INTRODUCTION TO WELDING OF THERMOPLASTIC COMPOSITES

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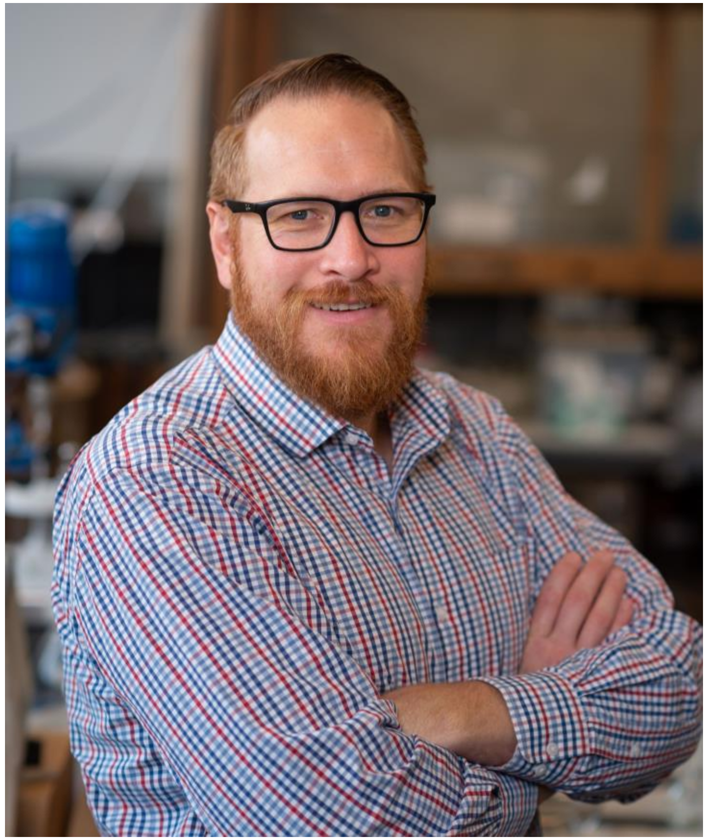

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Co-Director of Advanced Materials Manufacturing MEL Program, UBC
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- Ph.D. and M.A.Sc. in Composite Materials Engineering
- Over 15 years experience in industry and academia working on polymer matrix composites in aerospace, automotive, marine, energy, recreation and others
- Experience working with over 150 companies from SME to major international corporations
- Expertise in liquid composite moulding and thermal management

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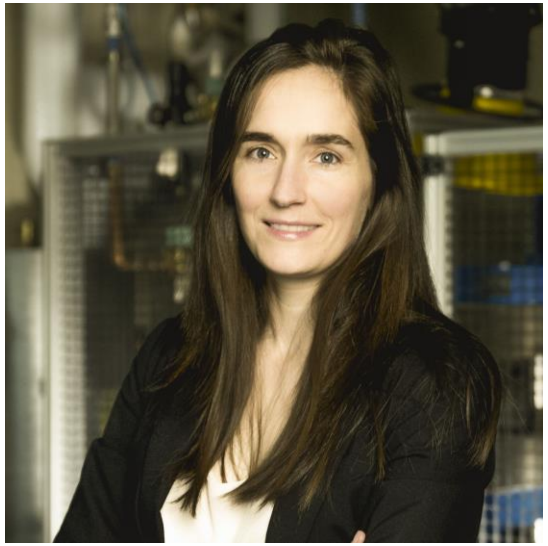

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- Ph.D. in Mechanical Engineering (Composite materials)
- 11 years of experience in academia on polymer matrix composites for aerospace industry applications and others
- Industrial experience from working at Bombardier in 2009-2011
- Expertise on thermoplastic composites processing and welding

ÉTS
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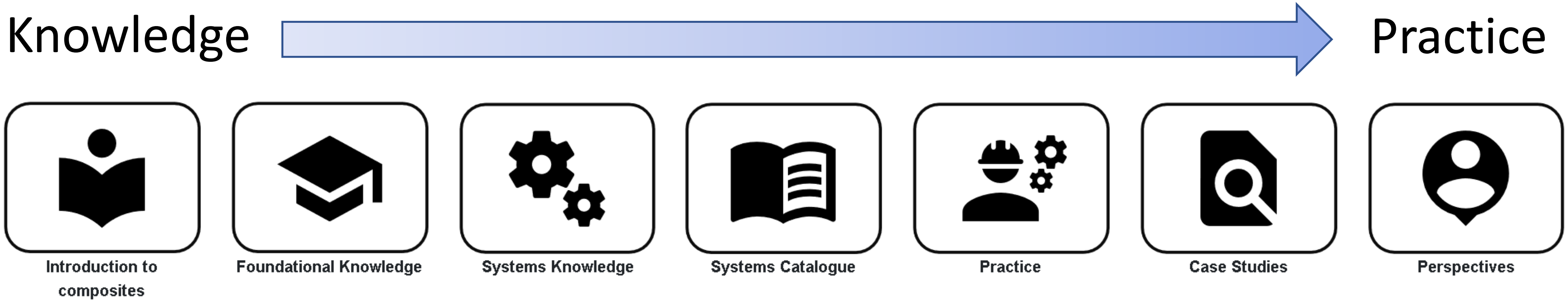
KNOWLEDGE IN PRACTICE CENTRE (KPC)

- A freely available online resource for composite materials engineering:

compositeskn.org/KPC

- Focus on practice, guided by foundational knowledge and a systems-based approach to thinking about composites manufacturing



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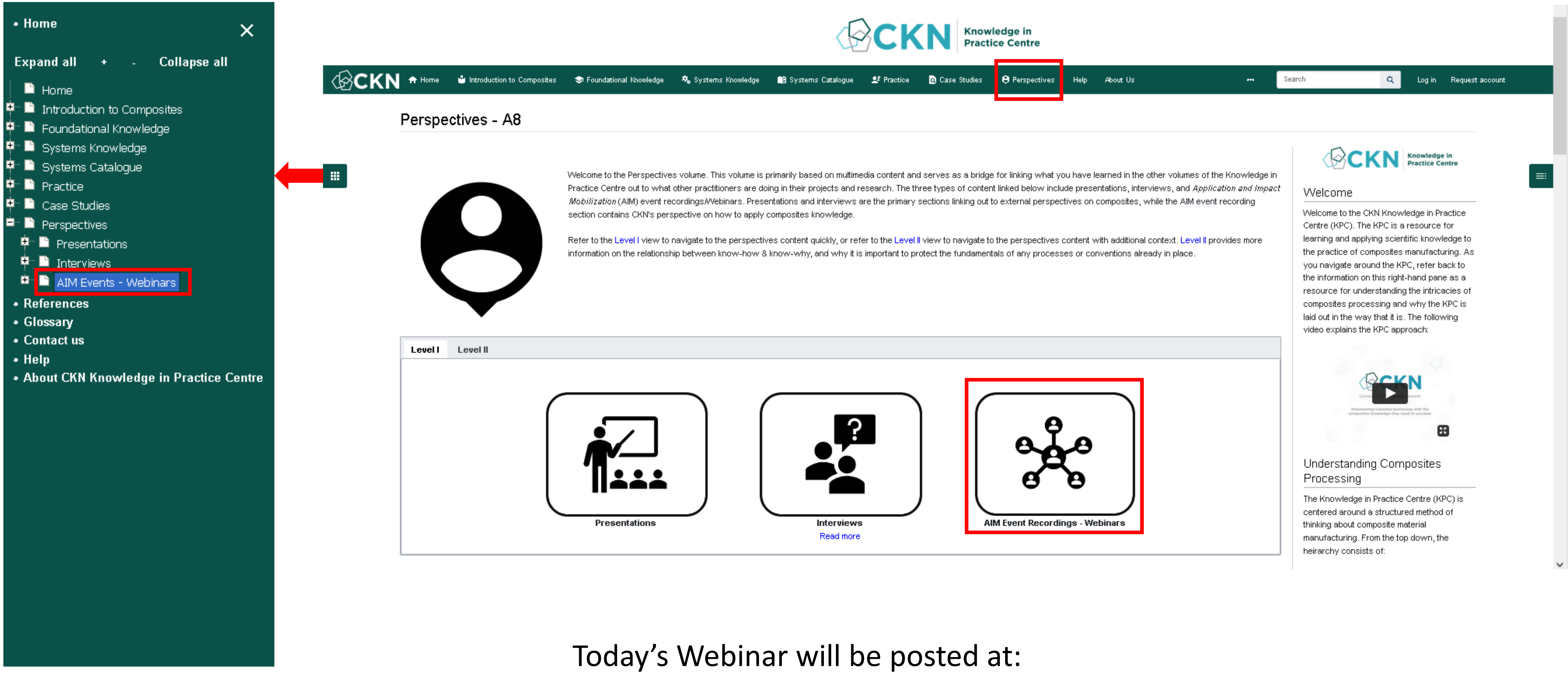

Today's Webinar will be posted at:
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TODAY'S TOPIC:

Introduction to the Welding of Thermoplastic Composites

OUTLINE

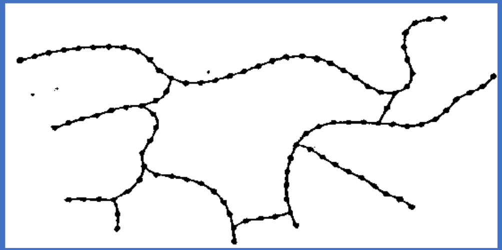
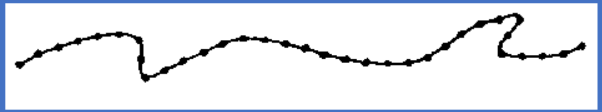
- Learning objectives
- What is welding of thermoplastic composites?
- Welding theory: How is a weld achieved?
- Welding processes for high performance thermoplastic composites
  - Heating mechanisms
  - Advantages, limitations
- Characterization of welded joints

LEARNING OBJECTIVES

- Today we will see how it is possible to join thermoplastic composites by welding, also called fusion bonding.

