STRENGTH-MISMATCH EFFECT ON STEEL WELD HAZ-TOUGHNESS IN CTOD AND CHARPY TESTS






Y. Chiba **K. Murayama** **S. Satoh** **K. Miyashiro** **M. Ohata** **F. Minami**

ABSTRACT

The effects of strength-mismatch between the base and weld metal in welded joints on CTOD and Charpy impact toughness of heat-affected zone (HAZ) are investigated in this study. Both toughness properties are compared, in consideration of the effect of the local brittle zone (LBZ) in HAZ, and strength-mismatch effects are discussed analytically. Two types of welded joints for 490 MPa strength class structural steel with the same thickness of 25 mm, which were strength-matched and overmatched joints, are prepared under the same welded conditions (heat input = 4 KJ/mm) with different welding consumables. The critical CTOD of the HAZ for the overmatched joint exhibits the lower values in wide temperature range of ductile-to-brittle fracture transition than that for the matched joint, whereas microstructures and total LBZ size along crack-tip are consistent with each other. On the contrary, significant difference between the matched and overmatched joints in the lower temperature range cannot be observed in the Charpy impact toughness. The reason why the strength-mismatch effects on the fracture toughness are different between the CTOD and Charpy impact tests is discussed.

IIW-Thesaurus keywords: *COD, Dynamic fracture tests; Frac mech tests; Impact toughness; Heat affected zone; Mechanical properties; Mechanical tests; Mismatch; Welded joints.*

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1 INTRODUCTION

In 1995, after the occurrence of the Hanshin-Awaji Earthquake, many fractures at beam-to-column connection were observed. Some of the fractures occurred from the heat-affected zone (HAZ) of both sides of the beam welds in a brittle manner (see Figure 1). Since then, an improvement of the joint detail and a methodology to control the heat input and interpass temperature have been suggested, to prevent the initiation of brittle fracture at the welds. On the other hand, it is also an important topic to evaluate the HAZ fracture toughness. The localized area at the beam-to-column connection will have a complicated thermal cycle due to the multi-pass weld sequence, which is prone to generate a low toughness region (e.g., Local Brittle Zone) due to grain coarsening. In order to assess the integrity of welded structures, it is important to evaluate the HAZ fracture toughness, taking into account the microstructure near the crack-tip.

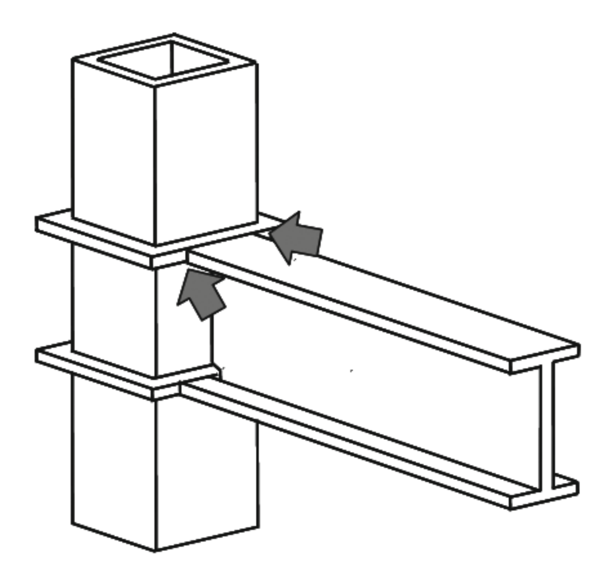


Figure 1 – Potential site of brittle fracture initiation at beam end

On the other hand, the welded joints in steel structures are commonly designed to have weld metal (WM) with higher strength than base metal (BM), to prevent the failure in welds resulting from strain localization. This kind of joint is called an "Overmatched joint". The HAZ toughness estimated with the fracture toughness tests, such as CTOD tests, depends on the strength mismatch and overmatch tends to provide a lower toughness value [1]. Therefore, an excessively high overmatch in the welds should be avoided, in terms of maintaining a required CTOD fracture toughness of the HAZ. However, the effect of strength overmatch on toughness properties obtained by the Charpy impact test that is commonly and widely used for evaluating material toughness properties, as well as correlation between the CTOD and Charpy impact toughness of the HAZ for strength-mismatched welds, have not been understood well.

