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Study on Precise Welding of Space-borne Heater Based on Flexible Filling Compensation

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Abstract. In order to solve the problem that the welding joint of the heating band wire is easily broken under stress, a method base on flexible and precise welding is presented in this paper. First, the traditional space-borne pipeline heating welding process and the existing problems are introduced. Then the principle of micro-environmental flexible filling compensation technology of solder joints is studied in detail, and the whole process of precise welding of pipeline heating band is described. Finally, through the verification experiment, it is proved that the method proposed in this paper has higher reliability and the average breaking force can be increased to 17N, meeting the requirement of batch production and assembly.

1. Introductions
Due to the stringent requirements of the pipeline layout on a spacecraft propulsion system, the assembly of the pipeline heater cannot be routinely guided by the electronic welding process of heating wire. In some spacecraft, lap welding method is adopted as conventional method, but this method brings about technical bottlenecks such as unstable quality, low operational consistency and easy-to-break characteristics [1].

In order to ensure the quality of welding joint, so as to ensure the reliability of the spacecraft on orbit, it is necessary to do special research, aiming to improve the performance of the heater solder joint under stress.

2. Traditional welding method for heating

2.1. Traditional welding process
In the process of spacecraft heating band welding, inconveniently always has been a factor for the inconsistency in welding quality. The heating wires usually have a diameter range of $\Phi 0.1\text{mm} \sim \Phi 0.3\text{mm}$, making it impossible to implement pressure welding methods. So lap welding by tin is the only practical method for welding. Considering the traditional lap welding technology is comparably less reliable [2] than other welding methods, it is critical that new technology is used to enhance the quality of lap welding.

The traditional process for lap welding is shown in figure 1.
Main points for implementing the traditional method are as follows.

The heaters for spacecraft pipeline shape like a band. Its heating wire is tinned copper-nickel alloy. This type of alloy cannot be treated with high temperature wire stripper (different with the extended wire). Oxide layer outside the surface has to be removed by abrasive paper.

Pyro condensation coat shrinks when heated. This type of coat is always used double-layered to protect the solder joint as well as providing an oxygen-free environment. Specification for each layer is $\phi 2.0\text{mm} / \phi 1.0\text{mm}$, $\phi 1.6\text{mm} / \phi 0.8\text{mm}$, according to the diameter of the heater wire and extended wire.

Scaling powder is specified as Alpha R. Tinning time must be less than 3s $[^3]$, with the surface smooth and threads in wire aligned evenly. Tin spread into every single thread of the wire.

Heat shrinkable coat cover the very center of the soldering joint.

2.2. Disadvantages for the technology

The specification of the extended wire is different from that of the heat band wire. The former is about six time larger than the latter in diameter, which will inevitably lead to sharp change at the combination of cross section. Shock or vibration put on the point will amplify the stress when it transmitting from the thick end to the thin end. In practice and production, most examples of heating band wire breaking is the case.

In general, there are 3 major disadvantages for the traditional technology.

a. Weak joint cause frequent breaking.

b. Operation parameters is hard to control.

c. Quality inconsistency $[^4]$.

3. Solution of precise welding based on flexible filling compensation

Micro-environment is solder joint and all the complexity around its boundary. For our new technology in lap welding, its micro-environment consists of primary wire (namely extended wire), secondary wire (wire of the heater), tinning segment, stress release segment, wire coat, solder joint reinforcement, side move preventer, silicon rubber reinforcement and so on. Each part is shown in figure 2.

![Figure 2. Micro-environment of soldering joint for flexible filling method](image-url)
Flexible filling method for lap welding is proposed to solve the problem. The method focuses on damping the possible shock or vibration that the welding point may suffer [5]. The method is easy to practice, material is safe and validated, and was field tested to be effective in spacecraft heater welding.

The flexible filling method process for lap welding is shown in figure 3.

