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MINIATURIZED CHARPY TEST FOR REACTOR PRESSURE VESSEL EMBRITTLEMENT CHARACTERIZATION[2]

REFERENCE: Manahan, Sr., M.P., "**Miniaturized Charpy Test for Reactor Pressure Vessel Embrittlement Characterization** , Effects of Radiation on Materials: 18th International Symposium, ASTM STP 1325, R.K. Nanstad, M.L. Hamilton, F.A. Garner, and A.S. Kumar, Eds., American Society for Testing and Materials, 1997.

ABSTRACT: Modifications were made to a conventional Charpy machine to accommodate the miniaturized Charpy V-Notch (MCVN) specimens which were fabricated from an archived reactor pressure vessel (RPV) steel. Over 100 dynamic MCVN tests were performed and compared to the results from conventional Charpy V-Notch (CVN) tests to demonstrate the efficacy of the miniature specimen test. The optimized sidegrooved MCVN specimens exhibit transitional fracture behavior over essentially the same temperature range as the CVN specimens which indicates that the stress fields in the MCVN specimens reasonably simulate those of the CVN specimens and this fact has been observed in finite element calculations. This result demonstrates a significant breakthrough since it is now possible to measure the ductile-brittle transition temperature (DBTT) using miniature specimens with only small correction factors, and for some materials as in the present study, without the need for any correction factor at all. This development simplifies data interpretation and will facilitate future regulatory acceptance. The non-sidegrooved specimens yield energy-temperature data which is significantly shifted downward in temperature (non-conservative) as a result of the loss of constraint which accompanies size reduction.

KEYWORDS: miniaturized Charpy V-Notch, Charpy V-Notch, impact testing, instrumented impact testing, reactor pressure vessel, absorbed energy, percent shear fracture area, lateral expansion

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[2]This paper presents information on miniature specimen testing and impact testing which is protected by existing patents and by pending patent applications.

Charpy V-notch (CVN) specimens are widely used within the nuclear power industry to monitor the effects of neutron damage to the reactor pressure vessel (RPV) beltline region. There is an ever-increasing need to obtain more notched bar impact data as plants age. Some plants have experienced more embrittlement than originally anticipated, and it will be necessary to develop plant-specific Charpy shift trend curve models to ensure continued safe operation. Since physically based trend curves have not yet been validated, and the physical basis of Regulatory Guide 1.99 (Revision 2) has been brought into question by several members (including the author) of the International Group on Radiation Damage Mechanisms (IGRDM), the use of plant-specific data will reduce operations costs for many plants since overly (arbitrarily) conservative models can be replaced by accurate, plant-specific models, provided sufficient data are available for development of the models. Since boiling water reactors (BWRs) typically only have three surveillance capsules, and pressurized water reactors (PWRs) only have three to five capsules, there will not be sufficient specimens available using the conventional technology to satisfy the data needs which have arisen over the past decade. The use of miniaturized specimens, which can be fabricated from previously tested full sized specimens, or from material cut from in-service components, offers one solution to this need for more fracture data. Miniature specimens can also be used to characterize the re-embrittlement rate after vessel annealing for those plants which exceed the established regulatory limits.

BACKGROUND

Prior to the current study, experiments were performed using sidegrooved miniaturized notch test specimens which demonstrated that 1/8 to 1/16 scale miniature specimens can be designed to yield transitional fracture behavior and that the fracture appearance and energy-temperature curves can be quantitatively related to the conventional ASTM Standard Test Methods for Notched Bar Impact Testing of Metallic Materials (E 23) specimen data [1]. However, since the specimen design used in these early feasibility studies was not optimized, the miniature specimen data required large correction factors to simulate conventional specimen ductile-brittle transition temperature (DBTT) data. Therefore, the study reported in Reference [2] was undertaken to optimize the specimen and test equipment design to produce a notch region stress field which closely simulates that of the conventional CVN and which minimizes, or preferably eliminates, the need for a post-test data correction. A combination of literature review, metallurgical analysis, and finite element analysis was used to consider such design parameters as minimum specimen cross-section, specimen length, notch acuity, the use of sidegrooves, sidegroove geometry, support span, and striker geometry. Two dimensional and three dimensional, elastic-plastic, large deformation, finite element analyses were used to compare stress/strain fields for standard and miniaturized specimens. Specimen and test machine geometries were developed which ensure: continuum requirements are met; the miniaturized Charpy V-notch (MCVN) specimen stress fields reasonably simulate those of the conventional specimen; and scatter for the miniature specimen data is minimized. This paper reports on the test results obtained using the Reference [2] optimized specimen geometry and test machine configuration.

