Analysis on magnetic control stud welding device with the open-close Structure

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Abstract. Arc stud welding is widely used to fix joints like studs, screws, pins, or similar elements on various products. The main defects in the process of large diameter stud welding are arc offset and non-uniform melting. In order to solve the problems, which seriously affect the installation strength of stud, the magnetic confinement device with the open-close structure is used to improve the quality of stud welding. An open-close magnetic confinement device suitable for robotic stud welding system is designed to create rotatable magnetic field. Rotating magnetic field can drive arc deflection. The magnetic field produced by magnetic confinement device is simulated. The distribution and intensity of magnetic field is analyzed. The influence of the design parameters of magnetic confinement device on the magnetic field is studied. According to the practicability and the size limitation of the magnetic confinement device, the appropriate parameters are selected. The prototype of the magnetic confinement device is tested by stud welding. The results show that the open-closed magnetic confinement device designed with reasonable parameters has good inhibitory effect on the arc offset.

1. Introduction
Stud welding is widely used to connect bolts, screws, pins and other cylindrical parts to a variety of products [1]. It has the advantages of low cost, simple structure, convenient operation and so on [2, 3]. Stud welding in this paper is mainly used in road and bridge construction. There is a great demand for stud in bridge and road construction, and it also requires high welding strength. Traditionally, studs are loaded manually. When welding, the worker needs to hold the welding gun [4-7]. The welding speed, the working efficiency and the pass rate of stud welding are low. After using stud welding robot, the manipulator clamps the stud to feed the automatic welding torch. The automatic welding of stud is realized, which reduces labor intensity of personnel and improves production efficiency. However, it easily produces defects like arc offset, non-uniform melting and so on. These defects affect the installation strength of stud seriously. The arc shape of stud welding can be changed by external magnetic field to improve weld forming [8]. In this paper, a magnetic confinement device apply to stud welding robot is designed. The distribution and intensity of external magnetic field are analyzed. It provides a reference to the design of magnetic confinement device. It will facilitate application of stud automatic welding.
2. Magnetic confinement device model and principle of magnetic confinement

2.1. Magnetic confinement device with open-close structure

Magnetic confinement device with open-close structure is shown in figure 1. The magnetic confinement device is mainly composed of excitation coil, excitation core and excitation power. The excitation core is made of soft magnetic material which is easy to magnetize. It has high permeability and low eddy current loss. In order to prevent the whole device from being charged once the enamelled wires is damaged. The excitation core should be insulated. Three pairs of excitation cores are parallel to the stud and evenly distributed around the stud at the same radius. Three pairs of excitation coils are electrified by three phase-single three beat mode. Three pairs of excitation coils pass on direct current in order, so they produce magnetic field in turn. Then the magnetic confinement device produces rotatable magnetic field. The rotating magnetic field controls the arc combustion, so that the arc evenly heats the stud. To help the manipulator feed the automatic welding torch, three pairs of excitation coils are installed on two semicircular of the open-closed structures, as shown in figure 1.

![Figure 1. Open-close magnetic confinement device.](image)

The excitation coil is wound on the excitation core, the open-closed upper semicircular structure can not only fix the excitation core, but also acts as a magnetic yoke [9, 10]. When the stud is fed on the welding torch, the magnetic confinement device is combined into a whole. There is a rotatable transverse magnetic field around the stud. In the figure, the upper and lower parts of the excitation core is designed with shaft shoulder, which can fix the wound excitation coil and avoid the damage caused by the friction of the coil.

2.2. Theoretical basis of electromagnetic field

The solenoid coil is the most common magnetic field generator. The solenoid produces a uniform magnetic field inside the solenoid. The Maxwell equations are summarized by the basic laws of the electromagnetic field, and they are mainly composed of four differential equations [11].

\[
\nabla \times E = \frac{\partial B}{\partial t} \tag{1}
\]

\[
\nabla \times H = J + \frac{\partial D}{\partial t} \tag{2}
\]

\[
\nabla \times B = 0 \tag{3}
\]

\[
\nabla \times D = \rho \tag{4}
\]

The two auxiliary equations are:

\[
J = \sigma E \tag{5}
\]

\[
B = \mu H \tag{6}
\]
Where $E$ is the intensity of the electric field, $H$ is the magnetic field strength, $B$ is the magnetic flux density, $D$ is the density of the electric field, $\rho$ is the charge density, $\mu$ is the permeability and $\sigma$ is electrical conductivity.

