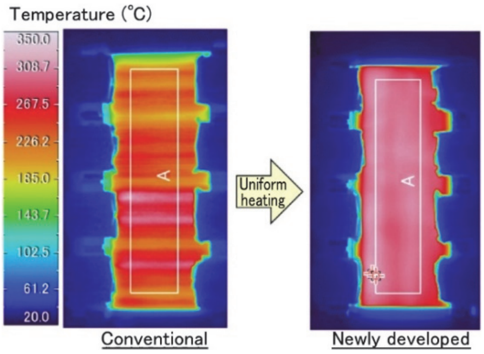
Efficient Joining Technology for Thermoplastic Composites Using Resistance Welding Method



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Toward achieving carbon neutrality, Mitsubishi Heavy Industries, Ltd. is working on the reduction of aircraft weight to improve fuel efficiency, thereby causing less environmental impact. One of the options for reducing the aircraft weight and the assembly time is the fusion bonding of thermoplastic composites. Of the bonding methods, resistance welding in which heating takes place only at the joining interface is addressed in this report, together with a summary of the newly developed process for ensuring weld quality.

1. Introduction

Having declared its commitment to achieve carbon neutrality by 2040 (MISSION NET ZERO), Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) aims to lower the environmental impact of aircraft by reducing its weight and improving the aerodynamic characteristics for less fuel consumption.

According to the project being undertaken mainly by civil aircraft manufacturers in Europe and North America, one of the research and development goals is to increase monthly aircraft production from the current ≈10 to 60-100 around 2035. This project also aims to enable fusion bonding of thermoplastic composites to replace the conventional bolted jointing and adhesive bonding. If realized, this will enable not only aircraft weight reduction but also substantial shortening of the cycle time, elevating the production rate. Research and development in this regard is therefore active worldwide, including MHI.

2. Resistance welding

2.1 Fusion bonding techniques

There are various types of fusion bonding techniques, such as hot press welding, vibration or ultrasonic welding, resistance welding, induction welding and laser welding. **Table 1** summarizes the major types, of which hot press welding allows the parent materials (hereinafter referred to as workpieces) to be heated externally using metal dies, etc., and the temperature therein is increased to a level high enough to melt/fuse the matrix in the workpieces. All the other types involve local heating of the joining interface. In vibration/ultrasonic welding, vibrations or ultrasonic waves are propagated to generate heat (i.e., frictional and viscoelastic) at the joining interface, thereby heating/fusing the workpieces together. For resistance welding, a conductive film called the heating element is sandwiched between the workpieces at their joining interface. An electric current is passed through to generate Joule heating at the interface (1), (2). In the case of induction welding, a conductive film called the susceptor is sandwiched. Heating due to eddy current loss is used to heat the joining interface. Laser welding allows a laser beam passing through one of the two workpieces to heat the joining interface.

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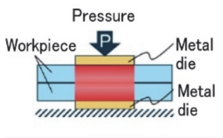
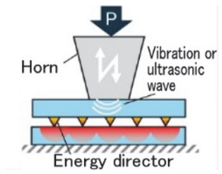
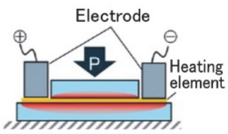
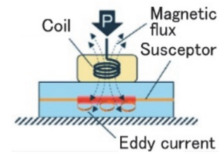
Of these fusion bonding techniques, this report focuses on resistance welding, which can locally heat the joining interface and is applicable to a very small area.

Table 1 Types of fusion bonding

Type of fusion bonding	Hot Press Welding	Ultrasonic Welding	Self-Resistance Welding	Induction Welding
Outline	The external metal dies, etc., are heated, from which heat is conducted through the parent materials in contact to their joining interface. The temperature therein is raised to a level high enough to melt/fuse the matrix.	Vibrations or ultrasonic waves are propagated to generate heat (i.e., frictional and viscoelastic) between the workpieces and the energy director or butt at the joining interface. The resulting heating in the interface enables fusion.	A conductive film called the heating element is sandwiched between the workpieces at their joining interface. An electric current is passed through the heating element to generate Joule heat, which then heats the interface, enabling fusion.	The workpieces are placed on either side of a conductive film called the susceptor. The magnetic flux from the coil causes eddy current loss to occur in the susceptor. The resulting heating of the susceptor then heats the joining interface, enabling fusion.
Schematic diagram				

2.2 Resistance welding

Maintaining stable quality in resistance welding involves keeping the temperature of the heating element within an appropriate range according to the materials constituting the workpieces, while avoiding overheating or underheating of the heating element and workpieces. It is therefore important to keep the temperature distribution range in the heating element to a minimum. In this report, heating elements with different types of materials were used to examine the temperature distribution during heat generation by each heating element and their weld strengths, and to determine the type of heating element that can produce stable weld quality.