![Flexible filling process flow for lap welding](image)

Figure 3. Flexible filling process flow for lap welding

Figure 4 presents the key process for welding heater band with new technology.

![Key process for welding heater band with new technology](image)

Figure 4. Key process for welding heater band with new technology

Main points for implementing the method are as follows.

a. Laying the bottom end of the flexible membrane.

The flexible membrane used in our product is 3M Company’s polyimide based pressure-sensitive tape (92# standard). This type of polyimide tape is coated with acrylic adhesive, which can be used repeatedly without becoming less adhesive. And it can endure a temperature range up to (-150°C, 200°C), CVCM volatilization can also meet the environment requirements of spacecraft.

The flexible film needs to be cleaned in advance and cut in accordance with the standardized size, as rectangle or trapezoid near the heater band. The width of the film should at least cover the wire coating and the polyimide base of the heater.
b. Laying the inner side of the solder point with flexible tape.
When completed laying the bottom flexible tape, another membrane should be stick to the same side – between the bottom membrane and the heater band – on the surface of solder joint to the heater’s joint.
Flexible membrane wrapping for the single lap welding wire can use finger compress, finger pinch should always be clean. The purpose for this step is to make the heater including the soldering joint and stress release segment compact, by stuffing the interstice between the heater and upcoming heat shrinkable coat.

c. Laying the outer side of the solder point with flexible tape.
With the same length of inner side flexible filling, another membrane should be stick to the opposite side to the inner side of the solder point. Instruction should be same as that of the inner one.

d. Heat the pyro condensation coat to make it shrink and contract.
Main point for the step is: Move the pre-shrink coat from aside to cover the soldering joint area. And the centre of the coat should be biased towards the end of the heating band. When heating, the blow dryer moves cycle wise to ensure heating the pyro condensation material uniformly. The polyimide base of the heater will naturally curl at the circular contraction of the coat, which is to be expected and will enhance the anti-vibration capacity.

e. Laying the top flexible tape.
3M tape is used as reinforcement. It shall be tailored to the exact shape of the shrink coat, and it shall stick to the bottom flexible tape.

f. Wire and band reinforcement.
Shrink coat and its reinforcement provide a sideward constraint for the solder point, leaving the axial constraint to be fixed. Silicon rubber is excellent in flexible fixing. GD414 is the specification used in spacecraft heating band fixing, for its additional advantage in CVCM controlling.

4. Welding quality experiment
In order to validate the new flexible filling technology for wires in heating band, an experiment is designed to examine the breaking limits for the soldering joints in the rigour condition. The tension measuring device is specialized MPT250B tension meter, with the precision of ±0.1N.

4.1. Experiment preparation
The experiment can be divided into three phases, the first stage completed the construction and test conditions and test piece preparation. The second stage get the record for break and surrender force base on the completed samples. In the third phase, data analysis and process verification is made and conclusion is get.

The experiment process is shown in figure 5. And the specific content of the experiment is shown in table 1.
4.2. Experiment outcome and data analysis

Description for the experiment:

a. Each group has 2 samples, with 4 solder joints in each sample.

b. Specification for heat shrinkable sleeve: The outer layer φ2.0mm/φ1.0mm, the inner layer φ1.6mm/φ0.8mm.

c. Temperature parameter is set to 300°C. For comparison we also set groups of lower or higher solder temperature.

d. Tension meter is special MPT250B model. The record is made by arithmetic average value.

e. In the experiment the sample solder joint usually surrender before it finally breaks, except containing some welding faults.

In order to fully validate and explain the reliability and stability of the new welding technology, the final drawing force data of each samples are compared and analysed, as shown in table 1.

