Ultra-low temperature effect on electron beam welding process

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Abstract. In recent years, electron beam welding has become the most important application technology for space welding and plays an important role in the orbital assembly and repair of spacecraft at home and abroad. In this paper, the combination of simulation calculation and experimental verification is used to design the welding deformation control process scheme and related fixtures for ultra-low temperature environment, and the deformation test verification study of welding/repair is carried out. TC4 welding and repairing weld static strength, the tensile strength reaches 90% of the strength of the base metal, and the micro-hardness is basically the same. It provides reference and reference for the future application of electron beam welding technology in space in China.

1. Introduction
In recent years, space station scientific experiments, space docking assembly, on-orbit maintenance and repair, in-orbit antennas, mechanisms and other manufacturing are inseparable from welding technology, and the development of welding technology suitable for space environment is particularly important. The former Soviet Union, the United States, and Japan conducted a series of studies on electron beam welding methods for space structural materials as early as the early 1960s. The former Soviet Union Barton Institute established a flight laboratory on the "Ty-104" aircraft, conducted a welding test using the aircraft to simulate the weightless environment, and conducted the first space test on the "Union 6" spacecraft; in 1984, the former Soviet Union "sacrificial gun" The space station Salute 7 used the "VHT" electron beam welding system to complete the first human space welding operation [1-3]. It can be seen from the research results of many years abroad that electron beam welding has become the most important application technology for space welding.

The ultra-low temperature environment in space affects the rapid melting/solidification characteristics of metal liquids in the electron beam welding/repair process, which has a great influence on weld formation and quality. At the same time, electron beam welding is a rapid and extremely uneven thermal cycle process, and a large temperature gradient distribution will appear near the weld. Therefore, different degrees of residual stress and deformation will occur in the post-weld structure, which may cause cracks and brittleness. Process defects such as breaks. Therefore, it is very important to master the variation of temperature, stress and deformation during electron beam welding to improve the performance of welded joints.
2. Electron beam welding technology
Electron beam welding (EBW) is carried out by using an electron generated by a cathode in an electron gun to be pulled out under the action of an electric field of high voltage (25 to 300 kV) between the anode and the cathode, and accelerated to a very high speed (0.3 to 0.7 times the speed of light). After the primary or secondary magnetic lens is focused, a dense high-speed electron flow is formed [4-5]. When it hits the joint of the workpiece, its kinetic energy is converted into thermal energy, which causes the material to melt rapidly to achieve the purpose of welding, as shown in figure 1.

![Figure 1. Electron beam welding schematic.](image)

As compared to other welding techniques, electron beam welding has the following advantages:

1. The electron beam welding process is carried out under vacuum, and the space itself is a high vacuum environment, which is very suitable for electron beam welding;
2. Electron beam welding has high energy density, and the weld seam can be melted rapidly for any material;
3. Due to its special welding mechanism, electron beam welding can obtain a large aspect ratio of the weld seam, and the weld seam is deep and narrow, so the welding deformation is small;
4. When welding two parts made of materials with large differences in physical properties, the two materials can be melted at the same time and then rapidly solidified.

3. Temperature field simulation
Based on the finite element professional welding simulation software SYSWELD, the electron beam welding process of TC4 titanium alloy is numerically simulated. By analyzing the variation of temperature, stress and deformation with time in the welding process, the welding structure design is further optimized and the welding process is guided to facilitate the welding process. Take effective measures to control welding deformation and residual stress and improve the performance of welded joints.

3.1. Numerical simulation
Electron beam welding is a process of rapid local heating to high temperatures followed by rapid cooling. As the heat source moves, the temperature of the whole workpiece changes abruptly with time and space. The thermophysical properties of the material also change drastically with temperature,
and there is also latent heat during melting and phase change. Therefore, electron beam welding temperature field analysis is a typical nonlinear transient heat conduction problem.

The governing equation for the three-dimensional nonlinear transient heat conduction problem is:

\[
\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z}\left( \lambda \frac{\partial T}{\partial z} \right) + Q
\]

where \( \rho \) is the density of the material; \( c, \lambda \) is the specific heat capacity and thermal conductivity of the material; \( T \) is the temperature field distribution function; \( t \) is the heat transfer time; \( Q \) is the internal heat source intensity; \( \rho, c, \lambda \) are all a function of temperature, as a function of temperature.

3.2. Temperature field simulation

3.2.1. Material properties. TC4 titanium alloy has a series of advantages such as excellent corrosion resistance, small density, high specific strength, good toughness and weldability, and is widely used in the aerospace industry.

