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SPECIMEN SIZE EFFECTS IN CHARPY IMPACT TESTING

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ABSTRACT: Full-size, half-size, and third-size specimens from several different steels have been tested as part of an ongoing alloy development program. The smaller specimens permit more specimens to be made from small trial heats and are much more efficient for irradiation experiments. The results of several comparisons between the different specimen sizes have shown that the smaller specimens show qualitatively similar behavior to large specimens, although the upper-shelf energy level and ductile-to-brittle transition temperature are reduced. The upper-shelf energy levels from different specimen sizes can be compared by using a simple volume normalization method. The effect of specimen size and geometry on the ductile-to-brittle transition temperature is more difficult to predict, although the available data suggest a simple shift in the transition temperature due to specimen size changes. The relatively shallower notch used in smaller specimens alters the deformation pattern, and permits yielding to spread back to the notched surface as well as through to the back. This reduces the constraint and the peak stresses, and thus the initiation of cleavage is more difficult. A better understanding of the stress and strain distributions is needed.

KEYWORDS: Charpy, fracture, size effects, constraint, cleavage, critical tensile stress, ductile-to-brittle transition temperature, upper-shelf energy, slip-line field theory, finite-element analysis.

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INTRODUCTION

The Charpy test is widely used for the study of ferritic materials. It is a rapid, inexpensive, and simple test which provides a qualitative measure of toughness. The large body of data and experience gained with the use of this test over many years gives added confidence to interpretation of test results, whether the test is used for alloy development or for monitoring the effects of irradiation on the mechanical properties of nuclear pressure vessel steels.

These two areas of research have created an impetus for a reduction in size of the Charpy specimen. Smaller specimens permit the measurement of mechanical properties during alloy development when only limited material is available, yet retain the advantages of simplicity and convenience of the traditional Charpy specimen. However, the major reason for considering smaller specimens is the fact that many more specimens can be irradiated in the space available in radiation facilities. Approximately eight half-size specimens or eighteen third-size specimens can be located in the same space that a conventional full-size specimen would require. This provides a tremendous advantage for irradiation effects studies.

The use of smaller specimens raises a number of important issues. It is well established that these smaller specimens show behavior which is qualitatively similar to the full-size specimens [1-4]. At higher temperatures ductile modes of fracture occur and the energy absorbed tends toward an upper-shelf level. As the temperature is reduced, a brittle mode of fracture occurs with a concomitant decrease in the energy absorbed. Thus these specimens show a ductile-to-brittle transition similar to that observed for full-size specimens. However, due to the reduction in size of the specimens, the stresses and strains which develop in the specimens differ with specimen size, and so the transition in fracture mode will occur at different temperatures for different specimen geometries. In addition, the energy absorbed will obviously vary with specimen size. Therefore, it is not clear how data generated with various specimen geometries can be compared and related. The subsize specimen geometries have not been standardized, with different researchers using different notch geometries for specimens having the same nominal dimensions. These slight differences may have significant effects on the stresses and strains, and thus the fracture process. Finally, it may be possible to analyze these impact tests to determine the values of material properties such as dynamic yield stress (σ_{yd}) or the critical tensile stress required for cleavage fracture, the cleavage fracture stress (σ_{fc}) [4,5]. This requires an accurate knowledge of the stress and strain distributions in these specimens, which will certainly vary with specimen size and geometry.

The aim of this research is to compare a large number of data sets which have been generated with different specimen sizes to see if the data can be normalized or adjusted to allow different specimen sizes to be compared directly. Most of the data given below have been generated at Oak Ridge National Laboratory (ORNL) through alloy development programs sponsored by the Fusion Energy Program. These efforts have been aimed at designing steels with improved resistance to irradiation, both through a reduction in radiation-induced embrittlement and an increase in the rate of decay of radiation-induced radioactivity. Different models proposed in the literature for normalizing the upper-shelf energy (USE) will be compared. The shift in the ductile-to-brittle transition temperature (ΔDBTT) as a function of specimen size and other material parameters will also be considered.

