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Effect of Specimen Geometry on Charpy Impact Test Results for Ferritic Steel Irradiated in JMTR*

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In order to develop the small-scale specimen technology in Charpy impact testing for ferritic steels, the effects of specimen size and notch geometry on the upper shelf energy (USE) and ductile-to-brittle transition temperature (DBTT) were investigated for Japanese Ferrite/Martensite Dual Phase Steel (JFMS). Miniaturized specimens with different sizes and notch geometry, together with full size specimens, were irradiated to $3x10^{22}n/m^2$ in the Japan Materials Testing Reactor (JMTR) and were Charpy impact tested. The USE for miniaturized specimens, normalized by Bb^2 or $(Bb)^{3/2}$ (B is the specimen thickness, b the ligament size), was essentially independent of specimen size and notch geometry and decreased by the irradiation, but the decrease was larger in full size specimens than in miniaturized specimens; the normalized USE for miniaturized specimens was distinctly higher than that for full size specimens. The DBTT of miniaturized specimens was strongly dependent on notch geometry, but its dependence decreased as compared with that for unirradiated JFMS. It is shown that these results may be useful in determining the USE and DBTT for full size specimens from those for miniaturized specimens.
KEY WORDS: neutron irradiation, upper shelf energy, ductile brittle transition temperature, specimen size, notch geometry

1. Introduction

It is well known that small specimen technology is required in mechanical testing for the fusion reactor materials development program, mainly because it must rely on accelerator-based high energy neutron sources that are quite limited in irradiation volume. In Charpy impact testing, with which the present paper is concerned, the major problems caused by the use of miniaturized specimens are that both the upper shelf energy (USE) and the ductile-to-brittle transition temperature (DBTT) are considerably lower than those of full size specimens. Many attempts to determine the USE and DBTT of full size specimens have been made by using one third sized [1-11] or more miniaturized specimens [11, 12]. However, it appears that the methodology to correlate the USE and DBTT of different sized specimens has not been yet established, and therefore it is necessary to develop that methodology.

Very recently, the present authors investigated the effects of specimen size and notch geometry (notch depth, notch root radius and notch angle) on Charpy impact test results for miniaturized specimens of unirradiated JFMS [11]. They found important results that allow to evaluate the USE and DBTT of full-size specimens directly from those of miniaturized specimens. They noted that such a study should be extended to neutron irradiated JFMS and other ferritic steels with less ductility in order to establish the small-scale specimen technology in Charpy impact testing. In this study, therefore, the effects of specimen size and notch geometry on USE and DBTT were investigated for neutron irradiated JFMS.

2. Experimental

The material used in this study was JFMS (Japanese ferrite/martensite dual phase steel). Full size and miniaturized Charpy specimens were prepared in which the axis of the specimen lay in the rolling direction. The miniaturized specimens were of four different sizes, 3.3 by 3.3 by 23.6 mm, 2.0 by 2.0 by 20 mm, 1.5 by 1.5 by 20 mm and 1.0 by 1.0 by 20 mm. They are here called 3.3 mm, 2 mm, 1.5 mm and 1 mm specimen, respectively. Each of them had three variations in notch dimensions (notch depth and notch root radius). The nominal and measured values are tabulated in Table 1, where the measured values correspond to the average of all the measured values, with the range of measured values given in parentheses. A notch root radius of approximately 0.02 mm is the minimum value that can be achieved by machining. A very large notch root radius of 0.25 mm for specimen type #11 is specially introduced to examine the effect of less sharp notch on the USE and DBTT for the smallest-sized 1 mm specimens. Neutron irradiation was performed to a dose of 3×10^{22} n/m^2 (E>0.1 MeV) at about 573K in the Japan Materials Testing Reactor (JMTR), in which it is possible to irradiate full size specimens as well as miniaturized specimens at the same time.

Table 1 Dimensions of V-notch and elastic stress concentration factor in Charpy specimens of JFMS irradiated in JMTR.

