FRACTURE STRENGTH EVALUATION OF WELDED STEEL JOINT BY MEANS OF SMALL PUNCH TEST

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It has been well known that the ductile-brittle transition temperature (DBTT) of each weld structure or its shift (ΔDBTT) from parent material is one of the very useful measures of the fracture characteristics in steel weldment. In order to present an applicability of small punch (SP) test technique to weldments, in this study, a fracture strength of microstructure at any localized region of interest on HAZ, weld metal and parent material in two steels was evaluated by using DBTT or ΔDBTT obtained from the SP test in relation to the data obtained from the COD test. The empirical correlation, $(\Delta\text{DBTT})_{SP} \cong 0.55(\Delta\text{DBTT})_{COD}$, was obtained from the SP and COD test. In addition, the effects of test materials, that is the microstructures of welded region and the orientations of specimens etc, did not appear at the empirical correlation.

Key Words: Ductile-Brittle Transition Temperature (DBTT), Shift of DBTT (ΔDBTT), SP Test, COD (Crack Opening Displacement) Test, HAZ, Weld Metal, Microstructure

1. INTRODUCTION

Designing against fracture initiation from welded joint is undoubtedly the most economic and practically feasible approach of tackling the problem for the safety of welded structure.

It was reported that the fracture toughness of HAZ was considerably influenced not only by residual stress due to weld thermal cycle but also by various metallurgical factors such as the gradient of grain size, the variations of microstructure and microhardness given as a function of the distance from fusion boundary (S.H.Chung et al., 1978, Kenneth Easterling, 1983).

This implies that the inherent strength of microstructure at a localized region of interest in HAZ and weld metal as well as parent material must be investigated in order to evaluate the fracture strength of weldment as a whole. Untill now, the toughness of welded joint has been commonly tested by using either the CVN impact specimen or the COD test. In both cases, however, it is not easy to locate exactly the notch root in a localized region of interest on the weldment and to evaluate its strength.

The SP test has been mainly carried out to evaluate the fracture strength of outer layer-degradated material since it was devleoped to study the irradiation damage effect of structural components in unclear power plant (O.Buck et al., 1986, H.Takahashi et al., 1987).

However, there is few research dealing with the application of the SP test technique on welded steel joint composed of various microstructures.

This work aims at investigating the applicability of the SP test technique to weldment and suggesting the empirical correlations of fracture strength characteristics between the results of the SP and the COD test.

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2. EXPERIMENT

2.1 Material and Specimen

Table 1 shows the chemical composition, mechanical properties and welding condition of two kinds of steel used in the tests. Each steel plate was perpendicularly butt welded to the rolling direction by the submerged arc welder. The SP and the COD specimens were machined from various weld microstructures to evaluate those fracture strengths.

Fig. 1 shows the dimension and the extracted location of the SP or COD specimen from SM50YB welded block. Two types of specimens in this figure were also focused on toe HAZ located in coarse grained HAZ adjacent to weld metal. The correct location of steel ball or notch root in the SP or the COD specimen was individually insured by etching the welded block prior to extracting the specimen.

Fig. 2 shows two types of specimens machined from three mutually perpendicular directions to investigate the fracture strength anisotropy due to elongation of nonmetallic inclusion etc., in rolling and secondary operation. Each orientation in the COD specimens is subsequently referred to by a two letter code ; the first being the direction normal to the macroscopic fracture plane and the second being the direction of crack propagation.

But each orientation in the SP specimens is referred to one code ; the direction of puncher falling down on the specimen surface. All the SP test specimens were finished with water resistent emery paper #1500 on upper die side and with alumina abrasive on lower die side.

2.2 Experimental Procedures

Fig. 3 shows the experimental equipments employed in the SP and the COD test. The SP specimen was set between upper

Table 1 Chemical composition, mechanical properties and welding condtions

chemical composition (wt. %)

	C	Si	Mn	P	S	Cu	Ni	V	Sol-Al	Nb	Cr	Mo
SM60YB	0.17	0.34	1.2	0.016	0.008			0.048	0.042	0.032		
SM50Q	0.17	0.48	1.44	0.021	0.006	0.014	0.017				0.017	0.007

mechanical properties

	yield strength (Mpa)	tensile strength (Mpa)	elongation (%)
SM50YB	447	567	25.0
SM58Q	408	561	38.0

welding conditions (submerged arc welding)

	heat input (KJ/cm)	preheating (℃)	current (A)	voltage (V)	welding speed (cm/min.)	wire dia. (mm)	electrode	flux
SM50YB	33	150	550	35	35	4.0	USW-588	MF38
SM58Q	45		750	32	32	4.0	US-49	MF38

