Development of Joining Method for Thermoplastic Composites

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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

Fig. Mechanical fastening component

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

Fig. Welding specimen

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

http://www.compositesworld.com

Contents

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

Fig. Mechanical fastening component

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

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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

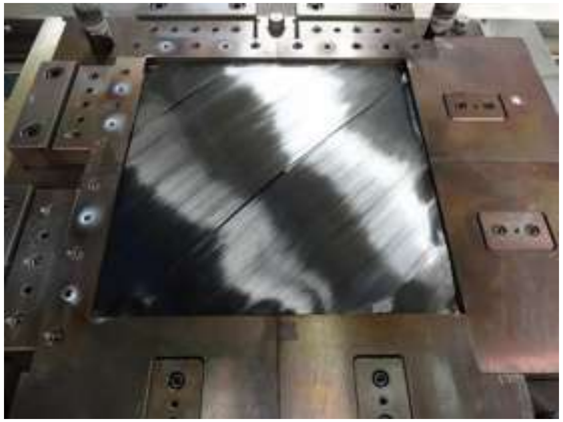


Fig. Lay-up

Fig. Hot platen press

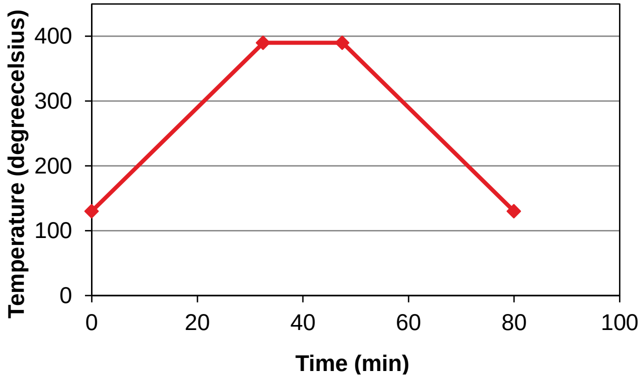
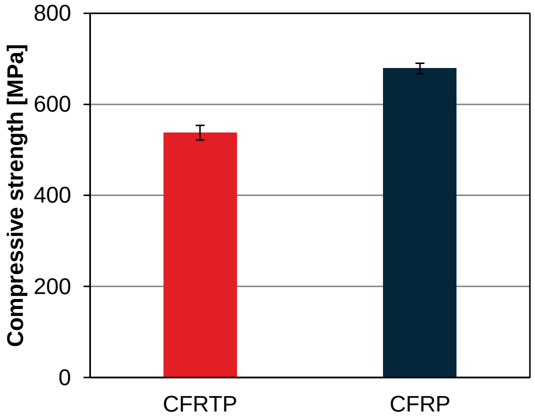
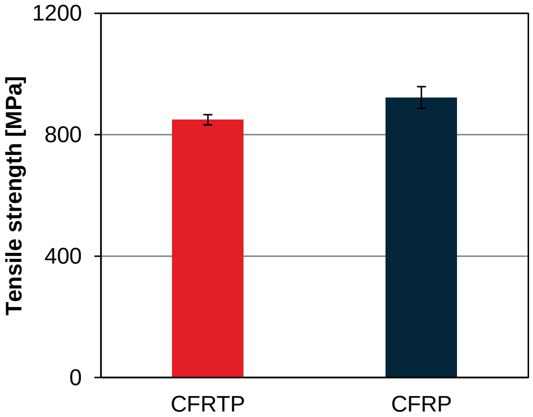