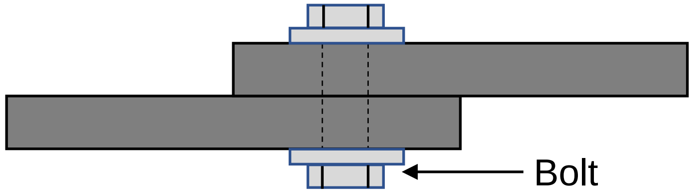
- Learning objectives:
  - Understand the physical mechanisms taking place at the interface during welding
  - Learn various welding processes and their advantages and limitations
  - Understand the important parameters to control for good weld quality

TYPES OF POLYMER MATRICES

Thermosets	Thermoplastics
	
Solidify via chemical reaction that causes polymer to cross-link	No chemical reactions during fabrication
Do not flow once cured due to 3-D cross-linking	Have the ability to remelt after solidification

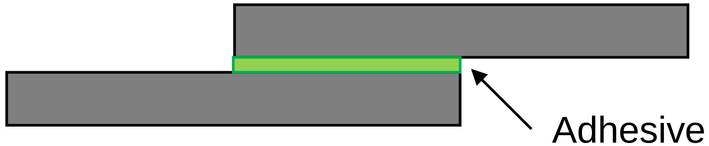
TYPICAL JOINING METHODS FOR COMPOSITES

Mechanical fastening



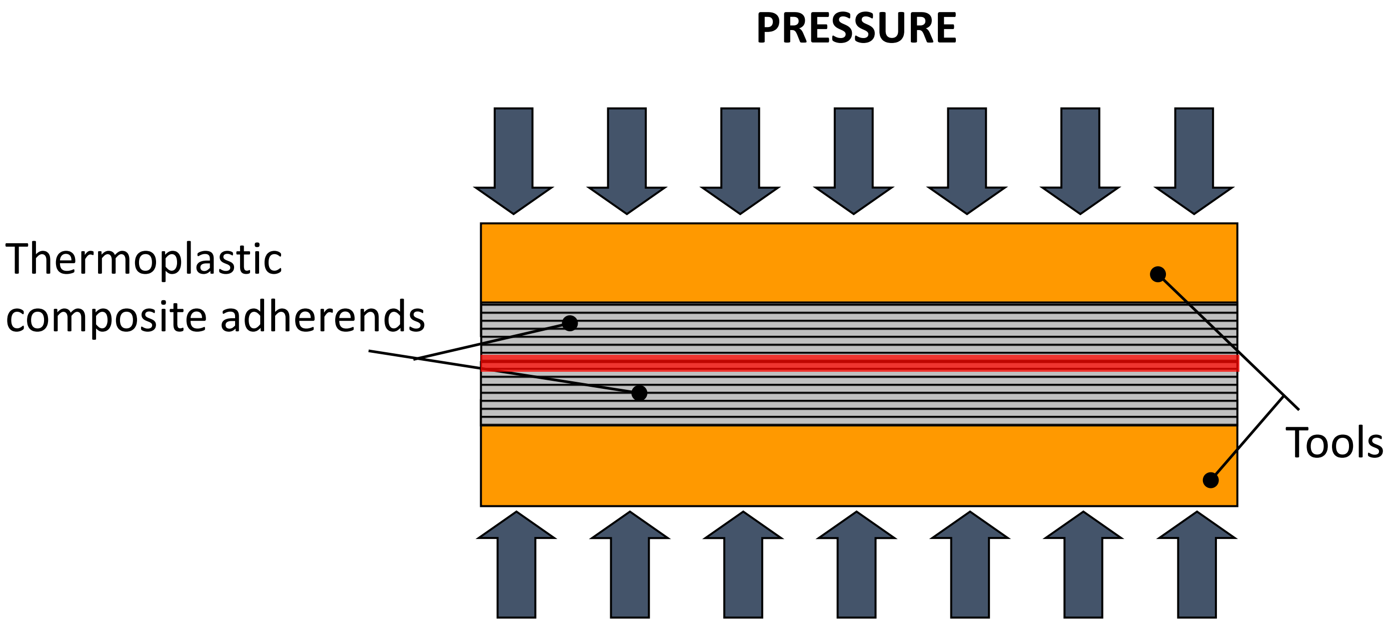
Cons
- Need to drill holes (stress concentration)
- Galvanic corrosion of some metals with carbon fibre adherents

Adhesive bonding



Cons
- Sensitive to surface preparation
- Adhesive needs time to cure
- Most adhesives not suited for thermoplastic polymers

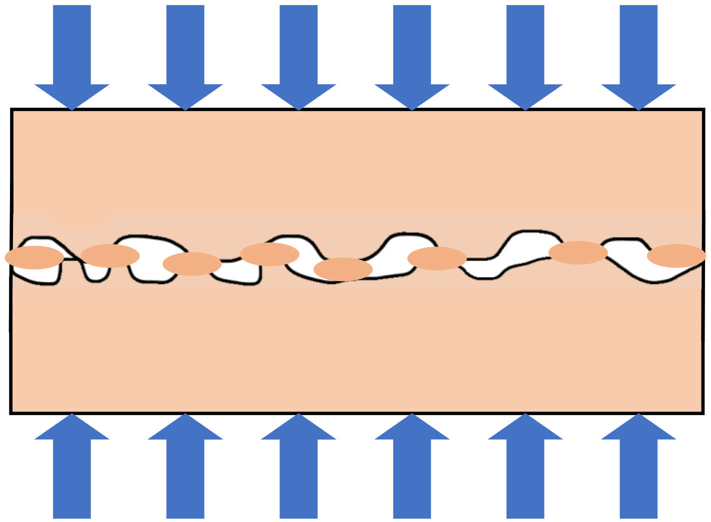
WELDING THEORY



Adhesion is achieved through:

1. Intimate contact development
2. Healing (inter-diffusion of the macromolecules across the interface)

WELDING THEORY: INTIMATE CONTACT



Development of intimate contact at the weld interface

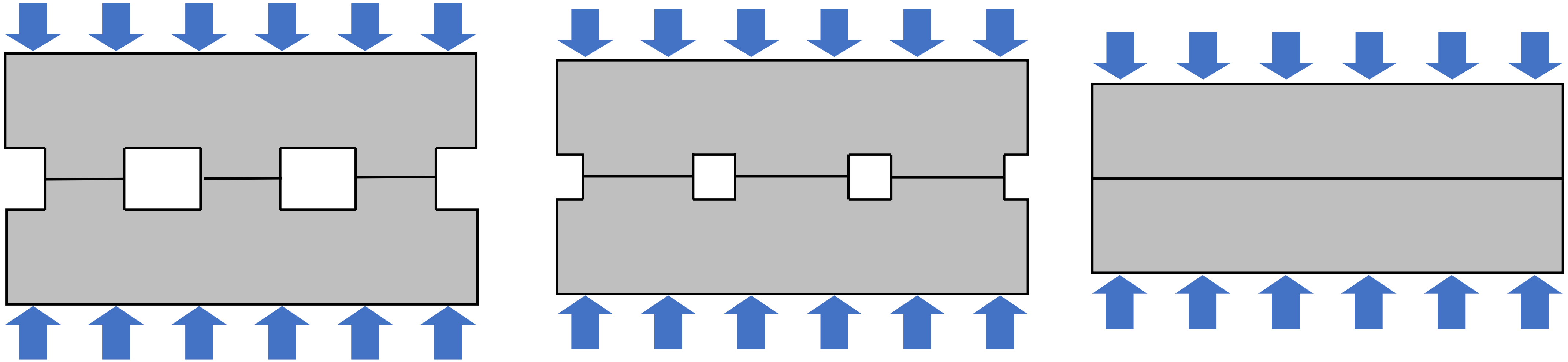
Intimate contact is promoted by :

