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Laser Weld Reconstitution of Conventional Charpy and Miniaturized Notch Test (MNT) Specimens

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ABSTRACT: As nuclear power plants approach end-of-license (EOL) and consideration is given to license renewal, there is an ever increasing need to expand the amount of data obtainable from the original surveillance specimens. A laser welding technique to reconstitute broken Charpy specimens is being developed to produce both conventional and miniaturized Charpy specimens. This paper reports on early laser welding development efforts and summarizes previous proof-of-principle experiments on a 1/16 scale miniaturized Charpy test. In order to benchmark the laser welding procedure, the laser-reconstituted specimen data have been compared with the original specimen data. In addition, the microstructure after welding has been examined to ensure that the material in the vicinity of the notch is essentially unchanged after the welding process. Data which characterize the thermal transient during welding are obtained by attaching thermocouples to the specimens. Other important considerations include perturbation of the stress field near the notch, dynamic stress waves, and contact of the weld region with the tup.

Precise control of welding parameters has been demonstrated, heat-affected zones as small as 0.25 mm can be achieved, and sufficient penetration depth can be obtained to enable welding thick sections (1T or greater) to yield conventional Charpy specimens or fracture toughness specimens and thin sections (~5 mm) to yield Miniaturized Notch test (MNT)[4] specimens.

KEYWORDS: Miniaturized Notch Test, Charpy test, laser weld, reconstitution

Miniaturized specimen technology (MST) permits the characterization of mechanical behavior while using a minimum volume of material. Hence, it has many applications, such as nuclear pressure vessel surveillance, failure analysis, and post-irradiation testing. It can also be used to characterize the mechanical behavior of in-service structures and components in cases where small pieces of material can be safely cut out. This paper focuses on the use

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[4] The processes described are explained in part in U.S. Patent No. 4,567,774, dated 4 Feb. 1986. A patent application on further improvements of the methodology is pending.

of innovative test techniques and the application of laser welding to obtain dynamic Charpy data from very small samples of material.

Reference *1* reported the first successful Charpy specimen miniaturization at a 1/16 size scale (as compared to conventional Charpy specimens). Since this specimen was designed close to the continuum limit of the material, further miniaturization in the cross-sectional dimensions is not possible. However, it may be possible to decrease the length requirement provided a suitable welding procedure can be perfected. To this end, several candidate welding technologies have been investigated and the laser welding process has been pursued. The laser welding approach also has the advantage of easy adaptation to larger cross sections for welding J_{IC} specimens. An example application is welding 1T J_{IC} specimen blanks used in surveillance capsule reinsertion programs [*2*]. This paper presents the results of a laser weld benchmark study using conventional Charpy specimens and summarizes the Miniaturized Notch Test (MNT). Based on the data reported herein, it is feasible to apply laser welding to fabricate MNT specimens using very small volumes of irradiated material.

Laser Weld Reconstitution

Although laser welding was chosen as the preferred method for reconstitution of radioactive materials, several other candidate methods were investigated. The welding approaches considered include: laser welding, electron beam welding, flash welding, arc stud welding, and friction welding. Since reconstitution is geared towards high-activity, hot-cell applications, an important requirement for the welding process is that it should be amenable to remote handling. Another key concern is the amount of material disturbed during the welding process. Two important parameters are the heat-affected zone (HAZ) and the net disturbed material (NDM). We have defined the NDM as the maximum distance (measured normal to the fracture surface) over which metallurgical transformation and/or microstructural changes have occurred. This distance is larger than the HAZ since most welding processes do not produce a planar HAZ which is parallel to the fracture plane. For laser welding, narrow HAZs can be obtained by optimization of three key weld process parameters: laser power, beam velocity, and focal length.

Laser Weld Penetration and HAZ

For the reconstitution of conventional Charpy V-notch specimens, it is desirable to have a single pass weld depth of at least one half of the Charpy thickness (5 mm). This minimum depth enables welding using a two-pass approach. Since the material ablation profile is parabolic, it is possible to adjust the welding parameters to achieve an essentially planar weld parallel to the fracture surface by using a two-pass procedure. In addition, it is best to use run-on and run-off tabs to avoid material distortion as the laser exits the material. The desired 5-mm depth was successfully achieved using a 3.0 kW CO_2 continuous wave laser at a power of 2700 W and speeds of 1.27 and 1.54 cm/s, respectively.

The peak temperature during welding was measured experimentally by attaching thermocouples to the specimen. A computer-controlled data acquisition system was used to collect data at small time intervals during welding to determine the peak of the thermal transient. For nuclear pressure vessel applications, the critical temperature of the fracture process region is taken to be 288°C to ensure that the radiation damage has not been affected. However, future work should focus on determining the maximum temperature allowable for short duration temperature pulses. Based on these measurements, we have concluded that a region extending 4 mm on either side of the weld plane contains material which is above reactor operating temperature for a short time during laser welding. Therefore, a 10-mm insert was chosen as the smallest insert for laser welding research on conventional Charpy specimens.

Plastic Zone Size Considerations

Other researchers have experimented with inserts as small as 10 mm using arc stud welding and had only limited success [*3,4*]. The poor results obtained using a 10-mm insert may be due to metallurgical changes, plastic zone interference, and/or contact of the tup with the hard HAZ region. At the present time, there are not sufficient data available to come to a definitive conclusion. The concern is that in minimizing the insert size, the weld planes, along with their HAZs, will perturb the plastic zone and influence the local stress field. The Belgians [*4*] have reported a truncation of the plastic zone for the arc stud welding approach when using a 10-mm insert.