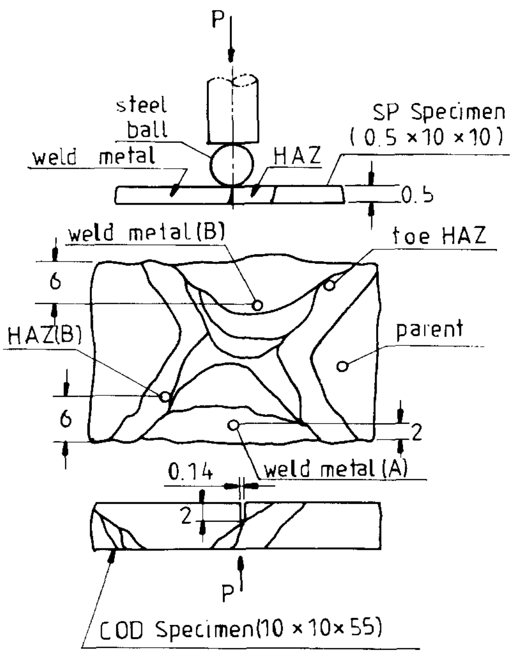


Fig. 1 Schematic illustration of multipass weldment in SM50YB steel. Marks indicate the extracted position of SP and COD test specimens

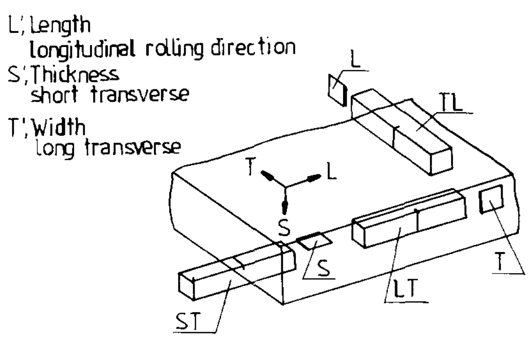
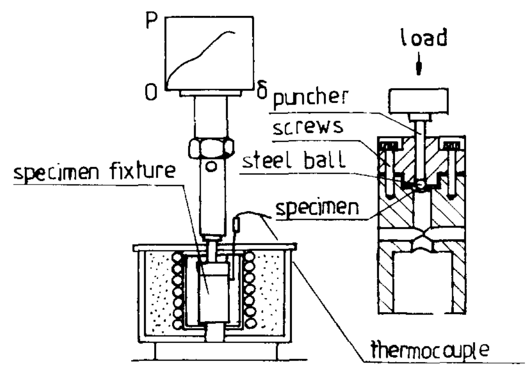
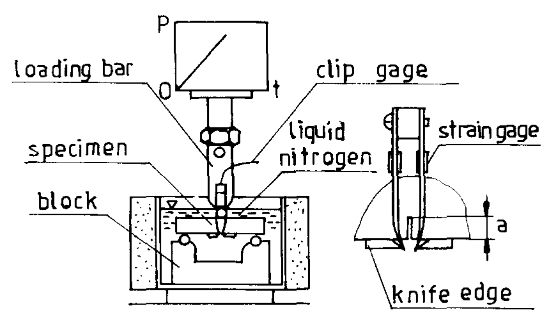


Fig. 2 Code system for specimen orientation and crack propagation direction of SP and COD test in SM50YB and SM58Q steels



Experimental equipment used for SP test



Experimental equipment used for COD test

Fig. 3 Schematic illustration of experimental equipments for SP and COD test

and lower die with four clamping screws tightened uniformly by using a torque wrench. A puncher for the SP tests was loaded onto the top surface of test specimen at a crosshead rate of 0.2 mm/min. by using a 2.4 mm steel ball with hardness of HRC from 62 to 67.

From the load-deflection curve recorded until the specimen was ruptured, the fracture energy value of the SP test, SP energy Esp, was defined as an area under this curve up to the maximum applied load. The critical COD value for the COD tests, δ_c, was calculated from the opening value at knife edges mounted on a specimen which was measured using a clip gage (BS5767-79, 1979).

All the SP and COD tests were performed on a universal testing machine over a range from −196℃ to room temperature. Test temperatures were achieved by using liquid nitrogen. The DBTT in the SP test was defined as the temperature where the fracture energy fell to the average value of upper and lower shelf energies(H.Takahashi et al., 1987), on the other hand the DBTT in COD test as the temperature where the evidence of ductile fracture mode at the notch root was first obtained.

3. EXPERIMENTAL RESULTS

3.1 Load-Deflection Relation

A typical example of the load-deflection curves obtained from SP tests at various test temperatures is shown in Fig. 4. These load-deflection curves have been obtained from the toe HAZ specimen in SM50YB steel.

It was found that an area under each curve increased with increasing test temperature. At the test temperatures below −150℃, the brittle fracture mode may be estimated from the low fracture energy and the sudden drop of load-deflection curve at the maximum load.

The ductile fracture mode may be also estimated above the temperatures of −150℃ at which the more increased energy are absorbed and the sudden drop of the curve is no longer developed. The behavior of load-deflection curve as shown in this figure was observed too at other microstructures of SM50YB and SM58Q steel used in the present work.

