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Post-welding behaviour of S690Q high strength steel butt joints

CHIEW Sing Ping[1], *CHEN Cheng*[2], *ZHAO Ming Shan*[1], *LEE Chi King*[3], *FUNG Tat Ching*[2]

(1. Singapore Institute of Technology, Singapore138683, Singapore; 2. Nanyang Technological University, Singapore 639798, Singapore; 3. University of New South Wales, Canberra, Australia)

Abstract: In this study, we investigated the post-welding behaviour of S690Q high strength steel butt joints experimentally. Three S690Q high strength steel butt joints were welded with 8 mm thickness plate by shield metal arc welding with different welding heat inputs. Microstructure observation and micro-hardness test of heat-affected zone were employed to reveal the welding influence on the joints at the micro level, and tensile test of S690Q high strength steel butt joints showed the welding impact at the macro level. The microstructure test indicated that the main microstructure of the S690Q high strength steel was tempered martensite and was transformed to granular bainite in the coarse-grained heat-affected zone and to ferrite and cementite in the fine-grained heat-affected zone after welding of the joints. In the tempering zone, some of the tempered martensite decomposed to ferrite. Based on the hardness test results, it can be observed there is a soft layer in the heat-affected zone with lower hardness compared with the base material. In addition, the width of the heat-affected zone increased in the joint welded with higher heat input. The subsequent tensile test showed that the formation of a soft layer directly impairs the tensile behaviour of S690Q high strength steel butt joints, and the strength deterioration becomes more serious with the increase of the welding heat input.

Keywords: high strength steel; butt joint; microstructure; hardness; tensile behavior

S690Q 高强钢对接节点的焊后性能

周诚彬[1],陈成[2],赵明善[1],李子敬[3],冯达清[2]

(1. 新加坡理工大学,新加坡 138683,新加坡;2. 南洋理工大学,新加坡 639798,新加坡;
3. 新南威尔士大学,堪培拉,澳大利亚)

摘　要:通过试验研究了 S690Q 高强钢对接节点的焊后性能。利用手工电弧焊焊接了 3 个厚度为 8 mm 的 S690Q 高强钢对接节点,焊接过程中对 3 个节点分别采用不同的焊接热量。在微观层面上,用微观结构测试和微观硬度测试研究焊接对于节点的影响;在宏观层面上,通过拉伸试验研究焊接对于节点力学性能的影响。微观结构测试结果表明,S690Q 高强钢的主要微观结构是回火马氏体。焊接后,在粗晶热影响区会转化为粒状贝氏体,在细晶热影响区会转化为铁素体和渗碳体,在回火区部分回火马氏体会分解成铁素体。基于硬度测试结果,可以在热影响区内发现软化层的存在,软化层与母材相比具有较低的硬度。此外,热影响区的宽度也随着焊接热量的升高而增大。拉伸试验表明,焊接对于 S690Q 高强钢节点的强度具有劣化作用,这主要是由焊接过程中形成的软化层造成的。所有测试节点的失效位置均位于热影响区,而且随着焊接热量的升高,强度的劣化

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Author brief: CHIEW Sing Ping (1958-), professor, main research interest: steel structures, E-mail: cchen8727@gmail.com.

现象也变得越来越严重。

关键词:高强钢;对接节点;微观结构;硬度;拉伸性能

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1 Introduction

High strength to weight ratio in steel structures is an important advantage since it can result in better architectural expression and economic benefits such as less labor and transportation costs[1]. With the development of metallurgical technology, the strength to weight ratio of steel is further improved by using high strength steel with yield strength higher than 460 MPa. Among different high strength steel available in the market, reheated, quenched and tempered high strength steel is preferred since it has prominent weldability due to similar chemical composition with normal steel. Generally, reheated, quenched and tempered high strength steel is available in the form of plate since it is more conducive to achieving uniform material properties under the quenching and tempering process. That means welding, which is usually accompanied by dramatic temperature change around the joint, is inevitable for the built-up reheated, quenched and tempered high strength steel structural member. According to related investigations, reheated, quenched and tempered high strength steel is quite susceptible to high temperatures[2-3], and its strength could be significantly reduced after cooling[4-5]. Previous study also revealed that welded high strength steel butt joints lost 3% to 8% tensile strength in the condition of the area with reduced strength (soft layer) ranging from 0.33 to 0.6 times of specimen thickness[6].

