EXPERIMENTAL STUDY ON FRACTURE TOUGHNESS OF HIGH-STRENGTH STRUCTURAL STEEL AND ITS BUTT WELD

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ABSTRACT: As steel strength increases, the fracture toughness may be quite different from that of normal steel, and the corresponding welded joints can be the critical spots due to possible brittle fracture behavior. Moreover, the design load for high-strength steel structure is larger and the steel with higher stress is more sensitive to defect, which increases the potentials of brittle fracture. The service of steel structures in cold regions increases the crisis of brittle fracture. Therefore, a series of three-point bending tests were conducted at low temperature to investigate the fracture toughness of high-strength steel and its butt weld. Fracture micro-mechanisms were analyzed through Scanning Electron Microscopy of the fractured surfaces in specimens. The fracture toughness indices (critical CTOD values) of high-strength steel and its butt weld all decrease as temperature decreases. The heat affected zone (HAZ) is more critical to fracture than the base material, indicated by much lower critical CTOD values and higher transition temperature. The fracture toughness of high-strength steel is relatively lower than the conventional steels (i.e. 235MPa, 345MPa and 390MPa). The results obtained in this paper provide reference for the fracture resistant design of high-strength steel structures in cold regions.

Keywords: fracture toughness; high-strength steel; butt weld; low temperature; brittle fracture

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1. INTRODUCTION

High-strength steel has been popular and applied in long-span structures and high-rise buildings for the advantage of light weight and high loading capacity [1-4]. However, the mechanical properties and toughness of the high-strength steel may be quite different from that of normal steel, due to the different rolling process, crystal phases and chemical components. As steel strength increases, the elongation decreases and the yield to ultimate strength ratio increases generally according to some related researches [5-14], which indicates the lower plastic deformation capacity when failure. Therefore, the use of high-strength steels is limited.

Further, the welding for high-strength steel is difficult, and welding defect is prone to occur in weld metal and heat affected zone (HAZ). Besides, the effect of the heat input during welding on the toughness of HAZ is significant [18-20]. Welded joints can be the critical spots for structural integrity due to possible brittle fracture behavior [21]. Besides, based on the fracture mechanics, the steel with higher stress is more sensitive to defect [22]. For high-strength steel structure, the design load is obvious larger than that for conventional steel structure, which increases the potentials of brittle fracture.

Additionally, a considerable number of steel structures were reported to be brittle fracture damaged in cold regions, and temperatures of the majority land area in China are quite low in winter [23-27]. For the study on brittle fracture of steel structure, despite the traditional impact toughness index can reflect the fracture resistant ability of materials to a certain extent, but it hardly gave an accurate evaluation for the structural security, while the fracture toughness index can evaluate it quantitatively.

Therefore, the extension and safe usage of high-strength steel welded structures especially requires investigations on the fracture toughness of the welded joints of high-strength steels at low temperature, as well as the ambient temperature.

2. OVERVIEW OF THREE POINT BENDING TESTS

A series of three-point bending (TPB) tests for the butt welds of high-strength steel with yield point of 460MPa and 960MPa were carried out at ambient temperature and low temperature in the present study. Five temperature points, i.e. +20, 0, -20, -40, -60 °C, were selected for the series of tests, and three replicated specimens were performed for each temperature point. The crack tip opening displacement (CTOD) as a fracture toughness parameter was investigated by TPB tests at five different temperatures, and the transition procedure from ductile to brittle for the butt welds of high-strength steel are studied, so as to provide technical basis for the brittle fracture prevention design of high-strength steel structure. Besides, microstructure and fracture mechanisms were investigated by Scanning Electron Microscopy (SEM) of fracture surfaces in specimens.

2.1 Specimen Materials

High-strength steel plates of 14mm thickness in the experiments were produced by the controlled-rolling technology, the chemical compositions of the 460MPa and 960MPa steel plates are given in Table 1.

Table 1. Chemical Compositions of High-strength Steel Plates wt%

460MPa					960MPa				
C	S	P	Si	Mn	C	S	P	Si	Mn
0.190	0.004	0.013	0.220	1.510	0.060	0.002	0.011	0.260	1.610

The welding process for the 460MPa and 960MPa steel plates adopt full penetrated gas metal arc welding (GMAW) and submerged arc welding (SAW) respectively. The welding process has been qualified in accordance with JGJ81-2002 "Technical specification for welding of steel structure of building" [28]. The welding process parameters are listed in Table 2. The butt welds are of V-groove, the geometries of which are shown in Figure 1.

