Process parameters and mechanical properties of SAPH440 steel in pulse arc welding with different heat inputs

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Abstract: Thermal cycling parameters of pulse arc welding for SAPH440 steel was experimentally determined for different heat inputs. The welding thermal cycle curves of the weld fusion and heat-affected zones were successfully constructed based on the thermocouple measurements through the back drilling hole. The hardness and tensile strength variations under different heat inputs were also analyzed. This provided a database for the determination and optimization of process parameters, improvement of microstructure and properties of weld fusion and heat affected zones, and overall quality of pulse arc welding of steels.

1. Introduction

SAPH440 steel is structural hot-rolled steel in the form of plates, sheets, and strips for automobile structural applications. Due to added Mn, V, Ti, and Nb elements, it has the advantages of high strength, high toughness and good corrosion resistance, which satisfies the design requirements of green vehicles for lightweight, energy saving, and emission reduction [1]. However, welding of this steel raises certain problems [2]: the instantaneous high temperature produces uneven temperature gradient distribution in the welded joint and its vicinity, and forms more complicated residual stress and deformation after cooling to room temperature, which directly affects the carrying capacity and structural stability of the weldment [3].

There are many factors that affect the distribution of welding temperature field, such as welding heat input, thermophysical properties of the metal being welded, thickness and shape of the welding structure [4-8]. Lv et al. [9] found the cooling rate of welding thermal cycle affect microstructure and properties of a similar SA508-3 steel. Therefore, in this paper, a thermocouple was used to construct the thermal cycle curve of the heat-affected zone (HAZ) in the pulse arc welding process of SAPH440 steel. The mechanical properties of the steel plate were studied by means of tensile test, microhardness test, and process analysis, which could guide the actual welding process and improve its quality in enterprises [10].

2. Experimental materials and welding method

2.1. Experimental equipment and materials
SAPH440 steel was used as experimental material. Its chemical composition is given in Table 1 and its mechanical properties are listed in Table 2. The microstructure, as shown in figure 1, is mainly composed of polygonal ferrite with a small amount of pearlite with no obvious banded structure. An LHM-315 pulse arc welding machine was used for butt welding of type I groove. The voltage was 200-240 V, the current was 140-160 A, the welding speed was 2.0-4.0 cm/min, the shielding gas flow rate was 10 L/min, and the gas flow was 2.5 L/min.

### Table 1. Composition of base steel (wt.%).

| Base steel | C  | Si  | Mn  | P  | S  |
|------------|----|-----|-----|----|----|
| SAPH440 steel | ≤0.21 | ≤0.3 | ≤1.5 | ≤0.03 | ≤0.21 |

### Table 2. Mechanical property of steel.

| Yield strength (MPa) | Tensile strength (MPa) | Ductility (%) |
|----------------------|------------------------|---------------|
| ≥315                 | ≥490                   | ≥30           |

![Figure 1. Microstructure of SAPH440 steel.](image1)

2.2. **Spot welding experiment of thermocouple**

The plate surface plate was cleaned from oil contaminants, rust, and other residues in the welding zone. A hole with a depth of 3 mm and a diameter of 2 mm was drilled to construct the thermal cycle curve of the characteristic position of the weldment. The characteristic position is illustrated in figure 2.

![Figure 2. Schematic diagram of a thermocouple.](image2)
3. Welding thermal cycle curve measurement method

3.1. Principle of thermocouple testing
At present, there are contact and non-contact methods for temperature measurement. Because infrared temperature measurement or thermal imaging technology is vulnerable to external interference in the detection process, especially the instability of welding arc heat source, the contact thermocouple temperature measurement method was adopted in this experiment. Thermocouple temperature measurement was based on the thermoelectric potential generated by the temperature difference between the two ends of the thermocouple. The junction of the thermocouple was spot-welded to the hole in the measured point, while the other end of the thermocouple was connected to the thermometric instrument to measure the thermoelectric potential during welding. The thermoelectric potential was invoked as the input signals of the thermometric instrument, which were automatically recorded by the thermometric instrument after being amplified. The temperature conversion of internal solidified thermoelectric potential was used for data processing, and the welding thermal cycle curve of temperature measurement point was constructed.

3.2. Thermocouple wire ball and spot welding
(1) A thermocouple with length of 100mm was used, the two wires of thermocouple were treated with catching ball equipment. The operation was to align the ends of the red and blue thermocouple wires and then wrapped it around, clamped with a hand pliers and contacted with "TE-WELDER" electrode for discharge. After the end, removed it and completed thermocouple wires catching.
(2) A 220V AC power supply was connected, with the power switch in the "charging" state. The welding machine power switch was adjusted to the welding voltage of spot welding.
(3) The positive electrode was clamped to the thermocouple wire with a sharp-nose pliers, and the magnetic electrode end was placed on the plate.
(4) The end of thermocouple wires was clamped to the head of soldering tweezers, placed into the hole position, and pressed gently. After the green light of the discharge indication was on for about 3s, the welder automatically discharged. After the thermocouple spot welding was completed, the power switch was shifted the "charging state" and spot welding was finished. The results are shown in Figure 3.

