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Effects of low temperature on properties of structural steels

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Abstract: The experiments were carried out to measure the mechanical properties of three grades of structural steels (Q235A, 16Mn and Q390E steel) at low temperature. It was shown that the strength of the steels increases while the plasticity and toughness decrease as temperature drops. In the transitional area the toughness drops rapidly with temperature. Among the three structural steels, Q390E steel has the best toughness and the lowest sensitivity.

Key words: low temperature; structural steel; mechanical property; strength; toughness; plasticity

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1 Introduction

Many mechanical properties of steel vary with temperature. Steel becomes less plastic and less tough at low temperature, and thereby vulnerable to brittle fracture. Research on steel fractures has been carried out for many years, therefore it is relatively mature in some aspects. However, much research was conducted on high strength steel used in pressure vessel, aviation, *etc*. The fracture problem of steel architecture is not widely studied, since steels used in architecture have low strength, fine toughness and plasticity.

Research on brittle fracture of steel structure at low temperature has been widely carried out in Russia due to low temperature in most of its territory. Some design methods are well-developed, such as CCCP method, ЦИИПСК method, *etc*. All these methods are founded on the basis of traditional mechanics, and the coefficients employed are concluded from impact toughness and lots of experiments [1].

In recent years, steel structure have been widely constructed in China and some projects are conducted in extremely cold environments, like the railway from Qinghai to Tibet, China. With high strength steel and welding connection method applied in modern steel structure, brittle fracture becomes a great danger in need of immediate and substantial concern.

In order to analyze the brittle fracture of structural steel in view of fracture mechanics, many mechanical properties of structural steel have been measured at low temperature, the change in mechanical properties of structural steel at low temperature is analyzed in the meantime.

2 Experimental

The main purpose of this experiment is to understand the effects of low temperature on the mechanical properties of structural steel. The ultimate goal is to promote the usage of steel structure in a wider field. There are mainly two types of structural steels used in China, namely, Q235 steel and 16Mn steel. High strength steel Q390E has been used in some projects. Therefore, these three structural steels (Q235A, 16Mn and Q390E) were selected as the experimental materials at low temperature. **Table 1** lists the chemical compositions of the three structural steels.

Table 1 Chemical compositions of three structural steels **wt%**

Structural steels	C	Mn	Si	S	P
Q235A	0.19	0.49	0.19	0.041	0.025
16Mn	0.18	1.60	0.44	0.025	0.017
Q390E	0.16	1.50	0.41	0.002	0.010

The experiment consisted of tensile test and three-points bending test. And the following mechanical

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properties of structural steels were examined at different temperatures: yielding strength (σ_s), ultimate strength (σ_b), elongation (δ), reduction in area (ψ), crack tip opening displacement (δ_m) and J integration (J_{IC}).

The low temperature for the experiment was achieved through liquid nitrogen. Tensile test was carried out at temperatures from 20°C to –60°C. For three-point bending test, the temperature range was from 20°C to 70°C.

Nowadays thick steel plates have been employed in many structures. But it should be noted that the increase in thickness would reduce the toughness of steel. As the thickness increases, three-directional tensile stresses occur near the crack tip. Also, the probability of larger flaws will increase with the thickness. Therefore, specimens of different thickness were tested in the experiment to evaluate comprehensive influences of temperature and thickness on the mechanical properties of steels.

In the experiment, the specimen need be tested at low temperature environment. There were many methods to refrigerate the segment of the tested members, the method of mixed gas (air and hydronitrogen) was adopted, and the special equipment was fixed on a common universal tester. **Figure 1** shows its mechanism, the refrigerant was mixed with air and liquid hydronitrogen.

