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Low temperature impact toughness of high strength structural steel

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ABSTRACT

Impact toughness properties of four kinds of high strength steel (HSS) were investigated with the nominal yield strength 460, 690, 800 and 960 MPa, respectively. The specialty of impact toughness among base metal, heat affected zone (HAZ) and weld metal were also compared and discussed. The correlations between the impact toughness of HSS and their nominal yield strength, plate thicknesses, testing temperature, welding methods were further studied. Combined with the scanning electron microscope (SEM) fracture surface observation, the microstructural features and corresponding fracture mechanisms have been analyzed. The results show that the impact toughness for HSS base metal deteriorated with the increasing nominal yield strength. The impact toughness of weld metal for HSS is much lower than that of the corresponding base metal. The impact performance of HAZ is discretized due to the welding thermal cycling on the HAZ where significant changes in grain structure and properties occur. The microcosmic fracture surface of HSS is examined to explain the reduction in impact performance under low temperature.

1. Introduction

Nowadays, the application of high strength steel (HSS) is growing in various fields, such as civil, mechanical and ocean engineering [1–5]. High strength steel is manufactured aiming for their optimal combination of physical and mechanical properties, including strength, ductility and toughness performance. The use of HSS may lead to an overall reduced weight and energy consumption due to light-weight HSS components. The mechanical properties of HSS are different from the conventional strength steel because of the different chemical composition and manufacturing process, and are worth investigating.

In the past large amount of work on HSS was focused on their chemical composition, melting processes and welding material compatibility. In terms of structural performance, studies were recently carried out on basic static performance [6–18], seismic behaviors [19–21] and fatigue stability [22–27].

Impact toughness, which is directly related to fracture resistance, is one of the most important properties for HSS in engineering applications. Generally, as the strength of steels increases, their impact toughness may reduce. Therefore, special attention should be paid to the impact toughness of high strength steels [28].

The impact toughness of conventional strength steels has been widely studied [29–33,54]. Through the impact test on Charpy V-notch specimens, the corresponding impact absorbed energy can be obtained. For example, Méndez et al. [33] have found a quantitative relationship between impact toughness CVN and fracture toughness K_{IC} for A36 steel (250 MPa), i.e. the CVN value can be proportionally converted to fracture toughness K_{IC} under certain conditions.

Because the research and application of high strength steel are still at an early stage [34–43], the study on the impact toughness properties of HSS is still limited. The current research shows that the content of alloying elements and the smelting process have a greater influence on its impact toughness. Shin et al. [34] studied the effect of Copper (Cu) and Boron (B) elements on the grain size and impact toughness of 600 MPa grade high strength steel. The results showed that element B reduced the grain size, improved the impact toughness and reduced the brittle transition temperature. Tanguy et al. [35] conducted an impact toughness test on a 600 MPa high strength steel and the results showed that the increasing content of sulfides reduced the impact properties. Liu et al. and Wang et al. [38,39] studied the impact toughness of Q460C (460 MPa) HSS and found its impact toughness was relatively lower than those of conventional strength steel such as Q235 and Q390 (235 MPa, 390 MPa). Maina et al. [40] studied the impact properties of 700 MPa high strength steel in two different impact directions (parallel and perpendicular to the rolling direction) and the results showed that the crack path mainly initiated and developed along the intergranular

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Nomenclature

A_1	The lower shelf energy LSE
A_2	The upper shelf energy USE
A_{kv}	Charpy impact absorbed energy
$A_{kv,T}$	A_{kv} at the temperature T
B	Thickness of Charpy impact specimens
b	Length of the remaining ligament at the Charpy specimen V-notch
$D_{kv,T}$	Relative decline rate of $A_{kv,T}$ for HSS base metal
$f_{y,n}$	Nominal yield strength
$f_{y,m}$	Measured yield strength
f_u	Tensile strength
H_l	The normalized toughness ratio
K	Modified stress concentration factor at the V-notch
L	Charpy impact specimen span
NF	Normalization factor for subsize Charpy impact specimens
Q	Nominal yield strength symbol in Chinese relevant codes for structural steels
Q690-20	The HSS with the nominal yield strength 690 MPa and the plate thickness is 20 mm, same for other HSSs
Q690-20-BM	The base metal BM of Q690-20 HSS, same for other HSSs
Q690-20-S(G)-WM	The weld metal WM of Q690 HSS in SAW (or GMAW-CO_2) process, same for other HSSs
Q690-20-S(G) -HAZ	The heat affected zone HAZ of Q690 HSS in SAW (or GMAW-CO_2) process, same for other HSSs
T	Testing temperatures in °C
T_0	The ductile-brittle transition temperature (DBTT)
Y_h	The shelf energy ratio which is the ratio of A_1 and A_2
$(1-Y_h)$	The transition shelf energy ratio
ΔT	The brittle-ductile transition region
δ	Elongation