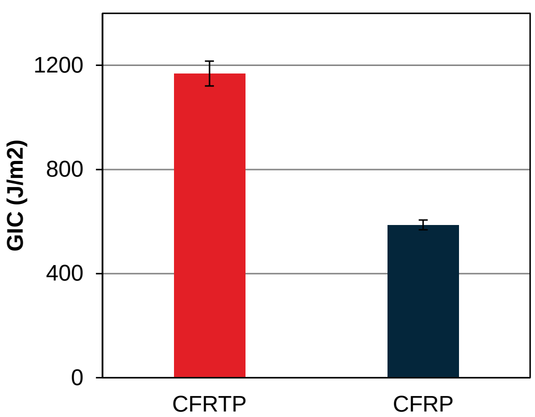
Fig. Thermal profile

Mechanical properties

- Compressive strength
- Tensile strength
- G_{IC} energy







Almost the same or higher compared to conventional thermoset composites

- Double notch compression shear test

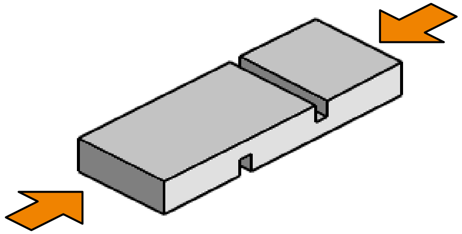


Fig. Schematic of double notch compression shear test

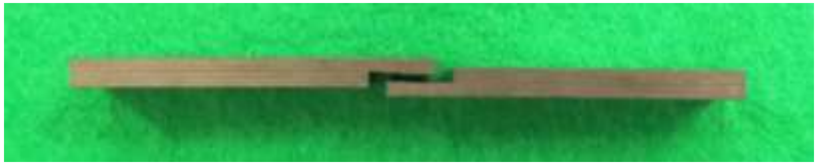


Fig. Picture of specimen after test

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

