

Development of X-in-1 TIG Welding Equipment for High-Quality and High-Productivity Welding

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Abstract

This report describes the development of a tungsten inert gas (TIG) welding system suitable for joining busbar and stator terminals of the new electric drive unit "X-in-1." TIG welding is used because of its superior welding quality and cost performance compared to conventional laser welding. The report describes how the welding system successfully enabled mass-production by achieving both welding quality and productivity. This was achieved by using a simultaneous clamping jig and a position correction system with a three-dimensional (3D) camera to address the variation issues in the position of busbar terminals and stator terminals as well as in the quality and productivity issues associated with welding at 24 locations.

1. Introduction

X-in-1 is a new type of electric drive unit that integrates a motor, a generator, an inverter, and a variable-speed gear within a compact package. The stator coils of the motor and generator are made of flat copper wire (hereinafter referred to as "flat wire") instead of conventional round copper wire. The current is controlled by the inverter and is supplied to the stator coils of the motor and generator through the busbars. The contacts between the busbars and the coils are welded together using copper terminals.

The busbars used in X-in-1 are rigidly molded with resin to guarantee insulation in a compact layout and to ensure durability against driving vibration. The busbars are bolted to the housing near the output terminal of the stator so that the welding terminal is firmly fixed in place.

However, stator terminals, which are the paired welded part, are made with copper wire bent into a three-dimensional (3D) form. This makes it difficult to maintain the position of tip of the welded parts with high precision.

In order to accurately weld a small area of approximately 3 mm square, a new welding equipment was developed by aligning busbar terminals, which are fixed to a rigid body, with stator terminals that are prone to elastic deformation.

This report describes the development of a tungsten inert gas (TIG) welding system that addresses this issue and achieves high target values both in terms of weld quality and productivity.

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2. Themes and issues

The overall view of the X-in-1 busbar and stator prior to welding is shown in Fig. 1a). A magnified view of the terminals at the welding point is shown in Fig. 1b).

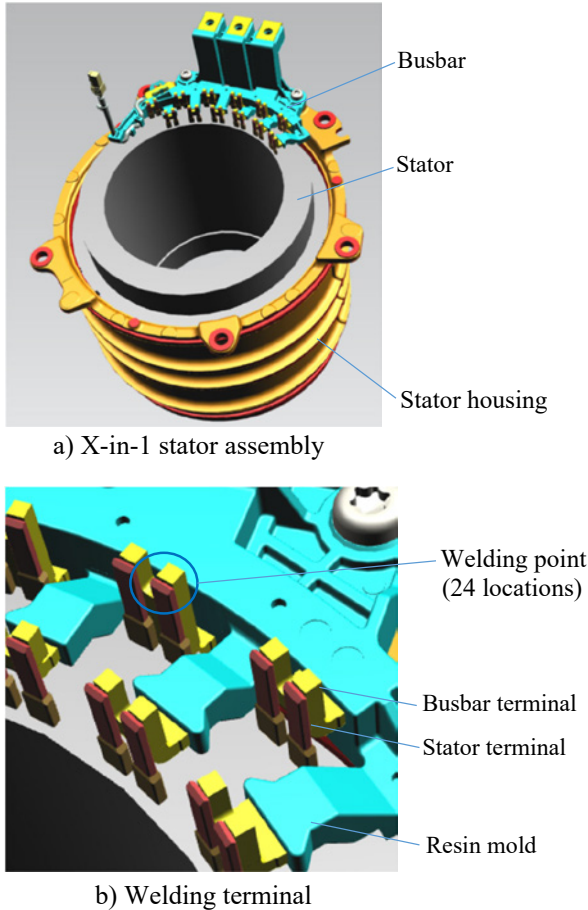


Fig. 1 CAD drawing of X-in-1 stator

There are two welding methods for motor flat wire, namely conventional laser welding and TIG welding. Laser welding is commonly used in Europe and the United States, whilst TIG welding is common in Japan. TIG welding has an advantage in terms of quality and cost, but laser welding has an advantage in terms of welding speed. (Table 1)

Table 1 Comparison of welding methods

	Laser welding	TIG welding
Quality (Q)	× Spatter is generated	○ No spatter
Cost (C)	× Welding machines are expensive	○ Welding machines are inexpensive
Time (T)	○ High welding speed	× Slow welding speed

Laser welding uses a high-energy laser beam to melt the base metal to weld, but sudden changes in temperature tend to cause violent convection and vaporization of the molten metal, resulting in the risk of spatter. In the case of TIG welding, as shown in Fig. 2, the entire welding point is heated by an umbrella-shaped arc from the tip of the tungsten electrode, which causes gradual liquefaction of the molten part and suppresses spatter generation.