EXPERIMENTAL METHOD

Specimen and Test Machine Preparation

The RPV material used in this study was taken from the Nine Mile Point Unit 1 (NMP-1) archive plate which carries the designation G-8-3. A heat treatment, which maintains the bainitic microstructure of the as-received plate, was developed to modify the microstructure of the material to induce a shift in the 41 J indexed transition temperature (ΔT_{41}) and a drop in upper shelf energy (ΔUSE) similar to those produced by exposure to neutron irradiation. Conventional CVN specimens were prepared and tested in accordance with ASTM standard E 23. As recommended in Reference [2], the miniaturized tests were performed using a nominal scale MCVN (4.83 mm x 4.83 mm x 24.13 mm) specimen. The cross sectional dimensions were chosen slightly under 5 mm to allow the MCVN specimens to be machined from broken CVN specimens. Testing was performed using a Tinius Olsen Model 84 Universal Impact Tester which is equipped with an optical encoder. However, the miniature specimen tests were performed using a scaled ASTM striker with a 4 mm radius and some tests were performed using a scaled ISO striker with a 1 mm radius. All of the strikers used in the study have been instrumented with strain gages. For both the scaled ASTM and ISO strikers, an anvil radius of 0.5 mm was used and the scaled span for all tests was 19.3 mm. Reference [2] recommended scaling the specimen, anvils, span, and striker radii because this has the advantage of standardization of approach and scalability of previously calculated finite element solutions.

In-situ Heating and Cooling

Conventional CVN specimens are usually heated in a liquid bath and transferred to the specimen support using precision centering tongs. ASTM standard E 23 requires that CVN specimens be struck within 5 seconds to ensure that the change in temperature resulting from the transfer to the support is negligible. As a result of the specimen size, manual transfer from a liquid bath and alignment of the miniature specimens is virtually impossible using centering tongs. Because of the reduced mass, the time for transfer from the thermal conditioning medium must be significantly reduced. While it is recognized that several laboratories have pursued an air-actuated robotic transfer approach, it is very difficult to remove and strike MCVN specimens in under 2 seconds with these systems. Further, the cost of such systems is high and the alignment accuracy and long-term reliability of these systems is questionable. Accordingly, an in-situ heating/cooling system has been invented to solve this problem. This approach has the inherent advantage that the specimen can be aligned to very high accuracy prior to starting the heating or cooling process. Another advantage is that the specimen is continuously thermally conditioned up to the instant of strike. Reduction of variability in these two critical experimental variables has substantially improved the quality of the miniature specimen data, and, although somewhat less dramatically, has improved the quality of conventional specimen data. Calibration of the in-situ heating/cooling system was achieved by placing a specimen, fully instrumented with thermocouples, in the support fixture and measuring the temperature as a function of time after installation.

Percent Shear and Lateral Expansion Measurement

The current E 23 methods for measurement of percent (%) shear fracture area are tedious and inaccurate. The use of a lateral expansion gage as specified in E 23 cannot be used with miniature specimens. In order to overcome these difficulties, a computerized image capture and analysis system has been developed. An accurate, digitized reproduction of the fracture surface at low magnification is stored on a personal computer. The digitized image is calibrated and precise area and length measurements are made which yield % shear and lateral expansion data in conformance with the intent of E 23.

RESULTS

Sidegrooved MCVN Specimen Data

Conventional specimens, miniaturized non-sidegrooved specimens, and optimized sidegrooved MCVN specimens were tested to determine how closely the optimized MCVN specimen simulates the stress fields present in the CVN specimen, and to compare the MCVN measured ΔT_{41} and ΔUSE data with the CVN data. The results of tests performed on the as-received material are shown in Figure 1. The sidegrooved MCVN specimens exhibit transitional fracture behavior over the same temperature range as the CVN specimens which experimentally confirms that the stress fields are similar as was demonstrated in the finite element calculations [2]. This result demonstrates a significant breakthrough since it is now possible to measure the DBTT using miniature specimens without the need for a correction factor. This development simplifies data interpretation and is expected to facilitate future regulatory acceptance. As shown in Figure 1, the non-sidegrooved specimens yield energy-temperature data which is shifted downward in temperature by 20°C (non-conservative) as a result of the loss of constraint which accompanies size reduction. It is important to note that the transition region slope for the sidegrooved MCVN specimens scales with the ratio of the fracture process volume as expected because the sidegrooved specimens are in plane strain over most of the length of the notch. The non-sidegroove specimens exhibit a downward shift in the temperature of the transition region because the material is being sampled under a plane stress condition.