In this study, the effects of strength mismatch between the base and weld metals on the CTOD and Charpy impact toughness of multi-pass weld HAZ for joints were examined and analyzed, in consideration of the toughness heterogeneity in the HAZ.

2 EXPERIMENTAL PROCEDURE

The steel used in this study is the structural steel SM490A (t = 25 mm) that is commonly used in steel building in Japan. The chemical composition and the mechanical properties of this steel plate are summarized in Table 1 and Table 2. To investigate the effect of strength-mismatch on the multi-pass HAZ-toughness, two types of welded joints, a strength-matched joint and an overmatched joint, which have respectively, almost the same and a higher strength of weld metal than base steel, were fabricated with the same bevel size and welding conditions (see Figure 2 and Table 3). The welding consumables used for the matched and overmatched joints are YGW11 and YGW21, respectively, as specified in Table 4.

Table 3 – Welding conditions

Welding process	CO_2 arc welding
Welding direction	Vertical to rolling direction
Heat input (kJ/mm)	4
Interpass temperature (°C)	150
Number of passes	6

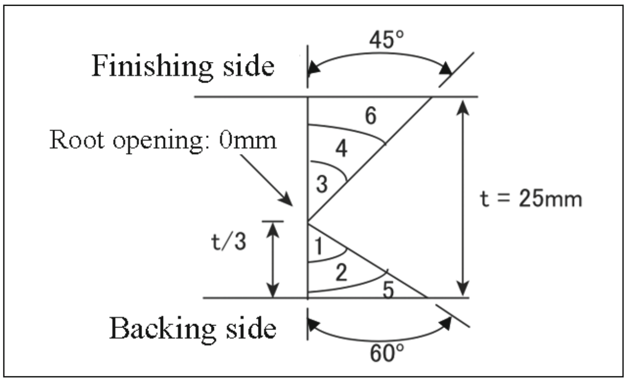


Figure 2 – Double bevel groove

Table 1 – Chemical composition of base metal

	Chemical composition (mass %)						Ceq	Pcm
	C	Si	Mn	P	S	Cu	(%)	(%)
SM490A	0.14	0.26	1.29	0.014	0.006	0.16	0.41	0.31

Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cr)/15.
Pcm = C + Si/30 + (Mn+ Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B.

Table 2 – Mechanical properties of base metal

	Mechanical properties				
	YP (MPa)	TS (MPa)	YR (%)	El (%)	vE_0 (J)
SM490A	412	527	78	30	206

YP: Yield point, TS: Tensile strength, YR: Yield-to-tensile ratio (YP/TS), El: Elongation,
vE_0: Charpy-absorbed energy at 0 °C.

Table 4 – Welding consumables

	Base metal	Welding consumables
Matched joint	SM490A	YGW11
Overmatched joint		YGW21

Figure 3 shows the cross-section of the welded joint. Figure 4 compares the Vickers hardness for the matched and overmatched joints and Table 5 summarizes the average Vickers hardness in each region in the welds (base steel, weld metal, FGHAZ and CGHAZ). As shown in Figure 4, the overmatched joint and matched joint have apparently different WM hardness, but with almost the same HAZ hardness.

Weld metal tensile tests were conducted using round-bar tension specimens shown in Figure 5. Test results are given in Table 6. Strength ratios (Sr) of the matched and overmatched joints are 1.17 and 1.39, respectively, in terms of the tensile strength ratio between the weld metal and base steel. This strength ratio is nearly equal to the hardness mismatch ratio given in Table 5.