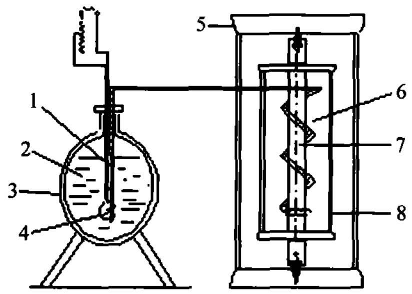

Figure 1 Equipment for acquiring low temperature, 1—hydronitrogen therapy pipe; 2—liquid hydronitrogen; 3—hydronitrogen container; 4—heater; 5—extension tester; 6—heat exchange; 7—tested member; 8—sealed attemperator.

The experimental results were the average values of several samples. The unqualified results were eliminated under the national standards before processing.

3 Tensile test

3.1 Tensile test specimens

The specimens for tensile test were produced under China national standard GB 6397-86 Metallic Materials-Test Pieces for Tensile Testing. The geometry of specimens is shown in **figure 2** [2].

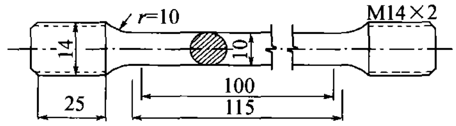

Figure 2 Geometry of tensile test specimens (unit: mm).

3.2 Phenomenon in the experiment

The typical stress-displacement curve for the tensile test can be divided into five phases: elastic phase, elastic-plastic phase, yield phase, hardening phase and shrinkage phase. At the shrinkage stage, three-directional tensile stresses occur in the shrinking segment, and the largest value lies in the direction of loading. The three-directional tensile stresses and the inherent flaws in steel result in initiation, elongation and final connection of cracks. The specimen finally breaks under the shear stress in the edge. As the temperature drops, the yield strength (σ_s) increases. When σ_s is larger than fracture stress (σ_f), the fracture is of brittle mode. The experiment showed that the tensile test of AISI 1020 steel is a typical brittle fracture with the temperature below 61.5 K [3], and there is little shrinkage in the cross-sectional area.

In the experiment, all the results of tensile test on the three structural steels are plastic failure at a temperature range from 20°C to –60°C. The tensile test curves have some changes under different temperatures. **Figure 3** is tensile testing curves of Q390E steel at 20°C, –20°C and –60°C.

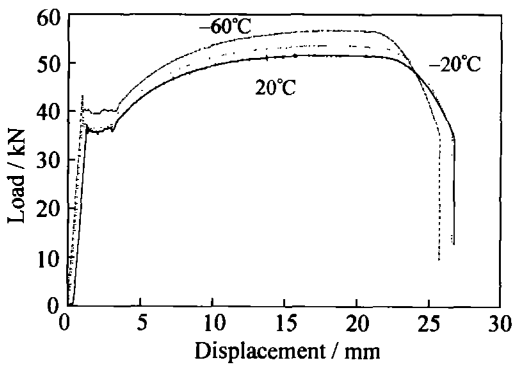

Figure 3 Tensile testing curves of Q390E steel.

3.3 Yield strength and ultimate strength

Figure 4 shows the strength of the three structural steels at different temperatures. It is indicated that the yield strength and the ultimate strength increase as temperature drops.

Various experiments show that the variations of yield strength and ultimate strength with temperature could be expressed as:

$$\sigma_s=\sigma_s'\exp[\alpha(1/T-1/T')] \quad (1)$$

$$\sigma_b=\sigma_b'\exp[\beta(1/T-1/T')] \quad (2)$$

where α and β are the sensitive factors of yield strength and ultimate strength to temperature respectively, σ_s and σ_b are the yield strength and the ultimate strength at the temperature T, and σ_s' and σ_b' are the yield strength and the ultimate strength at the temperature T'.

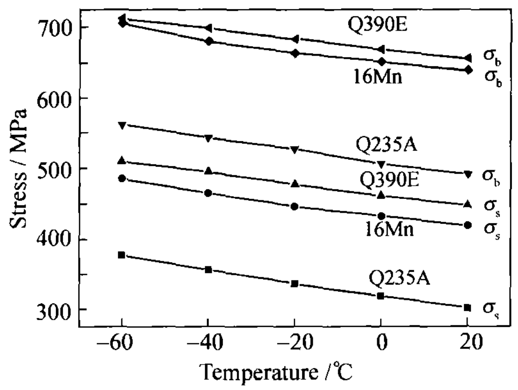

Figure 4 Influence of temperature on σ_s and σ_b.