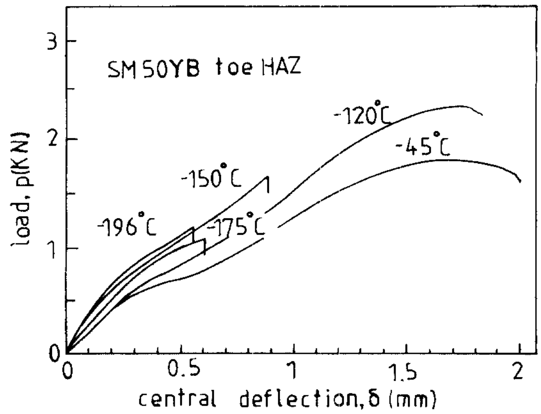


Fig. 4 Load-central deflection curves for SM50YB toe HAZ at various test temperatures

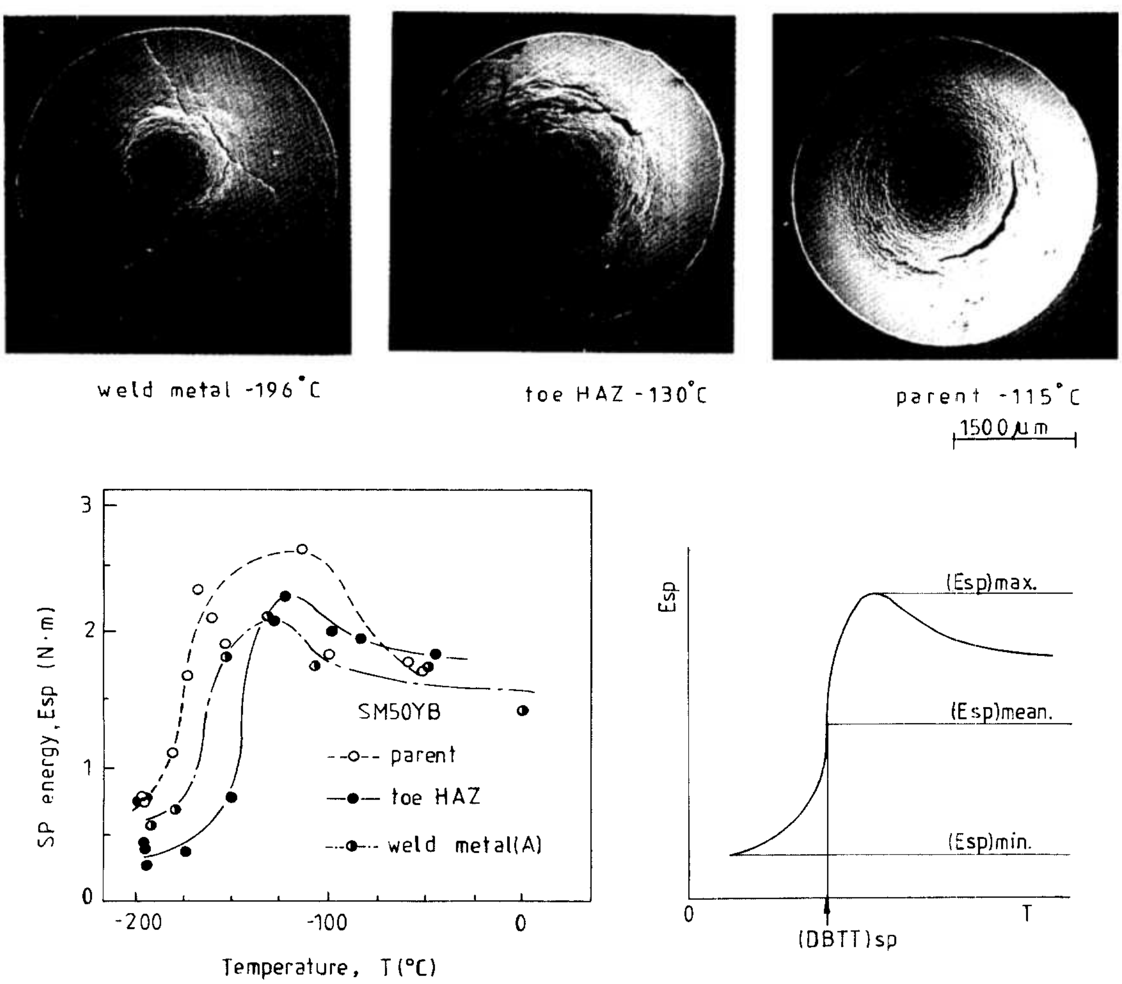


Fig. 5 SP energy transition behaviors and fractured appearances for SM50YB steel at various test temperatures (×20)

3.2 Variations of SP Energy and Fracture Appearance to Test Temperature

In Fig. 5, the fracture energy values obtained from these SP tests are plotted against the test temperatures. The macrographs of the fracture appearance are also given as a function of test temperature. It illustrates very well that the SP test produces a clear ductile-brittle transition behavior as associated with fracture energy change. It was shown that the SP energy transition curves of two weld microstructures were shifted to higher temperature side compared with that of parent material.

That is to say, the deterioration of fracture strength occurred in two weld microstructures, particularly toe HAZ, due to the metallurgical effects of weld thermal cycles on the parent material.

Judging from these fractographs, a fracture appearance tested at -196℃ showed a brittle fracture mode by rapid crack propagation of radial direction after very little plastic deformation. At the test temperatures above -130℃ including -115℃, the SP test specimens were ductily ruptured by circumferential crack propagation at the portion whose thickness remarkably decreased after hemispherically plastic deformation.

