Development of Joining Method for Thermoplastic Composites

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Summary

Development of Thermoplastic Composites
Joining Method for aircraft structures

Assembly method for composite parts
Mechanical fastening (state-of-the-art)

Thermoplastic composite: Can be melted
Capability of welding technique

Developed three joining method for aircraft structures
1. Ultrasonic Welding
2. Microwave Welding
3. Adhesive Bonding (Not welding technich)

Material: Continuous carbon fiber (CF) / Polyether ether ketone (PEEK)

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1. Overview

Continuous fiber reinforced thermoplastic composite (FRTP)
Possibility as material for future aircraft and automotive components

Feature compared to conventional fiber reinforced thermoset composite (FRP)
- Low production cycle time (No chemical reaction)
- Infinite shelf life (Not required refrigeration equipment for storage)
- Insensitive to moisture (Less degraded mechanical properties under Hot/Wet conditions)
- Superior impact and damage tolerance
- Can be welded
- Can be reformed
- Repairability

Fig. A380 thermoplastic J-nose (Fokker)  
Fig. CFRTP parts

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2. Purpose

Joining method of conventional FRP components
Assembled by mechanical fastening
- Stress concentration induced drilling holes
- Heavy weight (Fastener, Sealing and FRP thickness)
- Expensive assembly cost

Joining method of FRTP components
Required non-fastening joining method utilizing FRTP features
- Can be melted after formed

This study
Developed ultrasonic welding, microwave welding and adhesive bonding
as non-fastening light and low cost joining method for future aircraft structures

Fig. Mechanical fastening component

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3.1 Method of evaluation

Base material
- T800S continuous carbon fiber (CF) / polyether ether ketone (PEEK)
- Supplier: Toray Industries, Inc.
- Fiber volume content: 55%
- Form: Unidirectional
- Dimension: 330 mm x 300 mm
- Laminated constitution: Quasi-isotropic \([(+45^\circ / 0^\circ / -45^\circ / 90^\circ)]_{3S}\)
- Processing temperature: 390°C
- Consolidation pressure: 8 MPa
- Consolidation time: 15 min
- Cooling rate: 8°C/min
- Total fabrication time: 80 min
- Nominal thickness: 3.7 mm

Fig. Lay-up
Fig. Hot platen press
Fig. Thermal profile
3.1 Method of evaluation

Mechanical properties
- Compressive strength
- Tensile strength
- $G_{IC}$ energy

Almost the same or higher compared to conventional thermoset composites

- Double notch compression shear test

![Schematic of double notch compression shear test](image1)

Strength of compression shear strength: **66.7 MPa**

![Picture of specimen after test](image2)
3.1 Method of evaluation

Single lap shear test
- Test method: Single lap shear (ASTM D 1002) for technical feasibility
- Sample size: L:100 mm  W:25.4 mm
- Overlap area: L:12.7 mm W:25.4 mm
- Crosshead speed: 1.3 mm/min
- Test condition: Standard condition
- Number of specimen: 3 per set each joining conditions
- Joining method: Ultrasonic welding
               Microwave welding
               Adhesive bonding

Fig. Schematic of single lap shear test

Fig. Picture of specimen during test
3.2 Ultrasonic welding

Method of ultrasonic welding

![Diagram of ultrasonic welding process]

- High frequency mechanical vibration
- Energy director (Thermoplastic)
- Welding

Energy director
- Starting point of melting

Conventional
- Projection shaped energy directors (Difficult to attach on surface)

Replace
- Diameter: 0.5 mm

![Image of mesh shaped energy directors]

Fig. Principle of the ultrasonic welding method

Fig. Mesh shaped energy directors
3.2 Ultrasonic welding

Welding condition
- Ultrasonic welder: Seidensha Electronics JG3600S
- Frequency: 20 kHz
- Peak power: 650 W
- Amplitude: 80%
- Welding time: 9 s
- Welding pressure: 0.4 MPa
- Retaining time: 5 s
- Welding energy: 3500~5500 J
- Clamping tools: Prevent samples from horizontal shifting
  Allow vertical movement of the upper substrate

