Experimental Study on Welding Dynamic Mechanical Properties of Q460JSC and HQ600 High Strength Steel at High Strain Rate

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Abstract. In order to study the high strain rate effect of the high-strength steel structure weld and its heat-affected zone material under the action of explosion, in this paper, the Q460JSC and HQ600 high-strength steel welded specimens were quasi-static and high strain rate tensile test of 1500/s to 5000/s using electronic universal testing machine and Hopkinson rod tester. The dynamic mechanical properties of high strength steel welded joints were studied. The results show that both the weld and its heat affected zone have strain rate sensitivity, and the strength and ultimate strain are higher than quasi-static under high strain rate. The center weld strength is higher than that of the base metal but the plastic deformation ability is weak. The strength and ultimate strain of the Q460JSC heat-affected zone are about 10\% lower than that of the base metal, while the HQ600 high-strength steel has a smaller drop and better weldability.

1. Introduction
With the continuous improvement of modern production and processing technology, high-strength steel structures have shown broad development prospects in large-scale public buildings, traffic engineering, civil practical projects and military infrastructure, and have been widely used [1]. However, the anti-explosion situation in the face of terrorist attacks and accidental explosions faced by high-strength steel structures is unprecedentedly severe [2] [3]. For welded high-strength steel structures, welds and their heat-affected zones are often weakened by the presence of grain changes and residual stresses, and are more susceptible to damage under the high strain rate of blast loads. The research shows that the deformation capacity of high-strength steel specimens after welding is significantly reduced. The weld and heat-affected zone are deteriorated due to the influence of welding heat input, and the fracture toughness is lower than that of the base metal and weld [4] [5]. The welded joint is the main form of joint connection, and the high-strength steel structure inevitably has a welded joint. Therefore, the plastic deformation and explosive energy absorption capacity of welded joints of high strength steel structures will be more prominent than those of ordinary strength steel structures. The mechanical properties and damage mechanism of welded joints under explosion, such as strength, deformation and strain rate effect, are important factors affecting the safety performance of high strength steel structures under explosion.
The study of dynamic mechanical properties of materials is the premise of structural anti-explosion performance research. At present, the related research on high strength steel for building structures and their joints mainly focuses on the fracture toughness, simple mechanical properties and fatigue strength of welded joints under various working conditions, while the mechanical properties under high strain rate are seldom studied. Sungho Kim et al [6] have studied the fatigue properties of butt welds of high strength steel. The results show that the fatigue life of butt welds decreases gradually with the increase of the defect size due to the insufficient penetration depth of welds. Zou Jiquan [7] studied the fracture behavior of D406A ultra-high strength mechanical steel and its welded joints, including the effect of mismatch on the toughness of joints and the mechanical properties of welded joints. The surface crack fracture toughness of D406A steel and its welded joints was measured. The fracture toughness probability distribution of base metal and heat-affected zone of joints was compared with the finite element analysis method. Yanmo Li et al [8] studied the mechanical properties of welded joints of linear friction welding (LFW) joints with S31042 heat-resistant steel. The results showed that the precipitation of particles produced by high stress and high temperature would improve the mechanical properties of welded joints.

At present, the research on the mechanical properties of steel welding is mostly directed to ordinary steel, and the mechanical properties of high-strength steel welding at high strain rate are relatively few. In this paper, SHTB high-speed tie rod test method is used to study the dynamic mechanical properties of Q460JSC and HQ600 high-strength steel welds and their heat-affected zones. Combined with static tensile test, the comparison is made to lay a foundation for the study of explosion resistance of high-strength steel structures under explosion.

2. Experiments

2.1. Test materials and specimens

High strength steel is made of 6mm thick Q460JSC and HQ600MC sheets produced by Anshan Iron and Steel Group. The welding method adopts 80% argon and 20% carbon dioxide gas shielded manual welding.

In order to study the mechanical properties of high-strength steel welds and their heat-affected zones, the specimen sampling positions include weld metal and heat-affected zone, all of which are sampled perpendicular to the weld direction. The sampling position is shown in Fig.1, and the welding object is shown in Fig.2.