path due to the extension of the grain in the length direction. Mori et al. [41] focused on the variation of the impact toughness of the 4340 Steel (835 MPa) high strength steel subjected to hydrogen treatment, the change of characteristics in dimple structures under the microscopic scale were observed and discussed. Prasas and Dwivedi [42] investigated the basic mechanical properties of HSS joints under submerged arc welding (SAW) process. The results showed that the increase of heat input leads to the deterioration of impact performance with brittle failure. Langenberg [43] presented the relationship between the structural safety design and the yield ratios for three high strength steels (up to 890 MPa), and a comparison of their impact toughness.

The current researches for the impact performance of high strength steel are limited, the comparison and mechanism analysis for different high strength steels are still lacking. In this study, the impact toughness properties of four kinds of HSS were measured, with the nominal yield strength 460, 690, 800 and 960 MPa, respectively. The specialty of impact toughness among base metal (BM), heat affected zone (HAZ) and weld metal (WM) were also investigated. Furthermore, the microstructural features and corresponding fracture mechanisms have been studied using scanning electron microscope (SEM). The ductile-to-brittle transition process of HSS materials from microvoid coalescence to cleavage are discussed in detail with the decreasing temperatures.

2. HSS materials and charpy impact experimental procedures

2.1. HSS materials and specimens

Four typical high strength steels were selected to evaluate the low temperature impact toughness with the nominal yield strength 460, 690, 800, 960 MPa, respectively, with different thickness (10 mm, 20 mm and 30 mm). The specimen labels for the base metal are designed in Table 1 where Q stands for nominal yield strength followed by the value of the yield strength, BM stands for base metal and the number in between refers to the plate thickness. For example, Q460-20-BM refers to a base metal specimen with a yield strength of 460 MPa and thickness of 20 mm. The mechanical properties from tensile tests and chemical compositions from certification documents for the HSSs base materials are given in Tables 1 and 2, respectively.

Specimens for Charpy impact testing were extracted from the butt welded joints. A schematic representation of the locations from which specimens were extracted is given in Fig. 1. Standard Charpy impact specimens of $55 \times 10 \times 10\ mm^3$ in size and subsize specimens of a size of $55 \times 10 \times 7.5\ mm^3$ were fabricated following the standards ASTM A370 [44] and Chinese code GB/T 229–2007 [45], the V-notch of HAZ impact specimens are located 1 mm (to base metal direction) from the fusion line.

2.2. Welding procedure qualification (WPQ)

In order to assess the impact toughness of the weld metal and heat affected zone (HAZ), the HSS welding procedure qualification was employed before the impact tests in accordance with the guidelines given in AWS D1.1 Steel Structural Welding Code [46] and the corresponding Chinese code [47]. Quenched and tempered HSS plates, measuring 1000 mm × 400 mm, were machined so that they had double-V groove weld preparations to suit both the submerged arc welding (SAW) and gas metal arc welding (GMAW-CO_2) in the flat welding 1-G (down hand) position. The filler metals selected are matched with the base metal, and the details from certification documents are shown in the Tables 3 and 4. The Shanghai Ershiye Construction Co., Ltd conducted the welding procedure qualification (WPQ) and the WPQ results met the requirements of specifications. Welding parameters employed in the SAW and GMAW-CO_2 are shown in Table 5.

2.3. Testing procedures of Charpy impact

As shown in Fig. 2, a Charpy impact testing machine ZBC2302 has been used in the tests, equipped with a pendulum with a capacity of 300 J. These impact tests were carried out in the temperature range

Table 1
Tensile properties of the base metal of high strength steels in this test.

Specimen label	Nominal yield strength $f_{y,n}$ (MPa)	Plate Thickness (mm)	Measured yield strength $f_{y,m}$ (MPa)	Tensile strength f_u (MPa)	Yield ratio $f_{y,m}$ / f_u	Elongation δ (%)
Q460-20-BM	460	20	495	623	0.79	35.6
Q690-10-BM	690	10	801	842	0.95	18.8
Q690-20-BM	690	20	771	822	0.94	25.2
Q800-30-BM	800	30	876	920	0.95	22.8
Q960-10-BM	960	10	1033	1071	0.96	14.5