1. Pressure
2. Heating (polymer flow)

Degree of intimate contact

$$0 \leq D_{ic} \leq 1$$

WELDING THEORY: INTIMATE CONTACT



$0 \leq D_{ic} \leq 1$ $0 \leq D_{ic} \leq 1$ $D_{ic} = 1$

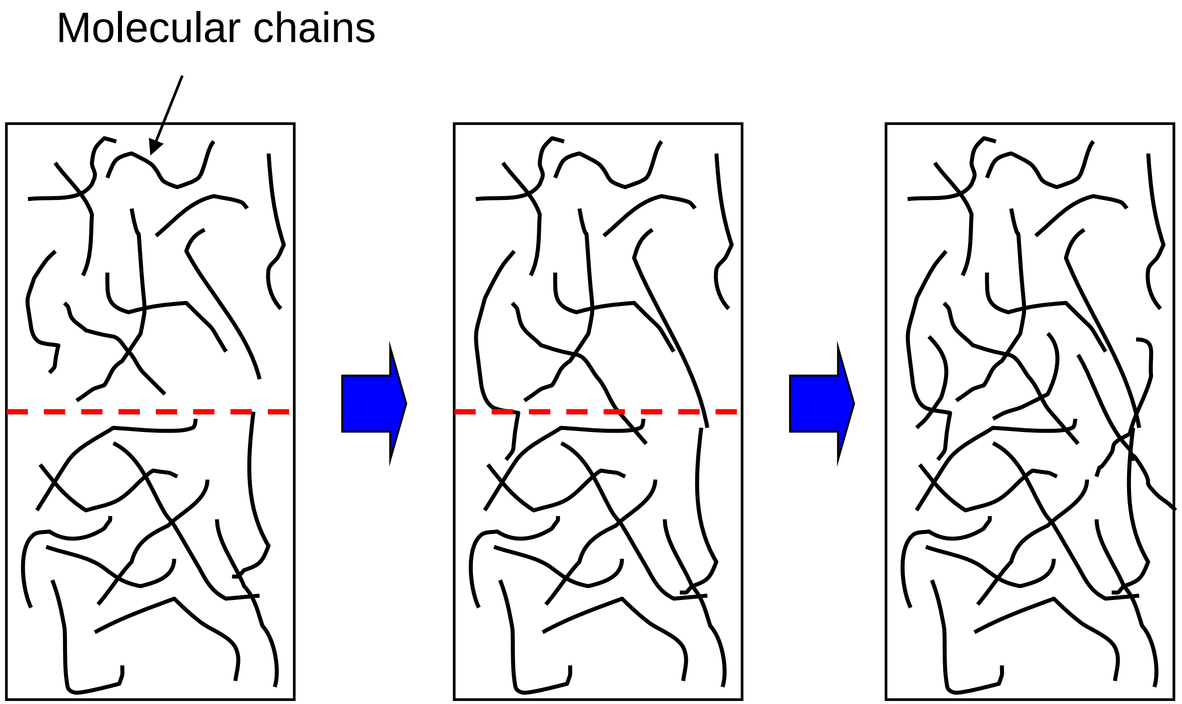
Evolution of Degree of Intimate Contact (D_{ic}) with time

Time to reach $D_{ic} = 1$ is the intimate contact time (t_{ic}) : $t_{ic} \sim \frac{\mu(T)}{P}$

$\mu(T)$ *is the temperature dependant viscosity*

P *is the applied pressure*

WELDING THEORY: HEALING



Initial contact
t = 0

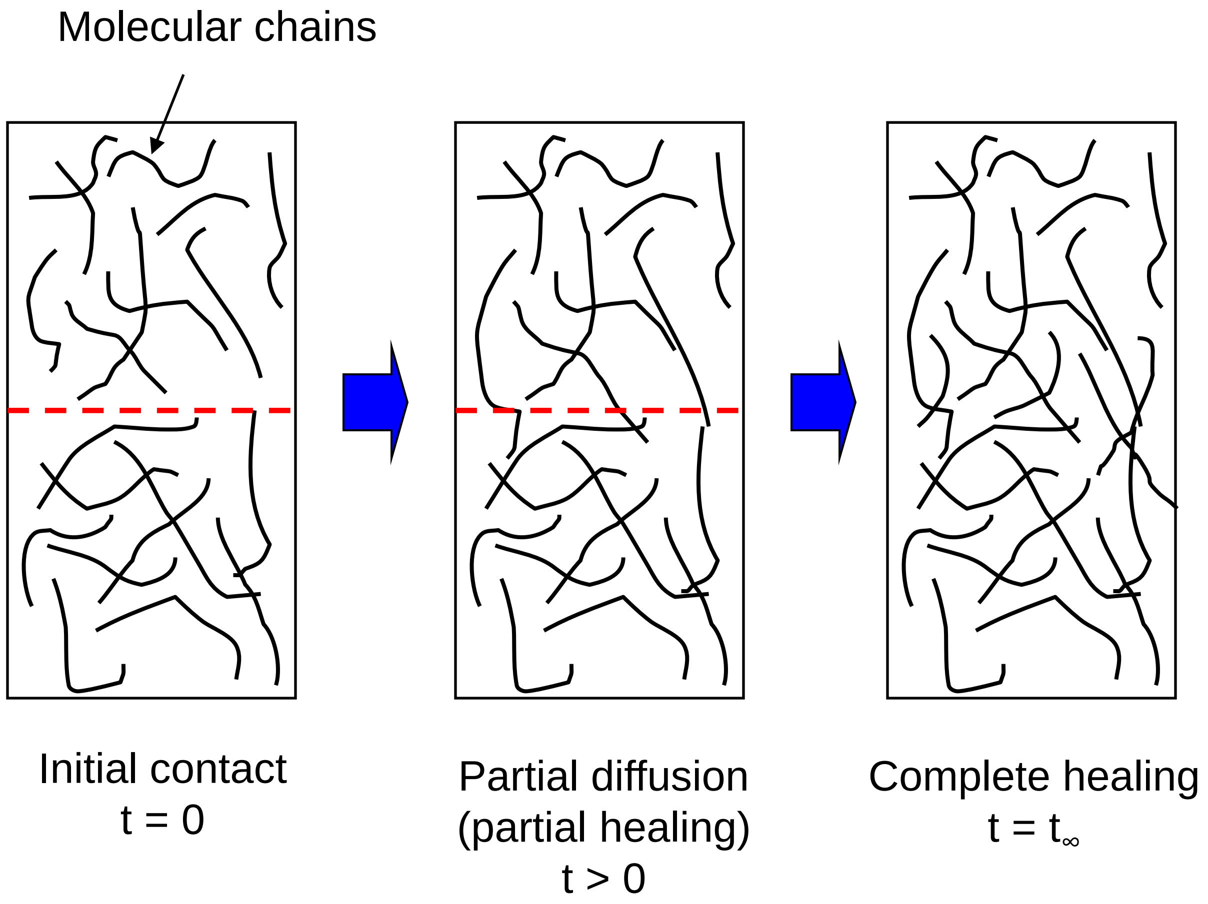
Partial diffusion
(partial healing)
t > 0

Complete healing
$t = t_\infty$

Degree of healing

$0 \leq D_h \leq 1$

WELDING THEORY: HEALING



$$D_h = \left(\frac{t_w}{t_{w,\infty}}\right)^{1/4}$$

t_w: Welding time

$t_{w,\infty}$: Welding time required for full healing

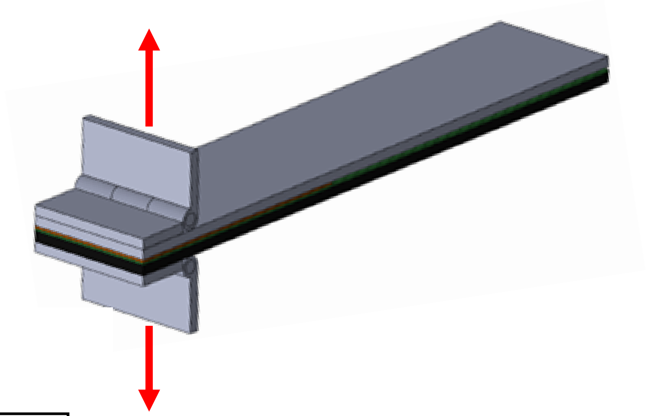
Degree of healing

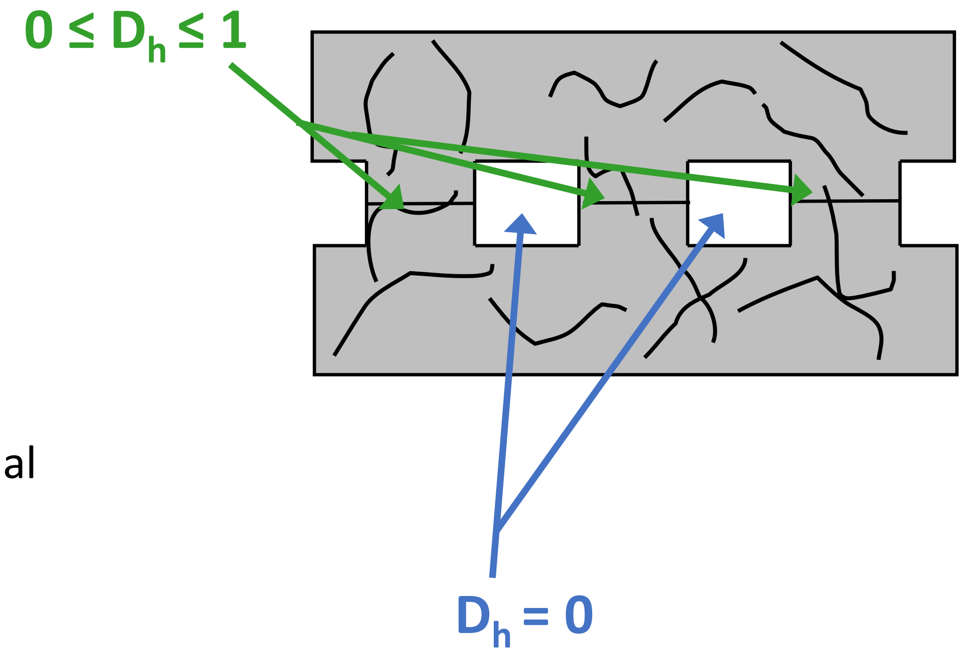
$0 \le D_h \le 1$

WELDING THEORY: ADHESION

$$D_a = \frac{\sigma}{\sigma_\infty} = \left(\frac{G_{ic}}{G_{ic,\infty}}\right)^{1/2}$$