The 3-point bend CTOD specimen and Charpy impact specimen are extracted from welds as shown in Figure 6. Figure 7 shows the dimensions of the test specimens. The fatigue pre-crack in CTOD specimen

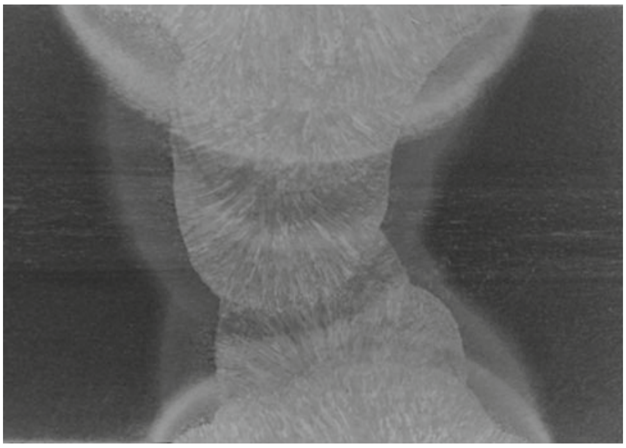


Figure 3 – Cross-section of overmatched joint

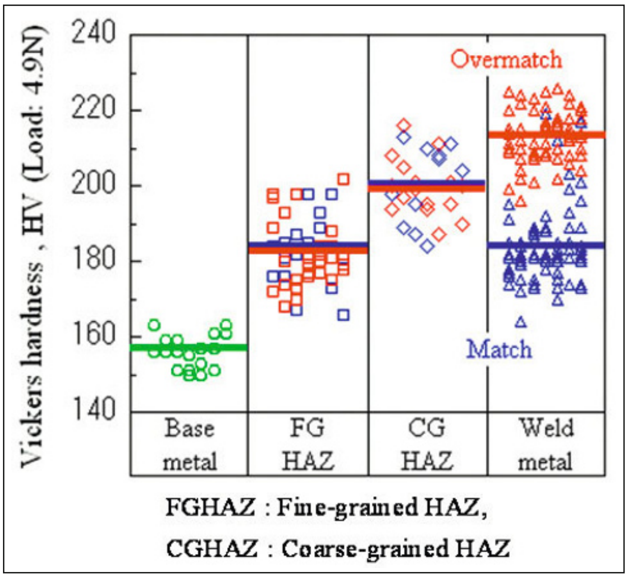


Figure 4 – Hardness distribution of welded joints

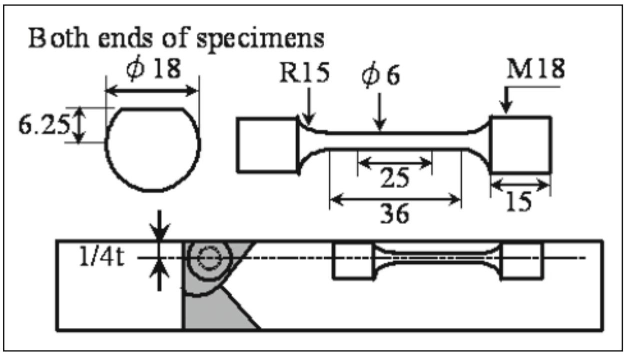


Figure 5 – Extraction of tensile specimens from weld metal

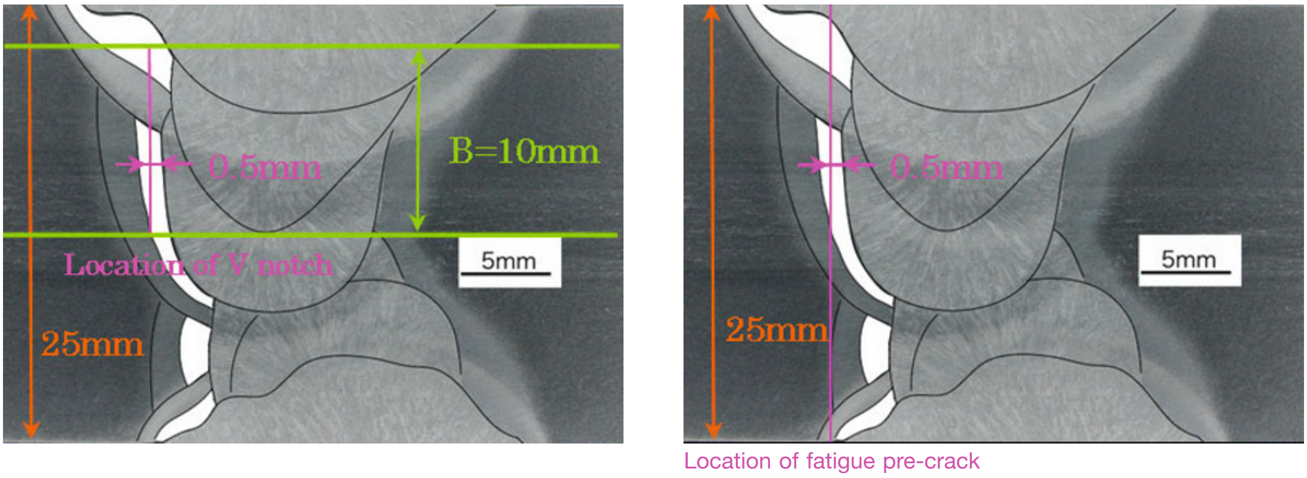
and V-notch in the Charpy specimen were located 0.5 mm away from the fusion line, to contain much coarse-grained HAZ (CGHAZ) along crack/notch tip. Fatigue pre-crack of CTOD specimen was introduced at the tip of the machine notch after local pre-compression