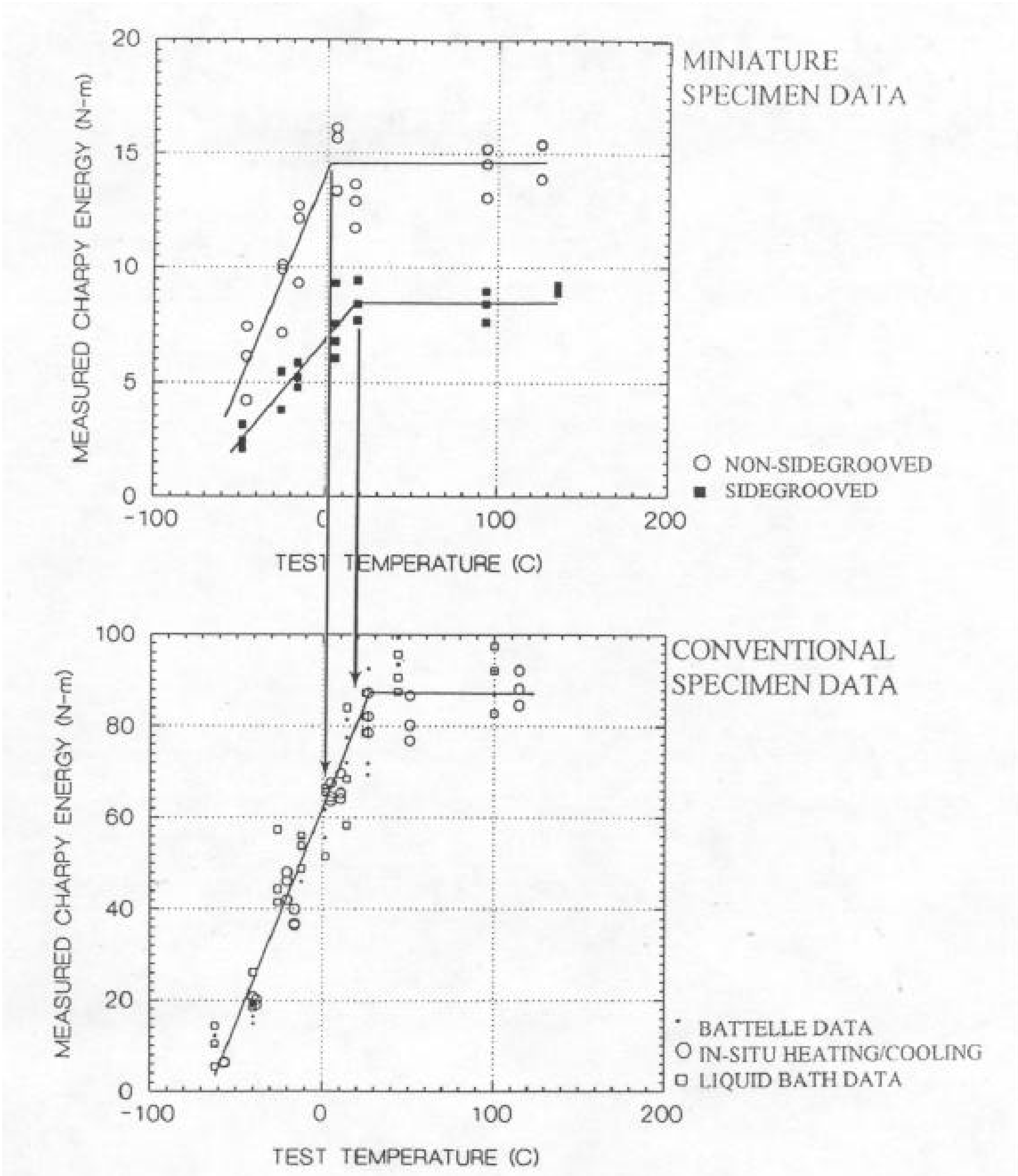

FIG. 1--Comparison of miniature and conventional specimen energy-temperature data. The sidegrooved miniature specimen stress fields closely simulate the conventional specimen stress fields and give the same temperature dependence of the fracture transition. The non-sidegrooved miniature specimens experience a downward temperature shift due to loss of constraint and require a correction factor.