The plastic zone normal to the crack plane (PZN) was calculated for test temperatures ranging through the transition region to the upper shelf. These results are summarized in Table 1 for the A302B steel. Based on these PZN data, it was estimated that plastic zone and HAZ interaction will not occur for a 20-mm insert until a 130°C (266°F) test temperature has been reached. For the unirradiated modified A302B material used in the current study, we concluded that inserts larger than about 15 mm would be needed to test on the upper shelf.

The PZN data were compared with earlier arc stud weld data. Battelle Laboratories conducted a study for EPRI on reconstituted Charpy specimens for insert sizes of 22.5 and 10 mm [*3*]. SCK-CEN of Belgium conducted a reconstitution study on A533B HSST 03 steel with 10-mm inserts [*4*]. Both studies used unirradiated A533B steel for Charpy reconstitution, and limited irradiated data were generated in the Battelle work. Overall, application of the PZN criterion for defining the minimum insert size is consistent with the literature data.

At the present time, it is not possible to draw firm conclusions concerning the importance plastic zone and HAZ interaction effects. The preliminary analysis reported here seems to suggest that when the PZN distance is approximately equal to the distance from the crack

TABLE 1—*Change in the plastic zone normal to the crack plane (PZN) as a function of temperature, strain rate, and irradiation for A533 Type B steel with an NDT = −17.8°C (°F).*

	Plastic Zone Normal to Crack Plane (PZN)[a]			
Temperature °C (°F)	Unirradiated Static,[b] PZN, mm (in.)	Irradiated Static, PZN, mm (in.)	Unirradiated Dynamic,[c] PZN_D, mm (in.)	Irradiated Dynamic, PZN_D, mm (in.)
−73.3 (−100)	0.913 (0.0360)	0.574 (0.0226)	0.374 (0.015)	0.229 (0.009)
−45.6 (−50)	1.24 (0.0489)	0.657 (0.0259)	0.510 (0.020)	0.269 (0.0106)
−17.8 (0)	2.27 (0.0894)	0.752 (0.0296)	0.806 (0.032)	0.325 (0.0128)
10 (50)	6.52 (0.257)	0.973 (0.0383)	1.56 (0.062)	0.425 (0.0167)
37.8 (100)	29.34 (1.15)	1.65 (0.0649)	3.95 (0.156)	0.637 (0.0251)
65.6 (150)	34.91 (1.37)	4.32 (0.170)	12.41 (0.489)	1.18 (0.0463)
93.3 (200)	35.96 (1.42)	17.98 (0.708)	28.33 (1.11)	2.79 (0.109)
121.1 (250)	36.95 (1.45)	28.28 (1.11)	29.23 (1.15)	8.34 (0.328)
148.9 (300)	37.88 (1.49)	29.02 (1.14)	30.07 (1.18)	22.9 (0.901)

[a] $PZN = \left(\frac{K}{\sigma_{eff}}\right)^2 \left(\frac{1}{2\pi}\right) \cos^2\left(\frac{\theta}{2}\right)\left[1 + 3\sin^2\left(\frac{\theta}{2}\right)\right] \sin(\theta)$; where: $\theta = 70.83$ for PZN = PZN (max).

[b] Static strain rate = 1×10^{-2}/s; dynamic strain rate = 3×10^2/s.

[c] Fluence = 3.2×10^{18} n/cm^2.

plane to the HAZ, energy loss may occur. However, other phenomena such as stress wave reflection during dynamic impact, residual stresses, and the interaction of the relatively hard HAZ with the tup must be carefully assessed in the future.

Comparison of Laser Weld and Conventional Charpy Data

Figure 1 shows the comparison of the laser weld reconstituted data with the conventional specimen data. The laser weld specimens were prepared from the broken halves of the conventional specimens. As shown in Fig. 1, the laser weld specimens prepared using 14 and 20-mm inserts compare well with the conventional specimen data. However, the laser weld specimens prepared using 10-mm inserts yield Charpy energy data below the conventional specimen level above the mid-transition temperature region. Future work should be focused on validating the use of 10-mm inserts for characterization of the 41 J transition temperature.

Miniaturized Notch Test (MNT)

Progress on the development of the MNT has been reported in References *1, 5, 6.* This section briefly reviews the key findings related to the MNT. It is anticipated that laser weld reconstitution technology will evolve and eventually be used to reconstitute miniature specimens.