The formation of a soft layer in welded high strength steel butt joints is mainly caused by microstructure transformation in the heat-affected zone. The heat-affected zone of the welded butt joints can be roughly divided into three sub-heat-affected zones, including the coarse-grained heat-affected zone, the fine-grained heat-affected zone and the tempering zone[7]. In the coarse-grained heat-affected zone, the bainitic microstructure and martensite-austenite (M-A) constituents constitute the main microstructure after welding[8]. These microstructures have slightly lower hardness compared with the base material (tempered martensite) but are sensitive to cleavage cracking, especially when some austenite is retained after the bainite transformation. The main microstructures of the fine-grained heat-affected zone are generally composed of ferrite, pearlite or cementite[9]. In the tempering zone, parts of the tempered martensite decompose to ferrite after the welding process. Since ferrite, pearlite or cementite commonly have lower hardness compared with tempered martensite or bainite, the fine-grained heat-affected zone and the tempering zone are usually regarded as soft layer[10]. Overall, the microstructure transformation caused by welding leads to not only the reduction of tensile strength but also significant nonhomogeneity of the material within the heat-affected zone[11].

In this study, the post-welding behaviour of S690Q high strength steel butt joints was investigated experimentally. Three butt joints were welded with 8 mm thickness reheated, quenched and tempered S690Q high strength steel plate by shield metal arc welding with different welding heat inputs. The microstructure transformation and hardness distribution in the heat-affected zones of the joints were revealed by light optical microscopy and micro-hardness tests, respectively. After this, tensile tests were conducted to find out the welding influence on the strength of the S690Q high strength steel butt joints.

2 Material property and joint fabrication

The high strength steel used in the tests was grade S690Q with nominal yield strength 690 MPa and tensile strength between 790 MPa and 930 MPa. The plate is delivered by the reheated, quenched and tempered procedure, and its chemical composition is similar to that of mild steel. Therefore, it has favorable weldability[12-13]. The weld material LB-80L was used as filler metal, satisfying the specification of AWS A5.5 E11018-G[14]. The mechanical property and chemical composition (together with the carbon equivalent CE) of S690Q high strength steel and LB-80L are listed in Table 1 and 2, respectively. It can be seen from Table 1 that the mechanical property of the filler metal is quite similar to that of the S690Q high strength steel used.

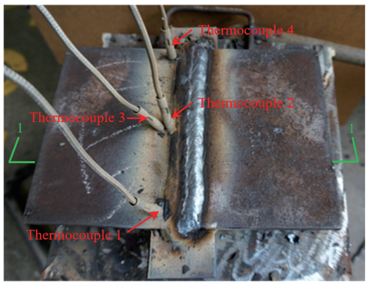
Table 1 Mechanical properties of S690 high strength steel and weld metal

Material	Elastic Modulus/GPa	Yield Strength/MPa	Ultimate Strength/MPa	Elongation /%
S690Q HSS	208.9	745.2	837.8	14.5
LB-80L	210.0	767.0	848.0	22.0

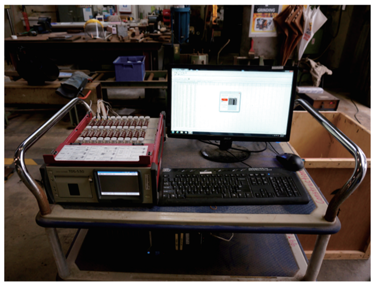
Table 2 Chemical composition of S690 high strength steel and weld metal %

Material	C	Si	Mn	P	S	Ni	Mo	CE
S690Q HSS	0.14	0.40	1.35	0.012	0.003	0.01	0.12	0.40
LB-80L	0.05	0.56	1.37	0.009	0.005	2.77	0.76	0.33

Three S690Q high strength steel butt joints with 8 mm thickness were welded by shield metal arc welding. Different diameter electrodes, such as 3.2 mm, 4.0 mm and 5.0 mm, were used to gain different welding heat inputs. Four type-K thermocouples with 1 000 ℃ measuring limitation were employed to monitor the temperature history of the butt joints during welding, named thermocouple-1, 2, 3 and 4, respectively. The arrangement of the thermocouples is presented in Fig. 1(a), and the corresponding positions are described in Fig. 3(a). The temperature measurement device is TDS-530 datalogger, as shown in Fig. 1(b). The joints were all welded with four passes marked by 1, 2, 3 and 4 in Fig 2.