The experimental data were regressed in accordance with the above equations to obtain the sensitive factors α and β of the three structural steels, which are shown in **table 2**.

Table 2 Factors α and β of three structural steels K^{-1}

Factor	Q235A	16Mn	Q390E
α	195.74	114.48	111.16
β	118.37	73.28	73.51

It can be concluded that Q235A steel is the most sensitive one to temperature, with respect to both yield strength and ultimate strength. As the temperature drops from 20°C to –60°C, the yield strength of Q235A steel increases by 25%, while 16% for 16Mn steel and 14% for Q390E steel.

3.4 Elongation and reduction in area

The plasticity of steel decreases as temperature drops. The elongation (δ) and the reduction in area (ψ) of the three structural steels are shown in **figure 5**.

The experimental results indicated that the plasticity does not decrease much as the temperature drops from 20°C to –60°C. The decrease in elongation (δ) is no more than 15%, and 10% for reduction in area (ψ). The plasticity of Q235A steel is most sensitive to temperature, similar to the situation of strength.

3.5 Fracture surface morphology

The fracture surface of tensile testing specimens consists of two parts, *i.e.*, fiber area and shear labium. No radiation area exists. This result showed that the collapse of tensile testing is ductile fracture caused by slow elongation of internal cracks. **Figure 6** illustrates the fracture surface of tensile testing specimens under scanning electronic microscopy.

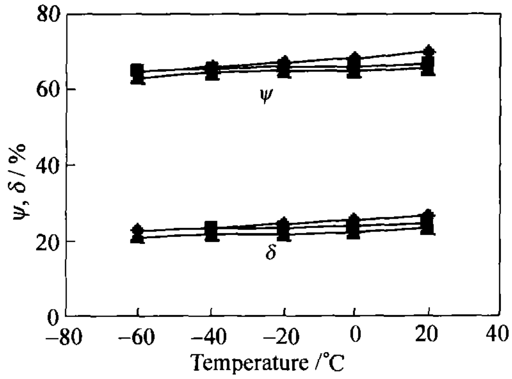

Figure 5 Plasticity of structural steels at low temperature (◆-Q235A, ■-16Mn, ▲-Q390E).

It can be observed from the scanned morphology photos that the fracture surfaces of three structural steels are ductile fractures surface consisting of many dimples at temperatures from 20°C to –60°C. As temperature drops, the dimples become smaller and flatter. Local cleavage fracture occurs in the fracture surfaces of Q235A and 16Mn steel as the temperature drops to –60°C.

It can be further found that Q390E steel has uniform properties and tiny flaws. The fine plasticity and toughness of Q390E steel are evidenced again by surface morphology, which is consistent with the testing of δ_m and J_{IC}.

4 Three-points bending testing

Steel fracture arises from internal flaws. Fracture mechanics is the most effective approach for fracture study, in which three main fracture toughness criterions are adopted. Stress intensity factor (K_{IC}) is merely applicable to cracks with small yield zone. The three structural steels tested have low or middle strength and high toughness, it is inappropriate to apply K_{IC} criterion. Thus, this experiment employed the other two criterions, *i.e.*, crack tip opening displacement (CTOD) and J integration (J_{IC}), which are also suitable for plastic fracture.

4.1 Specimens

Three-points bending testing specimens were manufactured under China national standards GB 2358-94 Test Method for Crack-Tip Opening Displacement Measurement of Metallic Materials [4] and GB 2038-91 Metallic Materials-Standard Test Method for J_{IC}, a measure of ductile fracture toughness [5]. Specimens of four different thicknesses were tested in the experiment: 12, 24, 36 and 48 mm. The geometry of specimens is shown in **figure 7**.