σ joint strength
σ_∞ strength of the bulk material
G_{ic} fracture toughness of the joint
$G_{ic,\infty}$ fracture toughness of the bulk material



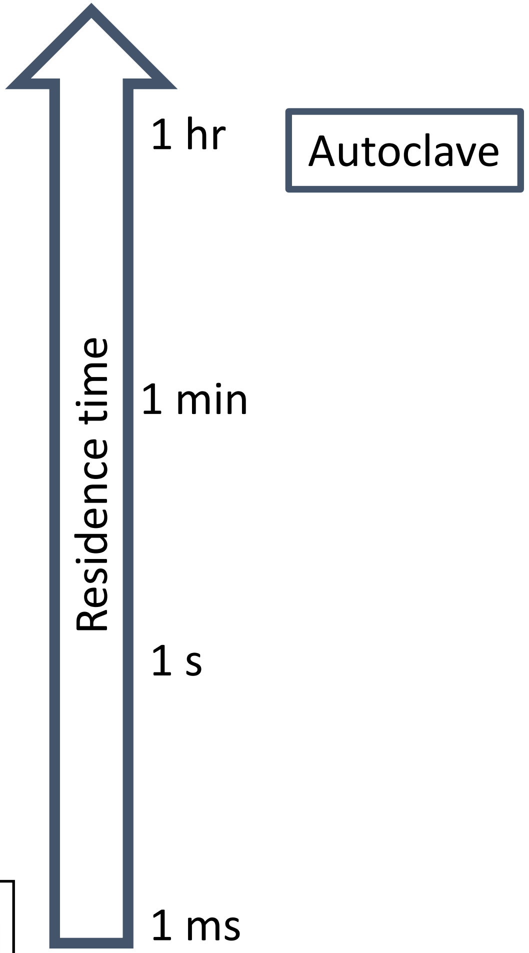


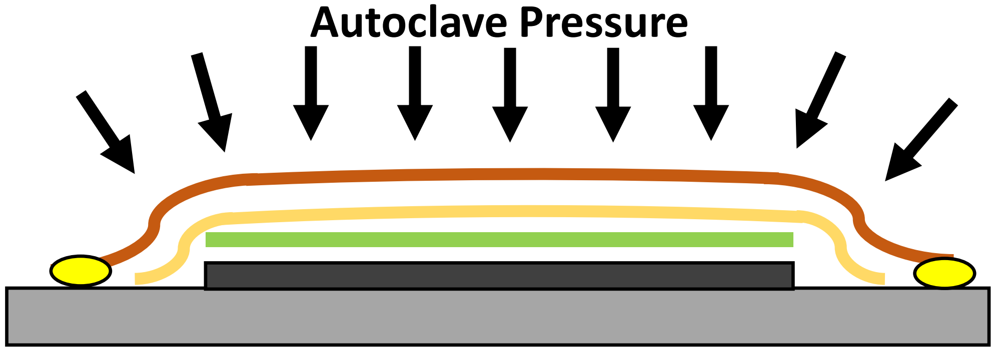
$0 \leq D_{ic} \leq 1$

$$D_a = D_{ic} \times D_h$$

WELDING THEORY

When processing or welding a thermoplastic composite, the time spent at the processing temperature is called the residence time.





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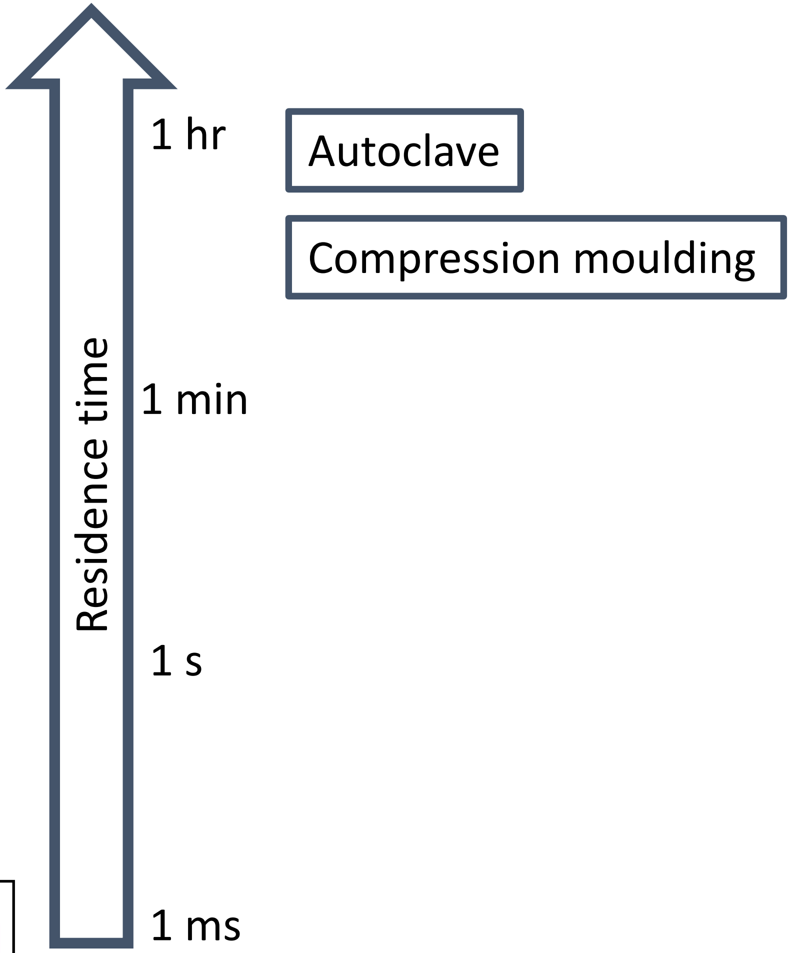