RESULTS

The subsize specimens were tested on a semiautomated Charpy impact machine modified for testing small specimens [2,6]. The full-size specimens were 10 × 10 × 55 mm with a 45° notch 2 mm deep, notch radius 0.25 mm. The half-size specimens were 5 × 5 × 25.4 mm with a 30° notch 0.76 mm deep, notch radius 0.075 mm, and the third-size specimens were 3.33 × 3.33 × 25.4 mm with a 30° notch 0.51 mm deep, notch radius 0.075 mm. Note that the subsize specimens are not geometrically similar to the full-size specimens, since the notch is relatively shallower (notch depth/thickness = $a/W = 0.15$ for the subsize specimens, while $a/W = 0.2$ for the full-size specimen) but sharper (30° for the subsize vs 45° for the full-size specimen).

The impact data were fitted to a hyperbolic tangent function which allowed the upper-shelf energy level and the transition temperature to be determined. The transition temperature was taken at the midpoint between the upper- and lower-shelf energy levels. Some investigators [2] have used half of the upper-shelf energy as the transition point: the difference between these definitions is very small, since the lower-shelf energies are very low.

The results of the tests are shown in Tables 1 and 2, which compare full-size specimens to half-size and third-size specimens, respectively [7-12]. Mechanical property data are included. Similar data from the literature which compare half-size and third-size specimens to full-size specimens are given in Table 3 [3,13]. These investigations employed subsize specimens with notch geometries identical to those described above. Some additional data [5] from subsize specimens have been included, although that investigation used third-size specimens with notches which were wider (45°) and deeper ($a/W = 0.2$) than those of the ORNL specimen (30° and $a/W = 0.15$). In addition, the span was reduced from 20 to 13.3 mm [4]. The values given in Table 3 were read from the figures [5].

DISCUSSION

The effect of specimen size on the USE can be considered by normalizing the energy by some factor related to the specimen dimensions. Various researchers have used different normalization factors [2,3,4] and a "volume" approximation in which the energy is divided by the nominal volume of the deformed zone beneath the notch has been shown to give the best results [2,3]. The nominal volume is given by $(Bb)^{3/2}$ where B is the specimen width and b is the remaining ligament thickness beneath the notch. This procedure gives better results than using Bb^2 as the nominal volume [4] or using an area normalization (Bb) [2-4].

The results of using this volume normalization are shown in Fig. 1, which compares the normalized data for subsize specimens to the full-size specimens. The solid lines in Fig. 1 indicate a 1:1 correspondence between the subsize and the full-size specimen data,

Table 1. ORNL data for full-size vs half-size specimens [2,7-12]

Alloy	Nominal composition (wt %)	Strength[a] (MPa)		Total elongation[a] (%)	Specimen size	Transition temperature (°C)	ΔDBTT (°C)	Upper-shelf energy (J)	Normalized USE (mJ/mm^3)
		Yield	Ultimate						
3590	9Cr-1Mo-V-Nb	541	656	10	F	-15	15	266	372
					1/2	-30		50.0	512
3591	9Cr-1Mo-V-Nb-2Ni	734	851	8	F	-45	35	177	247
					1/2	-80		28.2	289
3593	9Cr-1Mo-V-Nb-2Ni (adjusted)	817	927	8	F	-15	15	142	198
					1/2	-30		21.6	221
30176	9Cr-1Mo-V-Nb	539	630	13	F	-32	4	262	366
					1/2	-36		34.0	348
		b	b	b	F	-13	15	200	280
					1/2	-28		28.3	290
3587	12Cr-1Mo-V-W	553	759	10	F	0	15	137	191
					1/2	-15		21.1	216
3588	12Cr-1Mo-V-W-1Ni	576	800	11	F	-20	10	131	183
					1/2	-30		21.2	217
3589	12Cr-1Mo-V-W-2Ni	719	899	8	F	-30	10	106	148
					1/2	-40		17.8	182
3592	12Cr-1Mo-V-W-2Ni (adjusted)	769	938	8	F	10	0	101	141
					1/2	10		16.5	169
91353	12Cr-1Mo-V-W	549	716	10	F	10	25	149	208
					1/2	-15		20.2	207
9607-R2	12Cr-1Mo-V-W	556	738	14	F	0	19	115	161
					1/2	-19		20.8	213

[a] Room temperature properties.