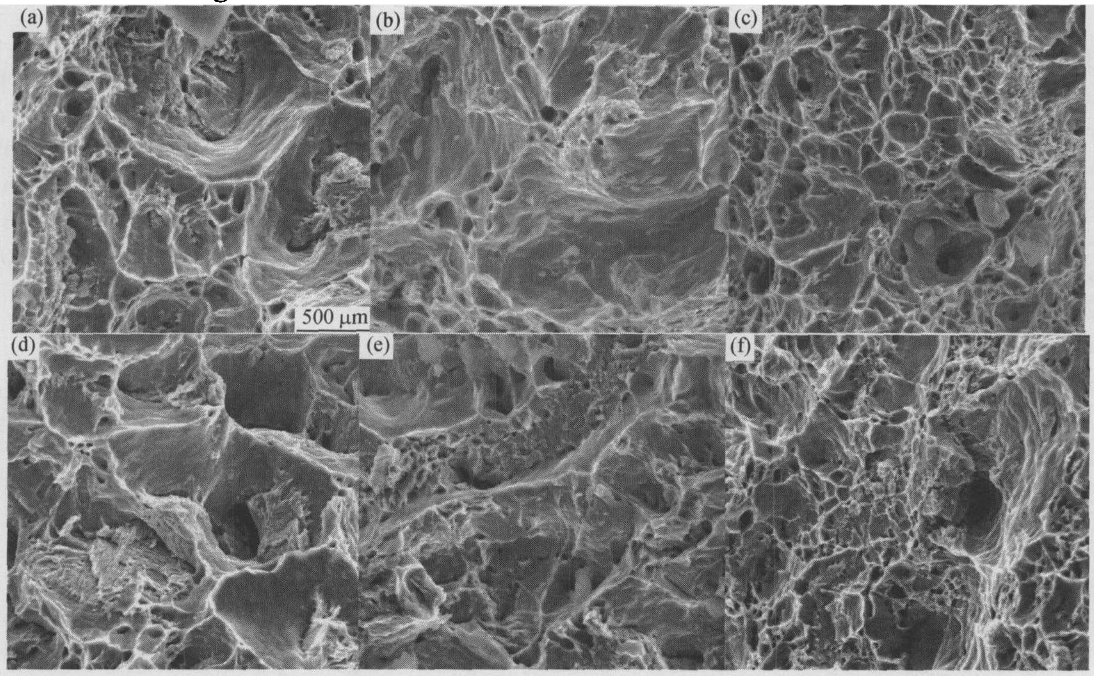

Figure 6 Tensile fracture surface morphologies of Q235A, 16Mn and Q390E steel (2000X), (a) Q235A, 20°C; (b) 16Mn, 20°C; (c) Q390E, 20°C; (d) Q235A, –60°C; (e) 16Mn, –60°C; (f) Q390E, –60°C.

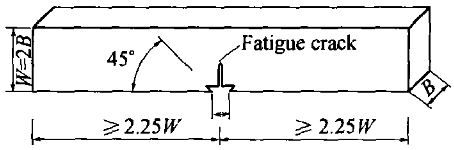

Figure 7 Geometry of a three-points bending testing specimen.

4.2 Testing process

The typical loading process consists of 5 phases, namely, elastic phase, plastic phase, hardening phase, descending phase and fracture. When the temperature is high or the specimen is adequately thin, the plasticity .and toughness of structural steels are in good situation. Cracks of the specimen expand slowly, and no brittle fracture occurs. As the temperature drops or the specimen becomes thick, brittle fracture appears at the end of the descending phase, which becomes shorter in the meanwhile. With the temperature drop further, fracture occurs at the hardening phase and the descending phase disappears. Finally, the specimen fractures at the elastic stage with no plastic distortion in the crack tip. The loading curves are shown in **figure 8**.