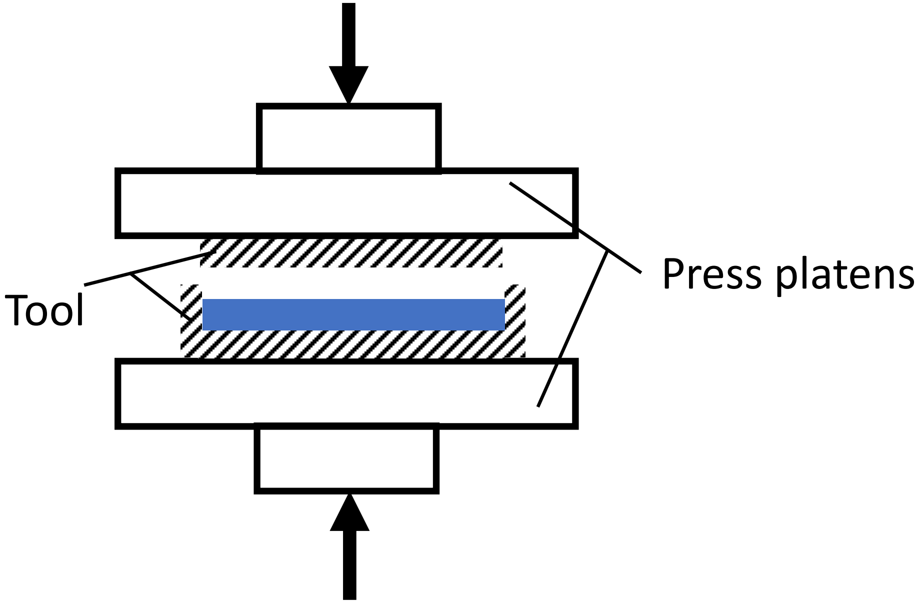

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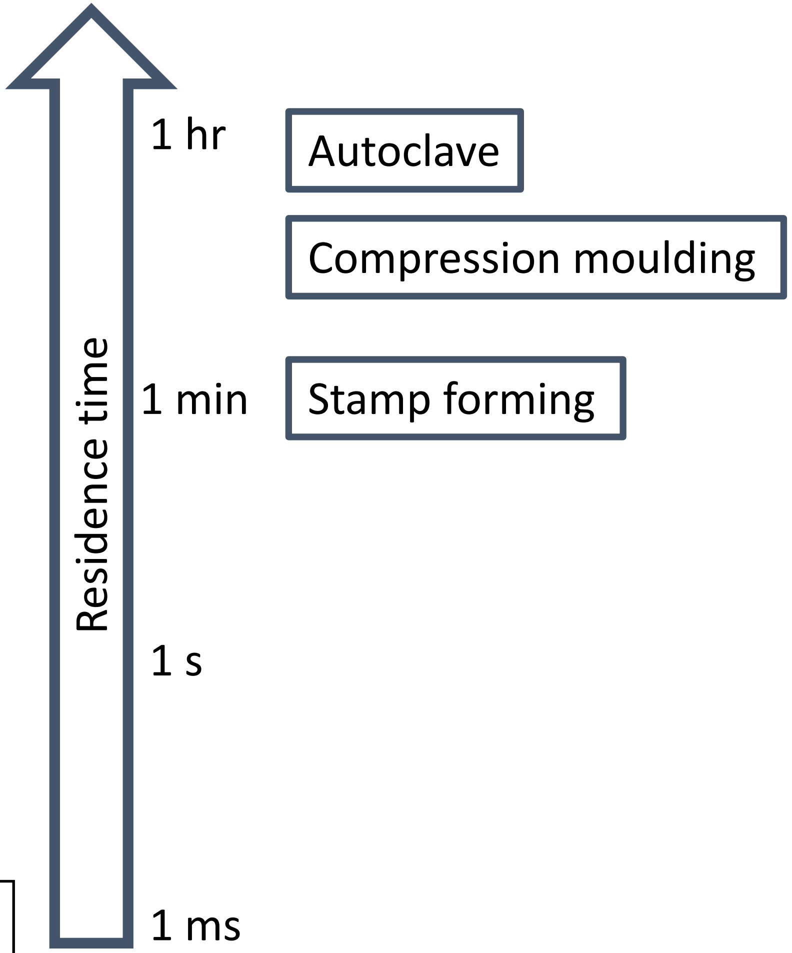
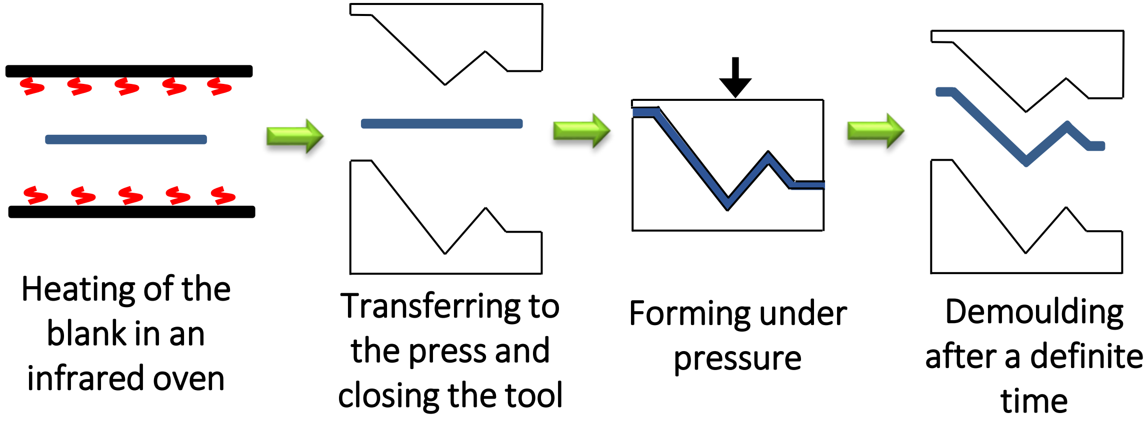
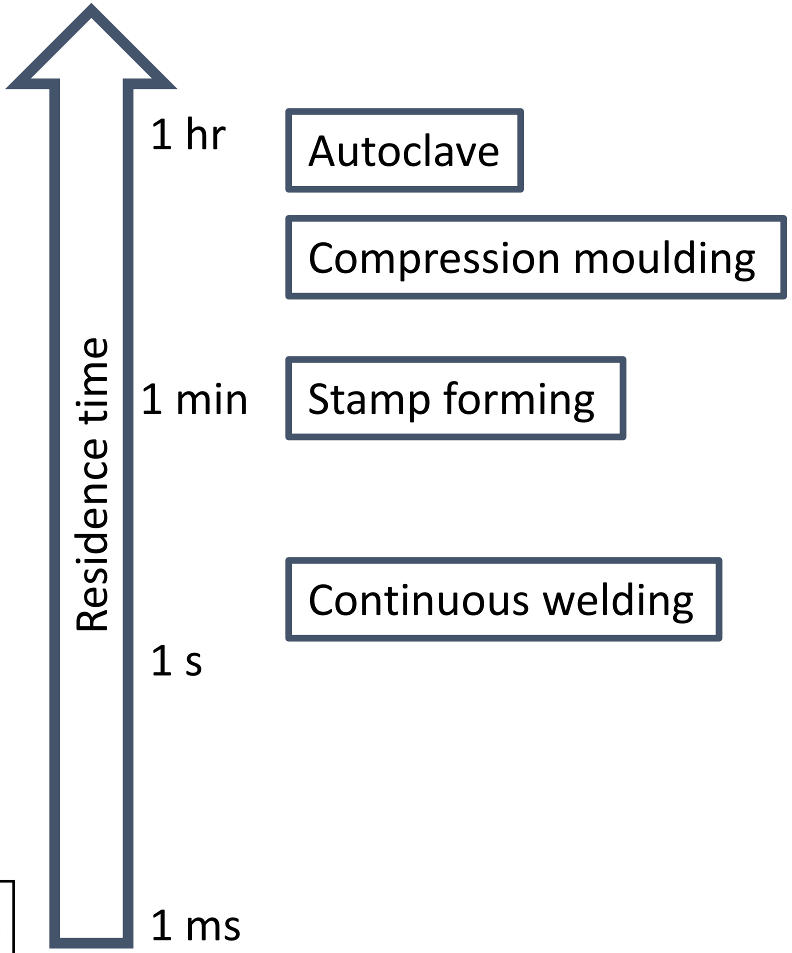


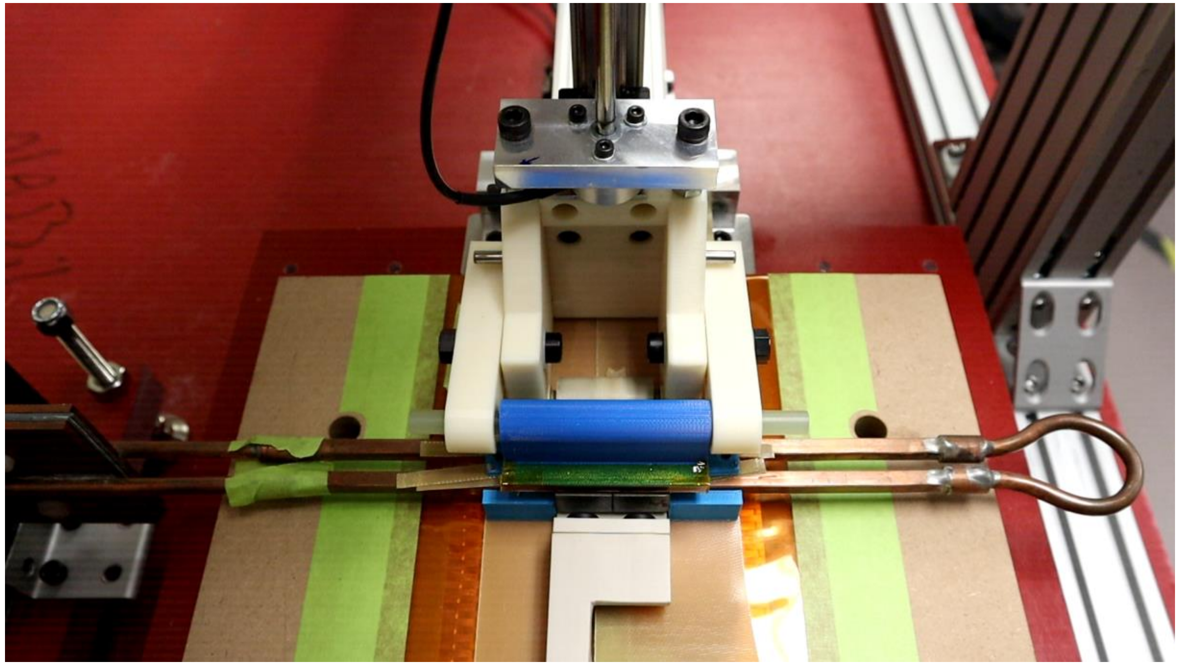


Fuselage clip made of thermoplastic composite

WELDING THEORY

When processing or welding a thermoplastic composite, the time spent at the processing temperature is called the residence time.