Static test loading is based on the standard "Tensile Test Method for Metal Material at Room Temperature" (GB/T 228.1-2010)[9], carried out at room temperature of 20°C. Detailed dimensions of tensile specimens are shown in Fig.3.
SHTB specimens according to the specification Metal material high strain rate tensile test Part 1: Elastic rod system (*GBT 30069.1-2013*) and ARCHIMEDES-ALT1200 separation Hopkinson compression and general-purpose test equipment features, finished into cylindrical specimens as shown in Fig.4.

2.2. Test device and method

Static tests were carried out on *Zwick/Roell Z100* universal material testing machine in the fatigue Laboratory of Tianjin Pipe (Group) Corporation. In order to reduce the test rate change and the measurement uncertainty of the test results when determining the strain rate sensitive parameters, according to *GB/T 228.1-2010*, when measuring the yield strength, the strain rate is 0.00025 s\(^{-1}\); in the tensile strength measurement period, the strain rate is 0.0067 s\(^{-1}\); the relative error is ±20%.

The SHTB test was carried out on a separate Hopkinson pressure-drawing universal test device *ARCHIMEDES-ALT1200*. The device is composed of transmitting system, console, coaxial incident rod and transmission rod, bullet and central support member composed of a base, positioning mechanism and the guide rail. As shown in Fig.5, during the test, the launching system adjusts the required air pressure, releases the high-pressure gas stored in the gas cylinder, and drives the sleeve bullet to move to the right. The bullet hits the flange of the end of the loading rod, forming a tensile loading wave propagating to the left in the incident rod. The strain gauge attached to the surface of the incident rod records the incident signal and the reflected signal, and the strain gauge attached to the transmission rod records the transmitted signal. Finally, based on the assumption of one-dimensional stress wave in the rod and the assumption of uniformity of stress and strain along the axis in the specimen, the stress-strain relationship of the material can be calculated by the two-wave method.

2.3. Test loading condition

Under explosive loading, the strain rate of steel can reach 10-10\(^3\)/s. Four high strain rates and one quasi-static condition are selected to carry out the test, and three repeated tests are carried out for each strain rate. The specific test conditions are shown in Table 1.
Table. 1 Test conditions

| Steel type                               | Design strain rate/s \(^{1}\) |
|------------------------------------------|---------------------------------|
| Q460JSC base metal/center weld/heat affected zone | 0.00025 2000 3000 4000 5000     |
| HQ600 base metal/center weld/heat affected zone | 0.00025 2000 3000 4000 5000     |

3. Results and discussion

3.1. Stress-strain curve

The stress-strain curve is shown in Fig. 6. The Q460JSC high-strength steel center weld seam has large dispersion in the test data under the strain rate of 5000/s, which may be caused by accidental error during the test. The analysis in this paper is no longer considered.

![Fig. 6 True stress-strain curves](image-url)
3.2. **Q460JSC weld and its heat affected zone results analysis**

According to the test results, the actual stress-strain related parameters are listed in Table 2. The yield strength of the weld and its heat affected zone in the table is the maximum stress of the elastic section.

| Strain rate/s | Picking position | Yield Strength/MPa | Tensile strength/MPa | Uniform elongation/% | Fracture strain/% |
|--------------|------------------|--------------------|----------------------|----------------------|------------------|
| 2000         | Base metal       | 922                | 1027                 | 22.68                | 29.38            |
|              | Heat affected    | 838                | 1025                 | 16.96                | 29.74            |
|              | Center weld      | 962                | 1312                 | 18.95                | 29.40            |
| 3000         | Base metal       | 967                | 1073                 | 24.85                | 40.78            |
|              | Heat affected    | 803                | 997                  | 18.69                | 35.62            |
|              | Center weld      | 1038               | 1338                 | 18.81                | 32.63            |
| 4000         | Base metal       | 971                | 1069                 | 20.88                | 33.55            |
|              | Heat affected    | 735                | 925                  | 18.73                | 41.63            |
|              | Center weld      | 938                | 1296                 | 8.70                 | 16.52            |
| 5000         | Base metal       | 1016               | 1118                 | 22.16                | 40.13            |
|              | Heat affected    | 833                | 986                  | 18.20                | 42.55            |