The similar failure behavior were also observed in SM58Q steels as shown in Fig. 6. From these test results, it was considered that the SP test in addition to other conventional tests might enable the prediction of the likely change in the mechanical properties of the practical weldment from the base steel.

3.3 Variations of Critical COD Value to Test Temperature

The COD tests are widely used as a conventional testing technique to characterize the fracture properties of welded steel joints (J.F.Lancaster, 1980, B.C.Kim et al., 1989).

Although a notch exists in a COD test specimen, both the COD and the SP test technique are based on the so-called elastic-plastic fracture mechanics and of which loading rates are equally selected in this study. Therefore it may be worthy that above test results are compared with the data from the COD tests. Two examples of such a comparison are shown in Fig. 7 and Fig. 8. These sampling orientations are LS corresponding to S of above stated SP tests.

It can be seen that the critical COD-temperature transition curves of two weld microstructures are shifted to higher temperature side compared with that of parent material as shown in the SP test results. However, the SP test results

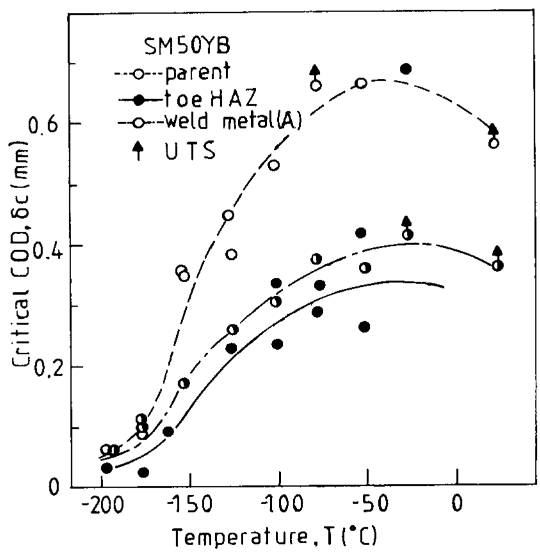


Fig. 7 Critical COD transition behavior of SM50YB steel at various test temperatures

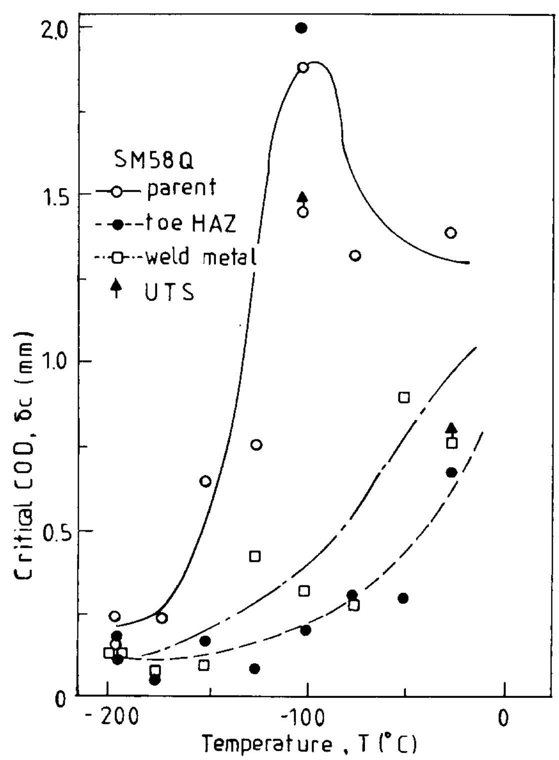


Fig. 8 Critical COD transition behavior of SM58Q steel at various test temperatures

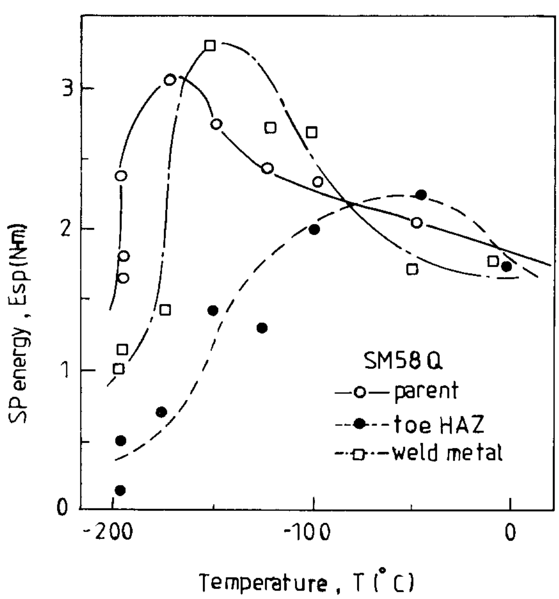


Fig. 6 SP energy transition behaviors for SM58Q steel at various test temperatures

showed a more precipitous fracture energy transition behavior than the COD test results.

3.4 Variations of SP Energy and Critical COD Value to Test Spcimen Orientation

It was known that the elongation of nonmetallic inclusions such as manganese sulfide or silicate and the banded structure of ferrite and pearlite occurred in rolling process may lead to the anisotropy in fracture toughness(W.P.A.Belcher et al., 1983, R.H.Sailors, 1976).