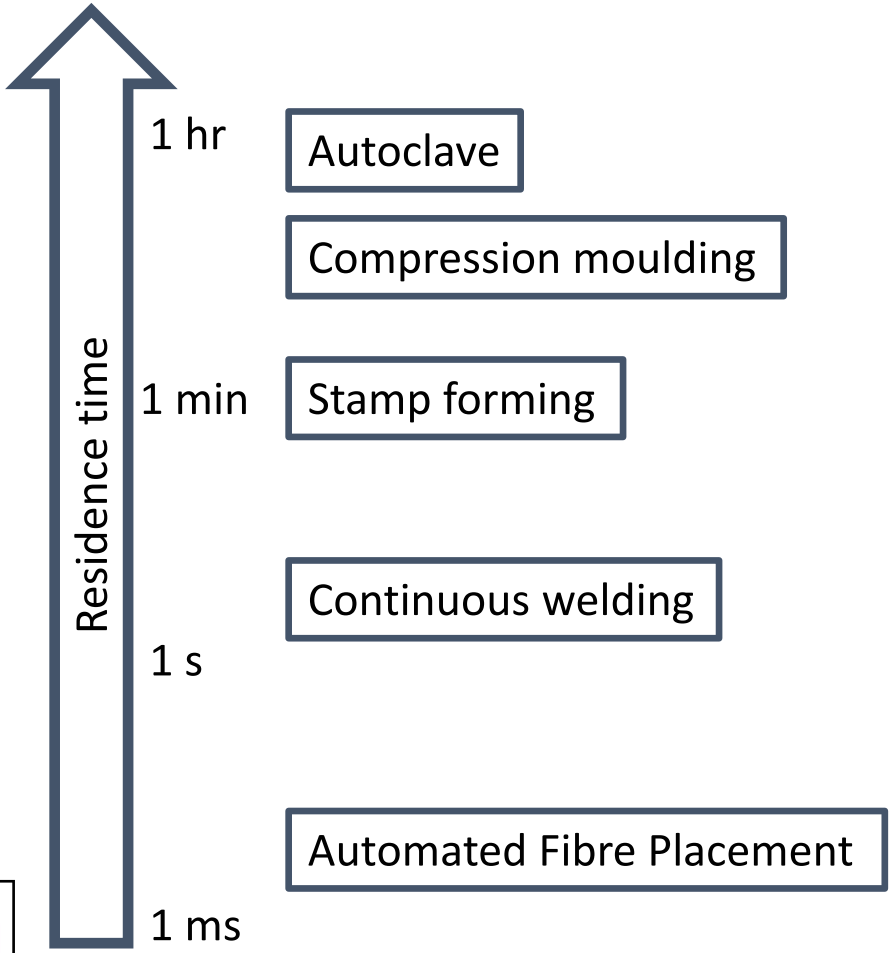


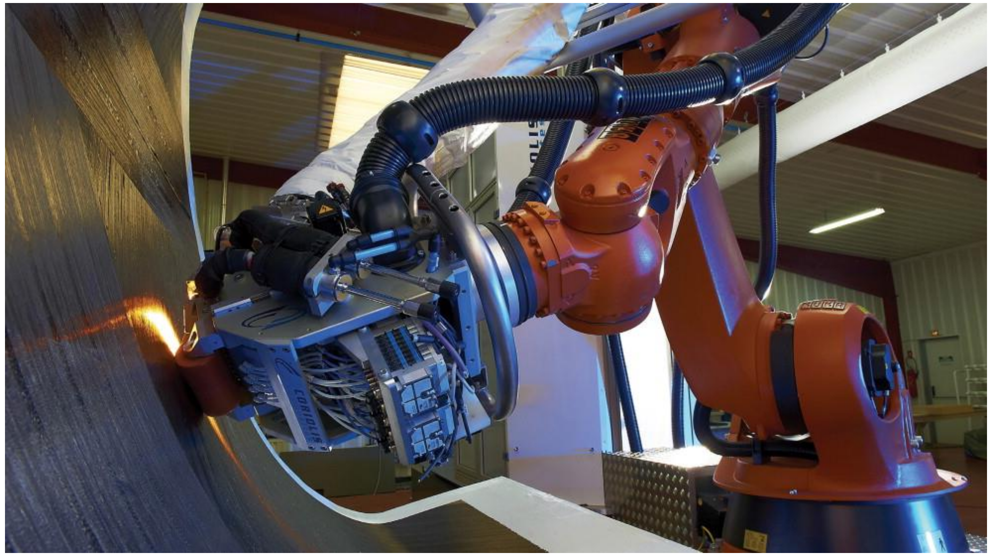


Continuous induction welding of a glass fibre/thermoplastic composite

WELDING THEORY

When processing or welding a thermoplastic composite, the time spent at the processing temperature is called the residence time.



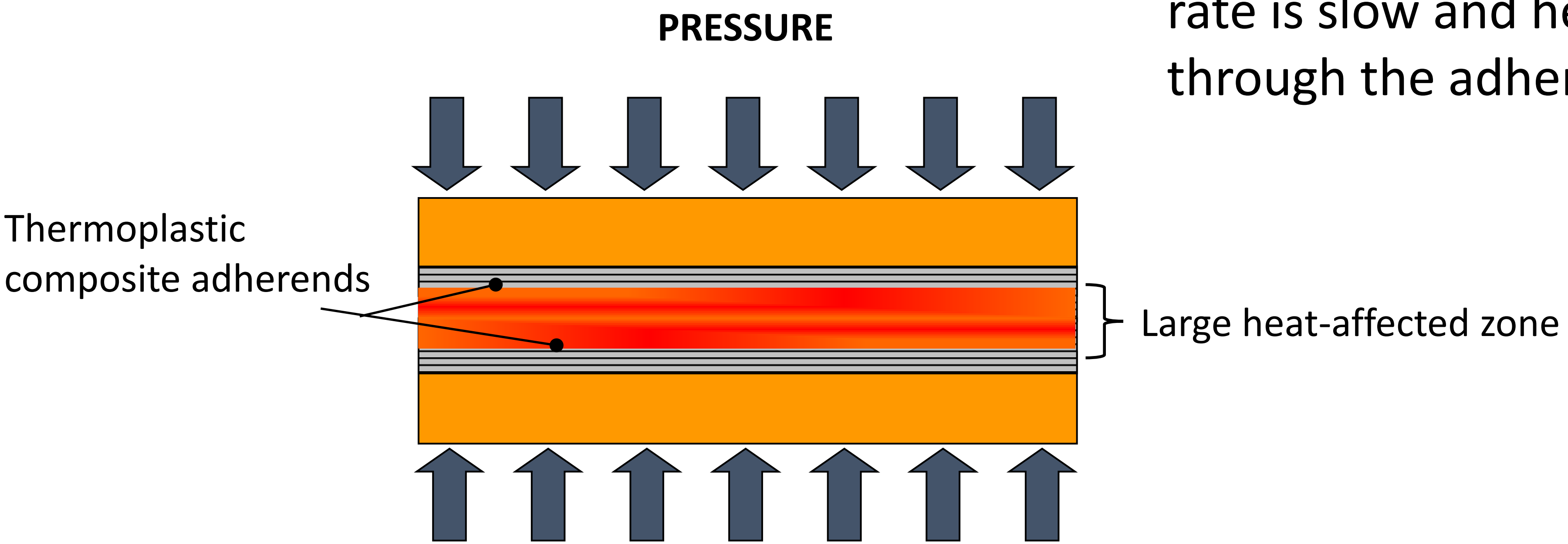


Courtesy of Coriolis

WELDING THEORY

Why do we want welding to be a fast process?

At low input power, the heating rate is slow and heat dissipates through the adherents.

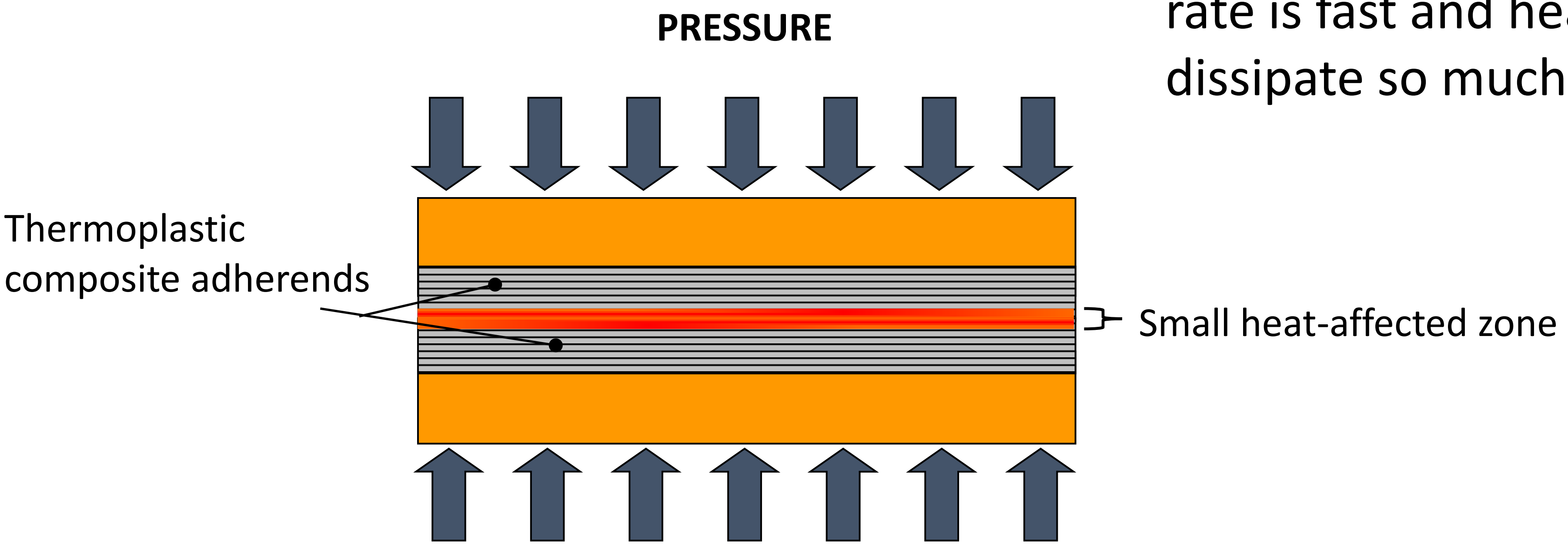


LOW INPUT POWER

WELDING THEORY

Why do we want welding to be a fast process?