4.3 Crack tip opening displacement (δ_m)

According to China national standard GB 2358-94, 5 CTOD values were calculated from load and crack opening curves. The shape of the curves varies greatly at different temperatures, and only δ_m parameter (CTOD at the max load point) can be obtained in each test. At the same time, the max load is an important parameter in both structure design and theoretical research. Therefore, δ_m is chosen as the representative value of CTOD in the analysis. δ_m values of Q235A, 16Mn and Q390E steel at different temperatures are shown in **figures 9**, **10**, and **11**.

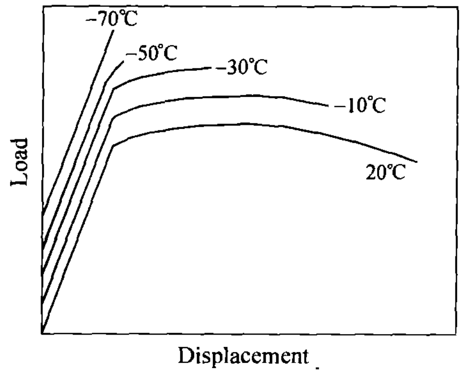

Figure 8 Load-displacement curves at different temperatures.

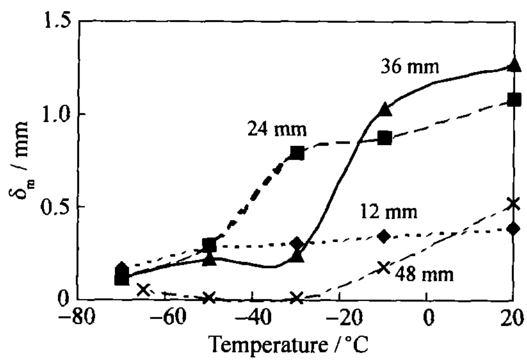

Figure 9 Curves of δ_m–temperature of Q235A steel.

Figures 9, 10, and 11 show that, as temperature drops, δ_m values decrease from several millimeters at 20°C to less than 1 mm at −20°C. It is indicated that the toughness of these steels decreases with temperature. The curves are in "S" shape, and composed of three parts: upper platform, transitional area and lower platform. The toughness varies slowly at upper platform and lower platform, but changes sharply at the transitional area. Notably, the transitional area of three structural steels is in the experimental temperature range (20°C-(−70°C)), which is very important in steel fracture prevention because of great variation in toughness in this range.

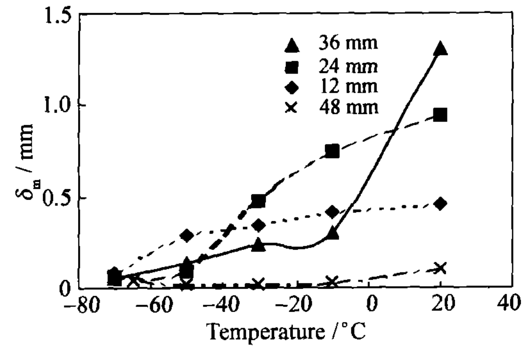

Figure 10 Curves of δ_m-temperature of 16Mn steel.

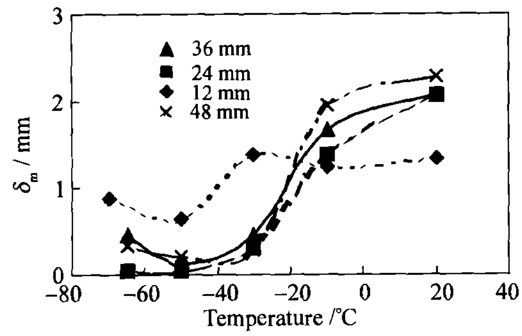

Figure 11 Curves of δ_m-temperature of Q390E steel.

The results show that thickness also has a considerable impact on toughness. At a higher temperature, δ_m of thin specimens is larger than that of thick ones. When the specimens are thick enough, the decrease in toughness gets slower. δ_m for specimens of four different thicknesses inclines to the same value as the temperature drops to −70°C.