Table 2 Welding Process Parameters

Base material	Method	Position	Wire	Φ/mm	Shielding gas (Flux)	Voltage/V	Current/A	Velocity/cm/min
460MPa	GMAW	flat	JM-60	1.2	$CO_2$20%+ A_r80%	28-35	250-300	30-45
960MPa	SAW	flat	SLD-80	4	SJ101	30-34	530-570	40-45

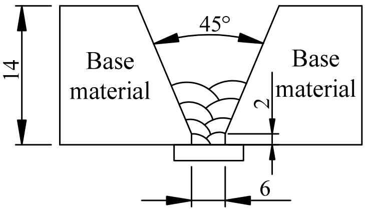


Figure 1. The V-shaped Groove Weld used in this Investigation

The samplings of specimen for weld metal and HAZ are shown in Figures 2(a) & (b), respectively. For the specimens sampled from weld metal, the center of specimen coincide with the center of the weld gap as shown in Figure 2(a); for those sampled from the HAZ, the center of specimen is located away from the vertical fusion line at weld root with the distance of 5mm as shown in Figure 20(b). The pre-crack direction is consistent with the rolling direction of plates.

The geometries and dimensions of the specimen as shown in Figure 2(c) were in accordance with the standard "Metallic materials-Unified method of test of determination for quasistatic fracture toughness" [29]. The specimen thickness B is 14mm, width W is 28mm, and distance between the bearing points S is 112 mm. The single edge crack of the specimen was machined by 8mm wire cutting and then headed by fatigue pre-crack of which the length is 3mm. The schematics of test specimen and test setup are shown in Figure 2(c).

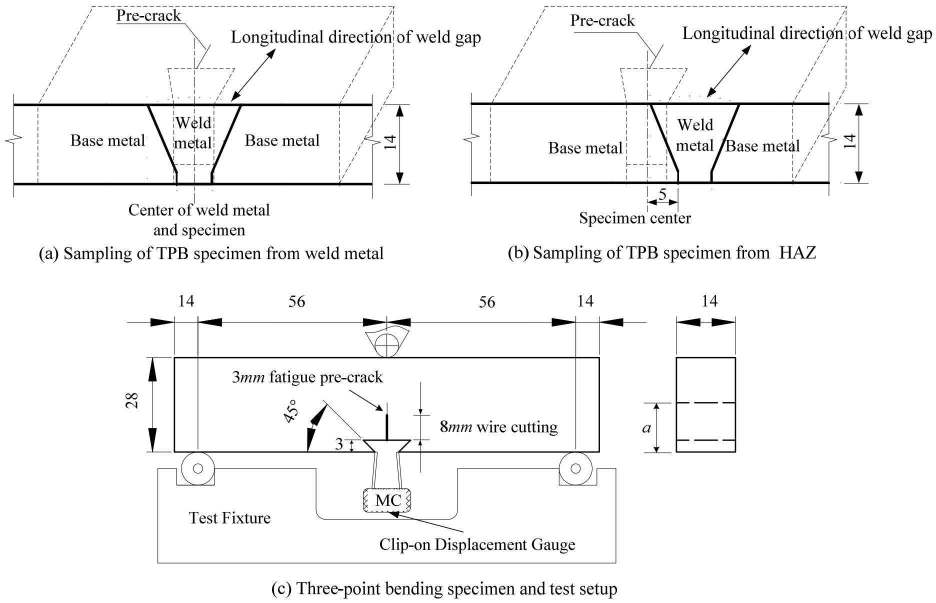
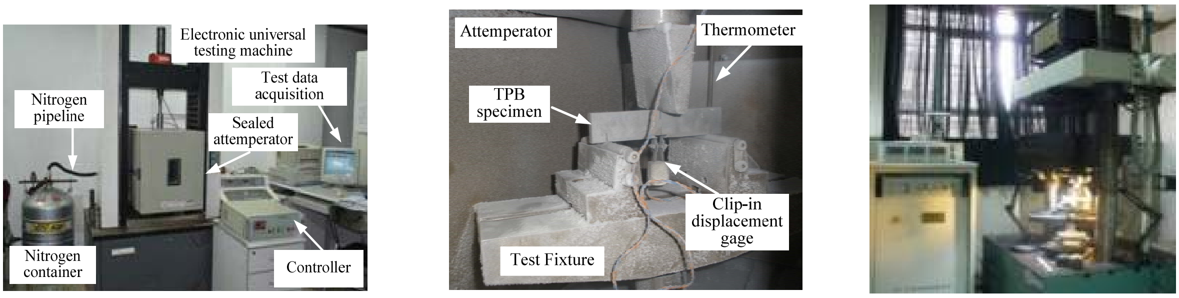