At high input power, the heating rate is fast and heat does not dissipate so much in the adherents.

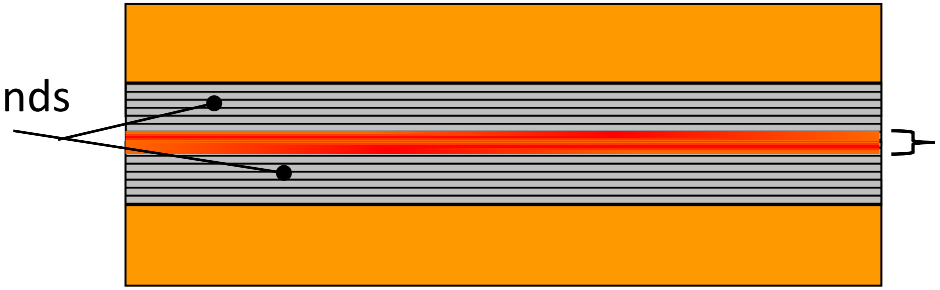


HIGH INPUT POWER

WELDING THEORY

How to make a good weld?

High input power



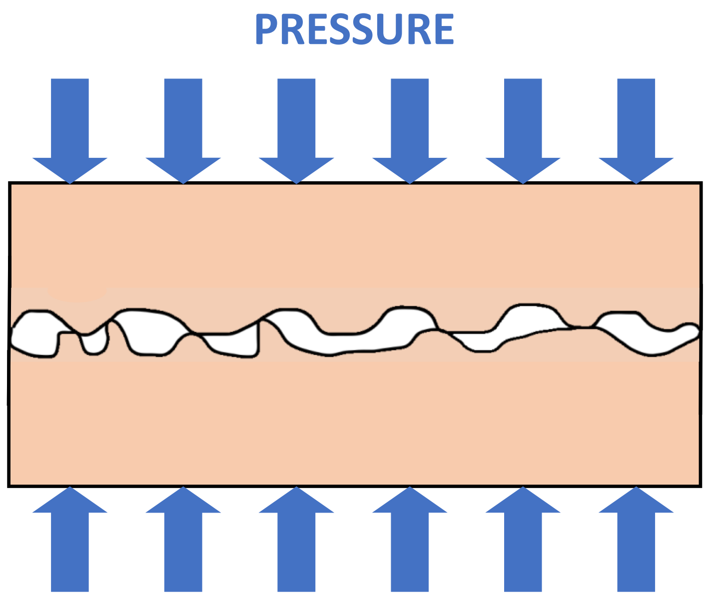
HIGH INPUT POWER

WELDING THEORY

How to make a good weld?

High input power

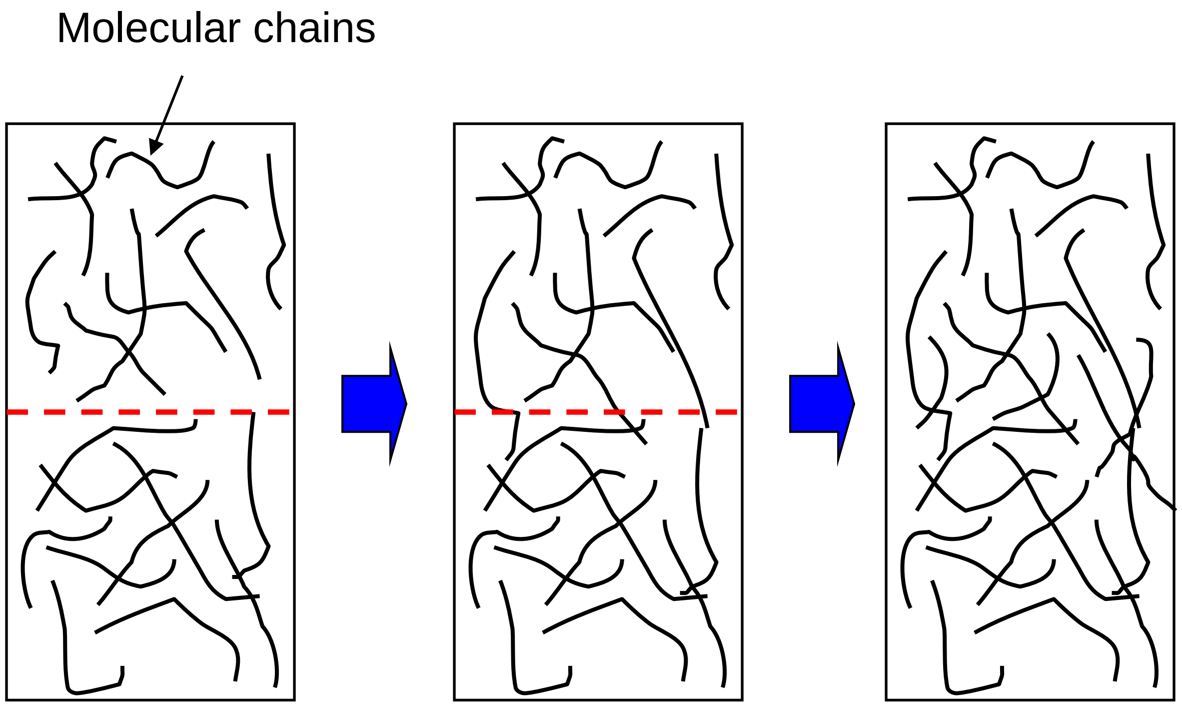
High pressure



Fast development of intimate contact at the weld interface

WELDING THEORY

How to make a good weld?