In-situ Thermal Conditioning Data

Prior to testing the miniature specimens using the in-situ system, conventional specimens were tested using a liquid bath with transfer to the specimen supports using tongs as specified in E 23, and these data were compared with data obtained using the in-situ system. As shown in Figure 1, the in-situ data fall within the experimental scatter of the liquid bath data developed in the current study and data measured under the Battelle Nuclear Quality Assurance Program. Although the data suggest that the in-situ approach reduces scatter due to misalignment and temperature variation, additional testing in the future is needed to prove that the in-situ method is superior to transfer from a separate thermal conditioning medium.

Percent Shear Fracture Area

Within the nuclear industry, Charpy absorbed energy and lateral expansion are used in regulation. At present, % shear fracture area is not widely used within the nuclear industry and ASTM Standard Practice for Conducting Tests for Light-Water Cooled Nuclear Power Reactor Vessels (E 185) presently states that the DBTT shift at 50 % shear is an optional determination. The lack of focus on % shear is due in part to the difficulty involved in accurate measurement of % shear. The importance of % shear in Charpy testing cannot be under emphasized. It should be recalled that the original purpose of the Charpy test was to characterize the transition of the fracture modes from brittle to ductile as the temperature of the test is increased. Therefore, it can be effectively argued that % shear is a more fundamental measure of DBTT than either absorbed energy or lateral expansion. In fact, because of the USE drop and the decrease in slope of the energy-temperature curve in the transition region as a result of neutron irradiation, the % shear at the 41 J index changes continuously with irradiation. For a steel which exhibits a large shelf drop, tracking the embrittlement shift using an energy-based parameter (ΔT_{41}) would be overly conservative. Therefore, given the current usefulness of the % shear parameter, and the possibility of future regulatory acceptance as a less conservative but more accurate parameter, a new method for accurate measurement of % shear was developed as discussed earlier.

The % shear measurements are shown in Figure 2 for both CVN and MCVN specimens. These data are a definitive demonstration of the efficacy of sidegrooving in simulation of the conventional specimen stress fields. The CVN and MCVN specimen DBTTs measured at the 50 % shear index occur at essentially the same temperatures and the shifts due to the heat treatment (neutron irradiation simulation) are in very close agreement. The key Charpy shift parameters are summarized in Table 1. As observed with irradiated RPV steels, the lowering of the upper shelf and decrease of slope in the transition region results in a larger measured DBTT shift when an energy-based parameter is used. The Charpy shift at 41 J, 50% shear, and 0.89 mm of lateral expansion can be correlated with the shift in K_{Ic} or K_{Ia} to determine the best Charpy parameter for representation of fracture toughness shifts.

Lateral Expansion

The lateral expansion was measured using the image analysis system as described earlier. The results are summarized in Table 1. The difference between the CVN shift