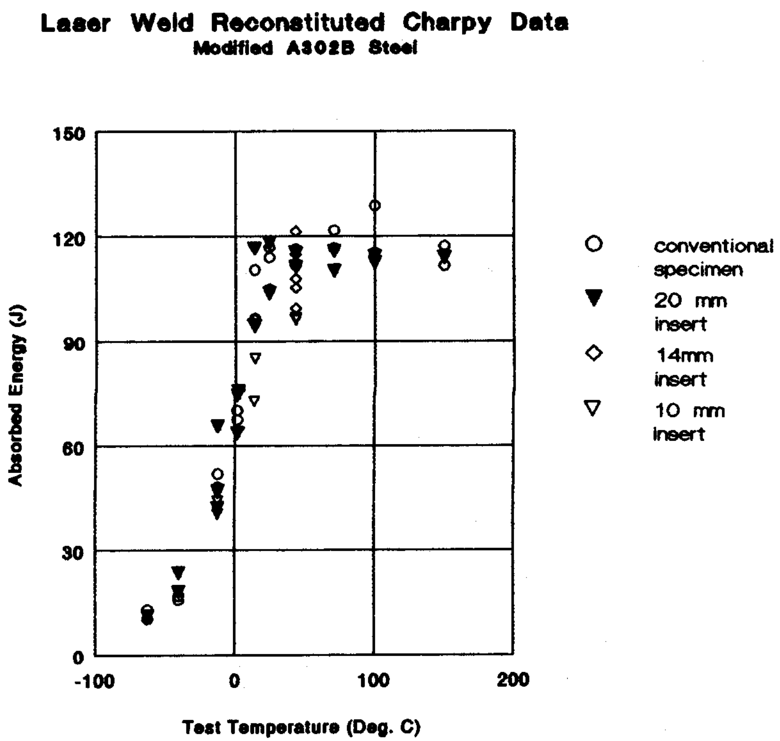

FIG. 1—*Comparison of laser weld data with conventional Charpy specimen data.*

In order to achieve successful test results at the 1/16 size scale, two key developments were necessary: (1) modify the stress field in the vicinity of the crack plane; and (2) develop an energy-based parameter and index that can be related back to the standard specimen test (energy and the 41 J index). An important limitation in miniaturizing any specimen is the extent of the material's microstructural inhomogeneities. The usual guideline dictates that the specimen be at least five to ten times as large as the characteristic heterogeneity dimension. Material for this work was taken from a special heat of ASTM A508 steel provided by Oak Ridge National Laboratory (ORNL) for crack arrest research as part of the Heavy Section Steel Technology (HSST) Program. Conventional mechanical property and microstructural data are available for three different heat treatments, designated 6, 5A, and 6R, in order of increasing toughness and increasing tempering temperature. Microscopy analysis indicated carbon segregates in slender bands about 0.25 mm wide. As a result of these findings, the minimum specimen dimension should be in the range of 3 to 5 mm. For a tension specimen, this minimum size limits the diameter or thickness, and, for a fracture behavior specimen, this minimum limits the dimensions of the crack plane.

Stress Field Modification

Early MNT tests demonstrated that 1/16 size scale miniature Charpy specimens, when tested in the transition region or upper shelf, yield data which cannot be properly analyzed nor related to conventional Charpy data. Figure 2 illustrates the severe nonplanar fracture surface which results. Therefore, to overcome this difficulty, the stress field in the vicinity of the crack plane must be modified. Stress field modification to achieve plane-strain conditions is discussed in Ref 7 in these proceedings. In the case of the MNT, achieving plane strain is neither necessary nor desirable. The fundamental objective is to modify the stress field so that flat fracture is obtained. In the current research, this is accomplished by side grooving the MNT specimen and locating the root of the side-groove notch such that the tensile fields at the root of the notch overlap and produce through thickness tensile stress. MNT specimens which have been stress field modified are shown in Fig. 2. Thus, the experimental hurdle of achieving flat fracture in MNT specimens designed at the continuum limit has been overcome.

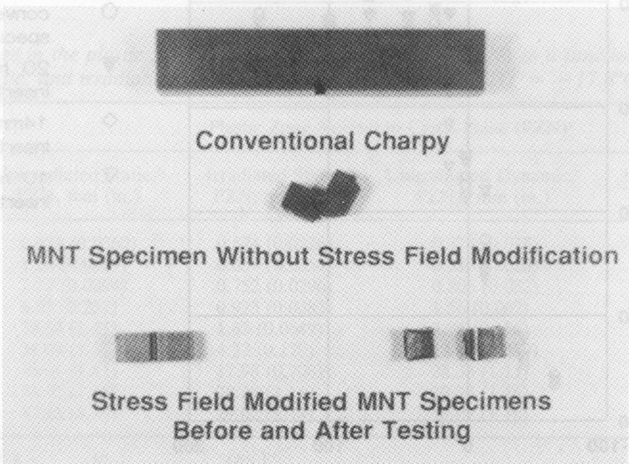

FIG. 2—*Photograph of MNT specimens tested at the same temperature showing the effects of stress field modification.*

MNT Energy-Based Parameter

Several ductile-brittle transition temperature (DBTT) criteria are used in different industries. Since nuclear pressure vessel surveillance is the application of current interest, the 41-J (30 ft-lb) energy absorption level was used as a reference. For the three heat treatments, the Charpy DBTTs are as follows: heat treatment 6, 40°C; heat treatment 5A, −7°C; and heat treatment 6R, −29°C. The key element of data interpretation is to be able to find a physically based parameter and an appropriate index that relate the miniature and conventional specimens. In this context, the term "parameter" means the range variable (e.g., energy, fracture appearance, lateral expansion) and the term "index" means the transition temperature indicator (41-J, 0.89-mm lateral expansion).

The criterion by which the parameters and indices were judged is that the fracture mode in the miniature specimen must be the same as that in the conventional specimen for a given parameter and index level. As shown in Table 2 for the material tested, the MNT specimen exhibits 70% shear at the 41-J index level compared to the conventional CVN specimen, which exhibits only 4% shear. Therefore, the absorbed energy alone is not considered to be a valid parameter for DBTT characterization with MNT specimens for the A508 steel.

It is well established [*8*] that the total energy absorbed in fracturing a Charpy specimen can be further partitioned into pre- and post-maximum load energies. The pre-maximum load energy can be partitioned into elastic stored energy, crack formation energy, and plastic deformation energy. The miniature specimen differs from the conventional one in size and in geometry. Since the miniature specimen has a different span-to-width ratio, different anvil and punch geometry, and has side grooves, the crack initiation energy and its ratio to total energy is different in the two specimen types and, therefore, is not a useful parameter.

