Overview

The chevron-notched (CN) test specimen has been the subject of experimentation for over 15 years; however, it has had the status of an ASTM standard only since December 1989. The CN specimen and test procedure was the subject of another ASTM symposium held in 1983; and a volume of those proceedings was published as a Special Technical Publication, ASTM STP 855. It is hoped that the contents of this current STP, which include papers presented at the symposium on 6 May 1991, will serve to promote greater interest in this unique specimen configuration, help refine the test method, and hasten its further acceptance.

The purposes of the symposium were three-fold:

1. To gather together the range of experience by users of the E 1304 Test Method when the method was applied to a variety of materials, in particular to uncover any problems, deficiencies, or opportunities so that improvements can be made when the E 1304 document is revised in 1993, according to ASTM regulations.
2. To examine applications and geometries outside the current standard, to assess their usefulness, and to provide data for possible inclusion in future revisions of the standard.
3. To invite the investigation of many different materials, including ceramics, so that the resulting data would aid in the development of standard fracture toughness tests for such materials utilizing the chevron-notched beam, the short rod, and the short bar.

In these respects, the symposium was a success. The papers included a bewildering variety of materials, representing metals, rock, plastics composites, adhesives, and ceramics. There is a very high probability that in the near future engineers and researchers will find within the experience summarized in this volume: (1) guidance that will help in the testing of most structural materials, (2) improvement of the E 1304 test method, and (3) aid to those concerned in the development of fracture toughness test methods for brittle materials.

The chevron-notched specimen has several advantages over other fracture toughness test specimens in providing a measure of fracture toughness. The specimen need be only half the size of an equivalent K_{Ic} (ASTM E 399) specimen to develop plane strain conditions at the crack tip. Further, it needs no fatigue precrack, which frees it from the need for fatigue equipment that can be both capital intensive and expensive to run. In addition, the specimen is particularly attractive to researchers testing brittle materials, such as ceramics, because a CN specimen will self-precrack without specially designed fixtures or a stiff loading system. Also, the specimen will fracture in a stable manner, and the maximum load is obtainable at a predetermined crack length; thus, the parameters required for fracture toughness are readily determined for brittle materials having a flat R-curve.

The remaining questions relate to the significance, applicability, and relevance of the numerical value determined by the test. It has long been seen by many researchers as a substitute for the well-accepted K_{Ic} test (ASTM E 399), but with some scientific and engineering conjecture over how well it fits the role. Is it a substitute, or is it a successor, or is it neither? This symposium has helped to resolve some of these questions.

Several papers examined the range of application of the CN specimen and are therefore extremely useful in establishing or modifying the ranges for future revisions of E 1304. In that regard, the paper by Orange et al. provides more general formulas for a wide range

of notch geometries for the short rod and short bar having geometries not included in E 1304. Three-point round bend bars having chevron notches and straight-through notches, as used by Qizhi and Xuefu, as well as the chevron-notched rectangular cross-sectioned beam tested by Jenkins et al. and Salem et al. are examples of potential standard geometries not included in the current standard. Further, they would be most appropriate as possible candidates for a standard fracture-toughness test method for both metals and more brittle materials.

Salem, Shannon, and Jenkins demonstrated that, although the CN toughness of metals and ceramics could agree well with those determined with other specimens, such as bend or compact tension, the CN specimen could give a nonconservative measure of toughness compared to established test methods, when "rising R-curve behavior" occurred, i.e., when toughness increased with crack extension. In some engineering endeavors, "nonconservative" translates to "possibly unsafe," so their conclusions should be indelibly noted.

The same observation is made by Bray, who correlated the results of ASTM E 399 and chevron-notched E 1304 testing on a wide range of aluminum alloys used in aerospace. He notes that the CN specimen yields a nonconservative measure of K_{lc} or K_q, as the toughness level increases. In some instances he explains this in the same manner as Salem et al., i.e., a rising R-curve effect, but in some cases the higher values are due to sample heterogeneity. Surface-to-center toughness variations are common in heat-treated aluminum alloy plates.

Bray proposes using the E 1304 method for the release testing of aluminum alloys for aerospace use, but only after establishing the correlation between K_{lv} and K_{lc} to confidence levels adopted by Military Handbook 5E. Given his data and information on the relative economics of the two test methods, it would appear to be only a matter of time before ASTM E 1304, i.e., K_{lv} testing becomes the most common method.