Referring to Fig.6 and Table 2, it can be seen that:

1) Q460JSC high strength steel base material has obvious strain rate sensitivity, dynamic strength is obviously higher than static strength, and dynamic stress-strain curve is also significantly higher than static stress-strain curve. When strain rate is 1500s-1-5000s-1, dynamic yield (tensile) strength is about 1.38-1.50 (1.28) times of static yield (tensile) strength. The stress-strain relationship presents a typical curve of low alloy steel, which has an obvious yield platform and the strength increases with the increase of strain rate. Generally, the dynamic plastic deformation capacity of Q460JSC high strength steel is larger than that of quasi-static steel. The uniform elongation and fracture strain are about 1.57-1.79 times and 1.58-2.29 times of quasi-static steel, respectively, and increase with the increase of strain rate.

2) According to Fig.6, the stress-strain curve of the central weld is approximately bilinear, and there is no obvious yield platform. The maximum stress of the elastic section is greater than the yield strength of the base metal. The central weld also has obvious strain rate sensitivity, and the strength at high strain rate is obviously greater than that at quasi-static state. Fig. 7 shows the relationship between dynamic amplification factor of weld and base metal and strain rate. Fig. 8 shows the comparison of weld strength and base metal under different strain rates. It can be seen that the dynamic amplification factor of yield strength of central weld is larger than that of tensile strength, and is larger than that of base metal when the strain rate is less than 4000s-1, which is about 1.4-1.7 times of that of base metal. When the strain rate exceeds 4000s-1, the stress decreases more obviously with the strain exceeding 10%, which is due to the inaccuracy of Eq. (1) and Eq. (2) under large strain conditions.
Table 3 shows that the dynamic plastic deformation ability of the central weld is significantly improved than that of the quasi-static weld, reaching about 20%. At high strain rate, the dynamic plastic deformation ability of the central weld is less than that of the Q460JSC base metal, so the dynamic plastic deformation ability of the central weld is relatively weak.

(3) Due to the input of welding heat during the welding process, the grain size of the material in the heat-affected zone may be increased, and the strength and toughness may be reduced to some extent. The heat-affected zone material also has similar strain rate sensitivity to the parent metal, but no longer has a yielding platform. The elastic section maximum stress and ultimate tensile strength have a certain degree compared to the base material's yield strength and ultimate tensile strength. The reduction. Fig. 9 shows the relationship between the dynamic amplification factor of HAZ and the strain rate. Fig. 10 shows the relationship between the strength of HAZ and the base metal at different strain rates.

3.3. HQ600 weld and its heat affected zone results analysis

As shown in Fig. 6, the real stress-strain parameters of HQ600 high strength steel and its central weld and heat-affected zone are listed in Table 3.
Table. 3 True stress-strain parameters

| Strain rate/s | Picking position | Yield Strength/MPa | Tensile strength/MPa | Uniform elongation/% | Fracture strain/% |
|--------------|-----------------|--------------------|----------------------|----------------------|------------------|
| 2000         | Base metal      | 969                | 1094                 | 16.12                | 29.75            |
|              | Heat affected zone | 921               | 1020                  | 12.03                | 27.48            |
|              | Center weld     | 979                | 1245                 | 19.78                | 30.45            |
| 3000         | Base metal      | 978                | 1117                 | 15.84                | 34.08            |
|              | Heat affected zone | 932               | 1008                 | 10.63                | 23.74            |
|              | Center weld     | 965                | 1294                 | 10.82                | 18.75            |
| 4000         | Base metal      | 947                | 1077                 | 13.45                | 35.46            |
|              | Heat affected zone | 963               | 1040                 | 16.08                | 33.57            |
|              | Center weld     | 975                | 1340                 | 26.87                | 30.48            |
| 5000         | Base metal      | 928                | 1084                 | 22.00                | 35.78            |
|              | Heat affected zone | 1008               | 1071                 | 17.12                | 31.02            |
|              | Center weld     | 988                | 1206                 | 16.59                | 23.26            |