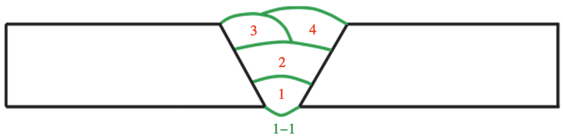


(a) Welded S690Q high strength steel butt joint



(b) Temperature measurement device

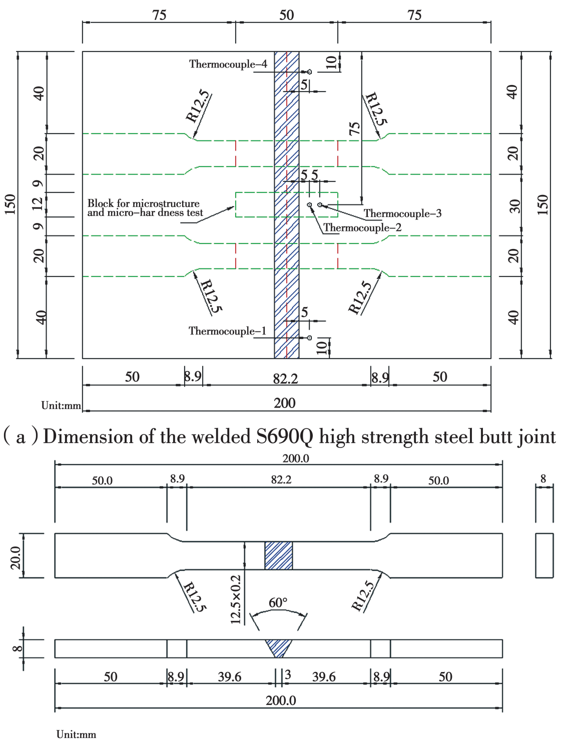
Fig. 1 Test setup for the welding process of the S690Q high strength steel butt joints



Noted: The number(1~4) represents the completion sequence of welding pass

Fig. 2 Configuration of the welding passes

The welding parameters of each welding pass for the three joints are listed in Table 3. It should be noted that the root pass for all the joints in this study was completed using a 3.2 mm electrode with voltage 30 V and current 73 A. In fact, the average welding heat input of BJ8-5.0 was lower than BJ8-4.0. That is because the deposition rate of the 5 mm diameter electrode was too high for BJ8-5.0 to control the welding quality if using the same welding speed for BJ8-4.0. Therefore, the welding speed of BJ8-5.0 was increased, and its average welding heat input was reduced. The temperature



(a) Dimension of the welded S690Q high strength steel butt joint

(b) Dimension of the machined-out coupon

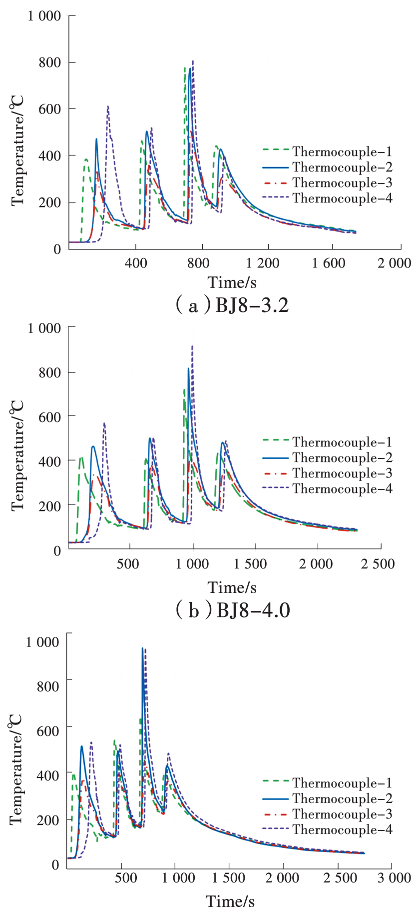
Fig. 3 Dimension of the welded S690Q high strength steel butt joint and machined-out coupon

history curves of the butt joint are described in Fig. 4.