Figure 2. Sampling and Geometry of Three-point Bending Specimen

2.2 Experimental Equipment

The three-point bending tests were implemented by the electronic universal testing machine (INSTRON) as shown in Figure 3(a). The specimens were refrigerated by mixed steam of air and liquid nitrogen in the sealed attemperator installed with INSTRON and the lowest temperature of -70 °C can be achieved. Testing scene inside attemperator is shown in Figure 3(b). The fatigue test machine for pre-crack of TPB specimen is shown in Figure 3(c).



(a) Cryogenic test equipments (b) Three-point bending test in attemperator (c) Fatigue test machine (INSTRON)

Figure 3. Experimental Setup

2.3 Experimental Protocol

(1) Load punching should be guaranteed to be located at the center of specimen.
(2) Tests were performed from +20 °C to -60 °C, and for each temperature points, the specimens were cooled at the same time, so as to improve test efficiency.
(3) The lasting time of cooling for specimens should not be less than 15 minutes and the deviation of test temperature to setting temperature should be within the range of ±2 °C during the test.
(4) Loading rate maintain constant and the velocity of the loading beam was controlled to be about 1mm/min during experimental process.
(5) Prior to the failure of specimens, the relationship of displacement and load was recorded by computer.

3. TEST RESULTS AND DISCUSSIONS

In the present study, δ_m (the CTOD value which is corresponded with the maximum load P_m) was taken as the critical value of CTOD, for this value can be applied in all varieties of fracture situations and is convenient for analysis, as well as it can be determined accurately. The load P and displacement V were recorded by force sensor and clip-on displacement gauge, respectively. The P values represent the load in the mid-span of specimen; V values represent the crack mouth opening displacement. According to the standard GB/T 21143-2007 [29], the critical values of CTOD can be determined by Eq. (1) as follows:

$$\delta = \frac{K_I^{\,2}(1-\mu^2)}{2\sigma_y E} + \frac{r_p(W-a_0)V_p}{r_p(W-a_0)+a_0+Z}, \qquad (1)$$

Where $K_I = YP/[BW^{1/2}]$, the value of Y can be obtained by table look-up based on the value of (a_0/W) according to the test standard [15], B is the thickness of specimen, W is the width of specimen; r_p is the plastic rotational factor, for TPB test specimen, r_p =0.44; the plastic component of crack mouth opening displacement V_p is obtained by the curve of P-V; the initial crack length a_0 was measured on the fracture surface; the Poisson's ratio μ is taken to be 0.3, the elastic modulus E and the yield point σ_y were obtained by the previous tensile tests; Z is the thickness of the knife-edge on which the displacement gauge clipped.

The test results of three replicated specimens for the two high-strength steels and the butt welds obtained at the varied temperatures are listed in Table 3 and Table 4, respectively.