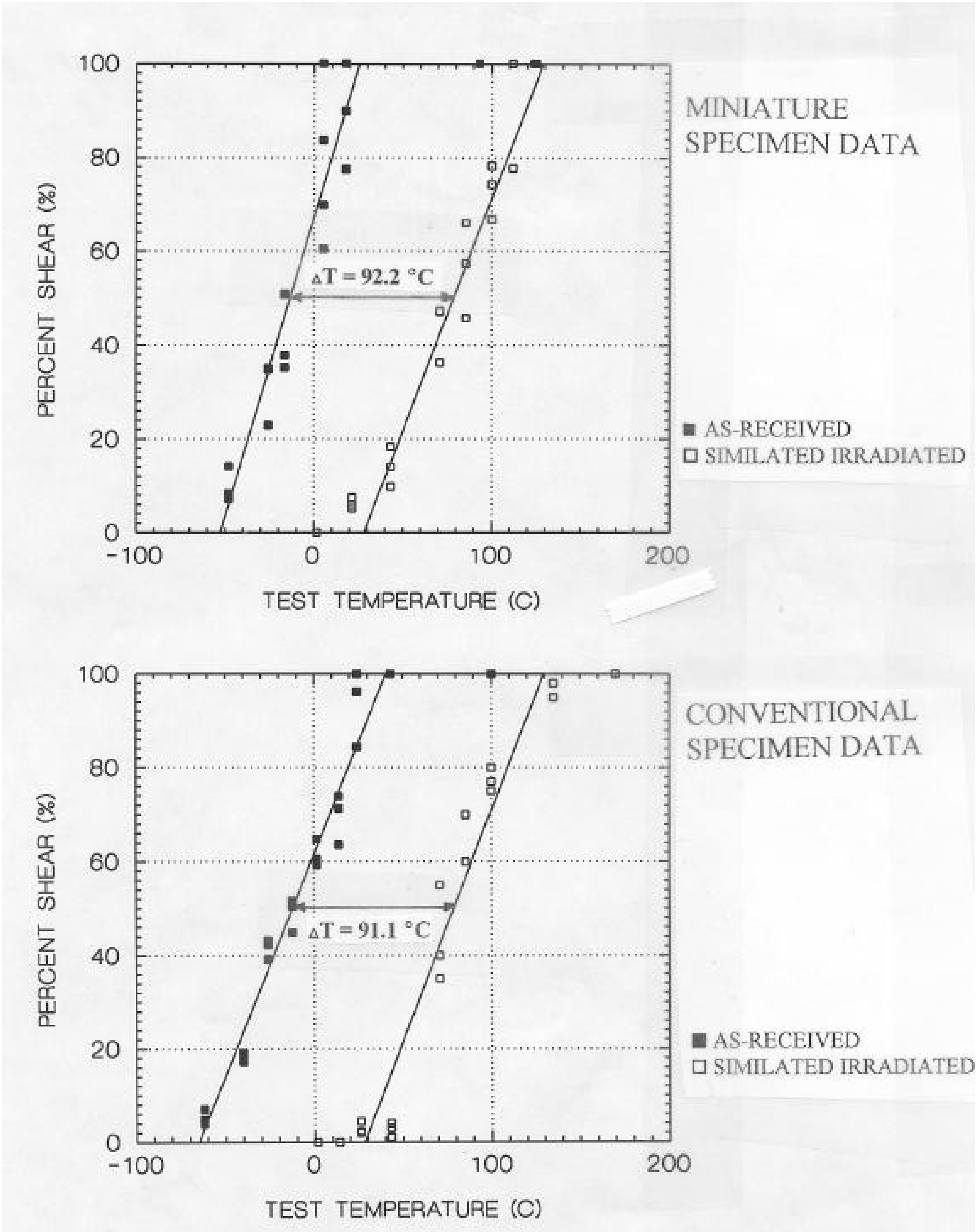

FIG 2--Comparison of fracture mode transition data for miniature and conventional specimens. Sidegrooving of the miniature specimens results in a notch region stress field which closely simulate that of the conventional specimen and precludes the need for analytical correction factors.

Table 1--Summary of Change in Key Charpy Parameters Due to Simulated Irradiation Heat Treatment. The Miniature Charpy Specimen Data Closely Simulates the Conventional Charpy Measurements.

Test Parameter	Conventional Specimen	Miniature Sidegrooved Specimen
Charpy Shift at 41 J[a] (30 ft-lb) Index (°C)	**152**	**149**
Charpy Shift at 50 % Shear (°C)	**91**	**92**
Charpy Shift at 0.89mm Lateral Expansion (°C)	**137**	**116**
USE Drop (J)	**42**	**40**

[a] The MCVN shift was measured at an energy which corresponds to the 41 J level in the CVN. This correspondance was established through a correlation with shear fracture energy.

and MCVN shift is larger than for the 41 J or % shear indices. This is believed to be a result of sparsity in the MVCN as-received material data which resulted in a poor regression fit. An interesting point related to the lateral expansion data is the fact that the magnitude of the measured lateral expansion is the same for both the CVN and MCVN specimens. This is because the stress fields (plane strain fields as demonstrated by finite element calculations) in the central portion of the specimen are similar in both specimens. Because of the presence of a free surface, the stress field near the side is plane strain and the lateral expansion deformation is controlled by this field. The net effect is MCVN lateral expansion of comparable magnitude to that measured in the CVN specimens. Since the magnitude of the lateral expansion does not change with specimen miniaturization, the index for the MCVN specimens can be taken the same as for the CVN specimens (0.89 mm).