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

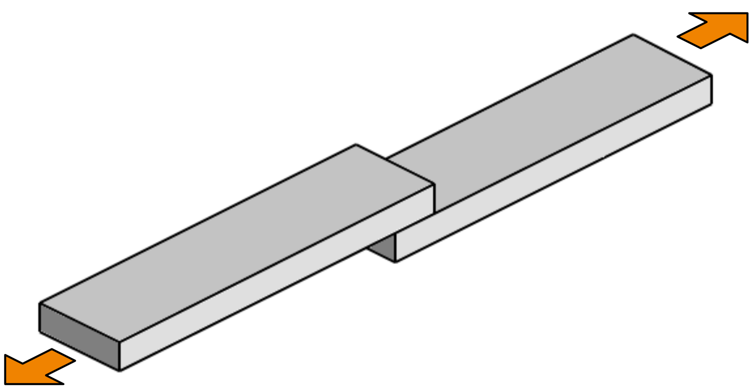


Fig. Schematic of single lap shear test

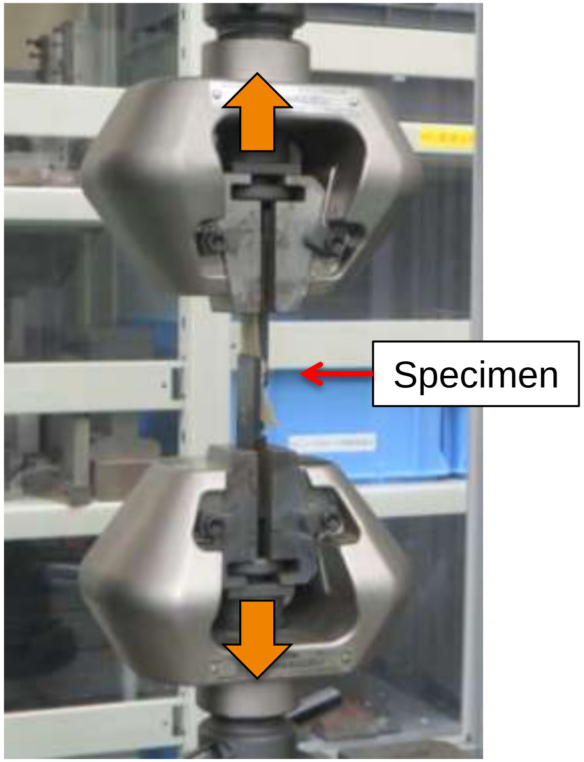


Fig. Picture of specimen during test

Method of ultrasonic welding

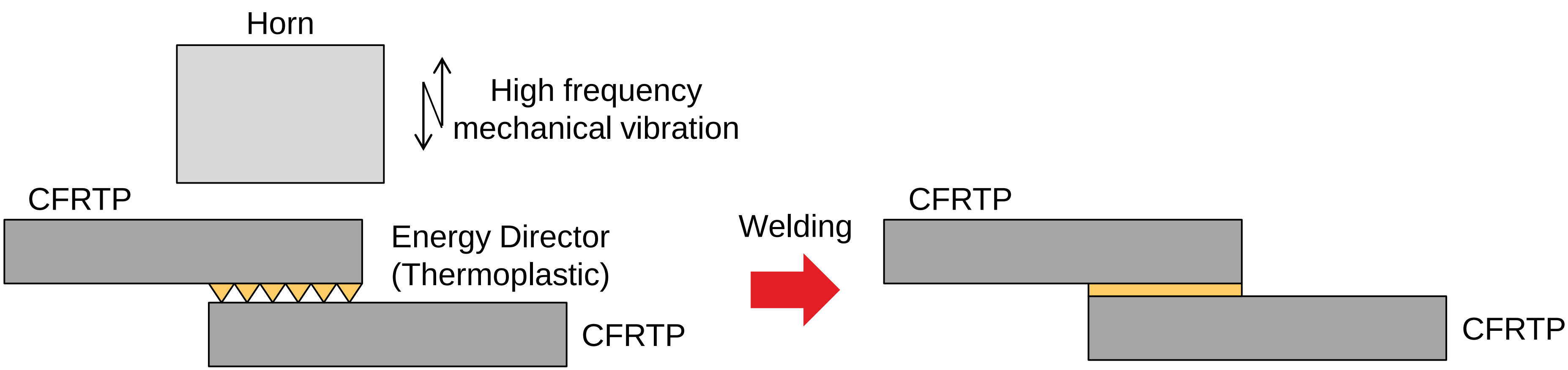
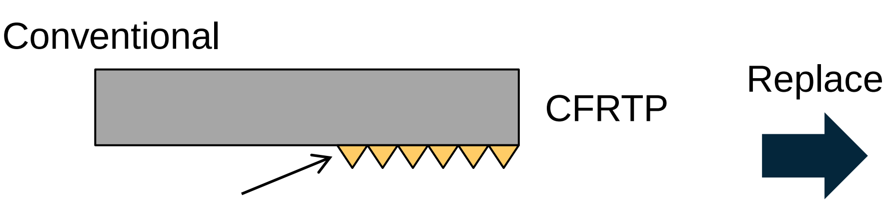


Fig. Principle of the ultrasonic welding method

Energy director

- Starting point of melting



Projection shaped energy directors
(Difficult to attach on surface)