The SP tests were performed on the specimens machined from three mutually perpendicular orientations in order to investigate the applicability of orientation sensitivity evaluation. The SP energy transition curves as a function of specimen orientation are shown in Fig. 9, which are focused on SM50YB parent material and illustrate clearly how the transition behavior depends on orientation of sampling the SP specimens.

It was presented that the SP energy transition curves of three different orientations were shifted to higher temperature region in order of S, T, L and the fracture strength of L orientation specimen was more deteriorated than S and T orientation specimen. To evaluate an availability of orientation dependency obtained from the SP test, it is worth comparing the SP test results with the data from COD test as a conventional test technique.

Fig. 10 shows the critical COD transition curves in which code systems LS, LT and TL are corresponding to S, T and

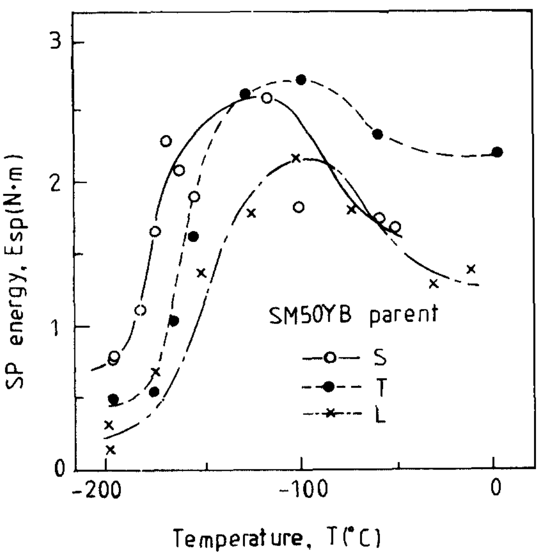
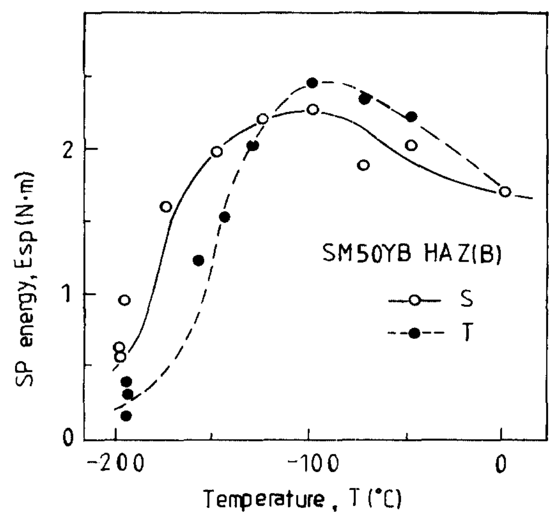


Fig. 9 SP energy transition behaviors of three perpendicular directions in SM50YB parent material at various test temperatures



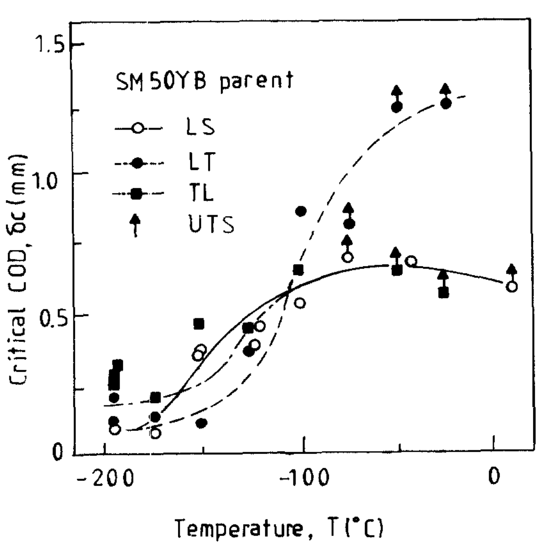


Fig. 10 Critical COD transition behaviors of three perpendicular directions in SM50YB parent material at various test temperatures

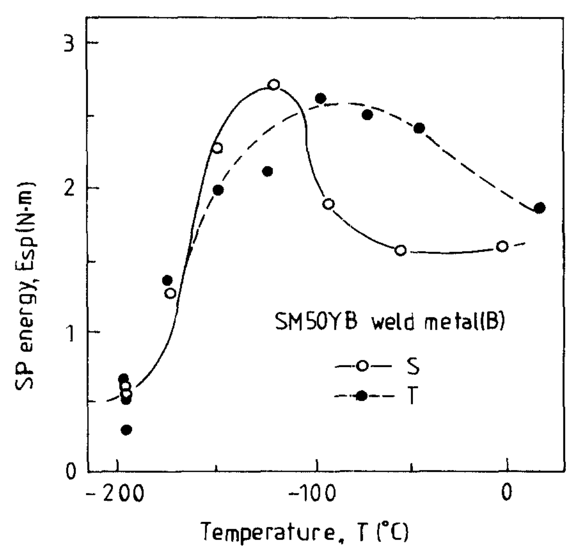


Fig. 12 Sp energy transition behaviors of two perpendicular directions in SM50YB weld metal(B) at various test temperatures

L of SP spcimen code systems respectively. It could be seen that the critical COD transition curve of LT orientation was shifted toward higher test temperature region and showed higher energy value at upper shelf compared with that of LS orientation as shown in the SP test result. But a critical COD transition curve of TL orientation showed a behavior similar to that of LS orientation. This SP test result of the anisotropy in fracture strength is in agreement with the reported CVN test results(W.P.A.Belcher et al., 1983, R.H.Sailors, 1976) in which LS and LT orientation showed a higher resistance to crack propagation than TS and TL orientation.