[b] Not measured.

Table 2. ORNL data for full-size vs third-size specimens [2,7-12]

Alloy	Nominal composition (wt %)	Strength[a] (MPa)		Total elongation[a] (%)	Specimen size	Transition temperature (°C)	ΔDBTT (°C)	Upper-shelf energy (J)	Normalized USE (mJ/mm^3)
		Yield	Ultimate						
3785	2.25Cr-V	674	742	8	F	87	51	245	342
					1/3	36		9.4	328
3786	2.25Cr-1W-V	727	773	6	F	54	58	224	313
					1/3	-4		9.7	340
3787	2.25Cr-2W	594	677	10	F	25	73	278	389
					1/3	-48		9.6	335
3788	2.25Cr-2W-V	649	729	6	F	33	33	272	380
					1/3	0		9.7	339
3789	5Cr-2W-V	577	712	10	F	-48	32	245	342
					1/3	-80		10.0	349
3790	9Cr-2W-V	597	735	9	F	-22	48	216	302
					1/3	-70		9.4	328
3791	9Cr-2W-V-Ta	645	784	8	F	-55	23	255	356
					1/3	-78		9.7	339
30176	9Cr-1Mo-V-Nb	539	630	13	F	-32	26	262	366
					1/3	-58		9.7	339
		b	b	b	F	-13	44	200	280
					1/3	-57		8.8	307
3792	12Cr-2W-V	606	767	9	F	10	60	192	268
					1/3	-50		9.0	314
9607-R2	12Cr-1Mo-V-W	556	738	14	F	0	46	115	161
					1/3	-46		5.9	206

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[a] Room temperature properties.

[b] Not measured.

Table 3. Literature data for subsize specimens [3,5,13]

Alloy	Nominal composition (wt %)	Specimen size	Transition temperature (°C)	ΔDBTT (°C)	Upper-shelf energy (J)	Normalized USE (mJ/m³)
Half-size specimens						
2W	9Cr-2W	F	-57	33	245	342
		1/2	-90		34.3	351
9607-R2	12Cr-1Mo-V-W	F	-2	45	129	180
		1/2	-47		19	195
Third-size specimens						
1W	9Cr-1W	F	-66	47	259	362
		1/3	-113		10.8	377
2W	9Cr-2W	F	-57	56	245	342
		1/3	-113		9.8	342
4W	9Cr-4W	F	-24	74	221	309
		1/3	-98		8.8	307
9607-R2	12Cr-1Mo-V-W	F	-2	62	129	180
		1/3	-64		6	210
A 302-B	1.5Mn-0.2C	F	6	63	64	89
		1/3	-57		3.8	131
A 508-B	0.6Mn-0.6Ni-0.6Mo-0.2C	F	-14	25	123	172
		1/3	-39		6.7	235
A 508-B reaustenitized	0.6Mn-0.6Ni-0.6Mo-0.2C	F	91	50	74	103
		1/3	41		4.1	142
A 710 as-received	1Ni-0.7Cr-1.2Cu-0.04C	F	-37	51	161	224
		1/3	-88		7.4	256
A 710 underaged	1Ni-0.7Cr-1.2Cu-0.04C	F	-52	29	188	262
		1/3	-81		7.7	268
A 710 overaged	1Ni-0.07Cr-1.2Cu-0.04C	F	-55	54	177	247
		1/3	-109		8.3	289
A 710 peak aged	1Ni-0.07Cr-1.2Cu-0.04C	F	-16	54	161	224
		1/3	-70		7.7	270