Whereas Bray compared the CN test results on aluminum alloys obtained with ASTM E 1304 with those obtained with ASTM E 399, i.e., K_{lc} or K_q, Purtscher et al. made their comparisons with ASTM E 813, the J_{lc} test method. They found that the CN specimens tended to give higher numerical measures of toughness, except in the case of lithium-aluminum alloys that suffered extensive interlaminar separation during fracture. In these alloys the delamination fracture mode is responsible for the relative changes in the measured toughness values.

The toughness of aluminum alloys was also the subject of the paper by Morrison and KarisAllen. Creatively, they compared the results of their side-grooved compact tension specimens (similar to those used to measure K_{lc}) with the results of CN specimens. It is generally accepted that it is the inherent side grooving of the CN specimen that permits the use of a smaller specimen size than that of the CT specimen; why then would side-grooved CT specimens not give more comparable results? For aluminum-lithium alloy 8090, the comparisons were good, but for other aluminum alloys, the CT side grooves reduced R-curve effects.

The CN results compared well with the CT results for aluminum alloy 6061, but they were marginally higher for the other alloys tested. Morrison et al. speculate, as did Bray, that this may be a result of the different volumes of nonuniform metal sampled by the differently sized specimens.

Martensitic stainless steels of high hardness were the subject of the Marschall et al. paper of side-by-side comparisons of the results of CN and CT specimens. They found that the CN specimen consistently gave toughness values 18% higher than K_{lc}, but, unlike Bray and Morrison et al., they could not attribute the difference to sample heterogeneity. They conclude that there is a different nature of the crack extension in the two specimens. In contrast, in a similar comparison of M-50 bearing steel, also of high hardness, Salem and

coworkers found no difference in measured toughness between 14 replicate CT tests and 9 CN tests of three different geometries. This suggests that there is a material dependency of crack growth behavior, and it lends credence to the warning in E 1304 that K_{Ic} and K_{Iv} cannot be used interchangeably unless correlations have been established previously. These authors also attempted to use the CN specimen to measure the fatigue crack growth rates in this steel and concluded that the chevron-notched shape accelerated crack growth.

In contrast to these high hardness steels, Tschanz, Matlock, and Krauss used the CN geometry of ASTM E 1304 to examine the static fracture behavior at various temperatures of much softer microalloyed steels with harnesses in the range 25 to 30 Rockwell C. In room temperature tests, the CN specimen sizes they used were all invalid, as were most of their low temperature tests, but they consider much of the data to be significant after considering the microstructural processes at the crack tips. They claimed that the processes, such as martensite formation, invalidate the validity checks in E 1304, and that the appropriate values should be considered "valid." This is an interesting concept that could apply to other nonferrous materials. If they are correct, then such changes could be considered for future revisions of the standard test method; but more work would be required to understand and characterize those materials that are detrimentally affected by the present validity checks of E 1304.

A number of authors sought to apply the chevron-notched geometry to the determination of interface toughness, or of the toughness of thin layers of a material between two thicker materials; this is probably because of the ability of this geometry to restrict crack growth to the region of the interface.

Rosenfield and Majumdar used a disc-shaped specimen loaded diametrically in compression, similar to ASTM standards used to determine tensile strength of concrete (C 496) and rock core samples (D 3967). The specimen used by these authors acted as a chevron-notched specimen for only a limited range of crack extension while the crack was within the chevron ligament. For greater extensions, the crack occupied the full specimen thickness, and, because of the absence of side grooves and the specimen being biaxially stressed, it was free to change mode. In this way, mode 1, mode 2, and mixed mode fractures could be studied in both monolithic and bonded specimens. Nevertheless, for large crack extensions, the specimen is no more a chevron-notched specimen than is a compact tension E 399 specimen with a chevron-shaped fatigue crack starter.

Lucas used the geometry of the 1304 standard method to examine a sandwich construction he calls a hybrid specimen. He claims reasonable agreement between the measured mode 1 toughnesses of materials measured by monolithic and by hybrid CN specimens after corrections were made for the different moduli of elasticity of the materials in the hybrid specimens. Rosenfield and Majumdar made no such correction because they claimed that the elasticity moduli of the materials were quite similar, but they also reported good agreement with data from bend specimens.