Table 3. The critical CTOD Values δ_m (mm) of 460MPa Steel and its Butt Weld

T/°C	Base material		Weld metal		HAZ	
	Test results	Average	Test results	Average	Test results	Average
	0.32406		0.56320		0.10746	
20	0.41195	0.3835	0.41370	0.5824	0.30255	0.2296
	0.41458		0.77032		0.27878	
	0.42019		0.62539		0.34708	
0	0.33587	0.3893	0.34522	0.5408	0.32018	0.3125
	0.41188		0.65190		0.27022	
	0.46500		0.48160		0.29333	
-20	0.36394	0.3929	0.35757	0.3662	0.31121	0.2841
	0.34989		0.25929		0.24766	
	0.27008		0.47094		0.26235	
-40	0.49135	0.3177	0.67253	0.4774	0.15917	0.1942
	0.19170		0.28874		0.16117	
	0.04461		0.07191		0.15507	
-60	0.1543	0.1296	0.14151	0.0925	0.04222	0.0835
	0.18997		0.06405		0.05311	

Table 4. The Critical CTOD Values δ_m (mm) of 960MPa Steel and its Butt Weld

T/°C	Base material		Weld metal		HAZ	
	Test results	Average	Test results	Average	Test results	Average
	0.16652		0.19019		0.11803	
20	0.27909	0.2016	0.18366	0.2034	0.11458	0.1877
	0.15911		0.23628		0.33039	
	0.27212		0.03827		0.10164	
0	0.08881	0.1673	0.36872	0.2477	0.10985	0.1320
	0.14099		0.33623		0.33453	
	0.1238		0.32006		0.00997	
-20	0.27781	0.1556	0.19872	0.1896	0.11661	0.0562
	0.06508		0.04991		0.04198	
	0.05651		0.1663		0.02698	
-40	0.03891	0.0497	0.0581	0.0970	0.05245	0.0452
	0.05381		0.06673		0.056	
	0.04726		0.08849		0.0081	
-60	0.04138	0.0389	0.05181	0.0608	0.05576	0.0293
	0.02793		0.04201		0.02417	

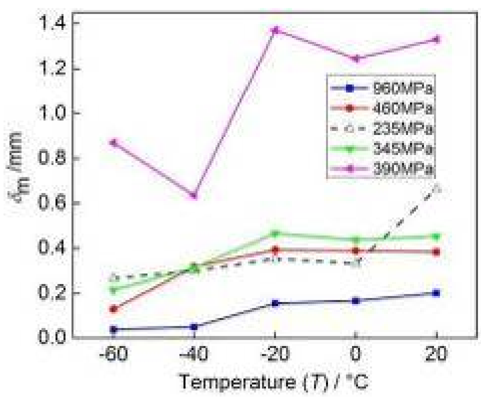


Figure 4. δ_m Versus Temperature Curves for High-strength Steel and Other Three Structural Steels

The tested δ_m average values of high-strength steels (460MPa and 960MPa) with 14mm plate thickness are compared with that of 235MPa, 345MPa and 390MPa steels with 12mm thickness [26] as shown in Figure 4. The variation trends of all the five structural steels are decreasing as temperature decreases, the fracture toughness for 390MPa steel is the largest one, and that for the 235MPa, 345MPa and 460MPa steels are similar, the value for the 960MPa steel is the smallest among the five structural steels. That indicates the fracture toughness of low-alloyed steel is relative higher than ordinary carbon steel, however, when the strength of steel increases to a certain value, the fracture toughness reduces.

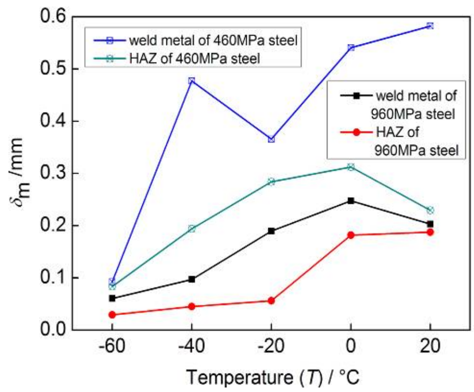


Figure 5. δ_m Versus Temperature Curves for Butt Welds of 460Mpa and 960Mpa Steels

The average values of δ_m versus temperature curves for the butt weld of 460MPa and 960MPa steel are shown in Figure 5. The variation trends of the δ_m average values for weld metal and HAZ all decrease as temperature decreases, except the value of weld metal for 460MPa steel obtained at -40 °C, which may result from the discrete results of weld metal as shown in Table 3. As a whole, the average results of weld metal are higher than that of HAZ for both 460MPa and 960MPa steel, indicating that the fracture toughness is relative higher in weld metal.