Table 3 Welding parameters of reheated, quenched and tempered S690Q high strength steel butt joints

Specimen	Electrode diameter/ mm	Voltage/ V	Current/ A	Pass number	Welding heat input per pass/ ($kJ \cdot mm^{-1}$)	Average welding heat input/ ($kJ \cdot mm^{-1}$)
BJ8-3.2	3.2	30	73	1	1.13	1.25
			117	2	1.33	
			117	3	1.17	
			117	4	1.36	
BJ8-4.0	4.0	30	73	1	1.37	1.58
			125	2	1.50	
			125	3	1.65	
			125	4	1.81	
BJ8-5.0	5.0	30	73	1	1.37	1.49
			160	2	1.54	
			125	3	1.62	
			125	4	1.43	

After the welding process was completed, an 8 mm×12 mm×40 mm block and two coupons were machined out. The position of the block and coupons in the butt joint is presented in Fig. 3(a). The block was further cut into two halves from the center line of the weld. One was used for microstructure observation, and the other was used for the micro-hardness test. The microstructure and micro-hardness tests were employed to reveal the welding influence on the joint at the micro level. The coupons were used in the tensile test to find out the welding impact on the strength of the S690Q high strength steel butt joints at the macro level. The corresponding dimension is illustrated in Fig. 3(b).



(a) BJ8-3.2

(b) BJ8-4.0

(c) BJ8-5.0

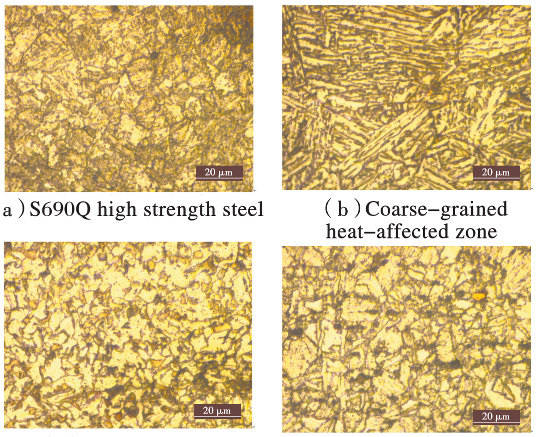
Fig. 4 Temperature history curves of S690Q high strength steel butt joints

3 Test results

3.1 Microstructure test

One half of the block was cast with epoxy, polished, etched with 2% nital solution and then observed under a light optical microscope to study the detailed microstructure transformation in heat-affected zone. In the welding process, the peak temperature of the coarse-grained heat-affected zone is almost up to the melting point (higher than Ac3), and the cooling rate of the coarse-grained heat-affected zone in the following cooling stage is quite fast. This welding thermal cycle directly results in the coarsening of the grain size[15]. From the perspective of microstructure, with the temperature of the coarse-grained heat-affected zone above Ac3, the growth of austenite grains is improved due to extended time at high temperature. The consecutive fast cooling leads to the generation of a coarse martensitic microstructure from the austenite[16]. The coarse-grained heat-affected zone of the high strength steel joint is generally accompanied by several detrimental characteristics (large prior austenite grain size, upper bainite, martensite-austenite (M-A) constituents, and microalloy precipitates) which may lead to lowest toughness in the heat-affected zone. Among the mentioned microstructural features, the M-A constituent (crack susceptibility) plays an important role in leading to the decrease of joint toughness[17]. The peak temperature of the fine-grained heat-affected zone also exceeds Ac3, resulting in a fully austenitized local microstructure. Nevertheless, the time above Ac3 in the fine-grained heat-affected zone is short and limits the grain growth. The microstructures mainly consist of ferrite and a little pearlite with grain size 1-3 mm. Compared with martensite in the coarse grain heat-affected zone, the ferrite and pearlite in the fine-grained heat-affected zone have lower hardness, and therefore have a softening effect on the mechanical performance of high strength steel welded joints[18].

Fig. 5 shows the microstructure of the base material, the coarse-grainedheat-affected zone, the fine-grained heat-affected zone and the tempering zone. As show in Fig. 5 (a), the main microstructure of the S690Q high strength steel used in the tests was tempered martensite. After welding, the tempered martensite of the base material was transformed to granular bainite in the coarse-grained heat-affected zone (Fig. 5(b)). The granular bainite was composed of a bainitic ferrite matrix and the martensite-austenite (M-A) phase as the second phase. In the fine-grained heat-affected zone, the microstructure was transformed to ferrite and cementite (Fig. 5 (c)). Compared with ferrite and cementite, granular bainite is generally harder, but is lower in toughness. In the tempering zone of the heat-affected zone, some of the tempered martensite decomposed to ferrite, as shown in Fig. 5(d).