Considering the importance of welding quality, this study used TIG welding to develop a busbar welding method because it eliminates the concern about spatter generation.

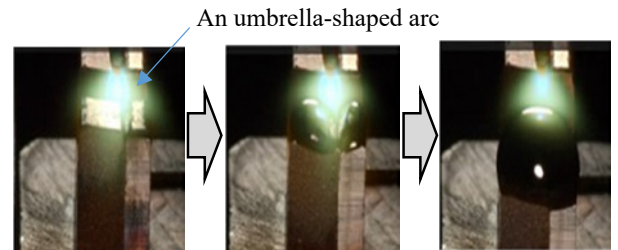


Fig. 2 Progression of TIG welding

3. Specification issues of X-in-1 TIG welding equipment

This section explains the three issues that need to be addressed in the development of X-in-1 TIG welding equipment.

3.1 TIG welding speed issues

When flat wires are joined using the conventional TIG welding method, the welding operation takes several times longer than using laser welding because the welding machine has to move at each welding point. Fig. 3 illustrates the movement of the welding machine.

- [1] Clamp: A terminal clamp that is integrated with the torch grips the terminal to be welded and positions it while maintaining close contact with it.
- [2] Touch: The welding torch makes contact with the weld and then moves up to the height at which the arc can be generated. Although the welding terminals have height variations, this movement ensures that the electrode is always at the optimum height.
- [3] Weld: The electrode (welding torch) at the appropriate height carries out welding.
- [4] Move: After welding, the torch and clamp move to the next weld point, releasing their grip on the terminal and avoiding the already-welded area.

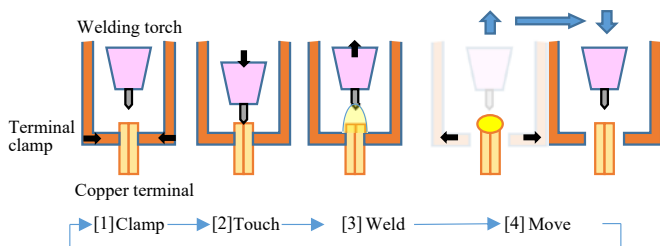


Fig. 3 Conventional TIG welding process

3.2 Geometry issues specific to X-in-1 components

As mentioned above, X-in-1 was designed such that the busbar components can carry electric current while set in a compact layout. As a result, the following issues related to mass production became apparent.

- [1] There are 24 welding locations, which is about four times as many as other companies' components. Therefore, the production time was prolonged and the risk of weld defects increased.
- [2] The busbar is molded with a resin and bolted to the housing, making it rigid.
- [3] Because the stator coil terminals are made by 3D bending of copper wire, the positional precision of the terminal tip varies greatly, and misalignment with fixed busbar terminals is likely to occur.
- [4] The X-in-1 motor and generator have different stator specifications for a total of five models, resulting in setup losses.

3.3 Weld quality issues

There are two main quality requirements post TIG welding. They are:

- [1] To ensure that the welded parts have sufficient tensile breaking strength
- [2] To prevent blistering on the enameled part of the flat-wire insulation (Fig. 4).

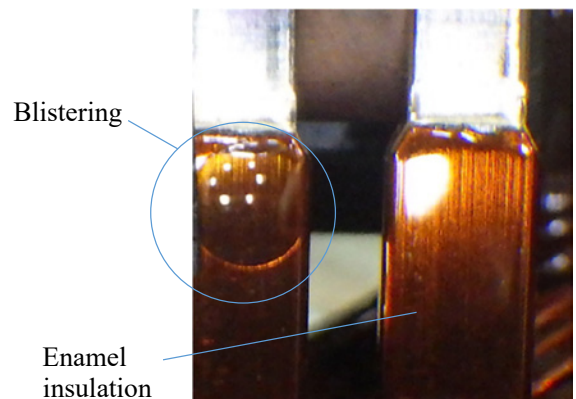


Fig. 4 Blistering

To guarantee an adequate breaking strength, the welded points should be strengthened by applying a large amount of energy during welding. In contrast, to suppress blistering, input heat energy must be suppressed to minimize the thermal effects on the enameled part. It is essential to balance welding conditions that satisfy these two opposing conditions.