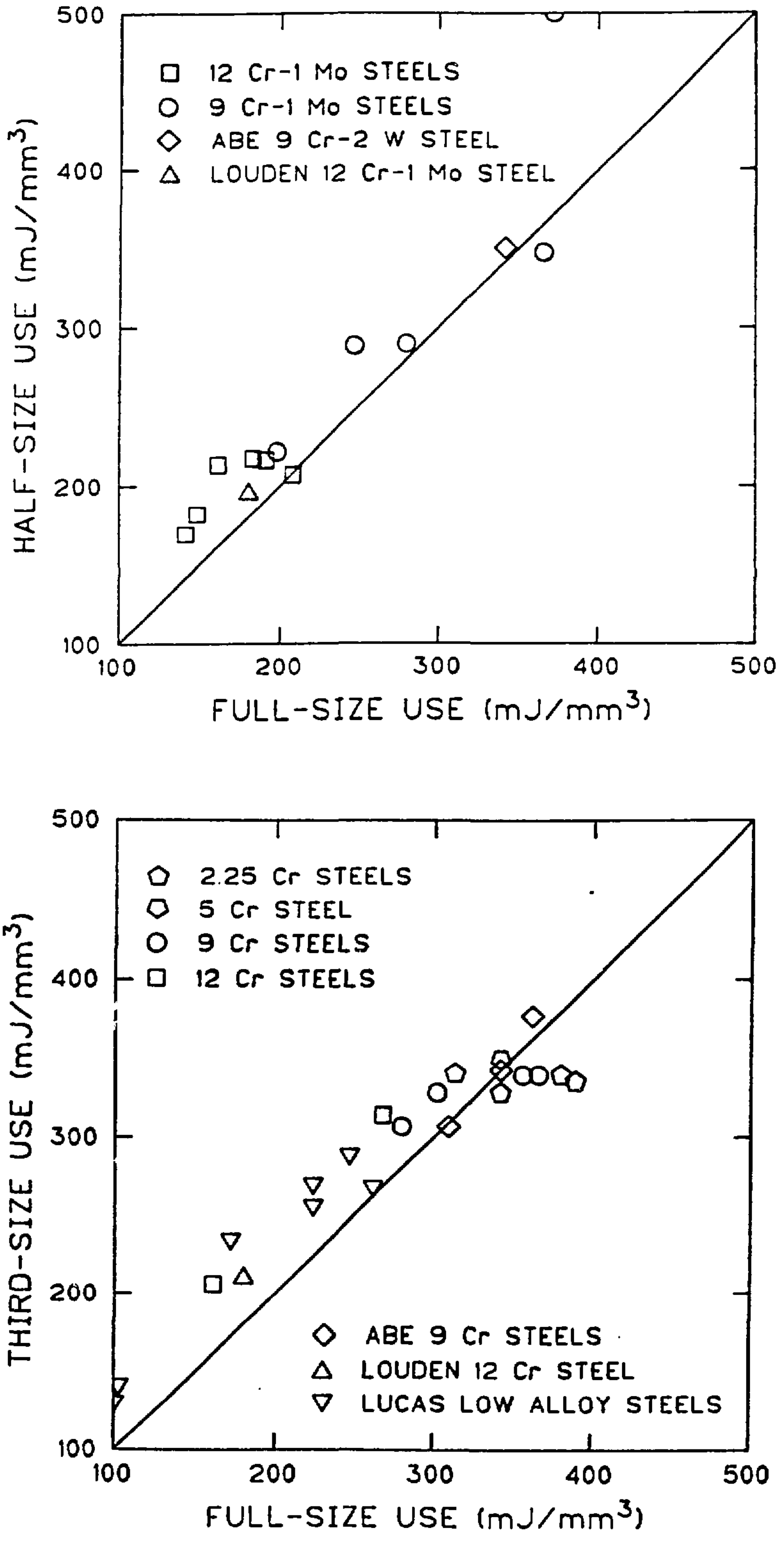


Fig. 1. Normalized upper-shelf energies for subsize specimens vs full-size specimens. Top: half-size specimens. Bottom: third-size specimens. The solid line indicates a 1:1 correlation rather than a fit to the data.