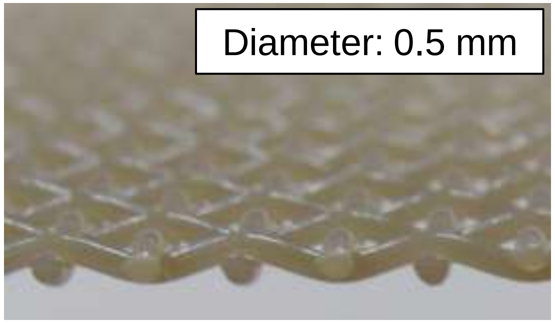


Fig. Mesh shaped energy directors

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

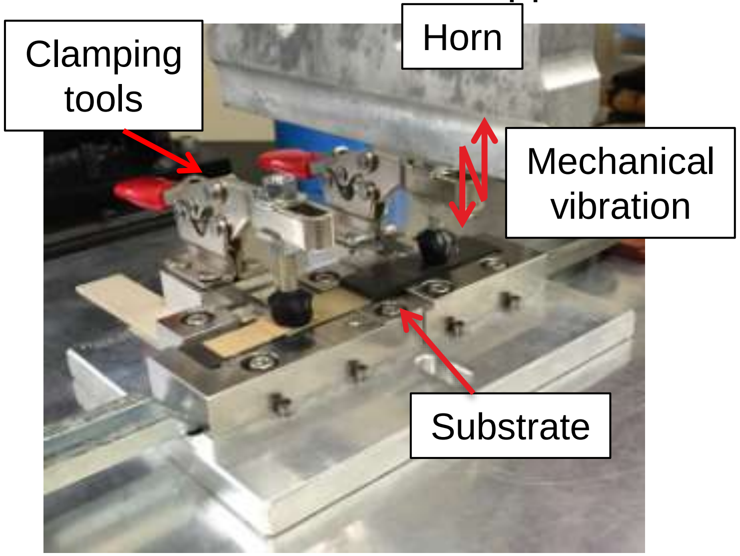


Fig. Set up of the ultrasonic welding method

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

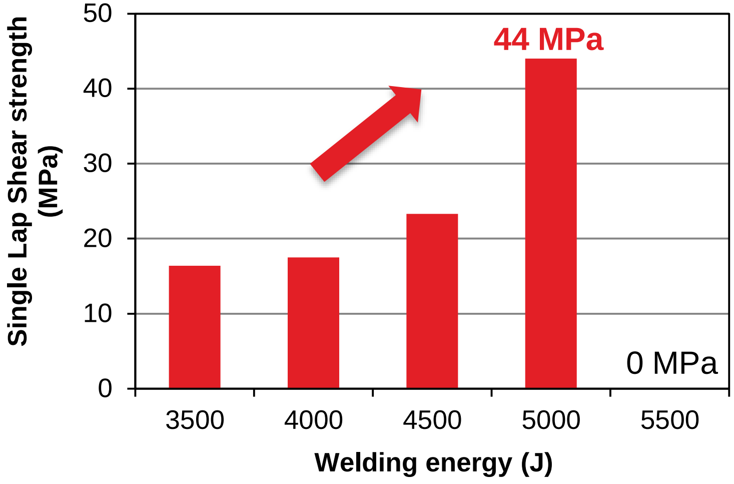


Fig. Result of single lap shear test

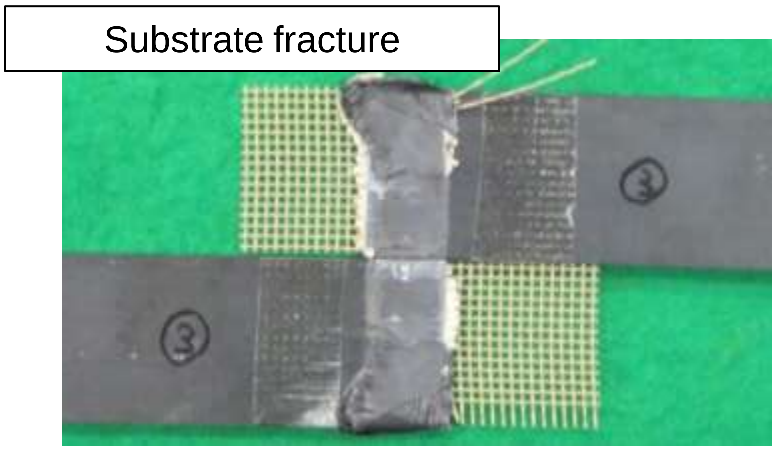


Fig. Fracture surface after single lap shear test
(Welding energy: 5000 J)

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

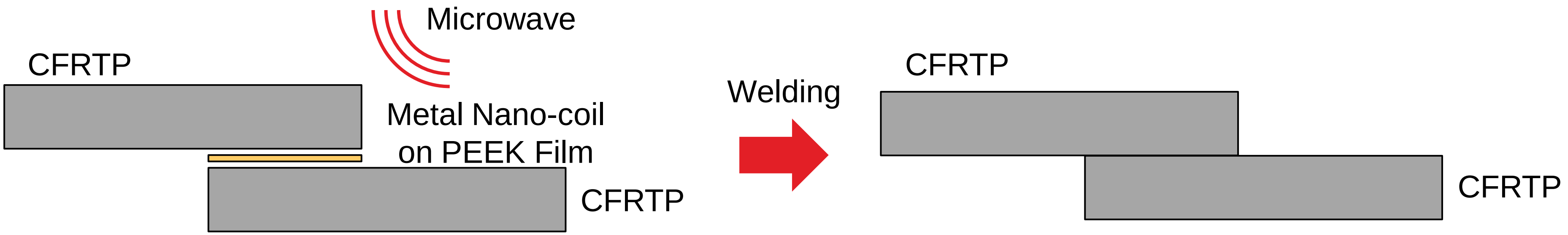
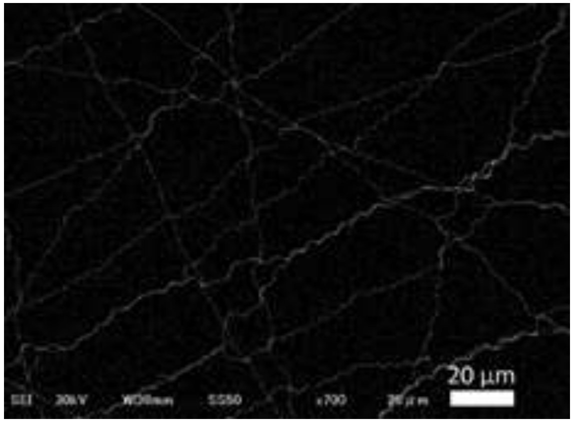