4. Determination of welding equipment specifications

4.1 Specifications for high productivity

As described in 3.1, repeating the terminal clamping operation for each contact point does not achieve a production speed comparable to laser welding. Terminal clamping has the following three purposes and is required for flat wire welding.

<Purpose of terminal clamp>

- (1) Alignment: To align the busbar terminals with the stator terminals and tightly attach them together.
- (2) Supply of electric current: To cause contacts to the terminals to be welded so that a welding-current circuit is formed.
- (3) Heat removal: To absorb weld heat before it reaches the enameled part and suppresses blistering.

In order to ensure reliable terminal clamping and minimize the machine operation time for clamping, a jig that simultaneously clamps all welding points (24 locations) (hereinafter referred to as the “clamping jig”) was developed and used. In addition, the operation time for terminal clamping can be reduced significantly by placing the clamping jig outside the TIG welding machine so that it can be assembled and disassembled outside the welding machine.

Fig. 5 shows a diagram of the clamping jig developed in this study. The jaws that clamp the terminals are arranged radially on a disk-shaped base plate, and a spring is used to provide a clamping force to slide each jaw individually. (A patent application for this technology has been filed with the Japan Patent Office.)⁽¹⁾

Furthermore, the clamping jig was designed according to the shape of each stator model and was stocked upstream of the welding machine, which enabled the random continuous production of five workpiece models.

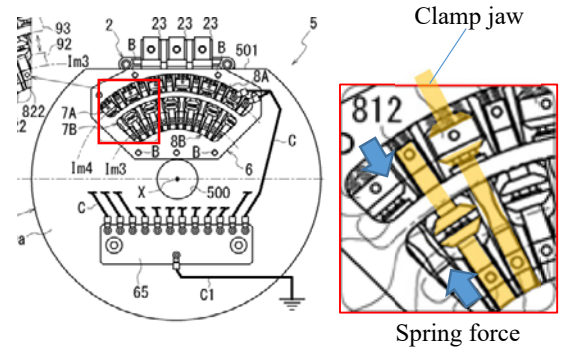


Fig. 5 All terminal simultaneous clamping jig

In addition, the operation step [2] Touch in Fig. 3 was eliminated to shorten the welding time. The role of the operation step is to maintain a constant height and distance between the welding terminal and the welding electrode. To guarantee this distance, a 3D camera was placed inside the welding machine. The camera takes pictures of the terminal position before welding, the terminal height is calculated, and the calculated value is fed back to the electrode height during welding.

As a result of using the above countermeasure, the torch is moved as shown in Fig. 6 during welding, which eliminated the time loss.

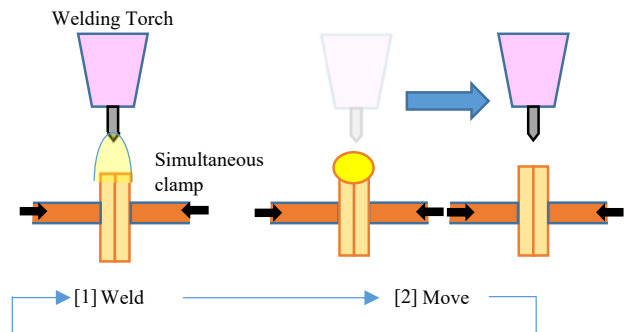


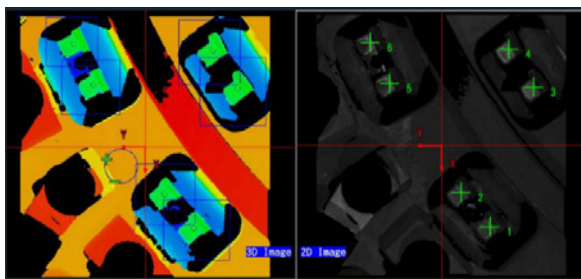
Fig. 6 Newly proposed terminal clamp

4.2 Specification for high quality

In the present busbar welding, all 24 terminals are welded to complete a single product. As described in 3.3, the precision of welding positions is important to enable a balance between weld strength and blister suppression. However, the position of the terminals in the component is determined by the position of the busbar, which is a rigid component. Hence, it is necessary to fine-tune the coordinates of the welding position for each component and each welding point.