Specimen	Size	Notch Root Radius ρ (mm)	Notch Depth a (mm)	Notch Angle θ (degrees)	Elastic Stress Concentration Factor, Kt
1	Full size	0.246	2.00	45	3.79
2	3.3 mm	0.071	0.502	30	3.71
3	3.3 mm	0.022	0.512	30	6.02
4	3.3 mm	0.023	0.654	30	7.69
5	2.0 mm	0.083	0.406	30	3.23
6	2.0 mm	0.021	0.399	30	5.57
7	2.0 mm	0.022	0.594	30	7.52
8	1.5 mm	0.077	0.301	30	2.92
9	1.5 mm	0.020	0.301	30	5.05
10	1.5 mm	0.020	0.452	30	6.27
11	1.0 mm	0.254	0.202	—	1.69
12	1.0 mm	0.055	0.206	30	2.82
13	1.0 mm	0.025	0.300	30	4.20

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The specimens were subjected to instrumented Charpy impact tests at temperatures between 93 and 473K using a specially designed electrically controlled hydraulic machine. The details of the machine and the procedures developed for testing were described earlier [13]. The values of USE and DBTT were determined from total absorbed energy vs temperature curves of all specimens tested. The DBTT was determined as the temperature at which one half of the USE was absorbed during fracture.

3. Results and Discussion

The effect of the notch geometry on the temperature dependence of the total absorbed energy in miniaturized specimens is shown in Fig. 1, taking the 3.3 mm and 1 mm specimens as examples. It is evident that the impact behavior is strongly affected by the notch root radius and notch depth. The USE is dependent on notch depth, but not on notch root radius, whereas the DBTT changes significantly with both of the notch depth and notch root radius. This trend was evident for other specimen sizes. The values of USE and DBTT obtained are listed in Table 2.

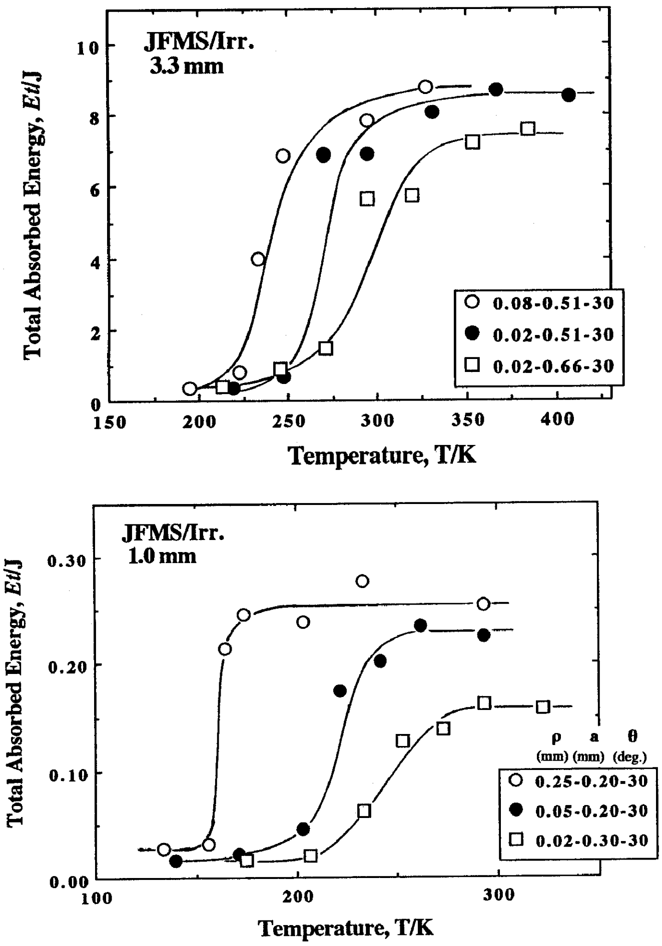

Fig. 1 Temperature dependence of total absorbed energy for impact-tested miniaturized Charpy specimens of JFMS irradiated in JMTR: 3.3 mm and 1 mm specimens having three different notch dimensions.

3.1 Upper shelf energy

To correlate the USE of miniaturized and full size specimens, the measured USEs were divided by Bb^2 or $(Bb)^{3/2}$ (Table 2), which was shown for the unirradiated

Table 2 Values of USE, volume normalized USE and DBTT for full size and miniaturized specimens of JFMS irradiated in JMTR.