Upper Shelf Energy

While the problem of obtaining transitional fracture data using MCVN specimens without the need for correction factors been solved by fabricating miniature specimens with sidegrooves, the magnitude of the energies measured using miniature specimens are significantly lower than for conventional specimens (compare the energy axes in Figure 1). Therefore, a scaling factor of general applicability is needed to provide quantitative USE data from MCVN specimens. Other researchers have attempted to formulate correlations for non-sidegrooved specimens. However, none of these correlations have been successful over wide ductility ranges. Therefore, work was performed in the current study which was focused on quantitative treatment of the MCVN measured USE to yield data of comparable accuracy to the CVN USE data. It was discovered that if the stress fields in the miniature and conventional specimens are similar, then a fracture process volume normalization can be applied directly to the miniature specimen data. The reason why the earlier attempts by other researchers were met with limited success is because the stress fields in the non-sidegrooved specimens do not closely simulate the conventional specimen stress field and the fracture process volume was not corrected for the ductility of the material being tested.

It was observed in the current work that when the stress field in the miniature specimen closely simulates that of the conventional specimen, then the energy required to initiate the crack (approximated as the pre-maximum load energy) at the root of the notch is ~ 1/3 of the total energy in both the CVN and MCVN specimens. This initiation energy proportionality is independent of the ductility of the material. Therefore, the pre-maximum load energy is proportional to the total energy absorbed by the specimen and finite element calculations of the plastic zone size prior to crack initiation can be used to correct the fracture volume to account for differing ductilities. This discovery is important since it precludes the need for performing finite element crack growth simulations. Since the ratio of the maximum load to the general yield load is proportional to the plastic zone size prior to crack initiation, this ratio can be used to adjust the calculation of the fracture process volume. This approach is appealing since the characteristic loads can be measured using the instrumented striker as discussed below.

In the case where the stress fields are similar, the ratio of the CVN USE to the fracture process volume (FPV) is proportional to the similar ratio for the MCVN specimens. In particular:

$$\frac{USE|_{CVN}}{FPV|_{CVN}} \propto \frac{USE|_{MCVN}}{FPVLINE_{MCVN}} \qquad (1)$$

The constant of proportionality is the degree to which the MCVN stress field simulates the CVN stress field and this constant is a function of ductility. Therefore, equation (1) may be written as follows:

$$\frac{USE|_{CVN}}{FPV|_{CVN}} = (PZCF)\frac{USE|_{MCVN}}{FPVLINE_{MCVN}} \qquad (2)$$

where,

$PZCF$ = plastic zone correction factor

Application of this approach to the G-8-3 plate resulted in very accurate MCVN USE data as shown in Table 1. This method must be validated in the future by applying equation (2) to a variety materials with widely varying ductilities.

<u>Analysis of Instrumented Striker Data</u>

Energy absorbed by the specimen was measured using the machine dial, an optical encoder, and separately by a strain gage instrumented striker for all of the tests performed in the current study. The accuracy of the conventional dial gage was not sufficient for the miniature specimen measurements. The instrumented striker provides applied load data as a function of time during the specimen impact event (see Figure 3).