The post-maximum load energy (PME) can be partitioned into elastic stored energy, plastic deformation energy, and stable crack propagation energy. The elastic stored energy is available to drive the cleavage fracture for tests conducted in the transition region. The remaining PME is associated with the plastic deformation work and work that goes into propagating a stable crack. Therefore, the PME would be less sensitive to differences in specimen geometry and correlates well with fracture appearance (i.e., percent shear). In the present study, it has been assumed in the analysis that the onset of the maximum load corresponds to crack initiation. While this assumption is reasonable for some materials and test temperatures, it was not actually measured in the test program. In future studies, this question should be resolved by using the electric potential method during testing.

By partitioning the total energy into pre- and post-maximum load energies and plotting these data against test temperature, it can be shown that the pre-maximum load energy does not show a conspicuous transition in fracture behavior. As stated earlier, pre-maximum load energy is associated with elastic stored energy, crack initiation, and plastic deformation near the notch. On the other hand, the PME exhibits a distinct transition because this parameter

TABLE 2—*Percent shear fracture appearance for MNT and conventional Charpy specimens for two indices.*

	Percent Shear Fracture Area at 512 kJ/m^2	Percent Shear Fracture Area at 41 J
Standard specimens[a]	~4	~4
Miniature specimens[a]	~1	>70

[a] All three materials.

is directly associated with the fracture process. Figures 3 and 4 illustrate this behavior for the Heat Treatment 6 material. The other two materials, 5A and 6R, exhibit the same behavior.

Crack initiation was defined as the complete formation of a full-width crack across the length of the notch. If crack initiation, as defined here, is complete when maximum load is reached, the PME should correlate with percent shear for various specimen sizes and shapes regardless of material. Assuming this to be the case, it was thus considered theoretically sound to use PME as a parameter for ductile fracture transition characterization. Differences in specimen size result in the absolute values of PME being different among specimen types. However, the relative proportion of the energy that goes into crack propagation and plastic deformation should correlate with fracture appearance for specimens of different sizes and

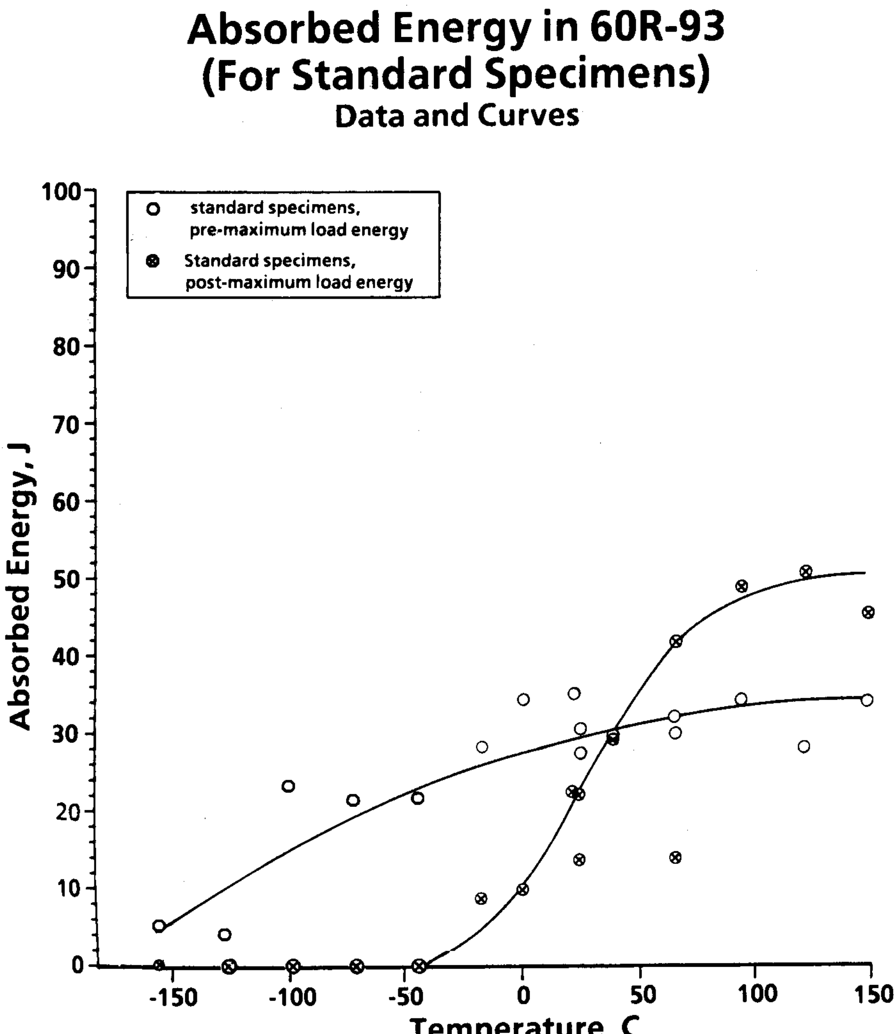

FIG. 3—*Pre- and post-maximum load energies compared (standard specimens, Heat Treatment 6).*