Specimen	Size	USE (J)	USE/(Bb)$^{3/2}$ (J/mm^3)	USE/Bb^2 (J/mm^3)	DBTT (K)
1	Full Size	168.0	0.235	0.263	273
2	3.3 mm	8.30	0.297	0.323	240
3	3.3 mm	8.38	0.300	0.326	263
4	3.3 mm	7.39	0.287	0.321	290
5	2.0 mm	1.63	0.285	0.318	233
6	2.0 mm	1.61	0.281	0.314	276
7	2.0 mm	1.15	0.245	0.293	286
8	1.5 mm	0.715	0.296	0.331	215
9	1.5 mm	0.711	0.294	0.329	240
10	1.5 mm	0.530	0.268	0.320	281
11	1.0 mm	0.397	0.355	0.397	160
12	1.0 mm	0.361	0.323	0.361	218
13	1.0 mm	0.327	0.273	0.327	243

JFMS to give the best correlation, where B is the specimen thickness and b the ligament size (b = W - a; W is the specimen width, a the notch depth). These volumetric parameters were originally employed by Corwin and coworkers [3] and are known to be related to the extent of plastic deformation below the notch after general yield [5]. In this study, $(Bb)^{3/2}$ was used as a volume normalizing factor since no appreciable difference was found between the results from $(Bb)^{3/2}$ and Bb^2. Figure 2 shows the effect of the notch geometry on the USE normalized by $(Bb)^{3/2}$ for all of the miniaturized and full size specimens. Here, the elastic stress concentration factor, K_t, was used to express the effect of the notch geometry, with the K_t of the experimental data reported by Nishida (14). The value of K_t is listed in Table 1. The reason why the K_t values by Nishida are used instead of the well known Neuber's formula [15] was described in a previous paper [11].

For the miniaturized specimens, all but one data point (1 mm specimen with notch root radius of 0.25 mm) show almost the same value. This means that the observed

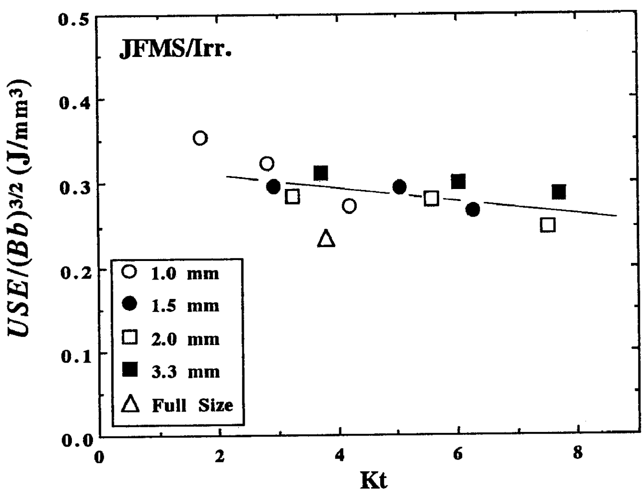

Fig. 2 Upper shelf energy normalized by volumetric factor, $(Bb)^{3/2}$, vs elastic stress concentration factor, kt, for JFMS in irradiated in JMTR.

dependence of USE on notch depth resulted only from the dependence of the USE on ligament size: the notch geometry is apparently unimportant for the USE. The higher normalized USE of the 1 mm specimen with notch root radius of 0.25 mm indicates that the estimated fracture volume, i. e., the normalization parameter $(Bb)^{3/2}$, is an underestimate and that the actual fracture volume is larger. These results are almost the same as those obtained for unirradiated JFMS.

A most important result to be noted is that the normalized USE of full size specimens is distinctly lower than that of miniaturized specimens. When these normalized USEs of full size and miniaturized specimens were compared with the corresponding values for unirradiated JFMS reported previously, the degree of decrease in the normalized USE due to irradiation was found to be much larger in full size specimens than in miniaturized specimens. In view of these results, it is considered that for full size specimens the normalization parameter, $(Bb)^{3/2}$, is an overestimate of the fracture volume and that the actual fracture volume should be smaller; in other words, the observed difference in the effect of specimen size on the USE may occur by a larger reduction in specimen volume associated with fracture for full size specimens than predicted using the volumetric parameters $(Bb)^{3/2}$. To demonstrate this concept, the ratio, α, of the normalized USE of full size specimens to that of miniaturized specimens was calculated for all the ferritic steels reported to date in the literature, including the unirradiated and irradiated JFMS. The results are shown in Table 3. The values of α were plotted against the unnormalized full size USE (Fig. 3). In the figure, the value of α given is for the third-size specimens, since the available data on the miniature Charpy specimens smaller than the third-size are very limited and no distinct difference was found between the normalized USEs of 3.3, 2, 1.5 and 1 mm specimens. It should be noted that the relationship between α and unnormalized USE of full size specimens is linear, with the consequence that the above concept is valid. It is therefore concluded that the effect of specimen size on the USE can be understood in terms of the specimen volume associated with fracture. Figure 4 shows the relationship between the unnormalized USE of full size specimens and the normalized USE of miniaturized specimens. In this case also, an almost linear relationship is obvious. This relationship allows us to determine the USE of full size specimens from the measured value of USE of miniaturized specimens.