To guarantee the optimal welding position for each component, the 3D camera mentioned in 4.1 was utilized. The system feeds back the detected terminal location to the welding position in terms of not only height but also X–Y coordinates.

The camera captures images as shown in Fig. 7. The 3D data image in Fig. 7a) is used to determine the shape and position of the terminal in the two-dimensional (2D) image, and the optimum welding point is then calculated and specified, as shown in Fig. 7b). The color in Fig. 7a) represents the height of the object; thus, the system was designed to also guarantee the appropriate welding height.



a) 3D image b) Welding position setting

Fig. 7 3D camera data

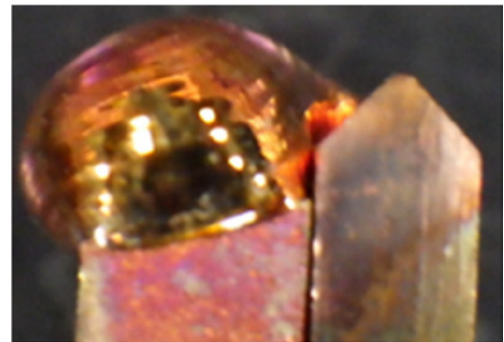
5. Status of the application for mass production

5.1 Pre-mass production issues and countermeasures

The trial production at this equipment found that the terminals were melted, the molten balls were unevenly distributed, and no bonding occurred between the terminals, as shown in Fig. 8.



a) Upper view



b) Side view

Fig. 8 Welding defect

This phenomenon, which is called “two-balls,” was observed and analyzed using a high-speed camera to detect the behavior of molten copper during welding. It was found to be caused by an imbalance in the magnetic field generated by the welding current, which attracts molten copper in a specific direction owing to the difference in electromagnetic force. Based on this, a control measure was designed so that the current flows evenly in the clamp. As a result, the two-ball phenomenon was suppressed.

5.2 Applications for mass production

After addressing the productivity and quality issues, the equipment was launched and mass production commenced in FY2025 (Fig. 9). The equipment met the target welding-speed, and the productivity was shown to be comparable to that of laser welding (Table 2).

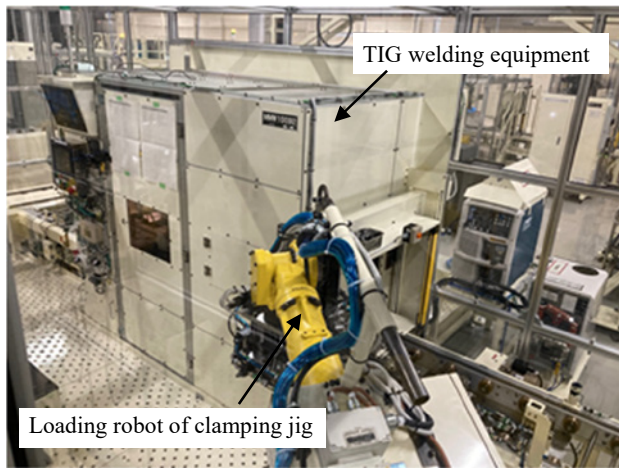


Fig. 9 TIG welding machine

Table 2 Comparison with JATCO welding method

	Laser welding	TIG welding
Quality (Q)	× Spatter is generated	○ No spatter
Cost (C)	× Welding machines are expensive	○ Welding machines are inexpensive (approx. 1/5)
Time (T)	○ High welding speed	○ Production cycle time is the same as for laser welding

6. Summary

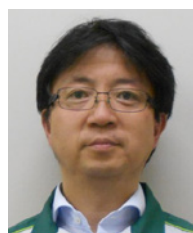
The TIG welding equipment is currently used for mass production. Although some problems have occurred, we have solved all of them. In solving these problems, we realized the importance of analyzing phenomena in accordance with fundamental principles, such as the basic laws of electric circuits, analysis of heat transfer around welding points, and the structure and deterioration analysis of clamping fixtures.

It is expected that welding and joining methods will be further expanded for electrified units in the future. We will use the experience gained from this project to contribute to the future of electrified units.

7. References

- (1) Kiyoto Tamura, Daisuke Hitokoto, Tatsuya Ishikawa, Masashi Kajita: A clamp jig, Patent Application 2024-038513, 2024.

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