchmark validation has often been pointed out, these papers present only limited data pertaining to yield stress, while ultimate tensile strength, uniform elongation, and total elongation values determined from disk bend tests have not been compared with uniaxial data obtained in such a benchmark experiment.

For the MDBT technique to accomplish what has been proposed, it will be necessary to determine if the entire disk bend curve can be related to uniaxial tensile behavior. At present, there appears to be some uncertainty on this point. Until now, tensile results from the MDBT have generally been presented by comparing unirradiated and irradiated disk bend curves to show that the expected trends are followed. No ultimate tensile strength values have been presented, and no mention has been made of determining the total elongation, an important parameter when testing irradiated specimens. It is implied that the uniform elongation can be obtained from the power-law relationship for stress-strain curves. In actuality, this will present considerable problems, for, even under idealized testing conditions using large conventional tensile specimens, agreement between the experimentally obtained uniform elongation and that predicted by the power-law relationship for most engineering materials leaves much to be desired.

In summary, much developmental work is required on the MDBT. If the MDBT is capable of generating typical tensile test parameters, this should be demonstrated for several materials by conducting side-by-side tensile and MDBT tests on the same unirradiated materials over a range of temperatures and comparing the results. To our knowledge, no such tests have been carried out.

M. P. Manahan—Miniature specimen testing should begin with a careful characterization of the material microstructure. The largest microstructural heterogeneity can then be used to define the minimum specimen dimension. This approach, in conjunction with other size effect considerations (e.g., fracture mechanics parameter limits of validity) and careful benchmarking, will ensure that the results obtained are representative of large specimen and/or in-service component behavior. The miniature disk specimen design reported herein has been sized to meet continuum requirements, and this was verified by benchmarking with large specimen data.

The results of this initial phase of research indicate that the MDBT technique, when implemented properly, is capable of delivering accurate mechanical behavior data. However, additional research will be necessary before the MDBT can be used routinely with a high degree of confidence. It will be necessary to assess the overall data inversion accuracy, benchmark the finite strain solution, and perform sensitivity studies on the friction coefficient parameter. With regard to the latter, it may be possible to use lubrication to effectively eliminate the friction coefficient from the analysis. In order to enhance cost-effectiveness, a code is being developed which will interpolate between finite element solutions to find the actual stress-strain curve for a given experimental load/deflection curve. Eventually it will be possible to use the interpolation code solely when a large enough data base is developed for a given base alloy.

Provided this research is successful, the MDBT will prove to be a useful and cost-effective tool for materials characterization in a variety of applications. The miniature disk is among the smallest specimen ever used to determine macroscopic material behavior. By loading the disk transversely, gripping material is not needed and the fixturing time greatly reduced. Some likely applications include determining environmental effects (nuclear and non-nuclear) on materials, studying materials produced in small lots, and characterizing material removed from in-service components.