Rosenfield and Majumdar also examined the fractography of the failed interfaces between dissimilar materials and established the significance of the measured values in terms of the component being fractured. The fractures in the study by Lucas were, with little doubt, entirely within the expected layer, which was relatively thicker than Rosenfield's interfaces or "adhesive" material. To avoid generating misleading data, an investigator using thinner layers would have to follow the example of Rosenfield and Majumdar and take the precaution of making a mechanistic fractographic study.

It is also likely that other hybrid systems may be influenced strongly by residual stresses, such as those generated in high-temperature bonding or heat treatment or by shrinkage of adhesives. In the systems studied above, the selection of materials has enabled these prob-

lems to be avoided, perhaps fortuitously, or perhaps by the skillful avoidance of compli-
cations by the experimenters.

With these caveats in mind, it seems that the authors have demonstrated clearly that
chevron-notched specimens can be of use in measuring the fracture properties of interfaces.

The practical usefulness of the chevron-notched specimen is demonstrated in the paper
by Mueller. He used the specimen to demonstrate the effect of corrosion on the toughness
of dental amalgams. Dental amalgams are materials from which it is difficult to obtain
fracture test specimens from field exposures, but which can easily be used to produce a cast
CN specimen for laboratory exposure. Similar circumstances apply to the PMMA bone
cements studied by Bhambri and Gilbertson, to the benefit of those with cemented implants.
They examined the specimen size range over which useful data can be obtained, and they
noted strain-rate effects that might affect the design of equipment for impact sports, but,
tactfully, the authors stop short of imposing restrictions that might destroy the confidence
of patients indulging in these activities.

A number of papers dealt with ceramics, another class of nonmetallics. Qizhi and Xuefu
used three-point round bend bars containing straight and chevron-notches to measure the
toughness of limestone. They found the chevron-notched specimen easier to control and
obtain useful data because of the greater crack stability and the side groove constraint which
kept the crack in the desired plane. They did observe a size effect in the CN specimen: the
test value increased slightly with diameter, which was attributed to the R-curve effect. They
also noted that the CN specimen gave higher values of toughness than the straight-through-
notched specimen.

Jenkins et al. used the CN specimen to study the high-temperature fracture of a wide
range of ceramics, both monolithic and reinforced. The three-point bend bar was chosen
for simplicity of loading, which is an important consideration at elevated temperatures. They
acknowledge the usefulness of the geometry for material comparisons and extend the range
of parameters derived from the test to include R-curves and work of fracture. They conclude
that these parameters are necessary to fully evaluate materials showing nonlinear behavior,
an important point for those interested in developing a fracture toughness test for brittle
materials, as well as a possible addition to the present E 1304 test method.

Salem et al. also used the CN beam at elevated temperatures and examined the range of
geometry and sizes for which useful data can be obtained from the CN test. They concluded,
as did Jenkins and his colleagues, that test results on materials with flat R-curves are
independent of notch geometry and specimen size, but that this is not true for materials
with rising R-curves.

The papers briefly outlined here should provide the latest information and innovative
experimentation in the area of fracture-toughness testing using chevron-notched specimens.
Greater detail is provided within this volume to the reader having an interest in specific
papers.

Regarding the general but important questions posed earlier in this overview, i.e., is
ASTM Test Method E 1304 a substitute for ASTM Test Method E 399, a successor, or
neither? As with many general questions such as these, the answers are not clear-cut, but
have to be qualified. The results from several papers indicate that indeed the CN specimen
can be substituted if it is certain that the material being tested exhibits a flat R-curve response
or if statistical correlations have been established. The first, of course, implies *a priori*
knowledge of such material behavior. It also implies the employment of an R-curve test
prior to the use of E 1304. Thus, as cautioned in the test method itself, earlier in this
overview, and also by several authors, the E 1304 Test Method is neither a complete
substitute for the E 399 Test Method nor a successor. Nevertheless, it can and does serve
in many situations as a practical fracture-toughness test, as shown by all of the authors here.

Can a chevron-notched configuration be a candidate for a standard fracture toughness test of brittle monolithic materials? Again, from the results of several papers presented here (and of course elsewhere), it certainly appears so. Again; however, the same caveats are indeed applicable.

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