Research Article

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Hopkinson rod test results and constitutive description of TRIP780 steel resistance spot welding material

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Abstract: A quasi-static tensile test was performed on a 1.4 mm-thick TRIP780 steel strip with welding points. An MTS810 material test machine was used in the test, and a Split Hopkinson tension bar device was used in performing impact stretch loading at different strain rates. The dynamic tensile stress–strain curve of the spot welding material with different strain rates was obtained through the finely designed Hopkinson rod test, and the strain rate dependence of a TRIP780 steel spot welding material was discussed. According to the dynamic constitutive equation of the TRIP780 steel spot welding material, the test results were numerically simulated, the constitutive description and test curves were compared, and the simulation results and test results were discussed and analyzed. The fractures of the test recovery specimen were scanned with the scanning electron microscope, and the fracture mechanism of the TRIP780 steel spot welding material was explored by observing the fractures. The surfaces of the fractures surface showed obvious cleavage river patterns, and the evolution process of microcracks was determined and used in characterizing brittle fractures in specimen spot welding sample subjected to dynamic stretch loading.

Keywords: resistance spot welding, impact stretch loading, dynamic constitutive, brittle fracture

1 Introduction

Welding is the most economical and effective method of permanently connecting metals. The dynamic mechanical characteristics of resistance spot welding materials is essential to automobiles, ships, or spacecraft with resistance spot welding structure and under impact load. The dynamic mechanical properties of metals have been at the forefront of research on impact dynamics, and substantial research progress has achieved recently [1–9]. Under quasi-static tensile load, research progress [10–19] of damage evolution can also be popularized and applied to dynamic tensile fractures. The dynamic mechanical properties of steel-based materials have been extensively studied. For example, Oliver et al. [20], Sun et al. [21], and Sung et al. [22] studied the correlation between the strain rate and the failure mode of DP steel. Slycken et al. [23] described the mechanical properties and the phase composition of a TRIP steel under high strain rate loading conditions. Finally, Kang et al. [24], Nicholas [25], and Huh et al. [26] developed and improved the Hopkinson pole tensile test for steel bars. The mechanical behavior of materials has been simulated at high strain rates [27,28].

The quasi-static tensile test was performed on a 1.4 mm-thick TRIP780 steel strip with welding points. An MTS810 material test machine was used in the test. The Split Hopkinson tension bar (SHTB) device was used for impact stretch loading at different strain rates. By using the finely designed Hopkinson rod test, the dynamic tensile stress–strain curve of the spot welding material with different strain rates was obtained, and the strain rate dependence of the welding material was explored. The results of the dynamic tensile test were numerically simulated using the dynamic composition equation of a welding spot material used in our another other study and compared with the stress–strain curve obtained through an experiment. The recovered sample was observed with a scanning electron microscope, and the results of microdamage evolution were obtained.

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Figure 1: MTS 810 material testing machine.

Finally, the fracture pattern of the dynamic tensile fracture of the welding spot material was analyzed.

2 Quasi-static and dynamic tensile test

The TRIP780 steel plate was 1.400 mm thick. The time interval between two welding processes was 20 ms, and the welding time and holding time were 130 and 250 ms, respectively. Initially, the welding pressure was 4.300 kN. The quasi-static tensile experiment was carried out on a specimen by using the MTS 810 material test machine, as shown in Figure 1. The quasi-static tensile experiment on TRIP780 steel single-piece specimens was carried out on

Figure 2: Size of the single-piece steel strip specimen with solder joints, unit: mm.

the same test machine, and a solder pot was used. The stress-strain curve of the welding spot material was obtained, and the specimen and its size and design are shown in Figure 2. Resistance spot welding material was in the middle of the specimen, with a length of 3 mm.

The quasi-static tensile test stress-strain curve is shown in Figure 3. The front end of the curve is not linear possibly because of a connection problem between the specimen and the loading device, and a relative slip occurs between the specimen and loading device at the start of loading.

The dynamic tensile test of the specimen was performed on the Hopkinson rod. The test device is shown in Figure 4. In the test, the specimen was connected to the incident and transmission bars. When the compressed gas drives a cylinder-shaped projectile with a length of L_0 to hit the target plate at speed V_0 , the cylinder-shaped projectile, incident bar, and transmission bar are all in an elastic state, and the incident and the transmission bars have the same diameter and material, that is, these bars have the same elastic modulus E , wave velocity C_0 , and wave resistance $\rho_0 C_0$. Impact produces the incident stress pulse $\sigma_I(t)$ load, and the specimen is deformed at high speeds under the loading action of the incident pulse. Reflected stress pulse $\sigma_R(t)$ is transmitted to the incident bar, whereas stress pulse $\sigma_T(t)$ is transmitted to the transmission bar, which reflects the dynamic mechanical behavior of the test material.