The reduction amplitudes of HAZ for 460MPa and 960MPa steel in the range of 0°C to -60 °C are 73.3% and 70.1%, respectively, showing the significant influence of low temperature on the fracture toughness of welded high-strength steel, and indicating that the material transit from ductile to brittle in that temperature range. In addition, δ_m average values of the weld for 960MPa steel are smaller than that for 460MPa steel as shown in Figure 5, indicating that when the steel strength increases to a certain value, the fracture toughness reduces, which agrees with the conclusions reached before.

The transition temperature of ductile-brittle is applied as a critical criterion for fracture resistant design in engineering. The typical curve of toughness versus temperature is S-shaped, which consists of three parts, i.e. the lower shelf, the transition region and the upper shelf. The lower shelf corresponds to the “brittle” mechanisms of fracture. As the temperature increases, a combination fracture mechanism of brittle and ductile is achieved in the transition region. If the temperature increases even further, the fracture mechanism transits to completely ductile fracture mechanism corresponding to the upper shelf. However, it is almost impossible to obtain such a typical curve by tests, for the dispersion of experimental data is always great. Large quantities of experimental researches have shown that the Boltzmann function can well describe the correlation of toughness and temperature [30], and the physical meanings of each parameter are definite. So in this paper, the average δ_m values obtained by tests were regressed by Boltzmann function as Eq. (2), Where δ_1, δ_2, T_t and T_r are curve-fitting parameters; T represents the temperature variable; δ is the critical CTOD value at temperature T; δ_1 and δ_2 are the fracture toughness of the lower and upper shelf, respectively; T_t is the transition temperature of ductile to brittle; T_r is the temperature range of transition region.

$$\delta(T) = \frac{\delta_1 - \delta_2}{1 + \exp[(T\text{-}T_t)/T_r]} + \delta_2 \qquad (2)$$

The temperature transition curves of fracture toughness for 460MPa and 960MPa steels are shown in Figure 6, as well as the corresponding welds. Curve-fitting parameters in Eq. (2) by regress of the test data are listed in Table 5.

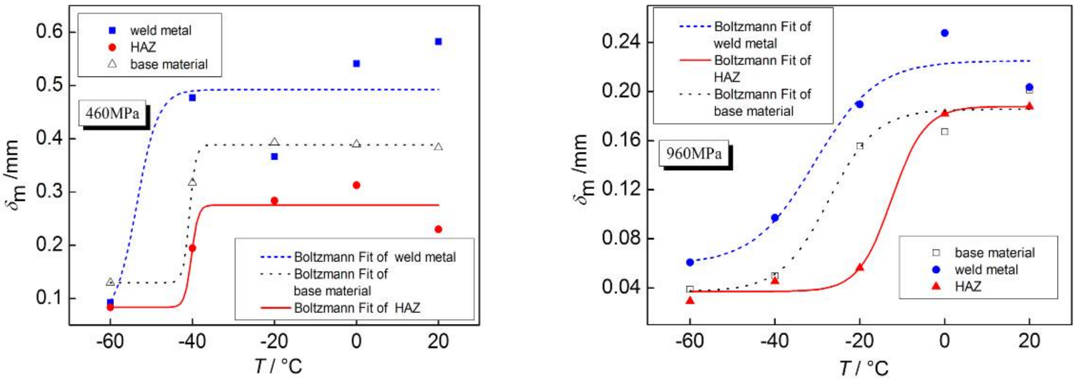


Figure 6. Temperature Transition Curves of
Fracture Toughness for 460Mpa and 960Mpa Steels

Table 5. Fitting Parameters of Boltzmann Function for δ_m Falues

Steel	Specimen	□δ_1/ mm	□δ_2/ mm	T_t/ °C	T_r/ °C	R^2
960MPa	Weld metal	0.06	0.23	-29.76	6.95	0.82
	HAZ	0.03	0.18	-12.45	3.92	0.98
	Base material	0.04	0.19	-27.33	5.6	0.90
460MPa	Weld metal	0.06	0.50	-53.58	2.62	0.77
	HAZ	0.08	0.27	-40.25	0.81	0.66
	Base material	0.13	0.39	-40.72	0.74	0.99

Indicated by Table 5, the upper shelf value and the transition range of weld metal for both 460MPa and 960MPa steels are larger than that of base material and HAZ, moreover, the ductile-brittle transition temperatures are lower than base material and HAZ, showing that the fracture toughness of weld metal is relative high and the fracture property of weld metal itself is not a controlling factor.