Fig. 11 and Fig. 12 are the SP energy transition curves illustrating the test results applied to two weld microstructures ; HAZ(B) reheated by subsequent weld thermal cycle lying adjacent to fusion boundary and weld metal(B), respectively. HAZ(B) specimen of S orientation showed a higher fracture strength than that of T orientation while weld metal (B) specimens showed little difference between S and T orientation. These qualitative behaviors of the SP and COD tests may be quantitatively discussed by using DBTT as a measure for evaluating the fracture strength.

3.5 Correlation between $(DBTT)_{SP}$ and $(DBTT)_{COD}$

Fig. 13 illustrates a series of SEM fractographs by the SP test from which the DBTTs for toe HAZ microstructures in two species of steel may be measured. The fractographs in SM50YB[SM58Q] steel showed a cleavage mode at −175[−196 and −175]℃, a mixture mode of cleavage and dimple at −150[−150]℃ and a dimple mode at −100[above −150]℃. It can be seen that the DBTT of toe HAZ in SM50YB[SM58Q] is about −150[−150]℃. Moreover these DBTT values agreed quite well with those defined as a temperature corresponding to a mean value of upper and lower shelf energies in the SP energy transition curve.

On the other hand, the observation of SEM fractographs by the COD test was also carried out on the same microstructures as the SP test. An example of this observation for SM50YB steel is presented in Fig. 14. The lower end of each fracto-