In the experiment, the diameters of the incident and transmission bars were 19 mm, with lengths of 2.7 and 1.5 m, respectively. The length of the bullet was 300 mm. The incident bar, transmission bar, target plate, and bullet were made of high-strength alloy steel with elastic modulus E of 190 GPa and Poisson ratio ν of 0.3. According to the one-dimensional elastic stress wave theory, in uniform stress and strain, the stress $\sigma(t)$, strain $\varepsilon(t)$, and strain rate $\dot{\varepsilon}(t)$ of the specimen can be calculated using the following equations:

$$\sigma(t) = \frac{A_b}{A_0} E_b \varepsilon_t(t), \quad (1)$$

$$\varepsilon(t) = -\frac{2C_0}{L_0} \int_0^t \varepsilon_r(t) dt, \quad (2)$$

$$\dot{\varepsilon}(t) = -\frac{2C_0}{L_0} \varepsilon_r(t), \quad (3)$$

where t is time; $\varepsilon_t(t)$ and $\varepsilon_r(t)$ are the strain signals of the transmission and reflected waves, respectively; A_b and E_b are the cross-sectional area and elastic modulus of the incident bar and transmission bar, respectively; C_0 is the

Figure 3: Quasi-static tensile stress-strain curve.

Figure 4: Hopkinson rod test device diagram

elastic wave speed of the rod; and A_0 and L_0 are the cross-sectional area and effective length of the effective segment of the test, respectively. The tensile stress wave was generated after the sleeve bullet travelled through the incident bar, and the surface was reflected when the incident bar and the target plate were free, thus applying multiple tensile loads to the specimen.

The dynamic tensile test stress-strain curve of the specimen at different strain rates is shown in Figure 5. Stress and strain increase with the strain rate although the resulting curve is somewhat irregular. The curve indicates that the spot welding material has a certain strain rate dependence.

The recycled photographs of the specimen for the quasi-static tensile and Hopkinson rod tests are shown in Figures 6 and 7, respectively. As shown in Figure 6,

Figure 5: Dynamic tensile stress-strain curve.

in the quasi-static tensile experiment, the specimen is sheared and broken, and the fracture is 45° . As shown in Figure 7, the specimen fracture is not an obvious 45° because of dynamic loading.

3 Constitutive description

The HV test was performed on the RSW materials of TRIP780 steel. To disclose the HV values of BM, HAZ, and FZ on the RSW material samples, points were set on the left BM and HAZ, center FZ, and right HAZ and BM successively along a biased line that runs through the FZ center. Specifically, points were set horizontally along the center line of BM of the steel plate (1 mm), then turning to the FZ center from the outer edge of HAZ and running through the FZ center and to the horizontal direction of the outer edge of the opposite HAZ (1 mm). The interval between the two points was 0.200 mm. Distribution of the testing points is shown in the dotted line in Figure 8. This study set five points in the right and right BM zones, respectively; four points in the right and right HAZ zones, respectively; and 26 points in the center FZ zone. Therefore, a total of 44 hardness test points in the RSW zone were set.

For a clear display of the HV hardness values of different parts of the RSW material samples, experimental results and length of RSW material samples were placed in the same coordinate system, and a variation curve of the hardness with length was drawn (Figure 9).

In the welding process, bainites in BM are transformed into austenites. With the continuous increase of temperature, ferrites in BM can also be transformed into austenites. Under this circumstance, plastic deformation

Figure 6: Recycling specimens under the quasi-static load test.

Figure 7: Recycling specimens under the dynamic tensile test.

is developed in the welding zone under spot-welding pressure. With the reduction of temperature, structures are recrystallized and martensitic structures are obtained after cooling. Figure 9 shows that the hardness values of FZ and HAZ are relatively high, whereas that of BM is relatively low. The main reason is that FZ and HAZ are mainly composed of martensites, while BM is mainly composed of ferrites. The hardness values of martensites are higher than those of ferrites. The hardness values of FZ are different from those of HAZ because HAZ components include some residual ferrites relative to the components of FZ, thereby resulting in lower hardness of HAZ than that of FZ. In Figure 9, point S shows the softening point of hardness, which is less than the hardness of wood. The microhardness

decreases as the steel plates receive fast thermal circulation at welding.