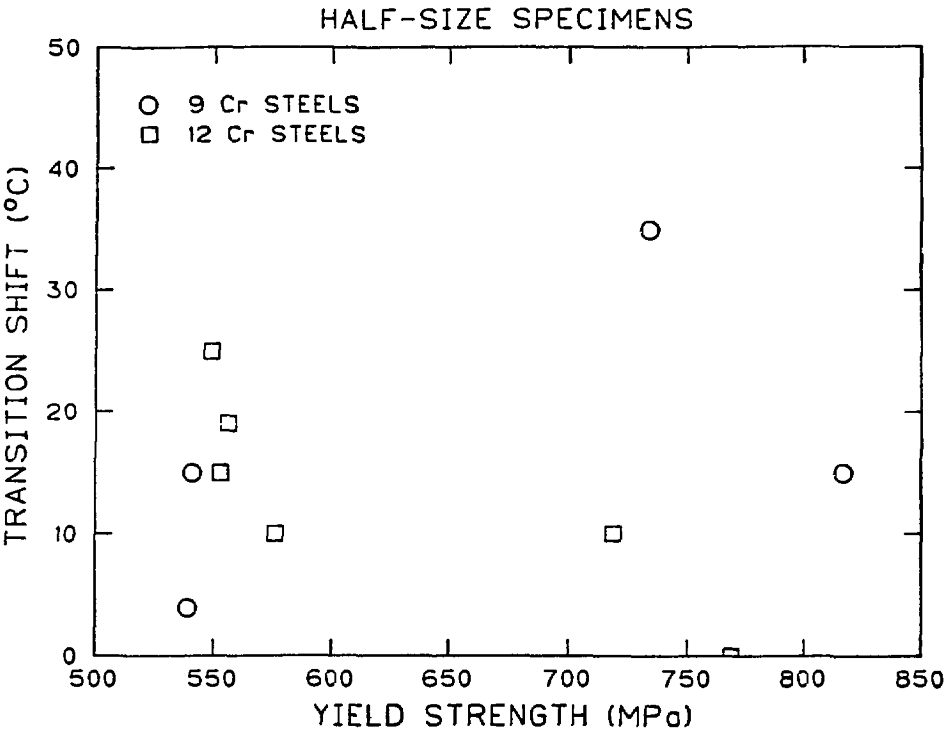
rather than a fit to the data. As the figures show, this simple normalization process provides a good means for comparing the data from different specimen sizes for several different steels.

Other methods have been proposed for accounting for the specimen sizes. Louden et al. [13] have developed a model which normalizes the USE by a factor which incorporates the specimen width, ligament thickness, and span, as well as an elastic stress concentration factor which will depend on the notch depth, angle, and root radius. Thus, all of the specimen dimensions are included. However, the use of an elastic stress concentration factor for the upper-shelf regime, where fracture is occurring only after extensive plastic deformation, and by a mechanism which is more likely strain controlled than stress controlled, is difficult to justify. The results of their normalization [13] give a correspondence similar to the much simpler volume normalization used here.

Kumar et al. [14] have developed a model to predict the USE of full-size specimens by using both notched and fatigue precracked subsize specimens. This allows the energy for crack initiation and crack propagation to be separated. Good agreement for a ferritic 12Cr-1Mo-V-W steel (HT-9) was observed. This procedure imposes the added complexity of testing precracked specimens. Although further testing is needed, the model is expected to be useful for a wide range of alloys and the study of irradiation effects also.