(a) S690Q high strength steel (b) Coarse-grained heat-affected zone
(c) Fine-grained heat-affected zone (d) Tempering zone

Fig. 5 Microstructure of S690Q high strength steel, coarse-grained heat-affected zone, fine-grained heat-affected zone and tempering zone

3.2 Micro-hardness test

Vickers hardness measurement was carried out on a micro-hardness tester according to ISO 6507-1[19] using 500 g force. Four lines of indentations were made at different thickness position of the butt joints, and the indentations were located through weld, coarse-grained heat-affected zone, fine-grained heat-affected zone, tempering zone and base material sequentially for each line, as presented in Fig. 6. The obtained micro-hardness values of the butt joints are shown in Fig. 7. The black line shows the physical boundary of the weld bevel which could be confidently taken as the boundary between the weld materials and the heat-affected zone.

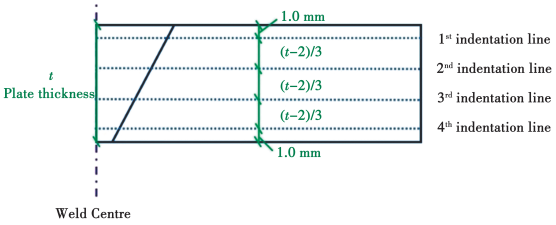


Fig. 6 Indentation distribution on S690Q high strength steel butt joint

As a result of the severe temperature changes in the heat-affected zone during the welding process, the microstructures with lower hardness formed in the fine-grained heat-affected zone and the tempering zone lead to the formation of a soft layer. In Fig. 7, the soft layer is defined as the area between the two red dash lines, having relatively lower hardness values compared with the base material (S690Q high strength steel) with the hardness ranging from 270 Hv0.5 to 280 Hv0.5. The width of the soft layer was 6 mm, 8.875 mm, and 7.125 mm for BJ8-3.2, BJ8-4.0 and BJ8-5.0, respectively, which means the relative thickness of the soft layer (the ratio of the width of the soft layer over the plate thickness) was 0.75, 1.11, and 0.89, respectively. Considering the average welding heat input for BJ8-3.2, BJ8-4.0 and BJ8-5.0 was 1.25 kJ/mm, 1.58 kJ/mm and 1.49 kJ/mm (listed in Table 3), respectively, it can be concluded that the soft layer becomes wider for the welded S690Q high strength steel butt joints with the same thickness when higher welding heat input is adopted. The same conclusion is also suggested by Hochhauser and Rauch[6].

3.3 Tensile test

Tensile tests of the S690Q high strength steel butt joints were conducted on the 5900 series universal testing instruments according to EN 10002-1[20]. An extensometer with 50 mm gauge length was used to capture the deformation of the coupon. The loading rate was set as 0.5 mm/min

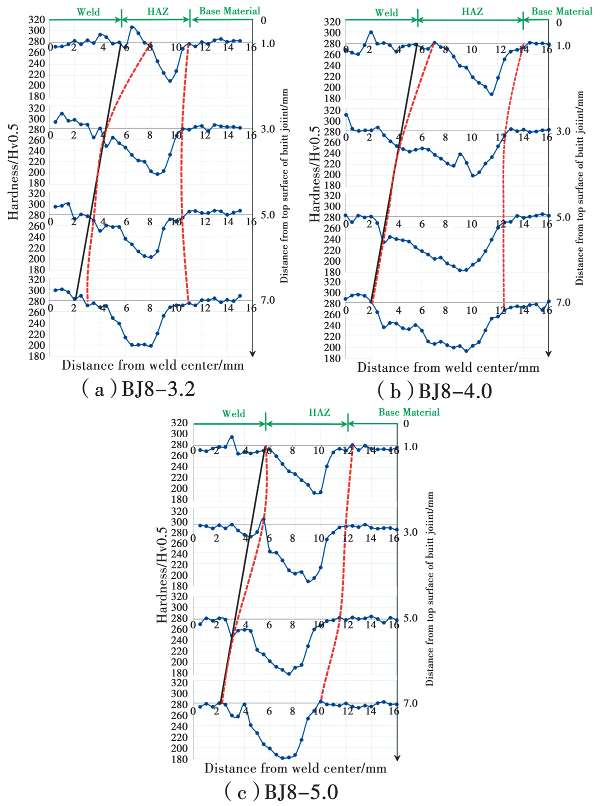


Fig. 7 Micro-hardness distribution of S690Q high strength steel butt joints

until the joint fractured. From Fig. 8, it can be seen that the tested butt joints all fractured within the heat-affected zone. The corresponding stress-strain curves are presented in Fig. 9.