3. Simulation of magnetic field of magnetic confinement device

When the excitation current is into the open-close magnetic confinement device, a rotating transverse magnetic field will be created near the magnetic guide rod. The magnetic field generated by the magnetic confinement device is analyzed by ANSYS. The stud diameter is 16 mm, it is made of 20 steel. The upper semicircular structure and excitation core is made of Q235, which is commonly used in pole head and magnetic circuit. Its relative permeability is 4000. The relative permeability of air is 1. Excitation coil is made of copper, and its relative permeability is 0.99990.

4. Simulation results and discussion

4.1. Effect of excitation core design on the magnetic field

The excitation core of the magnetic confinement device is made of soft iron which is easy to magnetize and demagnetize [12]. Once the excitation coil is electrified, the magnetic field is created. The excitation core is magnetized. The excitation core also creates the magnetic field. After the two magnetic fields are superimposed, it can enhance the magnetic field. At the same time, the excitation core can also change the direction of the magnetic field and create the transverse magnetic field. The influence of the diameter of the core on the magnetic field is analyzed by changing the diameter of the core without...
changing other conditions. The magnetic induction line distribution and magnetic field intensity of the magnetic confinement device are analyzed when the diameter of the core is 7 mm, 8 mm and 9 mm respectively.

![Graphs showing magnetic line distribution and magnetic field intensity for different core diameters.](image)

(a) The diameter of core is 7 mm; (b) The diameter of core is 8 mm; (c) The diameter of core is 9 mm;

**Figure 3.** Distribution of transverse magnetic field of magnetic confinement device with different core diameters.

Figure 3 on the left is magnetic line distribution map of the magnetic field created by a pair of excitation core with different diameters, and the magnetic induction intensity diagram of different positions on the magnetic guide rods connection line is on the right (taking the end face of the left magnetic guide rod as the origin). From the magnetic line distribution map, it can be seen that most of the magnetic induction lines pass through the excitation core, most of them are closed. The magnetic field in the stud welding area is mainly a transverse magnetic field. The vertical component of magnetic field is relatively small. The magnetic field is stronger at the end of the magnetic conducting rod. The magnetic field with a minimum at the midpoint of the two magnetic conductive rods. Under the condition that other things remain unchanged, as the diameter of the excitation core increases, the magnetic field between the magnetic conductive rods has been slightly enhanced.

4.2. The influence of the magnetic conductive angle on the magnetic field

The magnetic field created by magnetic confinement device requires the magnetic rod to transfer it to the stud welding area. In order to analyze the influence of magnetic conductivity angle on the magnetic field of the welding area, the distribution of magnetic inductance line and the magnetic field intensity of magnetic confinement device are analyzed when the magnetic conductivity angle is 65 degrees, 90 degrees, 115 degrees and 140 degrees.
(a) The magnetic conductivity angle is 65°;    (b) The magnetic conductivity angle is 90°

(c) The magnetic conductivity angle is 115°;    (d) The magnetic conductivity angle is 140°

Figure 4. Distribution of transverse magnetic field of magnetic confinement device with different magnetic conductor angle.

The left of Figure 4 are magnetic line distribution maps of the magnetic confinement device with different magnetic conductor angle. The magnetic induction intensity diagrams of different positions on the magnetic guide rods connection line is on the right (taking the end face of the left magnetic guide rod as the origin). The simulation results show that the change of the magnetic conductivity angle has a great influence on the magnetic field distribution and the magnetic field intensity. At first, the magnetic field intensity between the two magnetic guide rods increases with the magnetic conductivity angle. When the magnetic conductivity angle is 115 degrees, the magnetic field intensity at the middle point of the two magnetic guide rod reaches 2.96mT. Then with the increase of the magnetic conductivity angle, the magnetic induction intensity at the midpoint of the magnetic conducting rods will decrease.