A possible problem due to the smaller specimen dimensions may arise when testing tough materials with high USE levels. At higher temperatures extensive deformation may occur without fracture intervening. If the material is sufficiently tough, the specimen will bend to such an extent that it will be squeezed out between the anvils rather than fracturing. This behavior has been observed when testing stainless steel specimens. The shallow notch and reduced thickness of the subsize specimens increases the likelihood of this behavior, while the deeper notch and greater thickness of the full-size specimen favor the occurrence of fracture. This may affect the correlation of USE data, if these different behaviors are present. In addition, some investigators [3,13] use specimens which are shorter than that described above, i.e., 23.6 vs 25.4 mm. If the same span (20 mm) is used in both cases, the shorter specimens may be squeezed through the anvils more readily than the longer specimens, and thus give a lower USE. The width and radius of the tup may also play a role, as well as the span length. Despite these differences, the data from Lucas et al. [5] can be normalized quite well, as Fig. 1(a) shows.

The effect of specimen size on the DBTT is more difficult to account for. There is no obvious effect of material parameters such as the yield strength on the ΔDBTT caused by a change in specimen size, as Fig. 2 shows. Abe et al. [3] have noted a qualitative trend that brittle alloys show larger size effects, although considerable scatter was observed. In Fig. 3 the subsize specimen transition temperature is plotted as a function of the full-size specimen transition temperature. The data suggest that the subsize specimen transition temperature is related to the full-size specimen transition temperature. The solid lines in Fig. 3 have been drawn with a slope of 1, and are not fits to the data. However, these lines do suggest a reasonable correlation. If the slope is 1, then one can write:



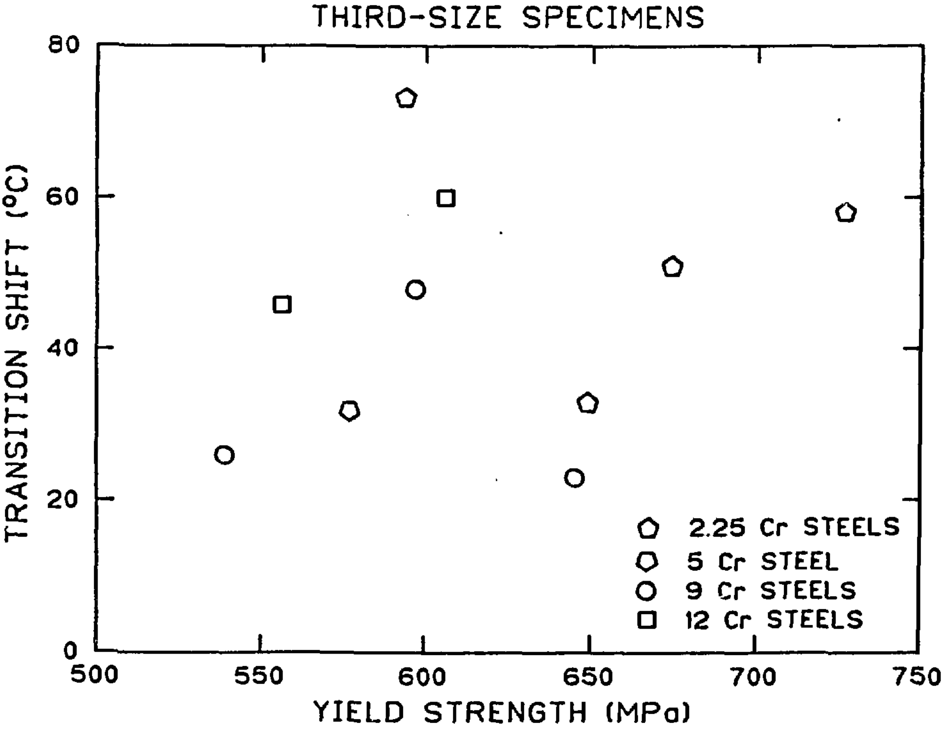


Fig. 2. Shift in ductile-to-brittle transition temperature as a function of yield strength. Top: half-size specimens. Bottom: third-size specimens.