Fig. Principle of the microwave welding method

Self-heat generation only joint surface

Platinum nano-coil



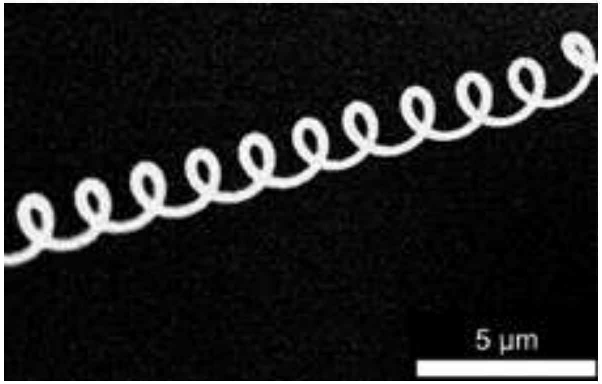


Fig. Picture of Pt nano-coil

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

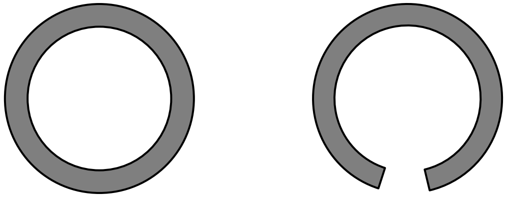


Fig. Schematic of cross section of Pt nano-coil

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/cm^2
- Nano-coil setting:	Inserted in joint surfaces with Victrex PEEK film
- Clamping tools:	PEEK resin (Low microwave absorption and reflection properties)

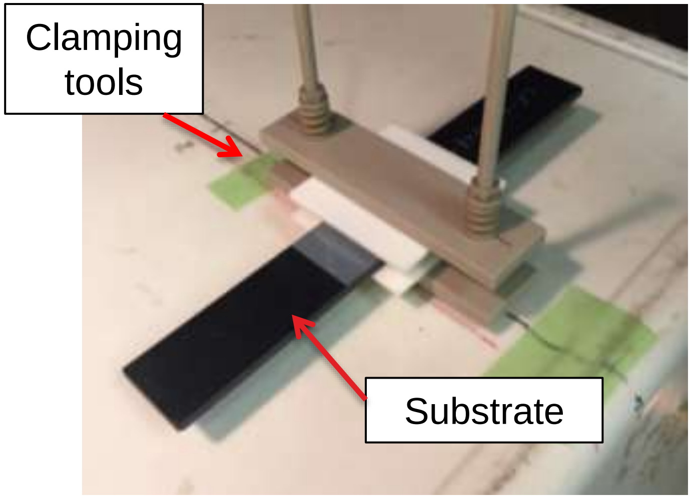


Fig. Set up of the microwave welding method

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

Fig. Fracture surface after single lap shear test

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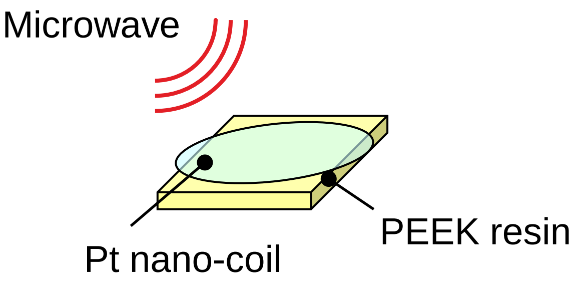
Temperature measurement test