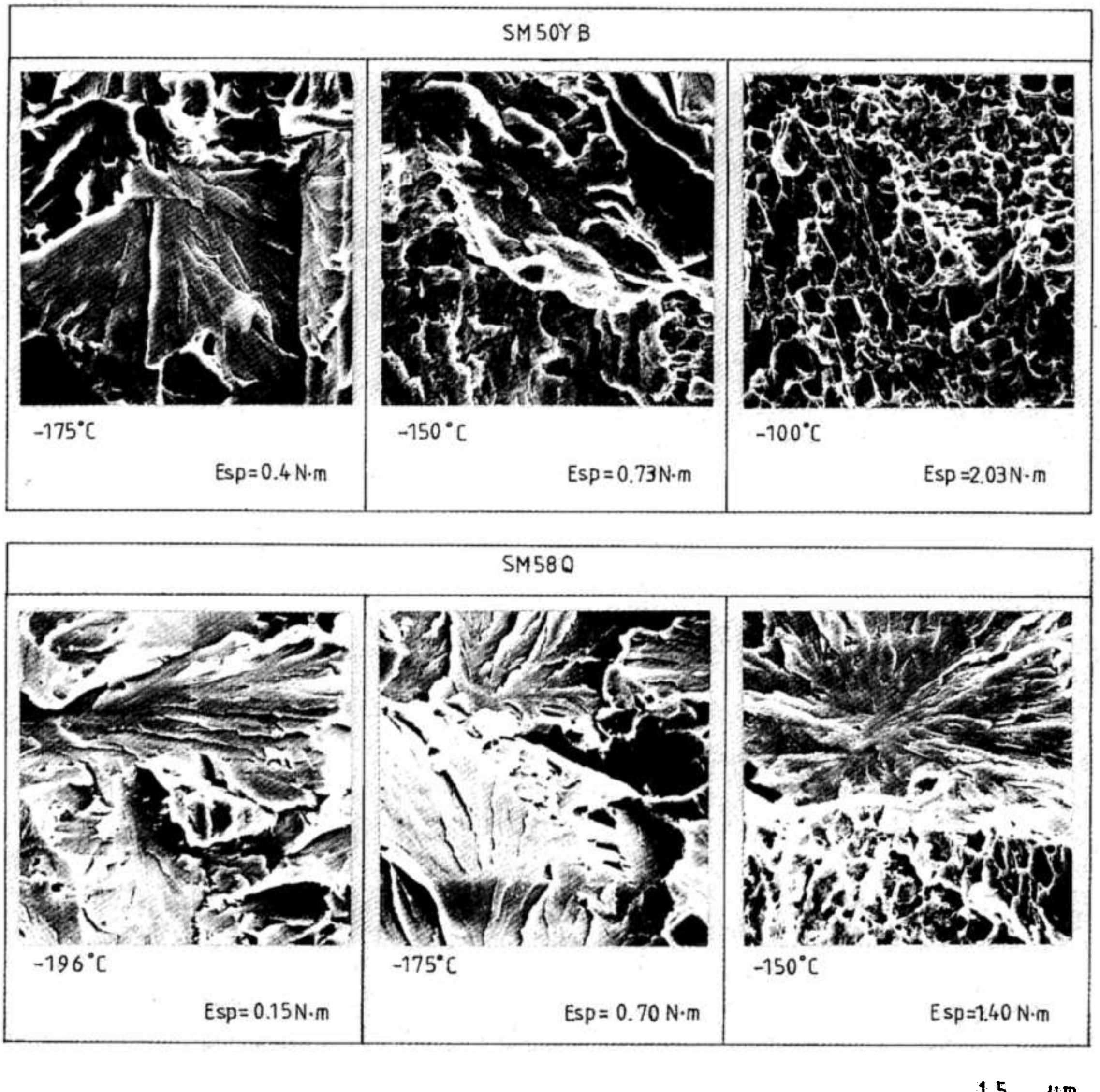


Fig. 13 SEM fractographs of toe HAZ in SM50YB and SM58Q steels by SP test. (×2000)

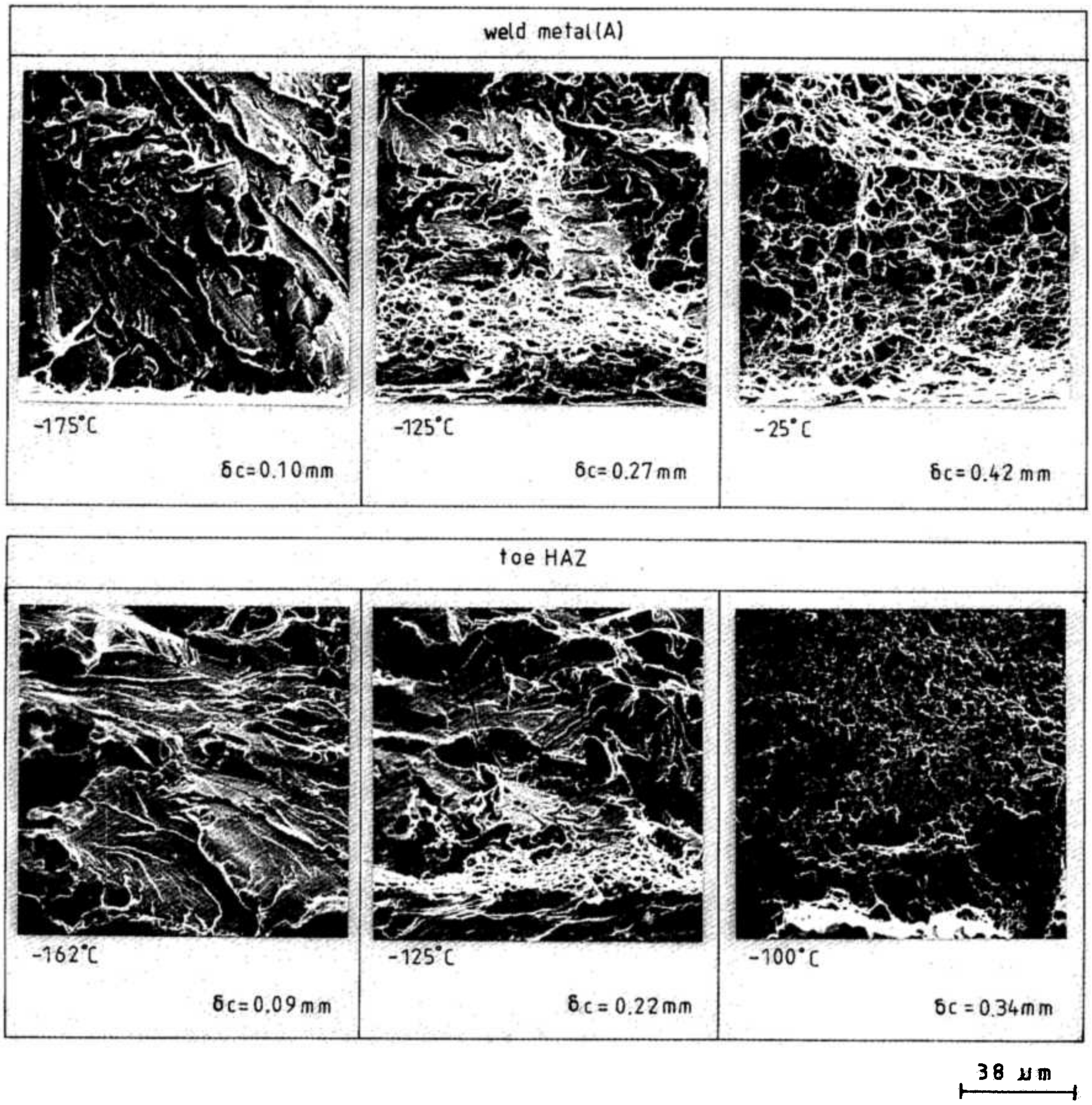


Fig. 14 SEM fractographs of toe HAZ and weld metal(A) in SM50YB steel by COD test. (×800)