On the other hand, the upper and lower shelf values of HAZ for the two high-strength steels are lower than base material, although the ductile-brittle transition temperature of HAZ for 460MPa steel (－40.28°C) is close to that of base metal(－40.94°C), that may result from the limited quantity of test specimens, correlation coefficient of fitting results for HAZ by Boltzmann function is relative small. For 960MPa steel, the transition temperature of HAZ(－12.45°C) is larger than that of base material(－27.33°C), indicating that the fracture toughness of HAZ deteriorate, and it is the weakest zone for the brittle resistant design of welded steel structure.

Compared with the fitting results of 460MPa steel, the upper shelf values of 960MPa steel and the corresponding welds are much lower, the ductile-brittle transition temperatures are higher than that of 460MPa steel, it demonstrates that as the steel strength increases to a certain extent, the fracture toughness decreases. Besides, the fracture toughness decreases more rapidly as the temperature decreases as shown in Figure 5, showing the more significant effect of temperature on the fracture toughness.

4. SEM OF TPB FRACTURED SURFACE

The micro-morphology of TPB fracture surface was scanned by the electron microscope as shown in Figures 7, 8, 9, 10, 11 and 12, the scanning position was close to the fracture surface center, the scanning magnifications for 460MPa and 960MPa steels were 2000 x and 1000x respectively.

As shown in Figure 7, the fracture surfaces for 460MPa steel at 20 °C and 0 °C have lots of dimples and tearing ridges existed; as temperature decreases, the fracture surfaces are dominated by the brittle fracture characteristics with shiny cleavage planes. As for the fracture surfaces for weld metal and HAZ of 460MPa steel , there are considerable dimples and tearing ridges at 20 °C as well, showing the feature of transgranular fracture, the dimples and tearing ridges gradually reduce until disappear and micro fractograph at -60 °C exhibits typical intergranular brittle fracture feature with river patterns and cleavage stages. The microscopic characteristics changing with temperature are in accordance with the macro toughness index (δ_m).

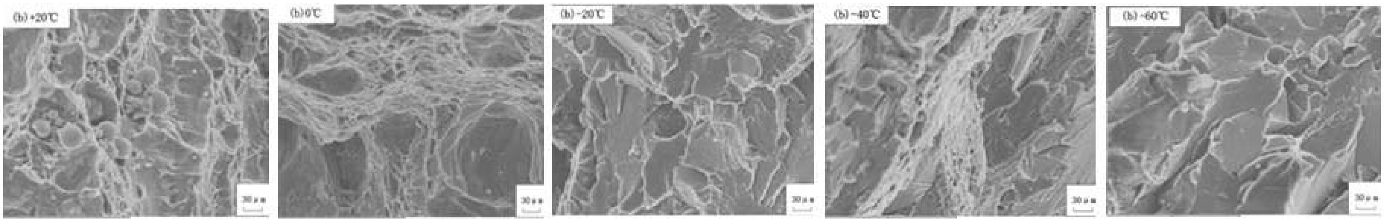


Figure 7. Micro-morphology of Fracture Surfaces for 460MPa Steel at Five Different Temperatures

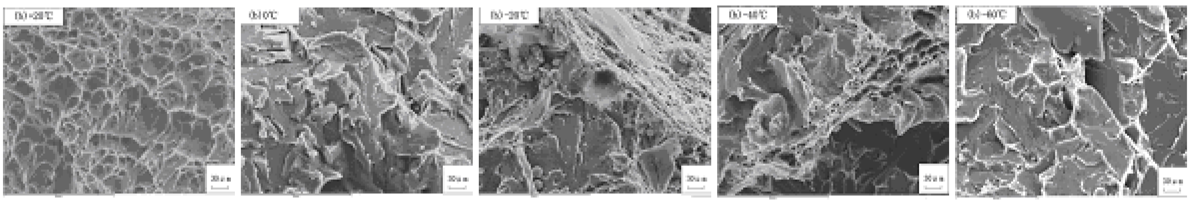


Figure 8. Micro-morphology of Fracture Surfaces for Weld Metal of 460Mpa Steel at Five Different Temperatures