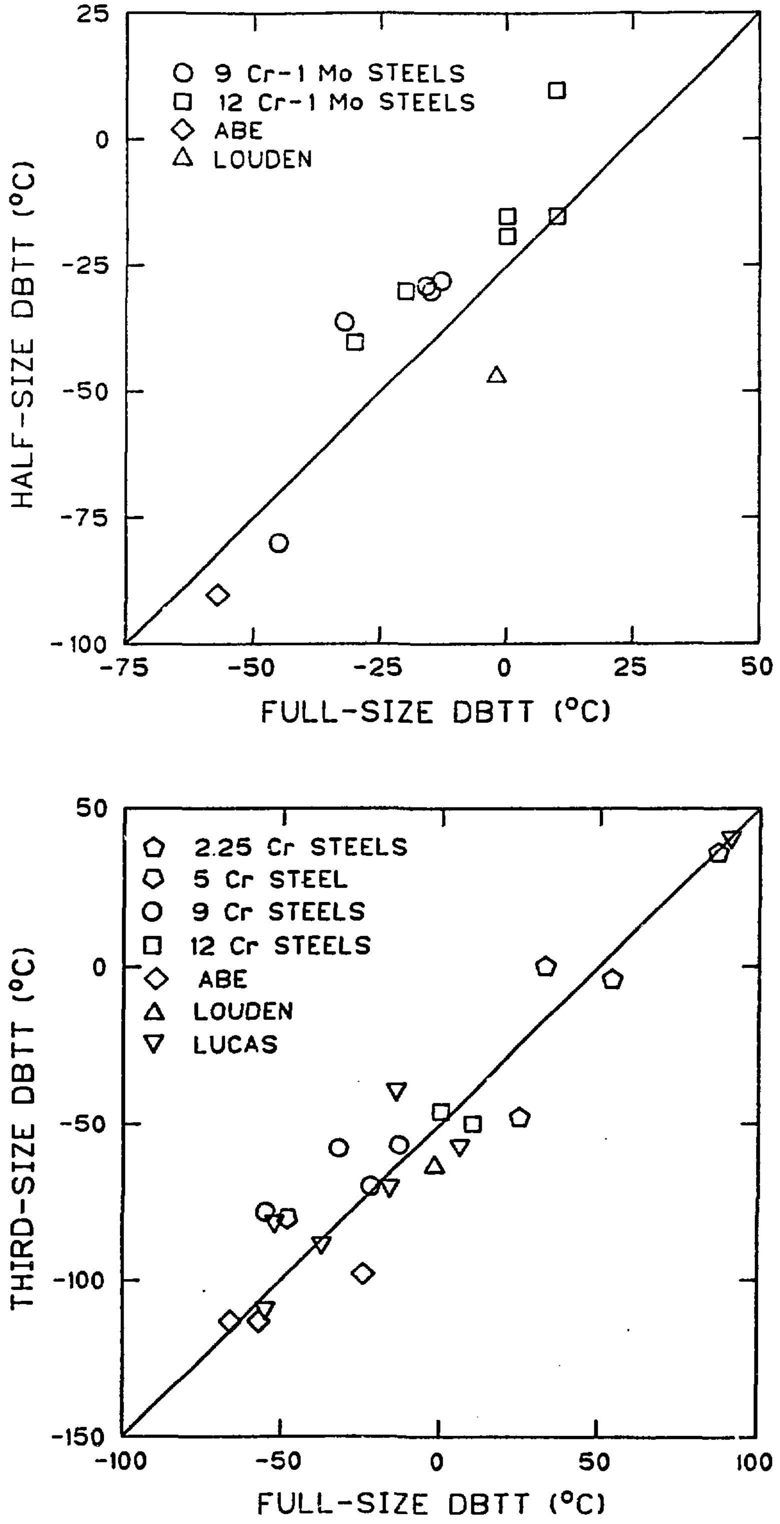


Fig. 3. Transition temperature of subsize specimens vs transition temperature of full-size specimens. Top: half-size specimens. Bottom: third-size specimens. The solid line has a slope of 1, and is not a fit to the data.