treatment to relax the welding residual stress [see Figure 7 c)]. The CTOD test was conducted at the temperature range of -80 °C to 0 °C and the Charpy impact test was conducted at the temperature range of -120 °C to 20 °C.

Table 5 – Vickers hardness of welds (average hardness)

	Averages of Vickers hardness (HV)				Hardness mismatch ratio
	Base Metal	FGHAZ	CGHAZ	Weld Metal	
Matched joint	157	183	200	184	1.17
Overmatched joint	157	183	200	213	1.36
Mismatch ratio = HV(WM)/HV(BM), WM: Weld Metal, BM: Base Metal.					

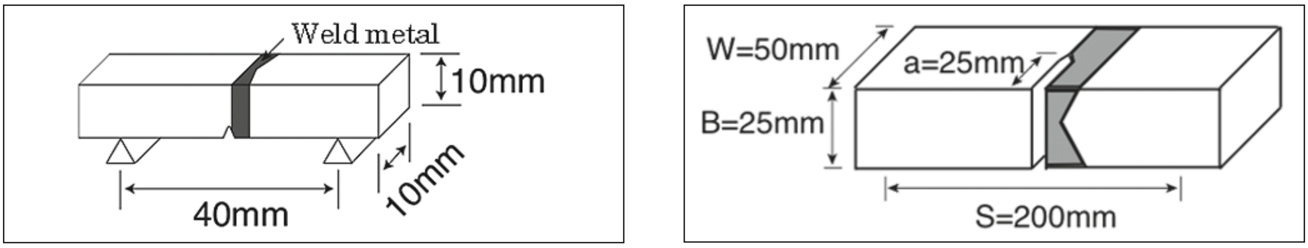
Table 6 – Mechanical properties of weld metal

	Mechanical properties of weld metal				
	YP (MPa)	TS (MPa)	YR (%)	ε_T (%)	Sr
Matched joint	487	596	82	13	1.17
Overmatched joint	623	706	88	13	1.39
Sr= TS(WM)/TS(BM).					