Table 2 Ductile-brittle transition temperature obtained from SP and COD tests

steel	microstructure	Orientation (SP/COD)	$(DBTT)_{SP}$, ℃	$(DBTT)_{COD}$, ℃
SM50YB	parent	S/LS	−174	−157
		T/LT	−155	−125
		L/TL	−147	−150
	toe HAZ	S/LS	−147	−115
	HAZ(B)	S/LS	−175	
		T/LT	−150	
	weld metal(A)	S/LS	−162	−135
	weld metal(B)	S/LS	−163	
		T/LT	−163	
SM50Q	parent	S/LS	−190	−170
		T/LT	−190	−170
		L/TL	−190	−170
	toe HAZ	S/LS	−150	−90
	weld metal	S/LS	−175	−145

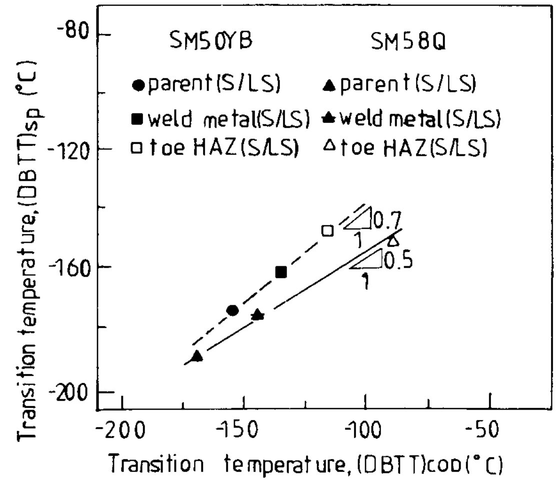


Fig. 15 Relation of transition temperatures between SP test and COD test in SM50YB and SM58Q steels

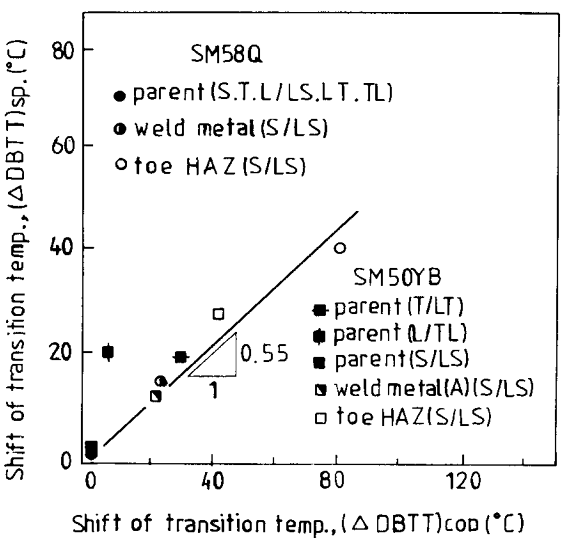


Fig. 16 Relation of transition shifts between SP test and COD test in SM50YB and SM58Q steels

graph in this figure indicates the notch tip. It was showed that a dimple mode was obtained for critical COD values δ_c more than 0.3 mm, and a cleavage mode was done for ciritical COD values δ_c less than 0.2 mm, at the notch roots. Therefore the DBTTs by the COD tests were defined as an temperature corresponding to the ciritical COD value $\delta_c = 0.25$ mm at which the first evidence of dimples was probably occurred.

The values of DBTTs obtained from the SP and COD tests are shown in Table 2.

Fig. 15 shows a good relation between two types of ductile-brittle transition temperature, $[\mathrm{DBTT}]_{SP}$ and $[\mathrm{DBTT}]_{COD}$, which can be expressed as two lines with different slopes depended on base steels.

The shifts in the transition temperature ΔDBTT, the difference between DBTT of parent speciment with S or LS orientation and that of any microstructure, have been commonly used to investigate the deterioration degree of fracture strength compared with the parent material (J.K.Lim et al, 1984, D.Y.Lyu et al., 1989). The correlation between $[\Delta\mathrm{DBTT}]_{SP}$ and $[\Delta\mathrm{DBTT}]_{COD}$ as shown in Fig. 16 was empirically developed from test results on various microstructures. It was found that a unique linear correlation of $(\Delta\mathrm{DBTT})_{SP} \cong 0.55(\Delta\mathrm{DBTT})_{COD}$ exists between these two species of steel. This empirical correlation is almost independent on experimental variables such as species of steel, microstructures of welded region and specimen orientations etc..

Although the surffícent test data with many species of steel have not been acquired, the present test result indicates that the SP test does provide a useful method of determining the fairly reliable values of transition temperature of various zones in welded steel joint.

4. CONCLUSIONS

In this paper, the fracture strength evaluation of microstructures at any localized region of interest in welded steel joint was carried out by means of small punch test and then was confirmed by using of COD test. The SP test may be considered as a useful test technique to be applied to evaluating the fracture strength of welded steel joint as well as the specimen orientation effect.

The empirical correlation, $[\Delta\mathrm{DBTT}]_{SP} \cong 0.55[\Delta\mathrm{DBTT}]_{COD}$, between the SP and COD test data was obtained. In addition the experimental variables such as species of steel, weld microstructures and specimen orientations etc. probably would not affect the empirical linear correlation markedly.

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