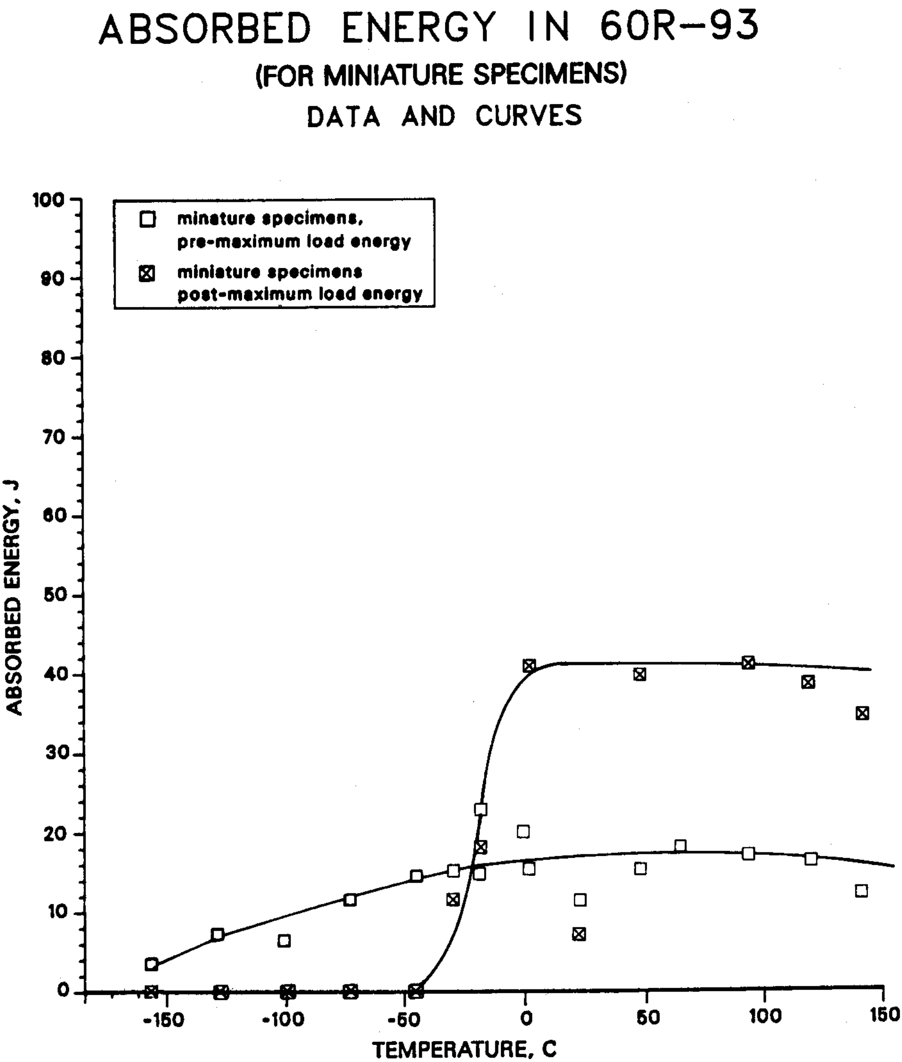

FIG. 4—*Pre- and post-maximum load energies compared (miniature specimens, Heat Treatment 6).*

shapes. Therefore, the absolute values of PME can be converted to percentages by dividing by the total energy (excluding shear lip formation energy). As stated previously, the total energy used in the calculations is defined as the sum of the absorbed energy up to the onset of cleavage. Therefore, any energy absorbed in the formation of shear lips was not included. A MCFRAC [9] plot of percent shear fracture appearance versus percent PME is given in Fig. 5. This figure shows that the data for all three materials in both specimen geometries fit the same curve. A correlation of this kind now allows the use of two criteria, one based on energy and the other on fracture appearance. It is recognized that this correlation is most likely base alloy dependent.