Table 3 Values of USE and normalized USE for full size and third size specimens, together with the ratio, α, of $USE/(Bb)^{3/2}$ for full size specimens to that for third size specimens in unirradiated and irradiated JFMS and the other ferritic steels reported in the literature.

Alloy	Full Size Specimens USE (J)	Full Size Specimens $USE/(Bb)^{3/2}$ (J/mm^3)	Full Size Specimens USE/Bb^2 (J/mm^3)	Third-Size Specimens USE (J)	Third-Size Specimens $USE/(Bb)^{3/2}$ (J/mm^3)	Third-Size Specimens USE/Bb^2 (J/mm^3)	α*
9Cr-1Mo-V-Nb Norm & Temp. LT [4]	262	0.366	0.409	9.7	0.347	0.378	1.05
9Cr-1Mo-V-Nb Norm & Temp. TL [4]	200	0.277	0.313	8.8	0.315	0.343	0.879
9Cr-1Mo-V-Nb Quenched LT [4]	111	0.153	0.173	5.7	0.204	0.222	0.750
9Cr-1Mo-V-Nb Quenched LT [4]	72	0.101	0.113	5.1	0.183	0.199	0.551
HT-9 [7]	129	0.180	0.202	6.0	0.209	0.227	0.861
A302 [5]	62	0.086	0.097	3.4	0.134	0.150	0.642
A508 [5]	118	0.165	0.184	6.5	0.253	0.284	0.652
A508 [5]	68	0.095	0.106	3.9	0.151	0.169	0.629
9Cr-1W [6]	259	0.362	0.405	10.8	0.387	0.420	0.935
9Cr-2W [6]	245	0.342	0.383	9.8	0.351	0.381	0.974
9Cr-4W [6]	221	0.309	0.345	8.8	0.315	0.343	0.981
2.25Cr-W (V) [8]	245	0.342	0.383	9.4	0.328	0.328	1.043
	224	0.313	0.350	9.7	0.340	0.338	0.921
	278	0.389	0.434	9.6	0.335	0.335	1.161
	272	0.380	0.425	9.7	0.339	0.338	1.121
5Cr-2W-V [8]	245	0.342	0.383	10.0	0.349	0.349	0.980
9Cr-W (Mo) [8]	216	0.302	0.338	9.4	0.328	0.328	0.921
	255	0.356	0.398	9.7	0.339	0.338	1.050
	262	0.366	0.409	9.7	0.339	0.338	1.080
	200	0.280	0.313	8.8	0.307	0.307	0.912
12Cr-W (Mo) [8]	192	0.268	0.300	9.0	0.314	0.314	0.854
	115	0.161	0.180	5.9	0.206	0.206	0.782
JFMS Unirr. [11]	190	0.265	0.313	8.2	0.295	0.333	0.898
JFMS Irr.	168	0.235	0.263	8.3	0.297	0.323	0.791

* $\alpha = [USE/(Bb)^{3/2}]_{full\ size} / [USE/(Bb)^{3/2}]_{third\ size}$

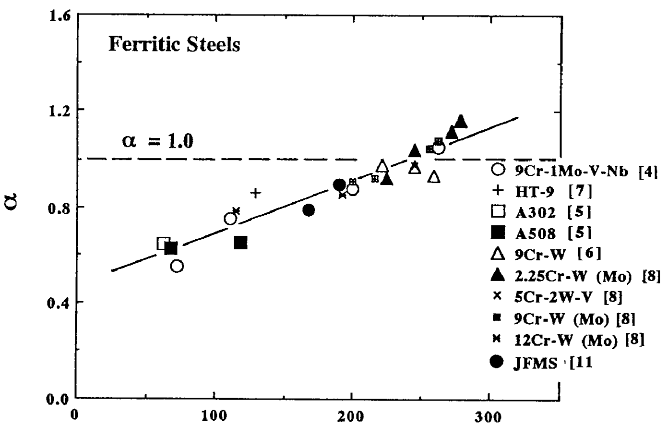

Fig. 3 Plot of the ratio, α, of $USE/(Bb)^{3/2}$ of full size specimens to that for third size specimens against the unnormalized USE of full size specimens in ferritic steels.