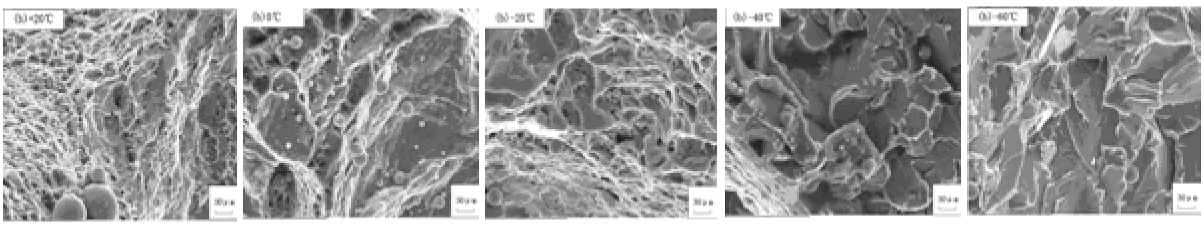


Figure 9. Micro-morphology of Fracture Surfaces for HAZ of 460Mpa Steel at Five Different Temperatures

As shown in Figures 10, 11 and 12, the micro-morphologies for 960MPa steel and its weld are different from that for 460MPa steel. The fracture surface for base material at 20 °C is quite uneven and the voids are relative large, while as the temperature decreases, the fracture surface becomes smooth and the voids change from large to small, from deep to shallow, the quasi-cleavage planes which exhibit some plastic deformation and the tearing ridges occur at -20 °C, showing the feature of quasi-cleavage fracture. When temperature decreases to -40 °C, the fractograph exhibits the cleavage step pattern. The transgranular fracture occurs at -60 °C with tongue patterns in the fracture surface.

As for the weld metal of 960MPa steel, there are dimples in the fractograph at 20 °C as shown in Figure 11, the micro fracture mechanism is void coalescence, as temperature decreases, the dimples become small and shallow until disappear. Dimples and cleavage steps both can be seen at 0 °C, showing the mixed characteristic of ductile fracture and brittle fracture. Many tearing ridges occur at -20 °C, and the fractographs are dominated by the shinny cleavage planes which are shaped like crystal when temperature reduces to -40 °C and -60 °C, showing the intergranular brittle fracture feature. Compared with the micro-characteristics of 960MPa steel and its weld metal, the fractograph of the HAZ has fewer and smaller dimples as shown in Figure 12, which indicates the worse toughness in HAZ. When temperature drops from -20 °C and -60 °C, the cleavage cracks develop, the brittle fracture feature is more obvious for HAZ than base material and weld metal, which corresponds to the lowest δ_m values and the highest transition temperature (-12.45 °C) for HAZ as listed in Table 4 and Table 5.

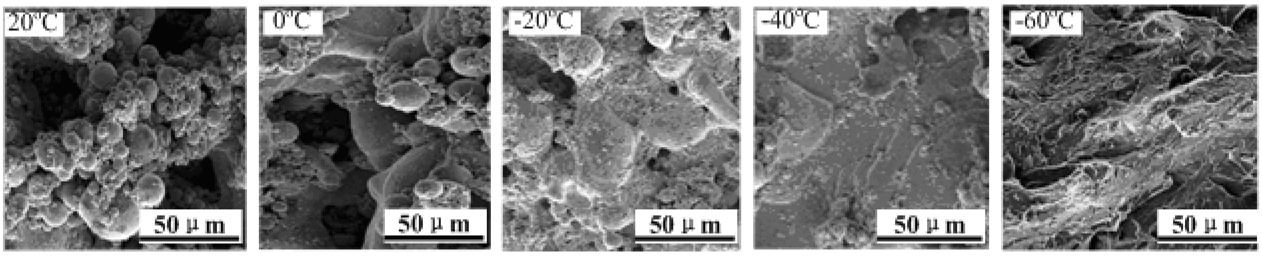


Figure 10. Micro-morphology of Fracture Surfaces for 960Mpa Steel at Five Different Temperatures