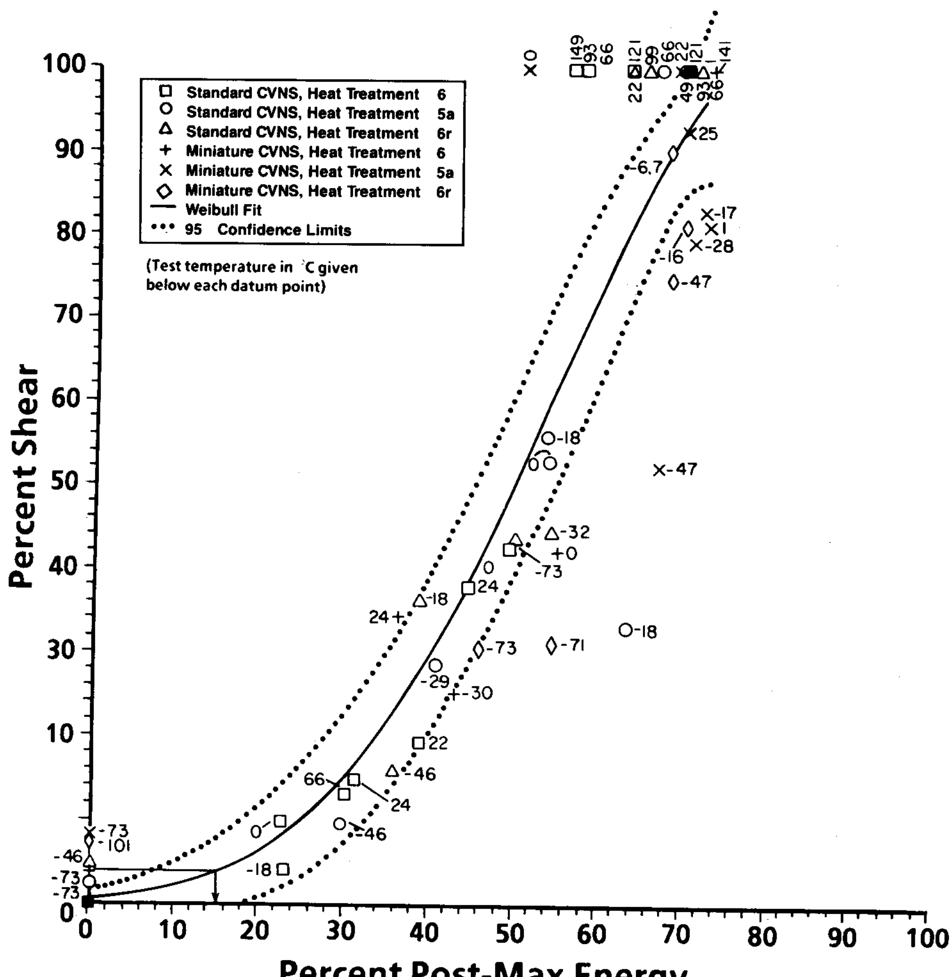

FIG. 5—*Percent PME as a fracture transition criterion (both specimen sizes).*

MNT Indices

As discussed in Ref *1*, either percent shear or present PME can be used as valid MNT parameters. Since the regulations within the nuclear industry are based on the 41 J index with absorbed energy as the parameter, the percent PME is preferable since it can be related directly to the conventional specimen absorbed energy and does not require tedious fracture surface analysis. Figure 5 provides the correlation for obtaining these indices for both specimen dimensions. This technique can be used to relate any specimen geometries that yield notched specimen fracture transition data. In particular, a Charpy energy level of 41 J corresponds to ~4% shear fracture appearance. Referring to Fig. 5, this level of shear corresponds to ~15% PME. Thus, when fracture appearance is used as the MNT parameter, the corresponding index is 4% shear. When percent PME is chosen as the MNT parameter, a value of 15% PME is used as the index. Therefore, when the PME parameter is plotted against test temperature (Figs. 6–8), transition temperatures for each material may be obtained at the 15% PME level. Table 3 summarizes these transition temperatures.

On comparing these transition temperatures with the standard dynamic CVN transition temperatures, correction factors due to rate effect and size effect are obtained. This is illustrated schematically in Fig. 9. The average shift due to rate effect for the conventional CVN is 45.3°C [*10*]. This shift was determined by averaging the static to dynamic shift at the 41-J level for the three materials using conventional Charpy specimens. As discussed earlier, this is in reasonable agreement with the correlation presented in Ref *11*.

Table 4 presents the shifts due to rate and size effect. These data can be used to relate the MNT data with conventional, dynamic Charpy data for the ASTM A508 steel. The

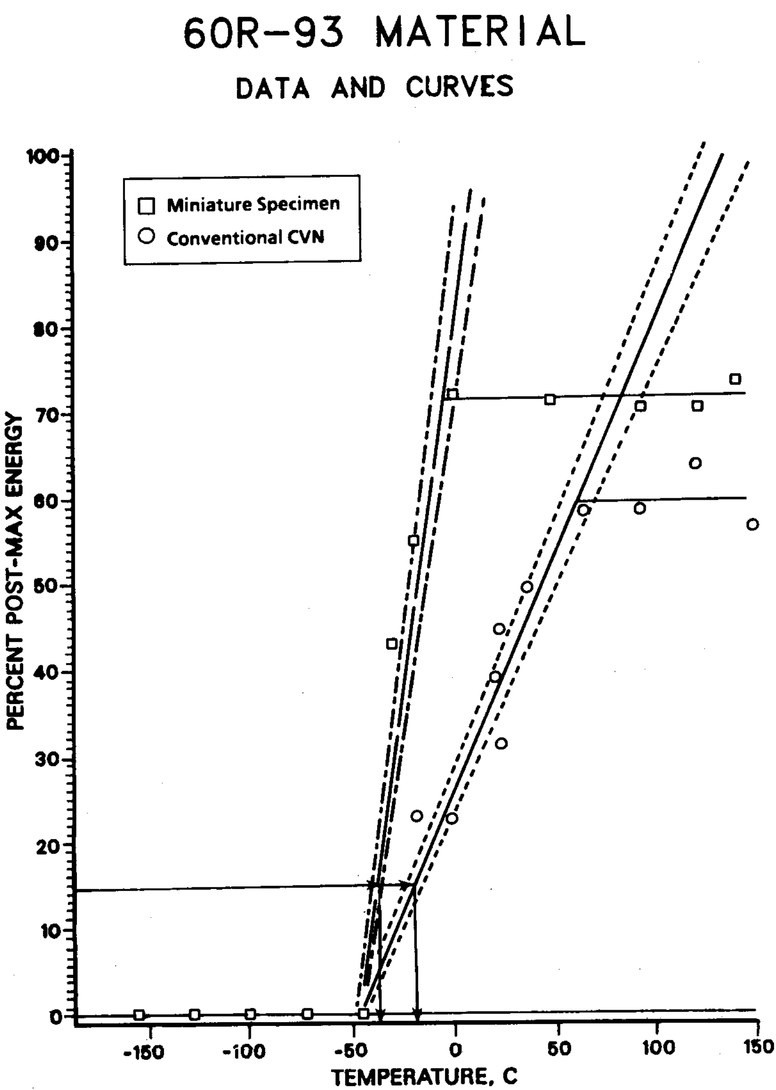

FIG. 6—*Transition temperature from 15% PME index (heat treatment 60R-93 material, both specimen sizes).*