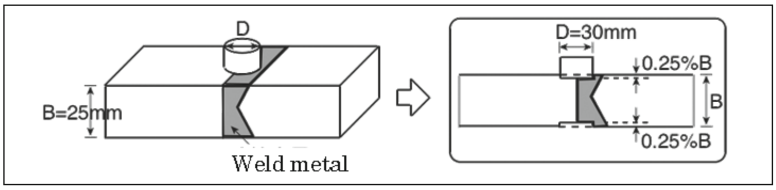


a) Extraction of Charpy specimens b) Extraction of CTOD specimens

Figure 6 – Microstructure and extraction of specimens



a) Dimensions of Charpy specimens **b) Dimensions of CTOD specimens**



c) Pre-compression treatment for CTOD specimens

Figure 7 – Configuration of specimens

3 RESULTS

The results obtained from the CTOD and Charpy tests are summarized in Figures 8 and 9. Notations δc, δu and δm follow the British standard BS 7448 [2]. As shown in Figures 8 and 9, no significant effect of strength-mismatch can be observed in the test results. However, these results could be influenced by the HAZ microstructure sampled by the fatigue crack front. For this investigation, sectioning [3, 4] was conducted as illustrated in Figure 10. In this paper, HAZ microstructures of multi-pass welded joints were classified on the basis of the simulated weld thermal cycle test [5, 6], as shown in Table 7. According to the literature [7], the peak temperature of each weld pass of multi-pass welding under the quasi-stationary state can be estimated by the line heat source. Equation (1) can be applied to evaluate the peak temperature T_p in the HAZ:

$$\frac{d}{d_{HAZ}} = \frac{\sqrt{850 - T_0}}{\sqrt{T_p - T_0}} \bullet \frac{\sqrt{T_{mp} - T_0} - \sqrt{T_p - T_0}}{\sqrt{T_{mp} - T_0} - \sqrt{850 - T_0}} \qquad (1)$$

where

d is the vertical distance from the fusion line,

d_{HAZ} is the width of Nital-etched HAZ,

T_{mp} and T_0 are the melting temperature and initial temperature (T_0 = 150 °C) of the base plate, respectively. (In this experiment, T_0 also corresponds to the interpass temperature of multi-pass welding.)

The maximum temperature of the etched HAZ boundary was estimated at 850 °C (A_{C3} transformation temperature).

In this study, UACGHAZ, ICCGHAZ and SCCGHAZ were identified to be the local brittle zone [7] and designed simply as the CGHAZ. The sectioning results were used for calculating the CGHAZ length along the crack-tip/notch-tip as defined in Figure 11. The crack opening stress in 3-point bend specimen, effective for cleavage fracture, is lower near the specimen surface, compared to that around the mid-thickness due to the plane stress condition. Therefore, the length of the CGHAZ along the fatigue pre-crack tip, except for the region of about 5 mm from the specimen surface termed L_{CGHAZ}, which would be effective to the fracture toughness, was measured. As for the Charpy specimen, the total CGHAZ length along the notch-tip front is