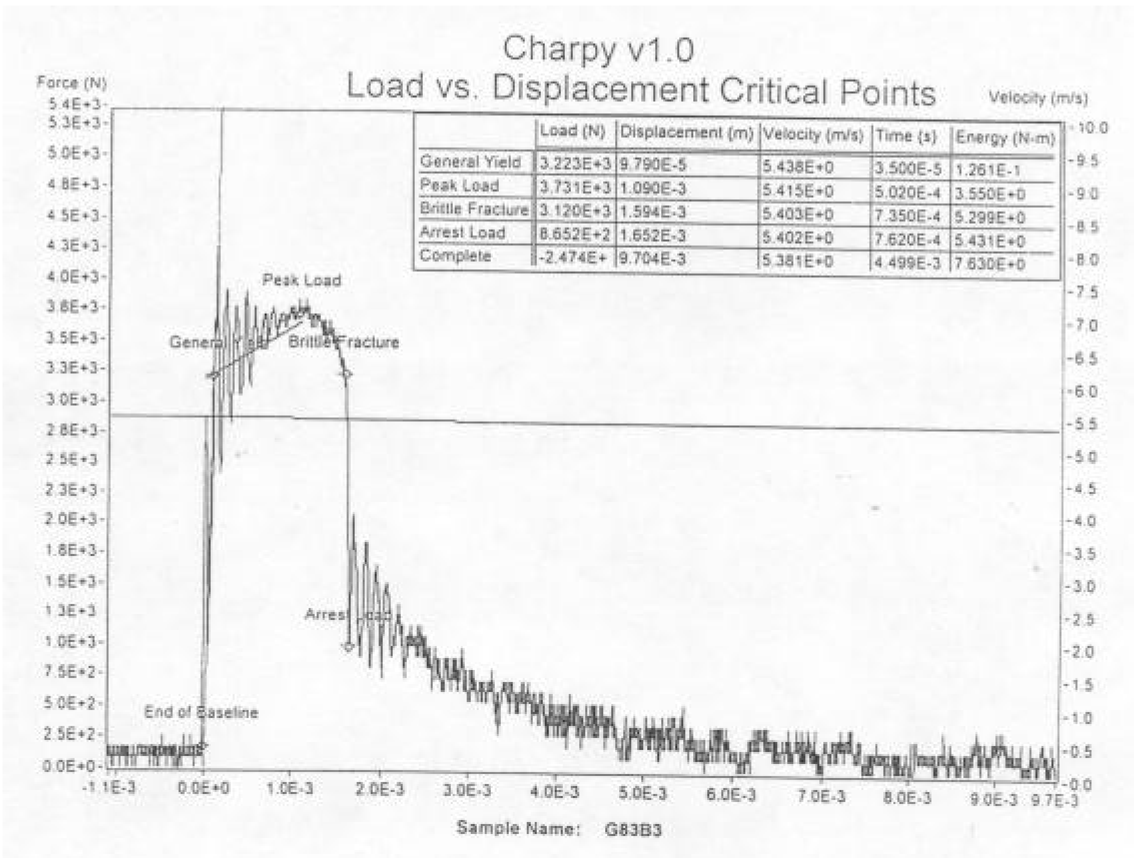

FIG. 3--Plate G-8-3 as-received material tested at 18°C (mid-transition) using MCVN specimens showing similar behavior as that observed for CVN specimens. The characteristic loads are used to define the onset of the transition region and the onset of the upper shelf. Integration of the load-deflection curve gives the energy absorbed by the test specimen.

These data can be analyzed to provide data which are very useful in characterizing transitional and upper shelf fracture behavior and to set temperature ranges for curve fitting. There are four characteristic load values of importance in instrumented Charpy testing: the general yield load, the peak load, the brittle fracture load, and the brittle fracture arrest load. The Charpy curve can be conceptually divided into three temperature regions: the lower shelf, the transition region, and the upper shelf. For tests conducted at lower shelf temperatures, the fracture surface is entirely transgranular cleavage. In this case, the maximum load is less than or equivalent to the general yield load. The general yield load is defined as the load at which the plastic zone below the notch extends through the entire specimen height. At the point where these loads are equivalent, the specimen begins to undergo plastic deformation prior to cleavage fracture and, therefore, by definition, this temperature marks the onset of the fracture mode transition region. The MCVN load diagram for Plate G-8-3 in the as-received condition is shown in Figure 4. As expected, the temperature at which the general yield load and the maximum load intersect is equivalent to the temperature at which the % shear begins to increase above zero.