Taking δ_m as the representative of toughness, it can be concluded that Q390E steel is the best in toughness and 16Mn steel is better than Q235A steel with the temperature ranging from 20°C to −70°C.

4.4 Fracture toughness J_{IC}

Specimens for J_{IC} test were the same as those for CTOD test. In the experiments, measurements for these two criterions were carried out simultaneously. The J_{IC} test was conducted in compliance with China national standard GB2038-91. Variations in J_{IC} with temperature is shown in **figures 12, 13, and 14**.

Apparently, the fracture toughness J_{IC} of all three structural steels descends as temperature drops. Relative research illustrated that J_{IC}-temperature curves are in "S" shape [6]. Due to the limited range of experimental temperature, most curves acquired in this experiment are not in a complete "S" shape. But it can be observed that the transitional area where J_{IC} varies rapidly is in the temperature range from 20°C to −70°C.

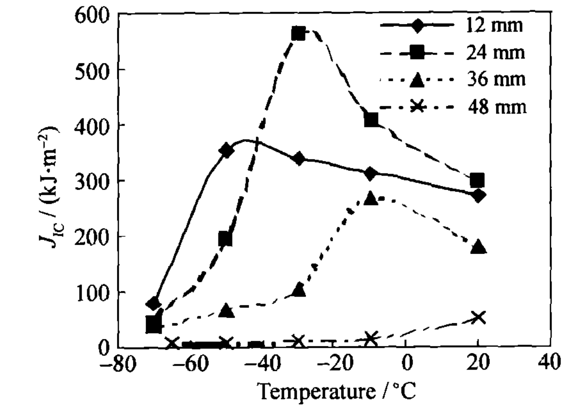

Figure 12 Variation in J_{IC} of Q235A steel with temperature.

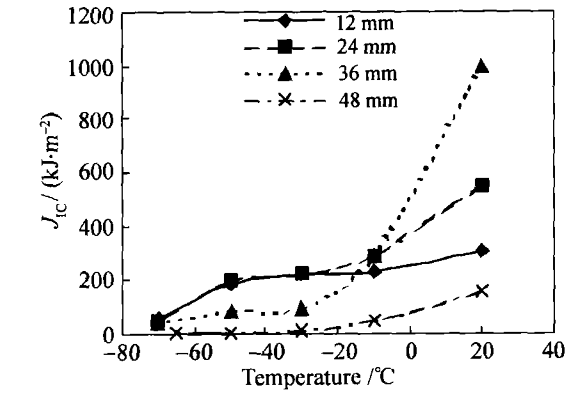

Figure 13 Variation in J_{IC} of 16Mn steel with temperature.

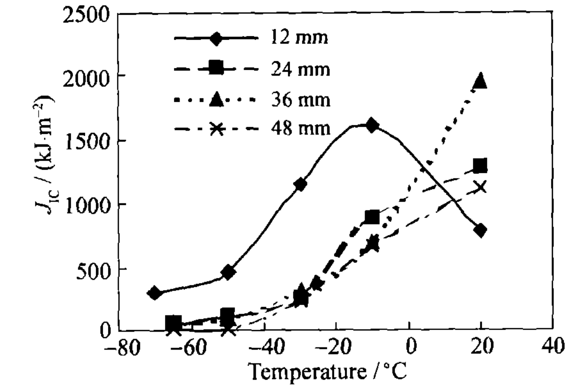

Figure 14 Variation in J_{IC} of Q390E steel with temperature.

The variation of J_{IC} with temperature is different from δ_m at the upper platform: J_{IC} of Q235A steel ascends as temperature descends. 12 mm specimen of

Q390E steel also shows the same trend.

Thickness also affects the fracture toughness J_{IC} of structural steels. As the specimens get thicker, there is a general trend for J_{IC} to decrease. It can be found from the figures that the fracture toughness J_{IC} decreases very rapidly in some ranges of thickness, which are 24 mm to 36 mm for Q235A steel, 36 mm to 48 mm for 16Mn steel and 12 mm to 24 mm for Q390E steel.