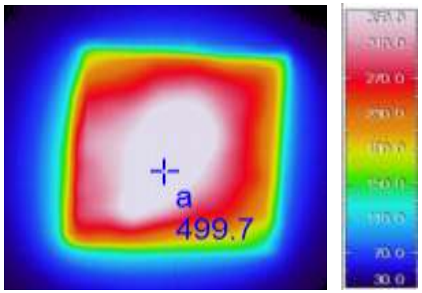


Fig. Temperature measurement by radiation thermometer

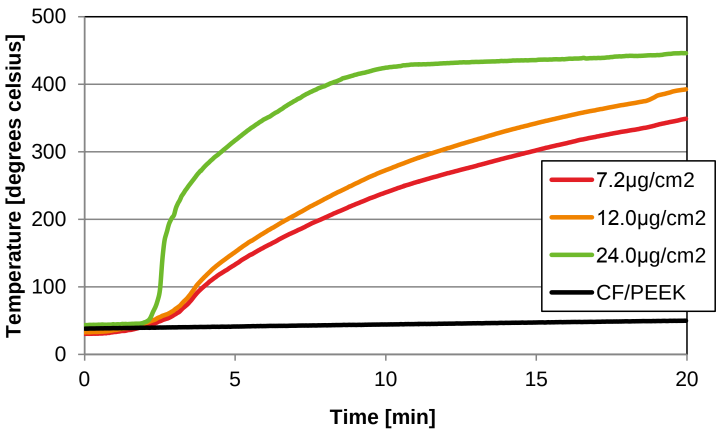


Fig. Temperature rise curves

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

 Confidential

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

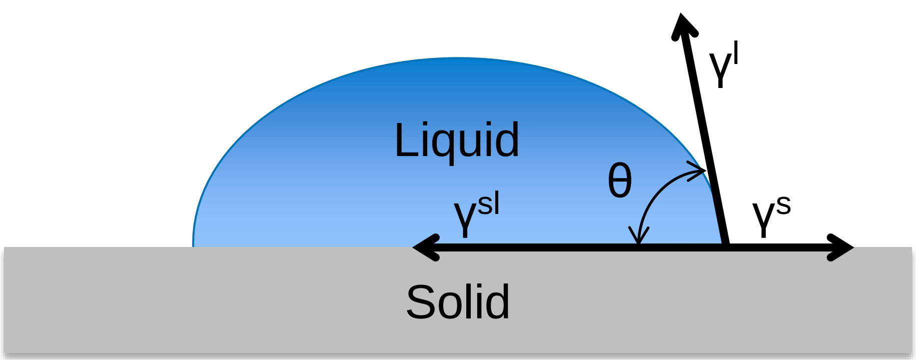


Fig. Schematic of contact angle measurement

Young's equation

$$\boldsymbol{\gamma^s = \gamma^{sl} + \gamma^l \cos\theta}$$

θ: Contact angle
γ^s: Solid surface free energy
γ^{sl}: Solid/liquid interfacial free energy
γ^l: Liquid surface free energy

Lowest contact angle θ: Highest solid surface energy

Select irradiance condition of plasma treatment (Pre-examination)

Criteria of selection

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

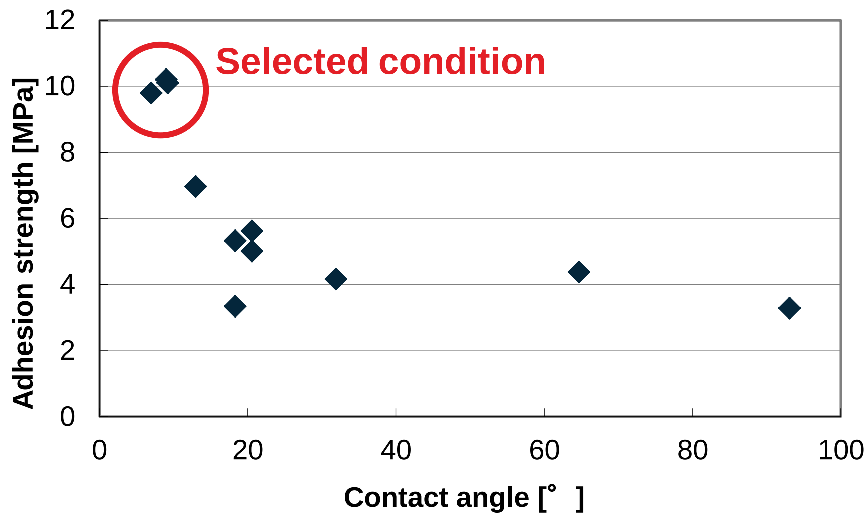


Fig. Pre-examination result

Selected condition for next test

- Treatment speed: 0.6 m/min
- Distance between work and specimen: 5 mm
- Atmosphere: Air

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

Treatment	Depth	Element content (Atomic %)		
		C	N	O
Plasma	Outermost surface	72.24	1.95	25.80
	5nm	93.95	1.21	4.84
Non-treated	Outermost surface	89.25	1.44	9.31
	5nm	96.34	0.70	2.96