$$DBTT_{1/2} = DBTT_F + C_1 \ , \tag{1}$$

or

$$DBTT_{1/3} = DBTT_F + C_2 \ , \tag{2}$$

where $DBTT_F$, $DBTT_{1/2}$, and $DBTT_{1/3}$ are the ductile-to-brittle transition temperatures for full-, half-, and third-size specimens, respectively, and C_1 and C_2 are constants. This relationship is very similar to that suggested by Louden et al. [13] but differs in that the transition temperatures have not been normalized.

It follows from this formulation that ΔDBTT will be a constant for any fixed change of specimen geometry. The existing data suggest that the shift in transition temperature is roughly 15°C for full- to half-size specimens, and 50°C for full- to third-size specimens. However, it must be emphasized that this approach is strictly empirical. In addition, irradiation or alloying effects may result in different shifts rather than merely changing the specimen size. Although the fit shown in Fig. 3 is encouraging, more testing and analysis is necessary to examine the validity of this simple relationship. A more rigorous model of size effects will require a better understanding of the cleavage process in subsize specimens.

It is generally agreed that cleavage fracture will occur when the peak tensile stress beneath the notch exceeds the cleavage fracture stress σ_{fc} [4,5,13]. The peak stress will be located some distance beneath the notch root surface, as analysis of notched bars has shown [15,16]. Abe et al. [3] have presented convincing fractographic evidence that fracture initiates at particles some distance beneath the surface in full-, half- and third-size specimens. Thus, the smaller specimens still show fracture at a critical stress level σ_{fc}. However, how σ_{fc} might be determined is unclear. A complete understanding of the stress and strain distributions in these small specimens is essential to determine the plastic stress concentration factor. At present, empirical results are used [4,5,13]. However, these procedures are based on slip-line field theory, which assumes elastic-perfectly plastic flow behavior, and plane strain conditions. In addition, general yielding is assumed to occur at the first deviation from linearity in the load-displacement trace as the specimen is loaded. Full-size specimens of materials which exhibit pronounced Luders deformation on yielding may approach these conditions [17] which may justify this approach, but this will clearly not be satisfactory for smaller specimens of smoothly yielding materials. Analysis of these specimens requires a better understanding of the constraint and stress distributions. Full three-dimensional finite-element calculations are required for these subsize specimens. Such calculations are being performed at ORNL, and the results will be reported separately.

The need for this type of calculation is emphasized by recent slip-line field analyses of three-point bend specimens with shallow notches [18]. These results indicate that deformation from the notch will spread back toward the notched surface, which relieves the constraint and thus reduces the peak stresses beneath the notch root. The critical notch depth for three-point bend specimens for fully constrained yielding through the specimen to the back face rather than to the notched surface has been shown to be $a/W = 0.18$ [19]. Note that the full-size specimen exceeds this critical depth, while the subsize specimens do not. Thus, the deformation patterns will be much more complicated than for the deeper notch. The edge effects for the smaller specimens will only increase the difference between the actual behavior and that predicted by slip-line field theory. Therefore, three-dimensional finite element analyses are needed.

CONCLUSIONS

Subsize Charpy specimens offer important advantages for alloy development and irradiation effects studies through their reduction in size. However, this size reduction raises concerns about the analysis of test data. Upper-shelf energies from different specimen sizes can be compared quite well by using a simple volume normalization of the energy absorbed during fracture. Understanding the shift in the ductile-to-brittle transition temperature as a function of specimen size requires a better understanding of the stresses and strains in these specimens, which may be provided by finite element analyses.

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