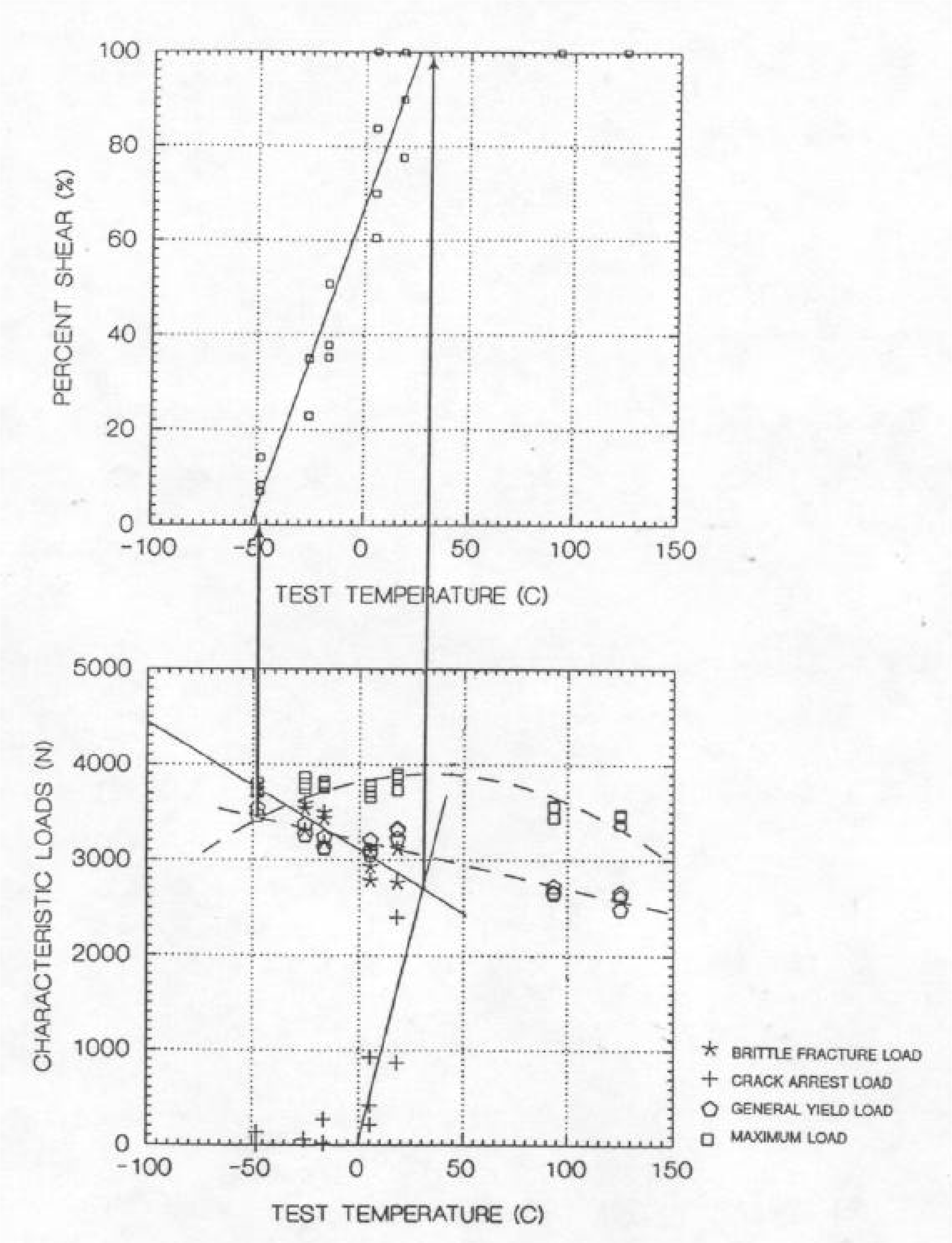

FIG. 4--Load diagram and fracture appearance data for Plate G-8-3 in the as-received condition tested using MCVN specimens. The temperature at which the brittle fracture load and the crack arrest load intersect defines the onset of the upper shelf. The temperature at which the maximum load and the general yield load intersect defines the onset of the transition region.

For tests conducted in the transition region, all four characteristic loads are determined (see Figure 3). The brittle fracture load is the point on the load-deflection curve where a sharp unloading occurs which corresponds to the rapid brittle crack propagation which terminates stable tearing. As the test temperature is increased, the brittle fracture load and the arrest load are closer in magnitude until the point of equivalency which marks the onset of the upper shelf. There is no brittle fracture component for tests conducted on the upper shelf, therefore, no evidence of rapid load drop. The temperature of the onset of the upper shelf can be determined by finding the intersection of the brittle fracture load and the crack arrest load. As shown in Figure 4, this temperature agrees with the temperature at which 100 % shear is observed.

Thus, the development of an instrumented striker system which enables accurate measurement of the characteristic loads provides additional data from the Charpy test which can be used to define the fracture transition region temperature range and to correlate the MCVN specimen measured USE with the conventional specimen data. The characteristic load data may also be useful in the future for calculating the % shear fracture area, and, perhaps for developing correlations for determination of fracture mechanics parameters.

SUMMARY

It has been demonstrated that miniature Charpy specimens can yield data which are essentially identical to that obtained using the conventional test. The miniature Charpy technology provides the opportunity to machine 8 miniature specimens from the broken halves of one conventional specimen. If the miniature specimens are tested and subsequently weld reconstituted, then a total of 24 miniature specimens can be produced and tested starting with the volume of a single Charpy specimen. Whether or not weld reconstitution technology is used, miniaturization dramatically increases the amount of data obtainable from a limited volume of material. This new technology provides the opportunity to develop plant-specific trend curves. For those plants which must undergo a vessel anneal, the miniature specimen technology offers a viable approach for accurate characterization of the benefits of the anneal and for monitoring of the re-embrittlement.

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