Fig. Set up of the ultrasonic welding method
3.2 Ultrasonic welding

Result of single lap shear test
- 3500 ~ 4500 J: Interfacial delamination
  Low welding energy
- 5000 J: Substrate fracture
  Welded in high quality
- 5500 J: Not jointed
  Damaged substrate
  Too high welding energy

Fig. Result of single lap shear test

Fig. Fracture surface after single lap shear test
(Welding energy: 5000 J)
3.3 Microwave welding

Method of microwave welding
Microwave heating
- High heating efficiency joining
- Rapidly heating by self-heat generation
- Capability to irradiate entire component and consequence joint large area
- High cycle

CFRTP
- Low microwave absorption property
- Required high microwave absorption property material
  Inserted metal nano-coil at joint surface

Fig. Principle of the microwave welding method

Self-heating generation only joint surface
3.3 Microwave welding

Platinum nano-coil

Electrospinning process
- Polyvinyl alcohol (PVA) nano-fibers made by electrospinning
- Platinum coated on PVA by sputtering
- PVA nano-fibers thermally decomposed by oven heating
- Very thin coating contracted in the shape of coil by heating

Cross section: Hollow or horseshoe shape

Fig. Picture of Pt nano-coil

Fig. Schematic of cross section of Pt nano-coil
3.3 Microwave welding

**Welding condition**
- Microwave welder: Fuji Electronic Industrial Co., Ltd microwave welder
- Frequency: 2.45 GHz
- Power: 1.5 kW (Multi mode)
- Welding time: 180 s
- Welding pressure: 0.087 MPa
- Nano-coil material: Platinum
- Nano-coil amount: 14 μg/cm²
- Nano-coil setting: Inserted in joint surfaces with Victrex PEEK film
- Clamping tools: PEEK resin (Low microwave absorption and reflection properties)

*Fig. Set up of the microwave welding method*
3.3 Microwave welding

Result of single lap shear test
- Applied Pt nano-coil: **43 MPa**
  Welded joint surface in high quality
- Without Pt nano-coil: **Not jointed**
  Not welded joint surface

![Substrate fracture](image)

Fig. Fracture surface after single lap shear test
3.3 Microwave welding

Temperature measurement test

Fig. Temperature measurement by radiation thermometer

Pt nano-coil: High microwave absorption property in spite of very low amount
CF/PEEK: Not remarkable

Compared to Pt nano-fiber (Linear shaped, same diameter with Pt nano-coil)
- Temperature raised gradually with wavelength 2.45 GHz
- Cause of heating difference by microwave: Based on the shape difference?

We continue the research in order to clarify a cause of this phenomenon
3.4 Adhesive bonding

Adhesive bonding
- Proven and established joint method for FRP
- Low adhesive strength applied epoxy based adhesive to FRTP
  Require to change FRTP’s surface condition suitable for adhesive bonding

Atmospheric pressure plasma treatment
- Pre-treatment method for bonding
- Cleaning effect
- Increase functional group on surface
- Easy to automation
- Uniform quality
- Low surface damage
- High speed

Ref. Plasmatreat
3.4 Adhesive bonding

Select irradiance condition of plasma treatment (Pre-examination)
- Machin: Nihon Plasmatreat Inc.
  FG5001 generator
  RD1004 plasma nozzle
- Evaluation item: Contact angle of water
  Adhesion strength
- Material: PEEK resin

Contact angle
- To obtain high bonding strength
  Required high solid surface energy

Young’s equation
$$\gamma_s = \gamma_{sl} + \gamma_l \cos \theta$$

- $\theta$: Contact angle
- $\gamma_s$: Solid surface free energy
- $\gamma_{sl}$: Solid/liquid interfacial free energy
- $\gamma_l$: Liquid surface free energy