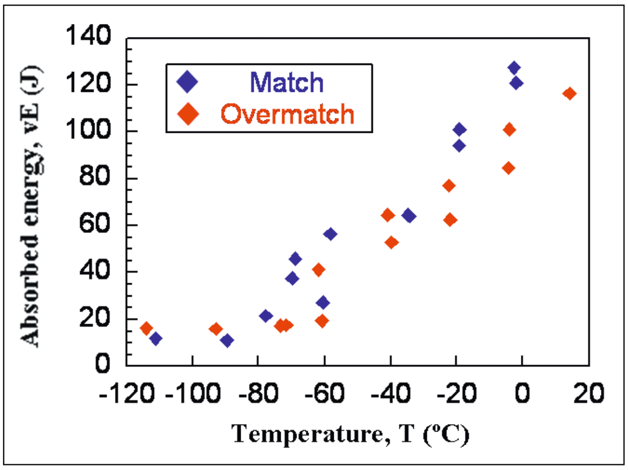


Figure 8 – Temperature transition curve of absorbed energy

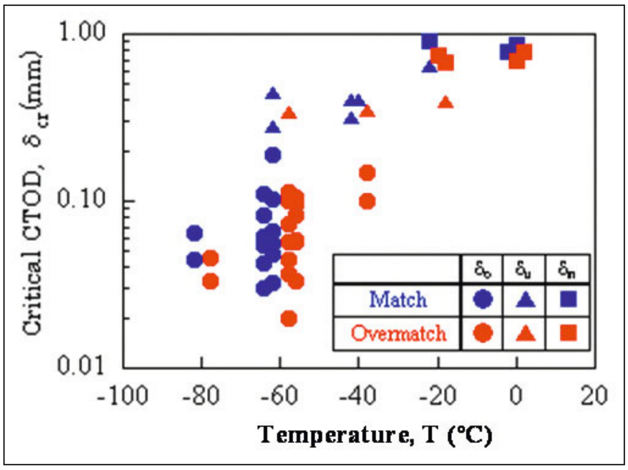


Figure 9 – Temperature transition curve of critical CTOD

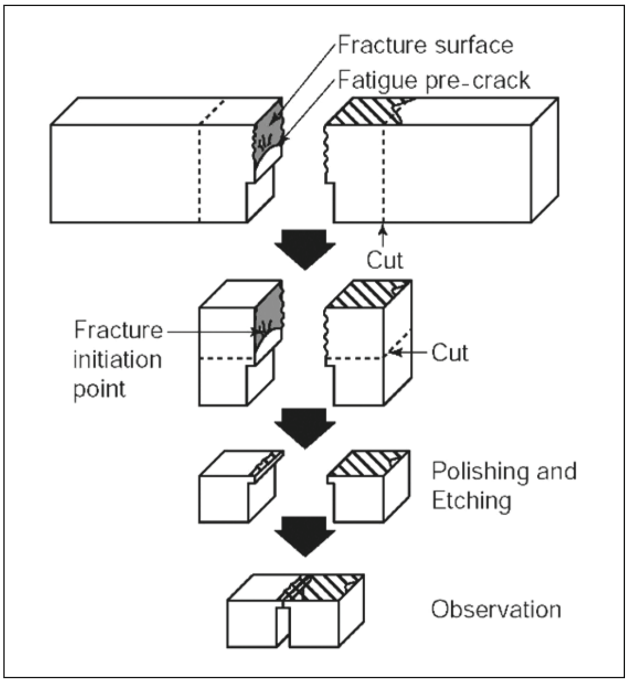


Figure 10 – Sectioning procedure for identification of microstructure

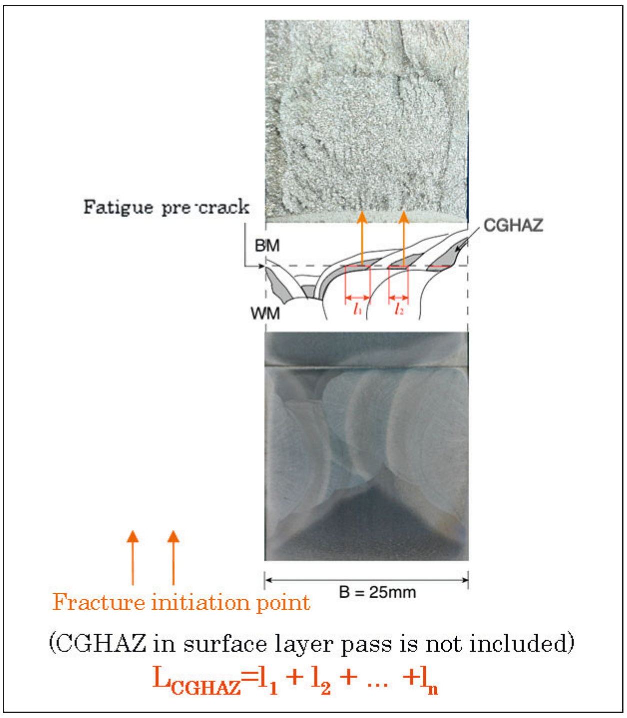


Figure 11 – Definition of CGHAZ length

Table 7 – Classification of HAZ microstructure for multi-pass welds

Peak temperature by first cycle	Peak temperature by subsequent cycles	HAZ microstructure
Melting point ~1 200 °C (CGHAZ)	Melting point ~1 200 °C	UACGHAZ
	1 200~850 °C	FGHAZ
	850~700 °C	ICCGHAZ
	700~450 °C	SCCGHAZ
	450 °C	UACGHAZ
1 200~850 °C (FGHAZ)	Melting point ~1 200 °C	UACGHAZ
	1 200~850 °C	FGHAZ
	850~700 °C	ICHAZ
	700 °C	FCHAZ
850~750 °C (ICHAZ)	Melting point ~1 200 °C	UACGHAZ
	1 200~850 °C	FGHAZ
	850 °C	ICHAZ

CGHAZ: Coarse-grained HAZ; FGHAZ: Fine-grained HAZ; ICHAZ: Intercritical HAZ.