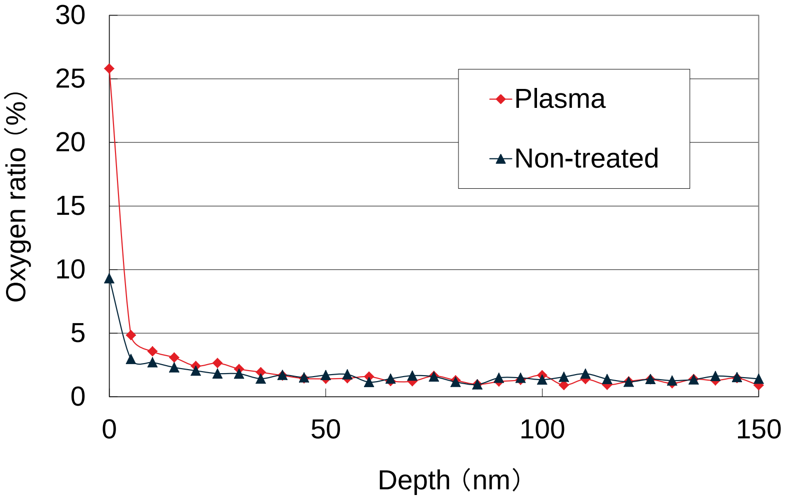


Fig. Amount of oxygen elements

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

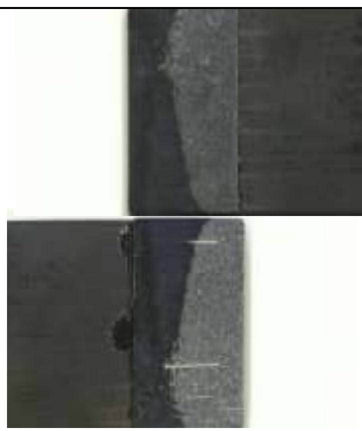
Result of single lap shear test

Atmospheric pressure plasma treated on joint surface before bonding

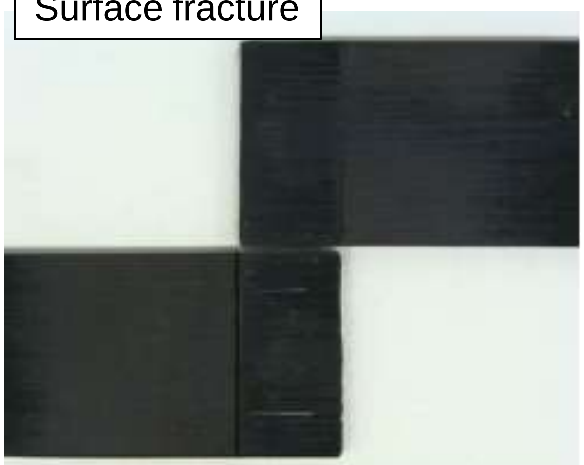
Adhesive: Two components epoxy based adhesive
(Nagase ChemteX corporation DENATITE 2204)

Result

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



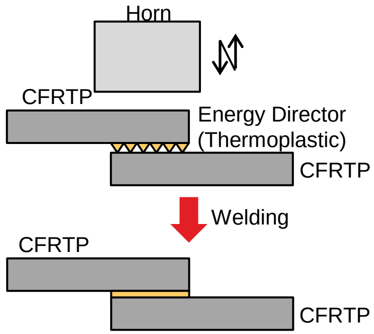
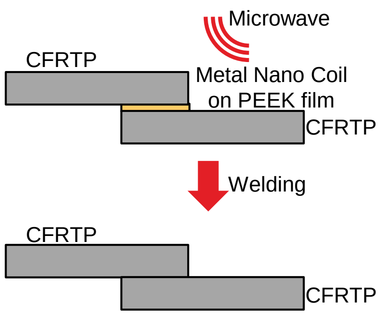
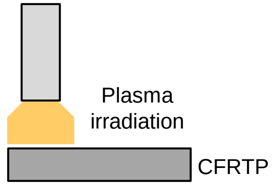
With plasma treatment



Without plasma treatment

Fig. Fracture surface after single lap shear

4. Conclusion

Joining Method	Schematic View	Advantage	Disadvantage
Ultrasonic Welding		- High rate joining - Not rise in temperature more than the resin melting point	- Applicable only spot joining - Require of exclusive-use facility - Require of energy director on joint surface
Microwave Welding		- High rate joining - Differential heating of material	- Difficult to control temperature - Require of exclusive-use facility - Require of intermediate-material on a joining surface
Adhesive Bonding	Atmospheric Pressure Plasma Treatment 	- Applicable conventional technique - Applicable on comparatively large-sized parts	- Require of activation before joining and surface condition management -Require of temperature and time for adhesives hardening

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

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