3. Heating test to evaluate heating element performance

3.1 Heating element

The following five types of heating elements were used for evaluation.

(1) Unidirectional prepreg
(2) 0/90° woven carbon fiber fabric
(3) 0/90° woven carbon fiber fabric, impregnated with matrix
(4) Carbon-based nonwoven fabric
(5) Carbon-based nonwoven fabric, impregnated with matrix

Heating element (1), a unidirectional prepreg, is a sheet of unidirectionally aligned matrix-impregnated carbon fiber, and is one of the materials conventionally in use as a heating element [(2)]. The 0/90° woven carbon fiber fabric is made of continuous fibers that are woven bidirectionally (i.e., in two orthogonal directions). With regard to heating elements (3) and (5), hot-pressing was used to impregnate the same thermoplastic matrix as the workpieces into heating elements (2) and (4), respectively. The thermoplastic material is a high-heat-resistant matrix called PAEK, with the melting temperature (Tm) of 305°C.

3.2 Heating test

The temperature distribution in each heating element is examined by the heating test. A schematic diagram of the test setup and its exterior view are given in **Figure 1**. The heating element is held on both edges by being sandwiched with an insulator and an electrode, both of which are then fixed with clamps. In the heating test, an electric current is passed between the electrodes through the heating element, causing it to generate Joule heat. The electric current is controlled in such a way that the rise and fall rates of the maximum temperature are kept constant for all the heating elements. The surface temperature of the heating element is measured from above using a thermo-viewer. The emissivity of the thermo-viewer is adjusted based on the temperature measured separately by a thermocouple attached to the surface of the heating element.

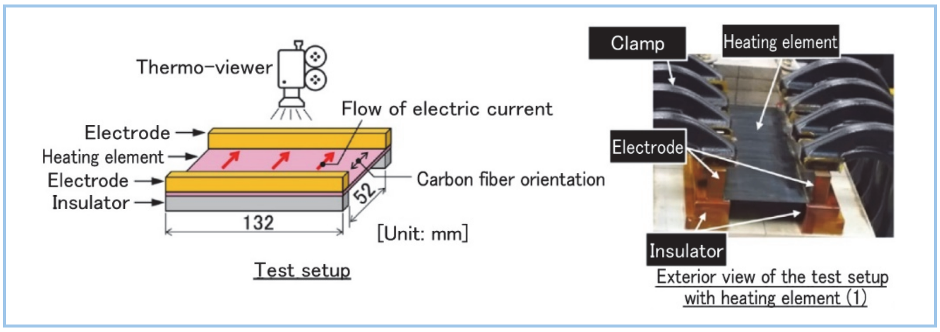


Figure 1 Heating test

3.3 Heating test results

The image in **Figure 2** (left) shows the temperature distribution obtained by the thermo-viewer during the heating test with the heating element (1) (i.e., unidirectional prepreg). Both the electric current flow and the carbon fiber orientation are in the vertical direction in the figure. There is almost no color change, when looking in the up/down directions. However, different colors appear in the right/left directions. This indicates that the temperature distribution range is small in the fiber orientation, whereas that in the direction perpendicular to it is large. The graph in Figure 2 (right) shows how the surface temperature changed over time during the heating test with heating element (1). The Tmax and Tmin values are the thermo-viewer's maximum and minimum temperatures observed in the area outlined by the white line in Figure 2 (left), respectively. Figure 2 (right) also shows the electric current required to heat the heating element.