Fig. 8 Failure modes of S690Q high strength steel butt joints

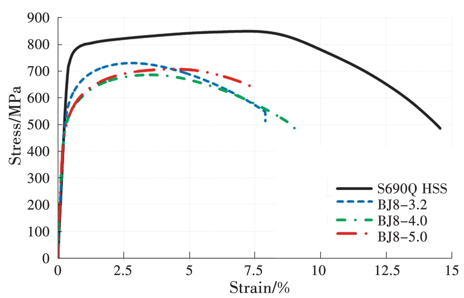


Fig. 9 Stress-strain curves of S690Q high strength steel butt joints

Both the strength and the ductility of the S690Q high strength steel butt joint deteriorated after welding, and the deterioration of mechanical performance became more serious with the increase of welding heat input. The characteristic strength of the three joints are listed in Table 4, as well as the fracture elongation. The reduction of yield strength ranged from 19% to 27% and the deterioration of ultimate tensile strength changed from 13% to 18%, when the welding heat input was increased from 1.25 kJ/mm to 1.58 kJ/mm, leading to relative thickness of the soft layer raised from 0.75 to 1.11. Compared with the conclusion obtained by Hochhauser and Rauch[6], the variation tendency of tensile strength with different relative thicknesses of soft layer was the same, although the strength deterioration was more serious due to the wider soft layer based on the results in this study.

Table 4 Mechanical property of S690Q high strength steel butt joints

Specimen	E/GPa	f_y/MPa	f_u/MPa	f_u/ f_y	e_f/%
BJ8-3.2	211.2	603.4	730.6	1.21	7.9
BJ8-4.0	209.3	542.9	686.6	1.26	9.0
BJ8-5.0	207.5	544.2	708.7	1.30	7.5

The mechanical behaviour deterioration of the S690 high strength steel butt joints tested after welding was mainly caused by the soft layer, which was generated during welding, due to microstructure transformation. Additionally, the residual stress caused by the welding process led to the stiffness reduction of the S690Q high strength steel butt joint, which explains why the deterioration of yield strength was more serious compared with the ultimate tensile strength. The decreased elongation can be explained by two reasons. The first is the high concentration of plastic strain caused by the welding process, and the second is that the deformation of S690Q high strength steel butt joints mainly occurs within the heat-affected zone due to the existence of the soft layer instead of uniform deformation in the whole gauge length.

4 Conclusion

This study reveals the post-welding behaviour of S690Q high strength steel butt joints, taking the welding heat input as the principle factor. By microstructure observation, the microstructure transformation was confirmed in the heat-affected zone during the welding process, such as the granular bainite formed in the coarse-grained heat-affected zone, the ferrite and cementite generated in the fine-grained heat-affected zone, and the ferrite occurring in the tempering zone. The micro-hardness test revealed that a "soft layer" was generated in the heat-affected zone and the relative thickness of the soft layer was increased from 0.75 to 1.11 with the welding heat input raised from 1.25 kJ/mm to 1.58 kJ/mm for the 8 mm thickness joints. In the followed tensile tests, the softening effect of the welding process on S690Q high strength steel butt joints was indicated in view of the fact that the reduction of yield strength ranged from 19% to 27% and the deterioration of ultimate tensile strength changed from 13% to 18%, when the welding heat input was increased from 1.25 kJ/mm to 1.58 kJ/mm for the fabrication of butt joints with 8 mm thickness with the relative thickness of the soft layer ranging from 0.75 to 1.11. The reason why the deterioration of the yield strength is more serious compared with the ultimate tensile strength is that the the residual stress caused by the welding process leads to reduction in the stiffness of the S690Q high strength steel butt joint.

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（编辑　胡英奎）