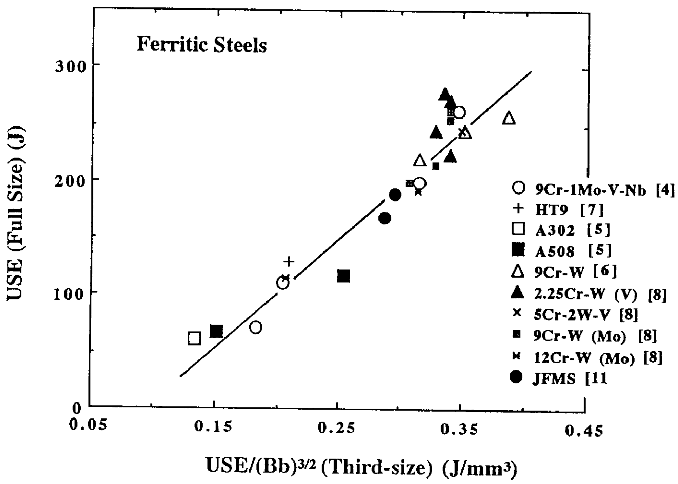

Fig. 4 Plot of the USE of full size specimens against the $USE/(Bb)^{3/2}$ of third size specimens in ferritic steels.

3.2 Ductile-to-brittle transition temperature

In the case of unirradiated JFMS, we showed that the DBTT for the miniaturized specimens was uniquely defined by K_t and the DBTT for full size specimens was approximately equal to that of the miniaturized specimens with $K_t \sim 4.8$. This provided the possibility that the DBTT for full size specimens can be directly obtained from the DBTT of miniaturized specimens with a notch giving a suitable value of K_t. In order to examine this applicability, all of the DBTT obtained for irradiated JFMS were plotted against K_t. Figure 5 shows the result together with that for unirradiated JFMS indicated by dotted line. Although the DBTT varies significantly depending on the notch dimensions and almost all the data points for miniaturized specimens lie on a single curve, the dependence of the DBTT for irradiated JFMS on Kt is distinctly different from that for unirradiated JFMS; in the former the Kt dependence of DBTT for miniaturized specimens is less than in the latter. In other words, the Kt dependence of DBTT for miniaturized specimens is decreased by irradiation. This result excludes the above-mentioned possibility for determining the DBTT of full size specimens. However, the observed difference between the Kt dependence of the DBTT for unirradiated and irradiated JFMS appears to give the expectation that there is some relationship between the DBTT of full size specimens and the Kt dependence of the DBTT for miniaturized specimens, which may allow us to determine the DBTT of full size specimens using miniaturized specimens. Therefore, the next step to be made is to examine the Kt dependence of the DBTT for the other ferritic steels having higher DBTT than the irradiated JFMS.

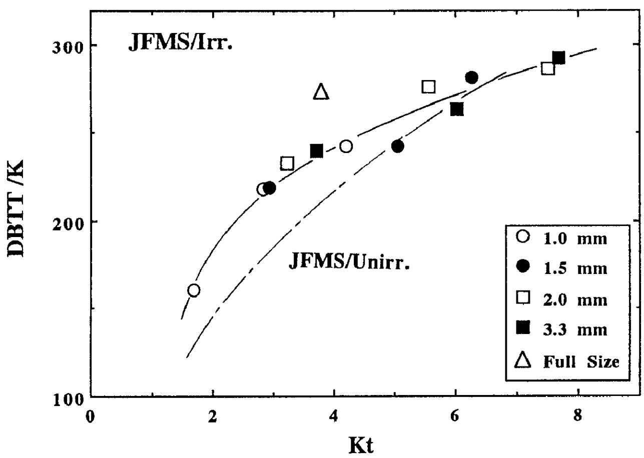

Fig. 5 Ductile brittle transition temperature vs elastic stress concentration factor, Kt, for JFMS irradiated in JMTR. For comparison, the curve for unirradiated JFMS [11] is also shown.

4. Conclusions

The USE for JFMS irradiated in JMTR depends on specimen size, but shows no significant dependence on notch dimensions. This specimen size dependence arises from the difference in specimen volume associated with fracture because unnormalized USE for full size specimens is uniquely related to the normalized USE for miniaturized specimens, regardless of alloy and neutron irradiation conditions. On the other hand, the DBTT varies significantly depending on notch dimensions, especially notch depth and notch root radius. The dependence of DBTT on notch dimensions decreases as the DBTT of full size specimens increases due to irradiation.

These results may lead to techniques for determining both the USE and DBTT for full size specimens from impact test results on miniaturized specimens.

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