Lowest contact angle $\theta$: Highest solid surface energy
3.4 Adhesive bonding

Select irradiance condition of plasma treatment (Pre-examination)

Criteria of selection
- Contact angle of water: Lowest
- Adhesion strength: Highest

Selected condition for next test
- Treatment speed: 0.6 m/min
- Distance between work and specimen: 5 mm
- Atmosphere: Air

Fig. Pre-examination result
3.4 Adhesive bonding

Chemical influence of atmospheric pressure plasma treatment
- Irradiance condition: Selected in pre-examination
- Evaluation method: X ray photoelectron spectroscopic (XPS) of CF/PEEK
- XPS equipment: ULVAC-PHI incorporated company PHI 5000 Versa Probe

Table Result of XPS analysis

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Depth</th>
<th>Element content (Atomic %)</th>
<th>Oxygen ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>N</td>
</tr>
<tr>
<td>Plasma</td>
<td>Outermost surface</td>
<td>72.24</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td>5nm</td>
<td>93.95</td>
<td>1.21</td>
</tr>
<tr>
<td>Non-treated</td>
<td>Outermost surface</td>
<td>89.25</td>
<td>1.44</td>
</tr>
<tr>
<td></td>
<td>5nm</td>
<td>96.34</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Result
- Decrease: Binding energy correspond to C-H and C-C bonds
- Generate: Binding energy correspond to ether (C-O), carboxyl (O-C=O) functional groups Chemical interactive with epoxy based adhesive
- Effect only low depth (Less 10 nm)
  No chemical changes of carbon fiber

Suitable pre-treatment method for chemical surface modification
3.4 Adhesive bonding

Result of single lap shear test
Atmospheric pressure plasma treated on joint surface before bonding
Adhesive: Two components epoxy based adhesive
(Nagase ChemteX corporation DENATITE 2204)

Result
- With atmospheric pressure plasma treatment: 25 MPa
- Without atmospheric pressure plasma treatment: 15 MPa

Fig. Fracture surface after single lap shear
## 4. Conclusion

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<th>Joining Method</th>
<th>Schematic View</th>
<th>Advantage</th>
<th>Disadvantage</th>
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<tr>
<td>Ultrasonic Welding</td>
<td></td>
<td>- High rate joining</td>
<td>- Applicable only spot joining</td>
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<tr>
<td></td>
<td></td>
<td>- Not rise in temperature more than the resin</td>
<td>- Require of exclusive-use facility</td>
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<tr>
<td></td>
<td></td>
<td>melting point</td>
<td>- Require of energy direct on joint surface</td>
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<tr>
<td>Microwave Welding</td>
<td></td>
<td>- High rate joining</td>
<td>- Difficult to control temperature</td>
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<td></td>
<td></td>
<td>- Differential heating of material</td>
<td>- Require of exclusive-use facility</td>
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<td></td>
<td></td>
<td></td>
<td>- Require of intermediate-material on a joining surface</td>
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<tr>
<td>Adhesive Bonding</td>
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<td>- Applicable conventional technique</td>
<td>- Require of activation before joining and surface condition management</td>
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<td></td>
<td></td>
<td>- Applicable on comparatively large-sized parts</td>
<td>- Require of temperature and time for adhesives hardening</td>
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</table>
4. Conclusion

In this study

Ultrasonic welding, microwave welding and adhesive bonding were developed as non-fastening light and low cost joining method for aircraft structures

Ultrasonic welding
- Using a mesh-shaped energy director which can be attach CFRTP easily
- Single lap shear strength reached 44MPa

Microwave welding
- Using metal nano-coil as susceptible filler heated by microwave
- Single lap shear strength reached 43MPa
- Only joint surfaces were heated and welded efficiently

Adhesive bonding
- Pre-treated by atmospheric pressure plasma treatment before adhesive
- Single lap shear strength improved compared with non-pretreated specimen

High joint strength over 25 MPa were obtained for each method
Basic processes were established and technical feasibility was demonstrated
Our Technologies, Your Tomorrow