The toughness comparison of three structural steels leads to a consistent conclusion; no matter which criterion, either CTOD or J_{IC} is adopted. In the temperature range from 20°C to −70°C, Q390E steel is the best in toughness and 16Mn steel is the second best among the three.

5 Discussion

Structural steels are polycrystalline alloys. The factors influencing their mechanical properties could be divided to macroscopic part and microscopic part. The macroscopic factors involve chemical composition, metallurgical technique, *etc.* The microscopic factors involve microstructures, crystal size, dislocation configuration and so on.

The increase and movement of dislocations arouse yielding. The total resistance to the movement of dislocations determines the value of yielding strength. Structural steels are bcc metals, and Peierls-Nabarro force plays an important role. Peierls-Nabarro force is a type of short-range force, which is very sensitive to temperature. Thermal activation is favourable for overcoming Peierls-Nabarro force, so the yielding strength of structural steels decreases as temperature increases.

Recent research showed that fracture toughness is also related with thermal activation. The fracture toughness could be divided into two parts; one of them is relative with thermal activation. Some research [7] for pipeline steel X65 showed that J integration could be express as follows:

$$J = J_a + A\exp(\frac{Q_f}{nkT}) \tag{3}$$

where J_a is the constant part of J integration, which is independent of temperature; A is a factor relevant to loading speed; Q_f is the fracture activation energy; n is a minus constant; k is Boltzmann constant; T is the temperature, whose unit is K. The equation describes the variation in toughness of structural steel at low platform and transition area.

Another research [8] was about the interaction between the fracture toughness K_{IC} and strength, which is shown in the following equation. For the crack tip opening displacement and J integration is relative with stress intensity factor, the equation also shows that the strength and toughness are interrelated as

$$K_{IC} = 2.9\sigma_y[\exp(\frac{\sigma_c}{\sigma_y} - 1) - 1]^{1/2} \rho_0^{\ 1/2} \tag{4}$$

where σ_c is the cleavage strength; ρ_o is the radius of crack tip. Equation (4) is applicable for the situation of cleavage brittle fracture. It correlates the yield strength and fracture toughness from transition area to lower platform.

As temperature increases, the failure mode of steel transits from brittle fracture to tensile fracture. The fracture mechanics is composed of shear fracture and micropore collection, which is the combined result of deformation and tensile stress. Change of fracture mechanics brings the variation of fracture toughness curves at upper parts. The decrease of yield strength plays an important role in the decrease of fracture toughness at upper platform.

6 Conclusions

(1) Tensile test showed that the yield strength and ultimate strength of three structural steels increase as temperature drops. Q235A steel has the largest increase in yield strength as temperature drops from 20°C to −60°C, which is 25% or so.

(2) The elongation and reduction in area (ψ) of the steels decrease with temperature. The fracture of tensile test is related to three-dimensional tensile stresses in shrinkage area. The higher reduction in area is, the better the plasticity is. As the temperature drops from 20°C to −60°C, the decrease of reduction in area is no more than 10%, and that of elongation is no more than 15%.

(3) The toughness of the steels decreases with temperature. The transitional area of δ_m and J_{IC} is located in a temperature scope of 20°C-(−70°C). The toughness at the upper platform is tens of times of that at the lower platform. Steel is liable to brittle fracture in the transitional area because the toughness varies substantially. Undoubtedly, it is the key scope of temperature for fracture prevention design.

(4) Q390E steel has the best toughness and least sensitivity to temperature among the three structural steels. Q235A steel is the worst in toughness, and its strength, plasticity and toughness is very sensitive to temperature. 16Mn steel is in-between in mechanical

properties. From the history of temperature data, the extreme minimum temperature in China is not lower that –50°C, so Q390E steel is the most suitable for steel structures located at freezing areas.

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