Referring to Fig. 6 and Table 3, it can be seen that:

The base metal of HQ600 high strength steel has the same strain rate sensitivity as that of Q460JSC high strength steel, and its dynamic strength is about 1.4-1.5 times of its static strength. When the strain rate reaches 2000/s or above, the strain rate effect of strength decreases. As the strain rate continues to increase, the change of yield strength and tensile strength is not obvious, and the strain rate sensitivity coefficient approaches 1. Generally, the fracture strain of HQ600 steel increases with the increase of strain rate, but decreases with the increase of strain rate. However, when the strain rate is greater than 4000s⁻¹, the strain rate sensitivity decreases and the strain rate effect is not obvious. This may be result of the offset between adiabatic warming softening effect and strain rate hardening effect.

The stress-strain curves of the central weld also show bilinear characteristics and are less sensitive at high strain rate stage. The maximum dynamic plastic strain is 0.3, which is smaller than that of base metal but higher than that of central weld of Q460JSC high strength steel. The maximum stress and ultimate tensile strength of elastic segment are higher than those of Q460JSC welded joint. It can be seen that the welding performance of HQ600 high strength steel is better than that of Q460JSC under this welding condition. Fig. 11 and Fig. 12 show the relationship between dynamic amplification factor and strain rate, and the relationship between weld strength and base metal at different strain rates, respectively. It can be seen that the yield strength and ultimate tensile strength of the central weld under high strain rate are larger than those of the base metal, but the dynamic amplification factor is smaller than that of the base metal. It can be seen that the strength of HQ600 high strength steel welded joint can basically match the base metal, but the strain rate effect is weak.
The HQ600 heat-affected zone exhibits a true stress-strain relationship similar to that of the parent metal. Both the strength and the plasticity have obvious strain rate effects, and increase with the increase of the strain rate, but the increase rate decreases. Fig.13 and Fig.14 show the relationship between the dynamic amplification factor of the heat-affected zone and the strain rate, and the relationship between the strength of the heat-affected zone and the base metal at different strain rates. It can be seen that the yield strength and ultimate tensile strength of the heat-affected zone are lower than that of the parent metal, but the decrease is within 2%. The dynamic amplification factor of the heat-affected zone varies with the strain rate curve and the base metal curve, and the difference is small. It can be seen that the strain rate effect in the heat-affected zone is close to that of the parent metal and is less affected by the heat input.

4. Conclusion
In this paper, quasi-static and dynamic mechanical properties of Q460JSC and HQ600 high-strength steel welds and their heat-affected zones at high strain rates were studied by quasi-static tensile test and SHTB high-speed tensile test. The test results show that:

(1)According to the welding method described in the paper, the two high-strength steel center welds and their heat-affected zones have strain rate sensitivity. The yield strength and ultimate tensile strength are higher than quasi-static under high strain rate, and the yield strength dynamic
amplification factor is greater than Tensile strength, but when the strain rate is greater than 2000s⁻¹, the strength increase decreases as the strain rate increases.

(2)The yield strength and ultimate tensile strength of the two high-strength steel center welds are higher than that of the base metal at high strain rate, but the plastic deformation ability is weak, about 60% of the base metal. It should be considered when designing the anti-explosion of structural members.

(3)The strength of the two high-strength steels is reduced by the heat input during the welding process. The strength of Q460JSC high-strength steel heat-affected zone is reduced by about 10%, while the strength of HQ600 high-strength steel heat-affected zone is only 2%, which indicates that HQ600 high-strength steel has better weldability.

(4)The plastic deformation of HAZ of two kinds of high strength steel at high strain rate is lower than that of base metal, but the range is smaller. It shows that the gas shielded welding method with 80% argon and 20% carbon dioxide is beneficial to reduce the influence of welding heat input on HAZ.

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