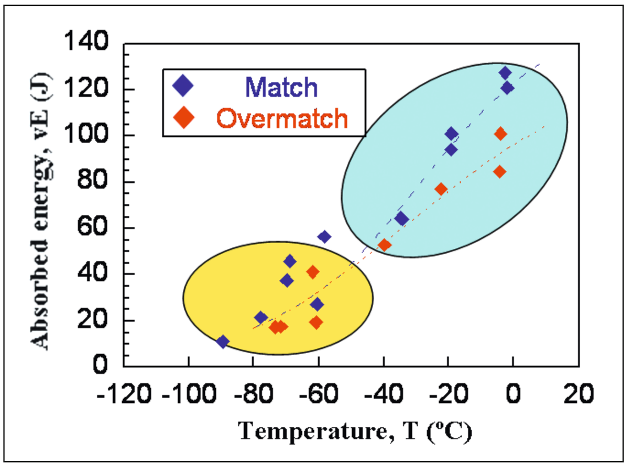


Figure 12 – Absorbed energy where the notch-tip front is located at GHAZ

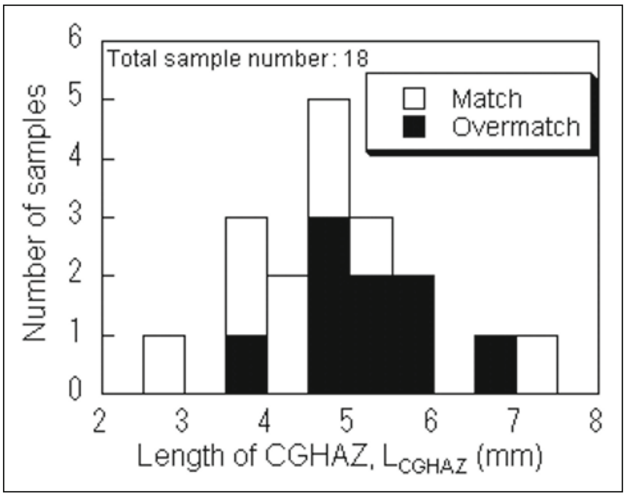


Figure 13 – Histogram of the CGHAZ length in CTOD specimens

measured before extracting the specimen from welded joints.

Figure 12 shows the absorbed energy for only the Charpy impact specimens, where the notch-tip front was located at CGHAZ. At a lower temperature, below ductile-to-brittle transition temperature, there seems to be no difference in the Charpy-absorbed energy for both matched and overmatched joints. On the other hand, at the higher temperature range near the upper shelf, the overmatched specimens to some extent give lower toughness values than the matched specimens.

Figure 13 shows a histogram of the CGHAZ length for all CTOD specimens fractured in a brittle manner. There exists a large scatter in the CGHAZ length. This implies that the CGHAZ length effect should be taken into account, in order to address the strength-mismatch effect on critical CTOD.

4 DISCUSSION

In order to clarify the strength-mismatch effect on critical CTOD, the effect of CGHAZ length on critical CTOD was normalized as follows. The critical CTOD was assumed to be in accordance with the "size effect" of the local brittle zone. Then, the critical CTODs for all specimens that have various CGHAZ length L_{CGHAZ} were corrected to the CTODs that have the L_{CGHAZ} of 5 mm by means of Equation (2) [8]

$$\delta_{cr-5} = \left(\frac{L_{CGHAZ}}{L_5} \right)^{\frac{1}{2}} \times \delta_{cr} \qquad (2)$$

where

δcr-5 is the corrected critical CTOD,

δcr is the critical CTOD obtained by experiment,

L_5: is the reference CGHAZ length (= 5 mm in this study).