In this paper, the thermal properties of titanium alloy TC4, such as thermal conductivity and specific heat capacity, are mainly from the literature, and some references are lacking in high temperature. The density is assumed to be constant, \( \rho = 4440 kg/m^3 \). TC4 contains titanium (Ti) balance, iron (Fe) \( \leq 0.30 \), carbon (C) \( \leq 0.10 \), nitrogen (N) \( \leq 0.05 \), hydrogen (H) \( \leq 0.015 \), oxygen (O) \( \leq 0.20 \), aluminum (Al) 5.5 ~ 6.8, vanadium (V) 3.5 ~ 4.5 [6].

3.2.2. Heat source model. Mathematical expression:

\[
Q(x, y, z) = Q_0 \exp\left(-\frac{x^2 + y^2}{r_0(z)}\right)
\]

\[
r_0(z) = r_o + \frac{r_- - r_o}{z_o}(z - z_o)
\]

Figure 2. Weld section.  Figure 3. Simulation result.

The conical heat source model [7] not only embodies the attenuation law of energy in the thickness direction, but also better reflects the distribution of energy in the electron interaction layer and the beam keyhole. In the actual welding, the energy first gathers the molten metal on the electron-active layer on the surface of the workpiece, thereby forming a larger molten pool, and forming a "nail" head.
after solidification; and then the energy is gradually attenuated in the beam keyhole to form a large penetration depth. After solidification, the bottom of the "nail" is formed, as shown in figure 2. Figure 3 presents a cross-sectional view of the weld of the TC4 electron beam welding after simulation using the SYSWELD software for heat source calibration.

3.2.3. Calculation results and analysis. Figure 4 depicts a thermal cycle curve calculated by simulation of titanium alloy welding test.

![Temperature field calculation results](image)

(Note: The distance between the points corresponding to curves 1, 2, and 3 is 6, 8, and 12 mm from the centerline of the weld, respectively)

Figure 4. Temperature field calculation results

4. Metal welding and repair solutions

The low temperature environment has great influence on the melting, microstructure and crystal growth of metal materials. For this reason, the melting behavior of TC4 materials in low temperature environment is studied, which provides guarantee for space applications. The damage structure to be repaired is depicted in figure 5.

![Schematic diagram of the damage structure of the test board.](image)

Figure 5. Schematic diagram of the damage structure of the test board.

4.1. Welding process test plan

During the test, in order to quickly study the influence of welding parameters on weld formation, only one parameter (including focus current, welding current, welding speed, scanning frequency, yaw amplitude, etc.) is changed in each welding. Other parameters remain unchanged, and the weld forming process should meet the double-sided forming effect.

Taking into account special requirements of the ultra-low temperature environment, the welding jig is used to pass liquid nitrogen, and the circulating conduction cooling is performed to make the
welding test plate reach the predetermined test temperature. Figure 6 for the welding fixture and assembly diagram. In the welding and additive manufacturing process, preheating and slow cooling process measures should be added to better control material forming. The process measures are mainly realized by high-speed yaw scanning of the electron beam current and integrated control of the focus state.

**Figure 6.** Welding fixture and assembly drawing.

4.2. **Additive and repair test plan**

The substrate material is blanked into a 12 mm thick test plate. Before the repair test, the damage area needs to be prefabricated on the surface of the substrate material according to the damage characteristics of the repair structure.

4.3. **Electron beam welding equipment**

The test electron beam welding equipment of this subject is shown in figure 7. The vacuum chamber of the vacuum electron beam welding machine has a space size of 2.0 m × 1.5 m × 2.0 m, and the vacuum chamber has a vacuum of 10⁻⁴ to 10⁻⁶ torr and a rated voltage of 60 kV.

**Figure 7.** Electron beam welding equipment.

4.4. **Measurement of temperature**

In this test, the thermal cycle curve of some points in the welding process is measured. Since the temperature at the near weld is very fast and the heat affected zone is small during the electron beam welding process, in order to improve the measurement accuracy, a diameter of 0.3 is adopted. The high sensitivity high temperature type B (platinum iridium 30-platinum iridium 6) thermocouple of
mm is used, and the ordinary K type (nickel chrome-nickel silicon) is used away from the weld. The other end of the thermocouple is connected to a visual recorder that responds quickly and records the transient thermal cycle curve, model number KSL-A16R32V0.