4.3. Effect of distance between excitation cores on magnetic field
The installation position of the excitation cores is also the influencing factor of magnetic field created by the magnetic confinement device. The magnetic field created by the magnetic confinement device changes with the distance between the excitation cores, so the magnetic field is analyzed when the distance between the excitation core and the stud axis is 30mm, 35mm, 40mm and 45mm respectively.
From the simulation results in Figure 5, it can be seen the magnetic field intensity of magnetic confinement device with different core distances. The distance between the excitation core and the stud axis is changed, while the excitation coil structure and excitation current remain unchanged. With the increase of the distance between the excitation core and the stud axis, the magnetic field intensity at the center axis of the stud decreases slightly, but the magnetic field intensity at the edge of the stud is basically unchanged.

4.4. Effect of excitation current on magnetic field of magnetic confinement device

In order to study the influence of current on the magnetic field of the magnetic confinement device, the structural parameters of the magnetic confinement device remain unchanged, only the excitation current is changed. The increment of the current is 5A. The magnetic field is analyzed when the excitation current is 35A, 40A, 45A and 50A respectively.

Figure 6 shows that the magnetic field intensity at the edge (red) of the stud and the center (blue) position of the stud are increase linearly with the current, but the increase of the excitation current does not changes the distribution of the magnetic field, the current only changes the magnetic field intensity.
5. Experimental results and analysis

Through the simulation results of the magnetic field created by the magnetic confinement device, the design of the magnetic confinement device needs to consider the limitation of practicability, economy and overall size. The diameter of the excitation core is 8 mm. In order to reduce the influence of welding high temperature on the excitation coil, the distance between the excitation core and the stud axis is 70 mm and the magnetic conductivity angle is 90°. The prototype is shown in figure 7. The effect of magnetic confinement device is tested by installing it on stud welding robot.

Stud welding robot is shown in figure 8, the welding torch is mainly composed of clamping mechanism and lifting mechanism. The main processes of stud welding include arc ignition, welding, compression and forming. To improve the stud welding efficiency and make the welding parameters more controllable to avoid the influence of human factors, the clamping mechanism and lifting mechanism are driven by cylinder and servo motor.

After the manipulator clamps the stud from the feeding plate, stud is sent to the bottom of the welding torch for positioning, then the magnetic confinement device is closed. After the stud is located in the center of the magnetic confinement device, the welding torch is electrified, the welding arc starts to burn. Then the end of the stud is melted. After the section bar surface produces the molten pool, the welding torch is pressed down to integrate the stud and the section bar.

![Figure 7. Magnetic confinement device.](image1)

![Figure 8. Robotic stud welding system.](image2)

The welded section bar and stud are made of 20 steel, and the diameter of stud is 16 mm. The stud and section bar surface are attached with impurities such as oil and oxide. In order to reduce influence of impurities on stud welding joint, the stud and section bar should be washed and polished before the experiment. And the surface should be wiped with acetone to remove oil stain. First, the stud and section bar are welded directly by robotic stud welding machine, and then the stud welding is carried out after the magnetic confinement device is installed. The stud welding experiment is carried out with the same welding parameters. Comparative experiment is to verify effect of the magnetic confinement device. The welding current, welding time and lifting height are 1100A, 800ms and 4mm respectively.

Figure 9a is the appearance of stud welding specimen which uses robotic stud welding machine directly. It can be seen from the appearance that the stud melted too much on the right, but the other side is not completely fused with section bar, and there are some defects such as porosity and crack. Arc offset is caused by the grounding of welding machine or the dense area of ferromagnetic material around the welding machine. Figure 9b is the appearance of the welded specimen while the magnetic confinement device is installed during welding. The magnetic confinement device plays a good role in guiding the arc, the stud melting is uniform and the appearance of stud joint is good.
6. Conclusion
(1) The model of open-closed magnetic confinement device is established by finite element method, and the distribution of magnetic field created by magnetic confinement device can be analyzed by ANSYS.
(2) From the results, it can be seen that the magnetic field produced by the magnetic confinement device increases with the diameter of excitation core and the excitation current. When the distance between excitation core and the stud axis is increase, the magnetic field will decrease. With the increase of the magnetic conductivity angle, the magnetic induction intensity increases at first and then decreases.
(3) The magnetic field produced by the open-close magnetic confinement device is analyzed by ANSYS. The result can provides a reference for the design and manufacture of the open-close magnetic confinement device. The open-closed magnetic confinement device has a good suppression effect on arc offset and non-uniform melting. As a result, qualification rate has climbed by 21% and better economic benefits have been reaped.

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