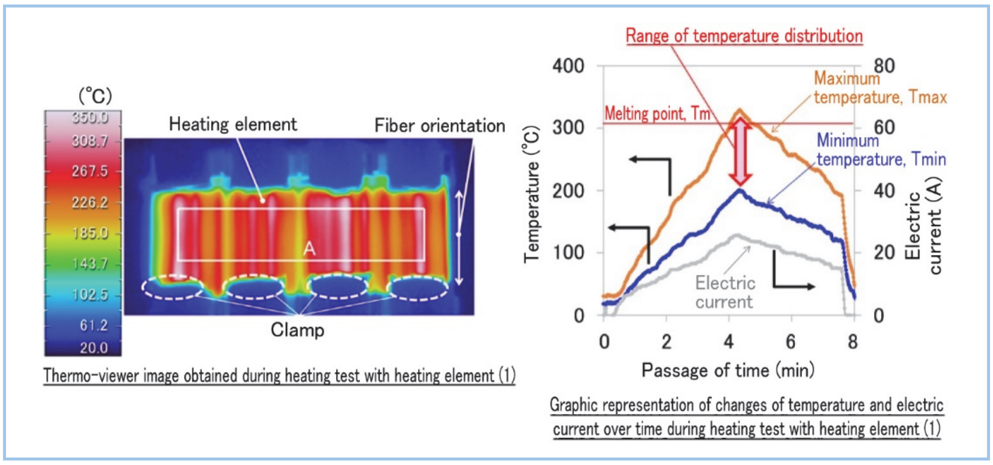
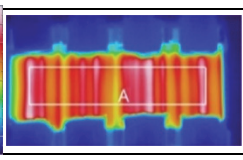
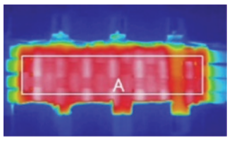
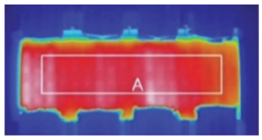
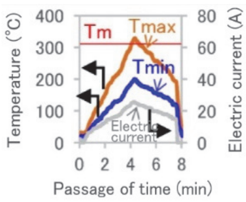
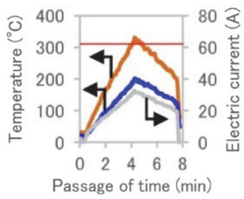
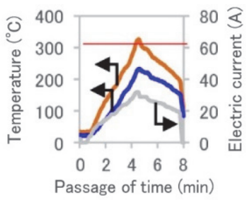
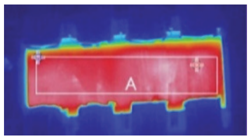
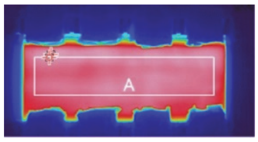
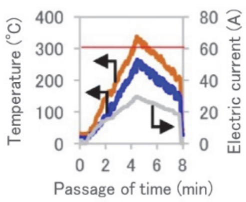
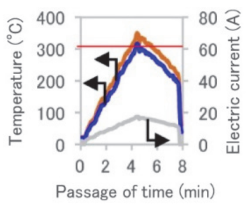


Figure 2 Results of heating test with heating element (1)

Table 2 gives the results of the heating test with five types of heating elements. When compared with heating elements (1) to (4), heating element (5) showed a significantly smaller difference between Tmax and Tmin, i.e., a smaller temperature distribution range on the heating element surface. To ensure complete fusion over the entire welded area, Tmin has to reach at least a certain temperature level. Tmax will become higher than necessary if the temperature distribution range is large, leading to thermal degradation of workpieces. Therefore, having a small temperature distribution range means that the welding temperature can be kept within an appropriate range for workpieces. The test results shown in Table 2 were obtained from one test sample of each heating element. For heating element (5), another four test samples underwent the heating test, all producing the results with small variations in the range of temperature distribution (a maximum of ≈10°C). As indicated by Table 2, the maximum electric current of heating element (5) is also lower than the other heating elements, consuming less power. In this test, the rise and fall rates of the maximum temperature were kept the same among all the heating elements for comparison purposes. Having a good thermal response, heating element (5) makes it possible to further accelerate the temperature rise/fall rate. The consequent shorter welding time leads to the shortening of the cycle time.

Table 2 Heating test results for all types of heating elements

No.		(1)	(2)	(3)
Heating element	Type	Unidirectional prepreg	0/90° woven carbon fiber fabric	0/90° woven carbon fiber fabric, impregnated with matrix
Heating test results	Thermo-viewer image 			
	Temperature and electric current			

No.		(4)	(5)
Heating element	Type	Carbon-based nonwoven fabric	Carbon-based nonwoven fabric, impregnated with matrix
Heating test results	Thermo-viewer image		
	Temperature and electric current		

4. Weld quality verification

4.1 Welding test

In the welding test, the workpieces, which are placed in contact on either side of the heating element, are heated by the Joule heat generated as a result of the electric current flowing between the electrodes through the heating element. This causes the matrix to melt and fuse. **Figure 3** shows the welding test setup and the thermo-viewer's image during welding using the heating element (5), together with the graphic representation of the changes of maximum temperature and electric current over time during the welding test. In the welding test, the electric current was controlled in such a way that the rise and fall rates of the maximum temperature were the same as the heating test.