Roth and Mohr [29] decoupled the strain hardening effect, strain rate hardening effect, and temperature softening effect of materials with reference to the Johnson–Cook constitutive model, thereby obtaining the following dynamic constitutive equation:

$$\sigma_e^{BM}(\varepsilon_p, \dot{\varepsilon}_p, T) = [\alpha A_* (\varepsilon_p + \varepsilon_0)^n + (1 - \alpha)(k_0 + Q(1 - e^{-\beta \varepsilon_p}))] \times \left[1 + C_* \ln \left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0} \right) \right] \left[1 - \left(\frac{\Delta T}{T_m - T_r} \right)^m \right], \quad (4)$$

Figure 8: The RSW cross-sectional micrograph and dot position.

Figure 9: Hardness–length curve.

where BM refers to the base material; ε_p denotes the equivalent plastic strain, $\dot{\varepsilon}_p$ is plastic strain rate, ΔT denotes increase in temperature caused by plastic powers; α is the linear combination coefficient; and k_0 , Q , and β are constants.

The expression of ΔT is

$$\Delta T = \frac{\eta_k}{C_p \rho} \int \bar{\sigma} d\varepsilon_p, \quad (5)$$

where η_k is the Taylor–Quinney coefficient, ρ is the mass density, and C_p is hot melting.

Model parameters of TRIP780 steel used in constitutive description of a typical experiment are listed in Table 1.

As the material properties of the welding zone are significantly different from BM in the welding process, we hypothesized that only changes of yield stress in the welding zone are considered in the numerical model, and other mechanical properties and failure parameters are constant in the specimens, as mentioned by Nielsen [30]. It is hypothesized that a linear correlation exists between microhardness and yield stress. Therefore, hardness in the RSW zone is attributed to the hardness of BM. On this basis, the dynamic constitutive equation of the RSW zone of TRIP780 steel is obtained as follows:

Table 1: The modified Johnson–Cook model parameters for TRIP780 steel used in simulation

A_* (MPa)	ε_0	n	C_*	$\dot{\varepsilon}_0$	m
1526.5	0.00519	0.242	0.00557	0.00321	1.025
T_r (K)	T_m (K)	E (GPa)	ν	C_p (J/kg K)	ρ (kg/m ³)
293	1806.7	185	0.33	420	7,850

$$\begin{aligned} \sigma_e^{\text{RSW}}(\varepsilon_p, \dot{\varepsilon}_p, T) &= \lambda_i \sigma_e^{\text{BM}}(\varepsilon_p, \dot{\varepsilon}_p, T) \\ &= \lambda_i [\alpha A(\varepsilon_p + \varepsilon_0)^n \\ &\quad + (1 - \alpha)(k_0 + Q(1 - e^{-\beta \varepsilon_p}))] \\ &\quad \times \left[1 + C \ln \left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0} \right) \right] \left[1 - \left(\frac{\Delta T}{T_m - T_r} \right)^m \right], \end{aligned} \quad (6)$$

where RSW represents RSW materials.

We use equation (6) to analyze the results of the dynamic tensile test performed on the specimen. Then, the stress–strain curve was obtained through constitutive description on the basis of the corresponding strain rate and compared with the experimental curve (Figure 10). The comparison results showed that the simulation and experimental results were basically in line with each other but not completely consistent. We believe that

Figure 10: Comparison between experimental results and constitutive description.

Figure 11: Scanning electron microscope image of the specimen fracture.

this result is related to the dynamic tensile test conditions and processes, including the machining accuracy of the specimen, the closeness of the connection between the specimen and the rod, and the paste quality of the strain gauge, which may have affected the experimental results.

The fracture of metal material on a microscale is caused by the nucleation, growth, and aggregation of cavities or cracks, which result in ductile or brittle fractures. The increase in the number of cavities or cracks must be aggregated or combined to form a continuous surface and split the specimen. We used an electron microscope to scan a fracture of the dynamic tensile test and the recycling test (Figure 11). By observing the fracture, we observed an obvious cleavage river pattern and the evolution of microcracks. The specimen spot welding part was a brittle fracture.

4 Conclusion

- (1) The quasi-static tensile and Hopkinson rod tests were carried out on TRIP780 steel with solder joints, and the stress–strain curve under the quasi-static tensile was obtained, as well as the stress–strain curve under dynamic tensile at different strain rates. The test results show that the TRIP780 steel spot welding material has a certain strain rate dependence.
- (2) The experimental results were numerically simulated using the dynamic material of TRIP780 steel spot welding material obtained. The comparative results show that the constitutive description and test curves were basically in line with the results, and what

caused the inconsistency was considered related to the test conditions and processes.

- (3) Through electron microscopy and dynamic tensile test, the fractures of the recycled specimen were scanned during the dynamic tensile test. The fracture had an obvious cleavage river pattern, microcrack evolution, and the specimen spot welding part was a brittle fracture.

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