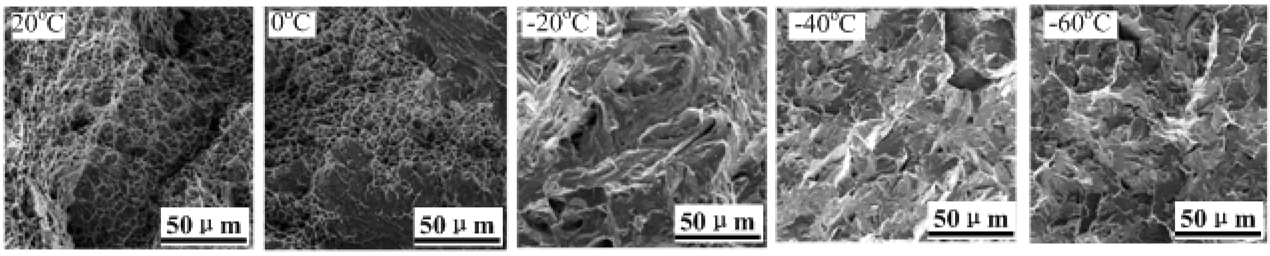


Figure 11. Micro-morphology of Fracture Surfaces for Weld Metal of 960Mpa Steel at Five Different Temperatures

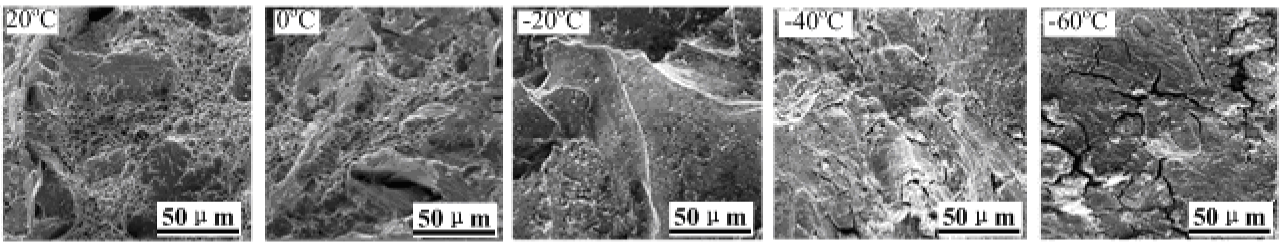


Figure 12. Micro-morphology of Fracture Surfaces for HAZ of 960Mpa Steel at Five Different Temperatures

5. CONCLUSIONS

(1) The variation trends of fracture toughness index (critical CTOD values δ_m) for high-strength steel and the corresponding butt weld are all reduced with temperature decreases. The decline amplitudes of δ_m for the specimens are all larger than 64% as the temperature drops from 20°C to -60°C, showing the temperature sensitivity to fracture for the welded high-strength steel.

(2) The fracture toughness of high-strength steels (460MPa and 960MPa) is lower than that of conventional steels, such as steels with yield point of 235MPa, 345MPa and 390MPa. The fracture toughness for 390MPa steel is the largest, and that for 960MPa steel is the lowest, which indicates that the fracture toughness of low-alloyed steel is relative higher than ordinary carbon steels, however, when the strength of steel increases to a certain value, the fracture toughness reduces.

(3) Compared with the base material, the fracture toughness in weld metal is higher than that in base material as a whole, and the δm values in HAZ are the lowest, indicating the fracture toughness deteriorate in HAZ. Moreover, the ductile-brittle transition temperatures of HAZ are higher than that of weld metal and base material, the values are -12.45°C and -40.25°C for 960MPa and 460MPa steels respectively, which is in accordance with the deterioration of fracture toughness in HAZ. Accordingly, the toughness of HAZ should be the major consideration in the fracture resistant design of high-strength steel structures.

(4) The micro-morphologies of TPB specimens also show the large effects of temperature on the toughness of high-strength steels and the welds, and the fractographs all exhibit the brittle fracture mechanism at -20°C. Besides, the brittle fracture feature at low temperature is more obvious for HAZ, which is consistent with the lower macro toughness index δ_m. The toughness of high-strength steel gets worse in cold regions, and the toughness of HAZ is critical for brittle fracture prevention and should be the main concern in engineering.

ACKNOWLEDGEMENTS

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