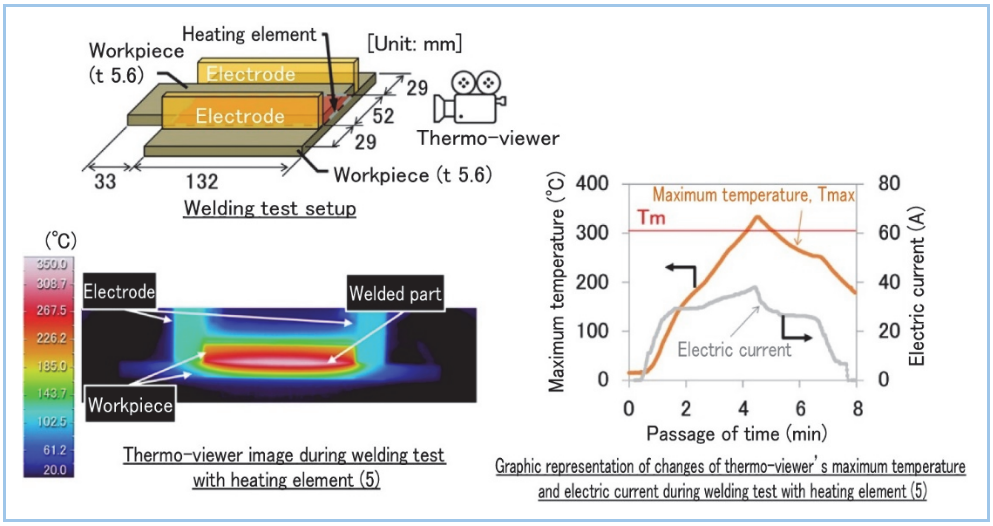


Figure 3 Welding test and test results

4.2 Weld strength test

The weld quality is assessed by conducting the slotted single-lap shear (SSLS) strength test. The dimensions of the test specimen are given in **Figure 4** (left), and the test results in Figure 4 (right). In the strength test, the ASTM D5868 test standard was referred to; tensile force was loaded lengthwise without out-of-plane deformation constraints. Two test specimens were prepared by cutting out from the welded workpieces in the welding test. The error bar in Figure 4 (right) represents the maximum and minimum strength of these two specimens. The SSLS strength of the welded workpieces with heating element (5) was 41 MPa, which is comparable to those with heating element (1). A fracture occurred in both the welded workpieces because of cohesive failure in the welded part.

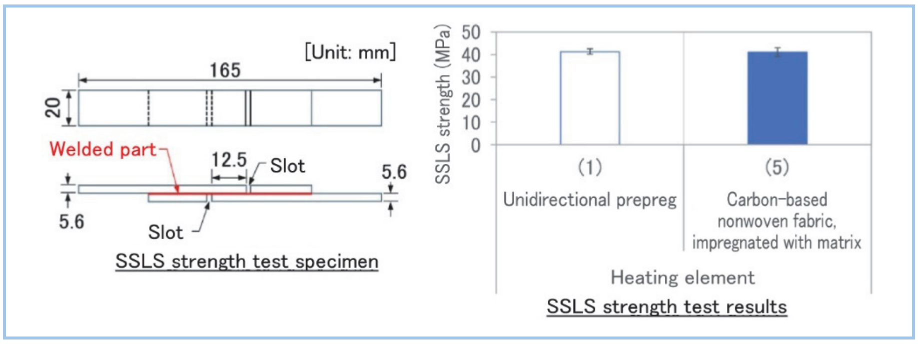


Figure 4 SSLS strength test specimen and test results

Thus, it has been demonstrated that heating element (5) can produce the weld strength comparable to that of the conventional heating element (1).

5. Conclusion

By considerably reducing the temperature distribution range over the joining interface, the heating element made of carbon-based matrix-impregnated nonwoven fabric allows the temperature to be kept within an appropriate range for the workpieces. This makes it possible to avoid their thermal degradation (caused by overheating) and incomplete welding (by underheating). In addition to less power being consumed during welding, this heating element produces the weld strength comparable to the conventional unidirectional prepreg. Thus, this type of heating element has been identified as one capable of achieving stable weld quality with the reduced risk of thermal degradation and incomplete welding, while ensuring the weld strength that is comparable to the conventional unidirectional prepreg.

References

(1) A. Yousefpour, et al., Journal of Thermoplastic Composite Materials, 17(2004), p.303-341
(2) M. Endrass, et al., ITHEC2020 (2020), p.219-222