5. Welding and repair results at low temperature

5.1. Welding test results
Install the 3mm TC4 test board and the temperature measuring thermocouple. The test board is clamped and fixed by a wrench. The preheating is started when the liquid nitrogen is kept through, and the preheating procedure is: X forward motion preheating, returning to the negative air travel. Table 1 lists the welding process parameters.

| Beam (mA) | Speed (mm/min) | Focusing current (mA) | Scanning frequency (Hz) | X/Y Yaw amplitude (%) | Ambient temperature (℃) | Effect |
|-----------|----------------|-----------------------|-------------------------|-----------------------|-------------------------|--------|
| 30        | 1000           | 1100                  | 100                     | 50%                   | 50%                     | Preheat 3 times, welding double-sided molding |

Table 1. 3mm TC4 low temperature welding process parameters

Figure 8. TC4 welding test.

Test results: As seen in figure 8, the weld is formed on both sides, the weld surface is smooth, and the weld preheating area has no obvious deformation.

5.2. Repair test results
Install a 12mm thick TC4 plate, install a thermocouple, and replace the TC6 special repair wire with φ1.6mm. At the end of the preheating, the metal was repaired. The program consisted of three layers with a layer height of 1.0 mm. The parameters are shown in table 2.

| Number of layers | Beam (mA) | Motion speed (mm/min) | Wire feed speed (m/min) | Focusing current (mA) | Scanning frequency (Hz) | X-direction yaw amplitude (°) | Y-direction yaw amplitude (°) |
|------------------|-----------|-----------------------|------------------------|-----------------------|-------------------------|-------------------------------|-------------------------------|
| 1                | 50        | 300                   | 1300                   | 1100                  | 400                     | 600                           | 600                           |
| 2                | 50        | 300                   | 1500                   | 1100                  | 400                     | 600                           | 600                           |
| 3                | 50        | 300                   | 1600                   | 1100                  | 400                     | 600                           | 600                           |

Table 2. TC4 low temperature repair process parameters

Test results revealed a good forming effect, a smooth surface with metallic luster (figure 9).
5.3. Mechanical test results
Tables 3 to 5 show the results of room temperature stretching, room temperature impact and microhardness testing of TC4 alloy sheet welding and additive repair. The microhardness test was carried out on a microhardness tester with a metallographic sample, the test load was 200g, and the loading time was 15s.

Table 3. Tensile properties of TC4 welded and repaired samples at room temperature.

| Sample          | Stretching at room temperature | Break position |
|-----------------|-------------------------------|----------------|
|                 | R_p02/MPa | R_m/MPa | A/% |                |
| 18IA Base metal | 915       | 1043    | 10  | —               |
| 18IA-1 welding  | 954       | 1086    | 13.5| Base metal     |
| 18IA2 Base metal| 1015      | 1090    | 13.5| Weld           |
| 18IA-2 repair   | 843       | 923     | 11.5| —               |
|                 | 796       | 899     | 7.5 | Base metal     |

Table 4. TC4 repair parts room temperature impact performance.

| Sample   | Room temperature shock |
|----------|------------------------|
|          | A_r/2, J | a_r/2, J/cm² |
| 18IA2 Base metal | 81        | 101.3       |
| 18IA-2 repair    | 83        | 103.8       |
| 18IA-2 repair    | 86        | 107.5       |
Table 5. Microhardness of TC4 repair area.

| Position | Microhardness | Position | Microhardness | Position | Microhardness |
|----------|---------------|----------|---------------|----------|---------------|
| 0        | 271           | Base     | 5             | 285      | Heat          |
| 1        | 288           | metal    | 6             | 282      | affected      |
| 2        | 292           |          | 7             | 285      | zone          |
| 3        | 304           |          | 8             | 262      |               |
| 4        | 292           |          | 9             | 288      |               |

It can be seen that the tensile strength of the electron beam welding and repairing samples at ultra-low temperature and the basic strength of the base metal meet the technical requirements of the static strength of the TC4 welded joint reaching 90% of the strength of the base metal. The impact performance of the repaired test piece is affected by the process. After adjusting the optimized parameters, the impact performance of the repaired test piece reaches 90% of the base metal. After heat treatment, the micro-hardness of the weld zone, heat affected zone and base metal zone are basically the same.

6. Conclusion
In this study, a comprehensive combination of simulation calculation and experimental verification is adopted. By analyzing the temperature and stress field distributions in structural welding, the welding deformation control process scheme and related fixtures suitable for space environment are designed. The welding is carried out under the ground simulated ultra-low temperature environment.

The results show that the electron beam welding and repair process of titanium alloy in ultra-low temperature is feasible, and a well-formed weld and repair structure can be obtained. The tensile strength and impact performance of the welded and repaired samples reach 90% of the base metal. After that, the microhardness of the weld zone, the heat affected zone and the base metal zone are basically equal; the output power of the electron beam is less than 3 kW. A key technical reserve for the development of light and small electron beam welding systems for future space-orbit maintenance and space stations.

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