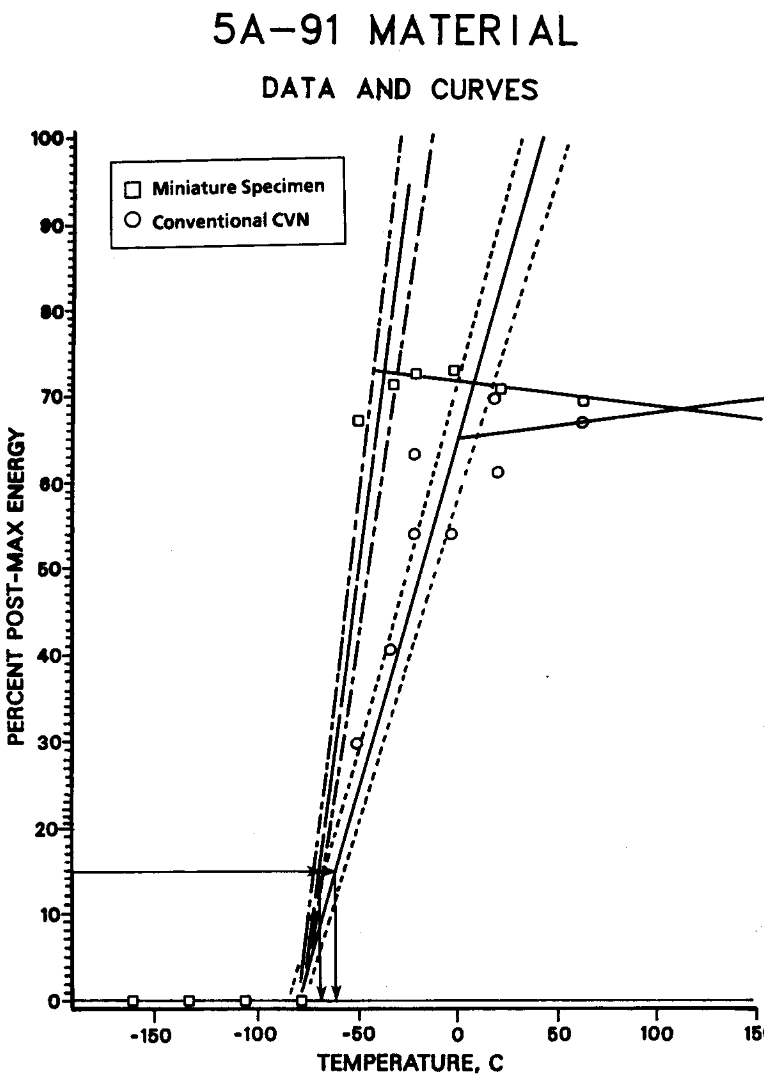

FIG. 7—*Transition temperature from 15% PME index (heat treatment 5A-91 material, both specimen sizes).*

dynamic 41-J transition temperature is obtained by adding the rate effect shift (44.1°C) and the size effect shift (21.3°C) to yield a 41-J dynamic conventional Charpy transition temperature. This is the approach that would be used in cases where the MNT is used to test irradiated pressure vessel steels and there is no archival material available for testing.

In cases where unirradiated archival material is available, it is possible to machine unirradiated and irradiated MNT specimens and measure the shift directly. The strategy would be to first develop the unirradiated MNT data, test the surveillance capsule Charpy specimens, machine the irradiated MNT specimens from the broken Charpy specimens, and test and/or reinsert the MNT specimens back into the reactor to generate plant life extension data.

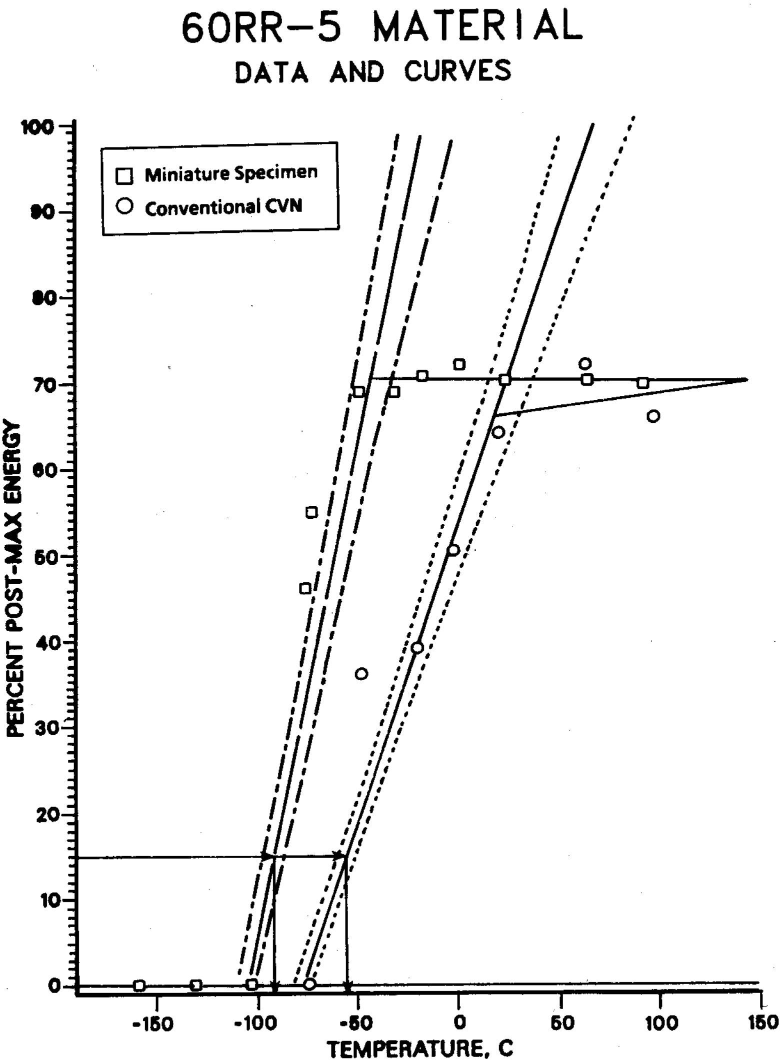

FIG. 8—*Transition temperature from 15% PME index (heat treatment 60RR-5 material, both specimen sizes).*