![Figure 3. Spot welding of thermocouples.](image)

4. Experimental results and analysis

4.1. Thermal cycle curve test analysis
The thermal cycle curves of coarse grained region and incomplete recrystallization region under different thermal inputs were obtained, as shown in figure 4. Respectively, thermal inputs Q1, Q2, and Q3 were 1.46, 1.37, and 1.28 kJ.
It can be seen from Figure 4 that the thermal cycle curves of each measuring point are similar in characteristics. The variation rule of the curve reflected the temperature distribution trend of the actual welding process. As the heat input decreased, the peak temperature of each measurement point also decreased; As it approached or left the heat source, the peak temperature rose or fell rapidly, and the rate of temperature rise was greater than the rate of decline. It can be seen from Figure 4(a) that the peak temperature was about 1226 °C when the heat input was Q1, the high temperature stayed for 4 s, while \( t_{8/5} = 17 \) s; In Q2, the peak temperature was about 1217 °C, the high temperature stayed for 0.6 s, while \( t_{8/5} = 7.2 \) s; At Q3, the peak temperature was about 1119 °C, the high-temperature stayed for 0.2 s, while the \( t_{8/5} = 7.8 \) s. Therefore, the peak temperature increased with heat input, and \( t_{8/5} \) had an increasing trend, which indicated the heat concentration. It can be seen from Figure 4(b) that the curve peak temperature of Q1 to Q3 was from 560 °C to 470 °C, the peak temperature decreases with heat input.

4.2. Microstructure analysis
According to the measurement data of thermal cycle curve, the welded joint was ground using sandpaper of 200 #, 400 #, 600 #, and 800 #. After polishing, it was etched with 4% nitric acid for 5s, and the microstructure at different positions of the welded bead was observed. The results are shown in figure 5.

Figure 5. Metallographic structure diagram for: a) Q3; b) Q2; c) Q1.
As seen in Figure 5, the formation temperature of the coarse grained region was above 1100 °C, the bainite structure was relatively coarse, the austenite grain undergoes a serious growth phenomenon, and after cooling, a coarse bainite structure was obtained. The metal in the fine-grained region was heated to a position above Ac1, and was cooled in the air to obtain a uniform and fine pearlite and ferrite structure. The formation temperature of incomplete recrystallization tissue was 717 ~ 900 °C, and it became the ferrite and pearlite with fine grains.

The metal in the completely recrystallized zone was heated above Ac3, and ferrite and pearlite phases were austenitized, with fine ferrite and pearlite obtained after cooling. In the incomplete recrystallization zone, only some structures underwent the phase transformation, such as fine ferrite and pearlite, and some large ferrite has not been dissolved into austenite. The base metal mainly had uniform grain ferrite and a small amount of pearlite, with no obvious banded tissues.

The microstructure of the weld and phase transition area was not obvious under different thermal inputs, but the microstructure of overheated zone increased with the thermal input.

4.3. Microhardness analysis
Under different thermal input conditions, the hardness variation rules of weld seams and various regions were similar, as shown in Figure 6.

![Figure 6. Hardness curves for different thermal inputs.](image)

As shown in Figure 6, with an increase in welding heat input, the grain size gradually increased, and its hardness value gradually decreased. In addition, the hardness decreased from the weld area to the base metal. The hardness of the weld was the highest, reaching 250 HV, while that of the base material was about 140 HV. The weld area is composed of fine and uniform acicular ferrite and bainite. The coarse-grained zone in the overheated area made the hardness in this area the smallest, and then the phase transformation occurred in the incomplete recrystallization area. The hardness of the fine-grained zone in the structure was increased, while that in the incomplete recrystallization zone was decreased again.

4.4. Tensile test results
Tensile fracture morphology under different heat inputs conditions is shown in Figure 7. The elongation of Q1 was 11.5%, and its maximal tensile load was 6.91 kN. The elongation of Q2 was 19%, and its maximal tensile load was 10.32 kN. The elongation of Q3 was 9.62%, and its maximal tensile load was 6.71 kN.
Figure 7. Fracture morphology of (a) Q1; (b) Q2; (c) Q3.

It can be seen in figure 7 that all fracture sections exhibit ductile dimples, which indicates that the material had good mechanical properties, such as plasticity and toughness, and the welding process is reasonable.

5. Conclusions
It can be concluded that the proposed method of thermocouple-based construction of thermal cycle curves can reflect the actual variation rule of welding temperature field, and features of each measurement point were similar. With an increase in heat input, the peak temperature also increased. Near the heat source, the temperature rose more rapidly, and the coarse-grained area was mainly bainite, while the fine-grained zone contained uniform and fine pearlite and ferrite structures. The incomplete recrystallization zone contained ferrite and pearlite, while the base metal contained uniform grains of ferrite and a small amount of pearlite, with no obvious band structure. In general, with an increase in thermal input, the peak temperature of the thermal cycle curve gradually increased, the microstructure of the weld and near-weld area became coarser, and the corresponding hardness gradually decreased. According to the tensile test, the fracture surface under different thermal inputs presented a ductile dimple morphology.

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