All specimens that exhibited maximum load plateau were confirmed to fracture at the CGHAZ in a brittle manner, with correction conducted only to the specimens that showed brittle fracture. Figure 14 exhibits the corrected critical CTODs for the matched and the overmatched specimens. The clear strength-mismatch effect can be seen in the critical CTOD over the wide temperature range. However, the difference in critical CTOD at the lower temperature range is smaller than that at the higher temperature range. This is explained in terms of the size of the plastic zone around the crack-tip, located about 0.5 mm away from the weld metal. At the lower CTOD level, the plastic zone is relatively small and does not expand to the weld metal sufficiently. Hence, even for the overmatched specimens, the crack opening stress would not be enlarged by the plastic constraint caused by the higher strength WM. On the other hand, at the higher CTOD level, the plastic straining in the HAZ can be strongly constrained by the overmatched WM. Therefore, the effect of strength-mismatch on critical CTOD can be more significant at the higher temperature.

The Charpy impact test is a dynamic fracture test and the strain rate around the notch bottom would be quite high. In general, the flow-stress of the material is highly influenced by a strain rate and amplified by an increasing strain rate. This tendency will be more significant in a lower-strength material. The HAZ in matched and overmatched specimens has the same strength proper-

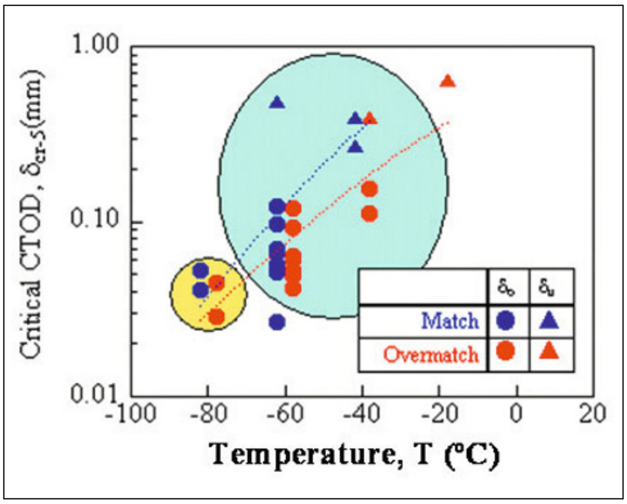


Figure 14 – Critical CTOD for L_{CGHAZ} = 5

ties and the flow stress of both HAZ regions ahead of the notch-tip in the Charpy specimens can be enlarged to the same extent. The flow stress of overmatched WM that has a higher strength than the HAZ cannot be enlarged by a high strain rate as much as the lower-strength HAZ. Accordingly, the difference in the strength between the HAZ and WM ahead of the notch-tip for overmatched specimen could be lowered under high strain rate loading, which results in the disappearance of the strength-mismatch effect on the critical CTOD in the Charpy impact test. On the other hand, as shown in Figure 12, the overmatched specimens showed a lower toughness value than matched specimens at the high temperature range. Additional investigation is required to interpret this phenomenon.

5 CONCLUSIONS

This study focused on the effect of strength mismatch on the HAZ fracture toughness of multi-pass welded joints of steel-framed structural steel, obtained with the Charpy impact test and 3-point bend CTOD test. Both test results were compared by taking into account the effect of heterogeneity in HAZ microstructures. The following results were obtained.

1) The overmatched joint showed a lower critical CTOD value than the matched joint over the wide range of test temperatures. This effect was more significant at the higher temperature range that provided higher fracture toughness. This would be due to the plastic constraint in the HAZ caused by the higher-strength WM.

2) In the Charpy impact test, strength mismatch effect was recognized only at the higher temperature range. The overmatched joint exhibited lower absorbed energy than the matched joint at a higher temperature range. However, at a lower temperature range, the strength-mismatch effect was not significant in the Charpy impact test.

It was found that the strength-mismatch effect on fracture toughness would be different between the Charpy impact test and 3-point bend CTOD test, especially at a lower temperature that provided lower fracture toughness. Hence, more attention should be paid to applying the Charpy impact test results to the evaluation of the CTOD fracture toughness of the HAZ for strength-mismatched welded joints.

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