TABLE 3—*Standard CVN and MNT slow-bend transition temperatures.*

	Heat Treatment					
	6		5A		6R	
Indices	Standard CVN, °C (°F)	MNT, °C (°F)	Standard CVN, °C (°F)	MNT, °C (°F)	Standard CVN, °C (°F)	MNT, °C (°F)
15% PME	−18 (0)	−37 (−35)	−57 (−70)	−65 (−85)	−54 (−65)	−90 (−130)

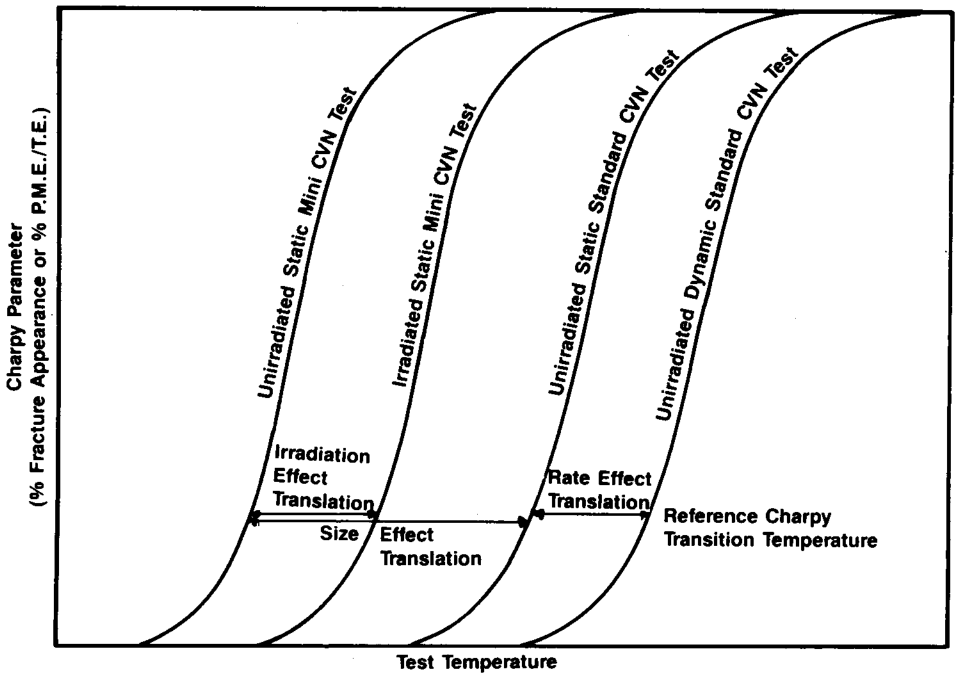

FIG. 9—*Relationship between reference Charpy transition temperature and irradiated miniature Charpy slow-bend transition temperature.*

Summary and Conclusions

Study of alternative weld technologies revealed that laser welding is readily adaptable for hot cell applications. Preliminary work has demonstrated that the required penetration depth can be realized and the control parameters adjusted to yield fairly flat weld planes parallel to the fracture surface. Comparison of laser-welded specimen data with that of conventional specimens showed excellent agreement. Continued successful development will enable reconstitution of 1/16 size scale MNT specimens as well as thicker section J_{IC} bend specimens. The miniaturized specimen design required only 6% of the volume of a standard Charpy specimen. These specimens have proven satisfactory for measuring transition temperature shifts due to heat treatment of a reactor-grade pressure vessel steel. Fracture appearance has been demonstrated to be a useful miniature specimen parameter. For applications in the nuclear industry, conventional dynamic ASTM A508 steel Charpy specimens exhibit ~4% shear at the 41-J energy level. Therefore, the appropriate index for miniature specimens is 4% shear for this material.

A new parameter, percent normalized PME, has been benchmarked for an ASTM A508 steel. This parameter is easier to use than fracture appearance since the data analysis can be easily automated. Like fracture appearance, percent normalized PME can be used to relate miniature specimen data with conventional dynamic, ASTM Test Methods for Notched Bar Impact Testing of Metallic Materials (E 23) specimen data. For the ASTM A508 material investigation, the result is a 41-J DBTT with accuracy equal to that obtained using conventional ASTM test practices. The data obtained thus far are sparse at the 15% normalized PME level. Future studies should provide data at the 15% normalized PME level to more accurately assess the uncertainty of the method.

TABLE 4—*Shifts due to rate and size effects.*

Heat Treatment	Standard Specimen Impact Transition Temperature, °C	Standard Specimen Slow-Bend Transition Temperature, °C	MNT Specimen Slow-Bend Transition Temperature, °C	(Rate Effect) Standard Specimen Impact to Slow-Bend Shift, °C	(Size Effect) Standard Slow-Bend to MNT Slow-Bend Shift, °C
	41 J	15% Normalized PME Index			
6	40	−18	−37	58	19
5A	−7	−57	−65	50	8
6R	−29	−54	−90	25	36

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