Table 1. Welding parameters and experiment data

| Group | Welding parameter | Welding joint condition | Micro-environment | Tension load |
|-------|-------------------|------------------------|-------------------|-------------|
|       | T (°C) | Lap length mm | Tin-free gap (mm) | Soakage | welding time (s) | Flexible filling | Casing length (mm) | Casing Position | Breaking (N) | Surrender (N) |
| P0    | 350    | 9          | 0.5~1          | Good    | <3           | None           | 25               | Center        | 7           | -           |
| P1    | 260    | 9          | 0.5~1          | mediocre | >3          | 3M             | 25               | Center        | 6.5         | Wire break  |
| P2    | 300    | 8          | 2~3            | Good    | 1~3         | 3M             | 25               | Center        | 8.5         | Wire break  |
| P3    | 300    | 8          | 2~3            | Good    | 1~3         | 3M             | 30               | Center        | 9.5         | 6           |
| P4    | 300    | 5~6        | 0.5~1          | Good    | 1~3         | 3M             | 25               | Center        | 8           | 4           |
| P5    | 300    | 8          | 2~3            | mediocre | 1~3        | None           | 22               | Center        | 7           | 5.5         |
| P6    | 300    | 5~6        | 0.5~1          | Good    | 1~3         | None           | 25               | Near heating band | 8           | -           |
| P7    | 300    | 9          | 0.5~1          | Good    | 1~3         | None           | 25               | Near heating band | 10          | 6.5         |
| P8    | 300    | 5~6        | 0.5~1          | Good    | 1~3         | None           | 25               | Near heating band | 8           | 4           |
| P9    | 300    | 5~6        | 1              | Good    | 1~3         | 3M             | 25               | Near heating band | 17          | -           |
| P10   | 300    | 9          | 1              | Good    | 1~3         | 3M             | 25               | Near heating band | 6           | -           |

From the experiment data, the following conclusions can be convinced.

a. First, the best welding temperature is 300°C. In 260°C case, tinning process for heating wire and extended wire will be too long. In 350°C case, although the tinning process is short enough, the lapping base material is at the risk of mechanical property lower because of high temperature erosion. The welding interval must be over 1 second and less than 3 seconds at this temperature.

b. The lapping length for the welding joint should be at the range of 5mm~6mm. And it is important that the former end is cut off at least 3mm. This parameter is validated by experiments and for the best of tin spreading among the threads of the wire.

c. When tinning, the heating wire and the extended wire should leave 1mm clean at the root side, for stress release purpose. Otherwise the wire is apt to break if insulating layer contact the welding tin. On the other hand, if the tin-free length is more than 1mm, the welding joints’ overlapping length is too short to endure a moderate tension. Furthermore, 1mm tin-free is a appropriate gap for the cantilever span to absorb vibrating load, considering the hardening effect of wire tinning.

d. Flexible filling should be applied between solder joints and vibration resistant stuff. When double heat shrinkable sleeves were applied only, there is little protection for heater wire. Whereas the flexible filling at the solder joint is applied, capacity of tension is significantly enhanced. This may result from
the impact load damping or absorbing effect provided by flexible 3M tape and the shrink heat sleeves outside.

c. The heat shrinkable sleeve should protect the heating band end, and length should be around 25mm. From the table 2 comparison, the break tension is improved obviously when the heat shrinkable casing shrink at the heating band end.

5. Summary

The new welding technology based on flexible filling compensation can improve the micro-environment of solder joints and improve mechanical endurance remarkably. By researching this technology, we get the following conclusions.

a. Preliminary discussion and research is made on the micro-environment of solder point flexible filling technique, that only the maximum compensation of the gap between the wire’s outer surface and the inner side of the anti-vibration reinforcement is achieved, it can produce significant damping to external impact load, thereby inhibiting the stress concentration of overlapping welding wire.

b. The research also believes that in the flexible compensation method, the sticking effectiveness of flexible film will affect the tensile strength of solder joints. So the method must be carried out accurately to ensure reliability.

c. Experimental validation showed that the proposed method can compensate the stress concentration and elevate the breaking force up to 17N, which is notably excelling the previous 8N or so.

d. The technology is overall high in quality consistency and is suitable for batch production.

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