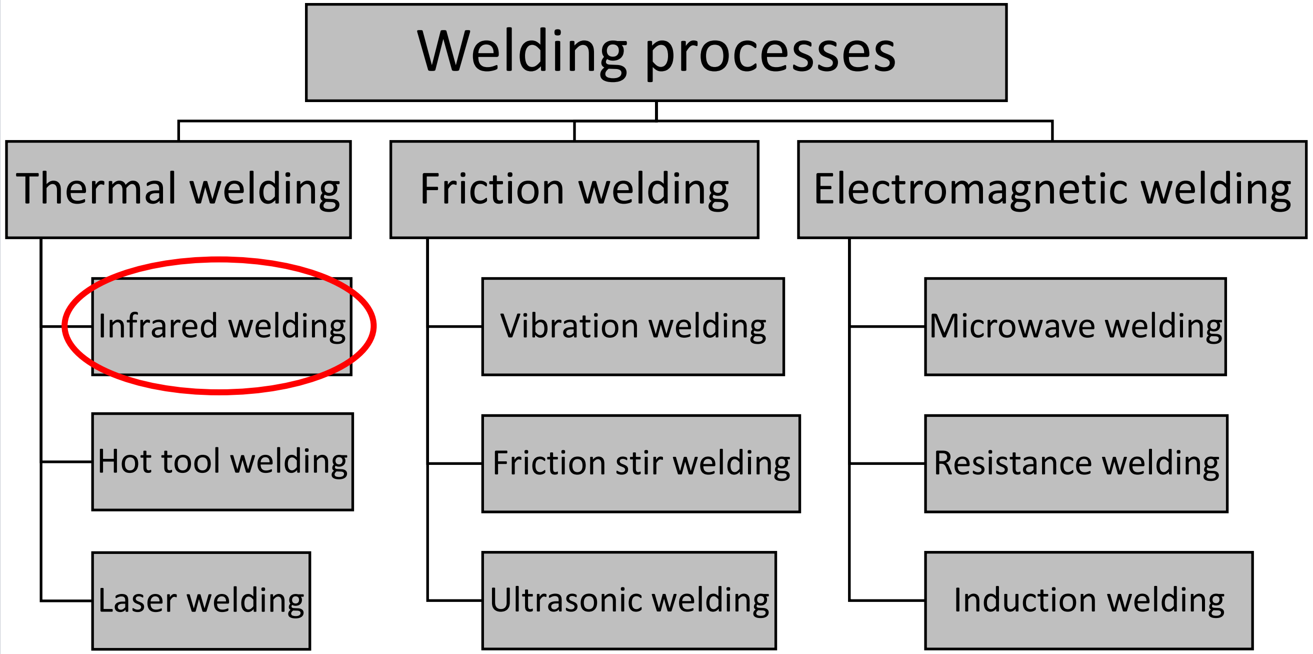
High input power

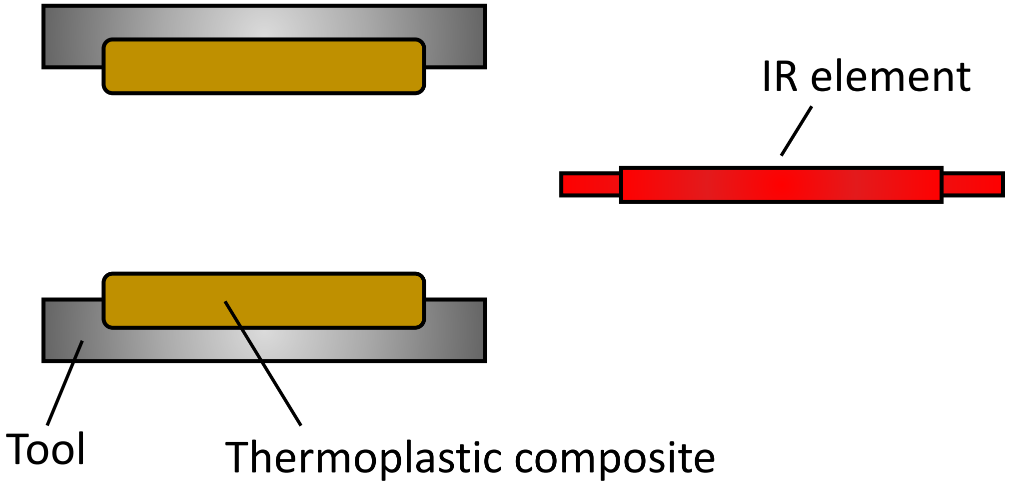
High pressure

High temperature – up to ~ 40°C above the typical autoclave or compression moulding processing temperature

WELDING PROCESSES

Welding processes are classified based on their heat generation mechanism.

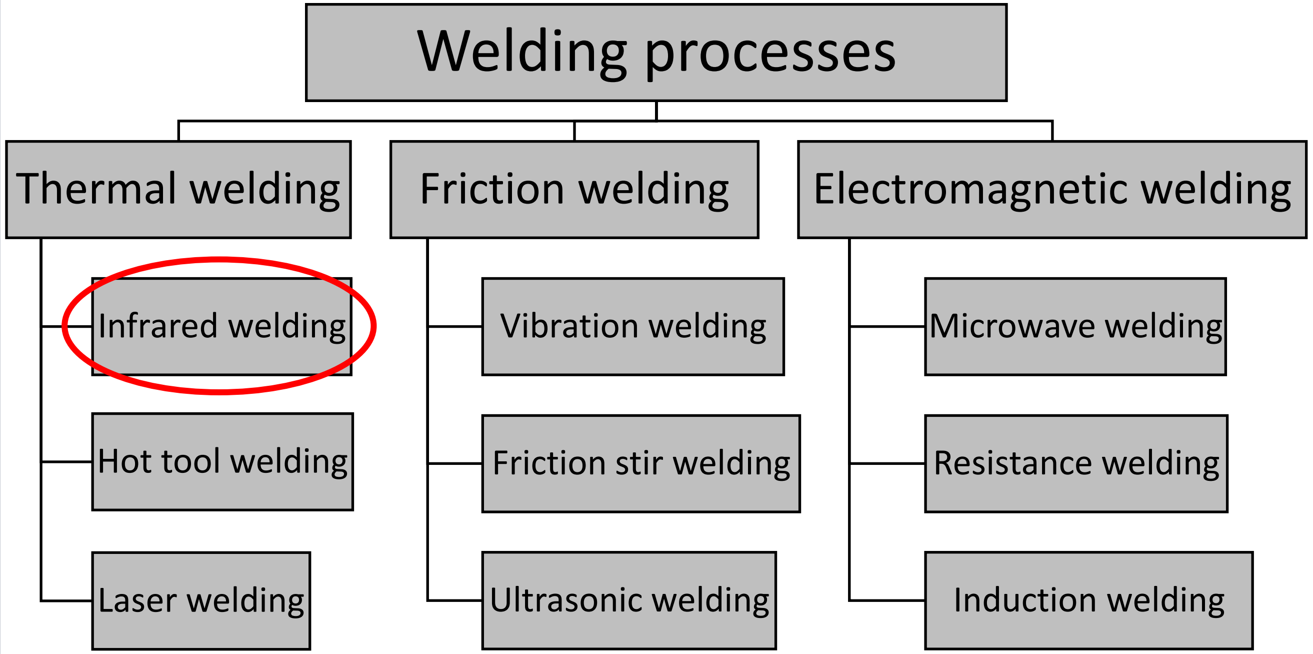


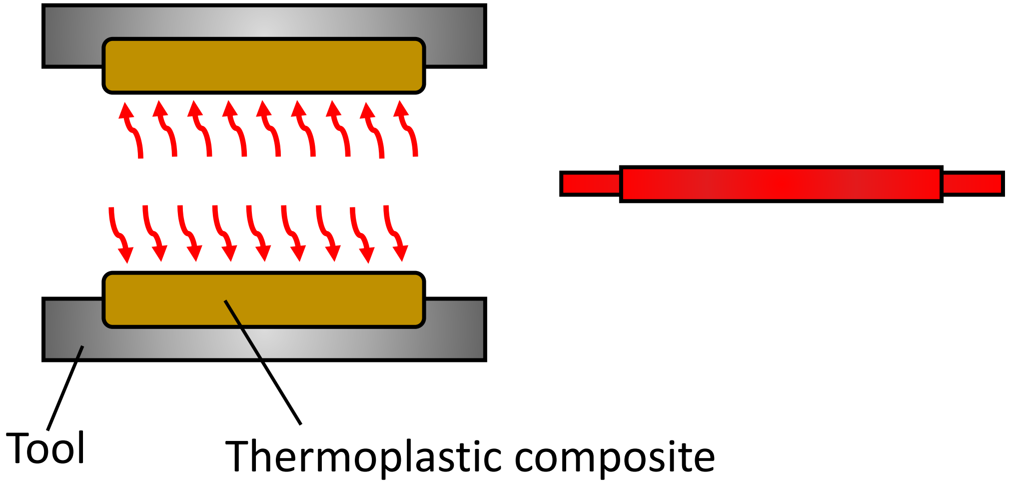


Infrared welding: Step 1

WELDING PROCESSES

Welding processes are classified based on their heat generation mechanism.



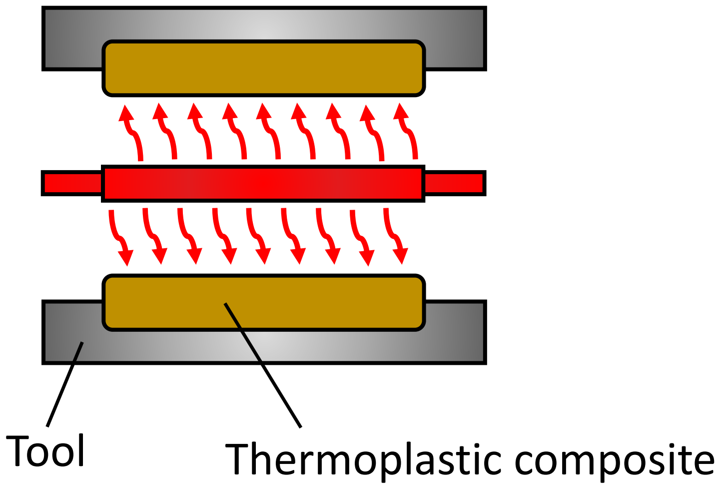


Infrared welding: Step 2

WELDING PROCESSES

Welding processes are classified based on their heat generation mechanism.

- Welding processes
  - Thermal welding
    - Infrared welding
    - Hot tool welding
    - Laser welding
  - Friction welding
    - Vibration welding
    - Friction stir welding
    - Ultrasonic welding
  - Electromagnetic welding
    - Microwave welding
    - Resistance welding
    - Induction welding

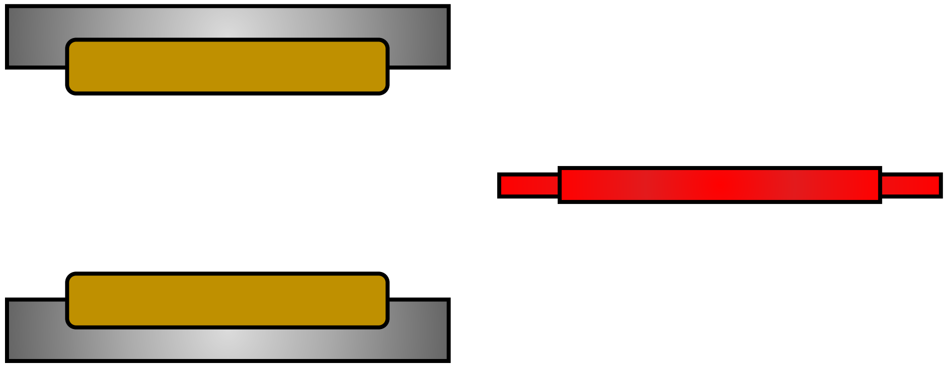


Infrared welding: Step 3

WELDING PROCESSES

Welding processes are classified based on their heat generation mechanism.

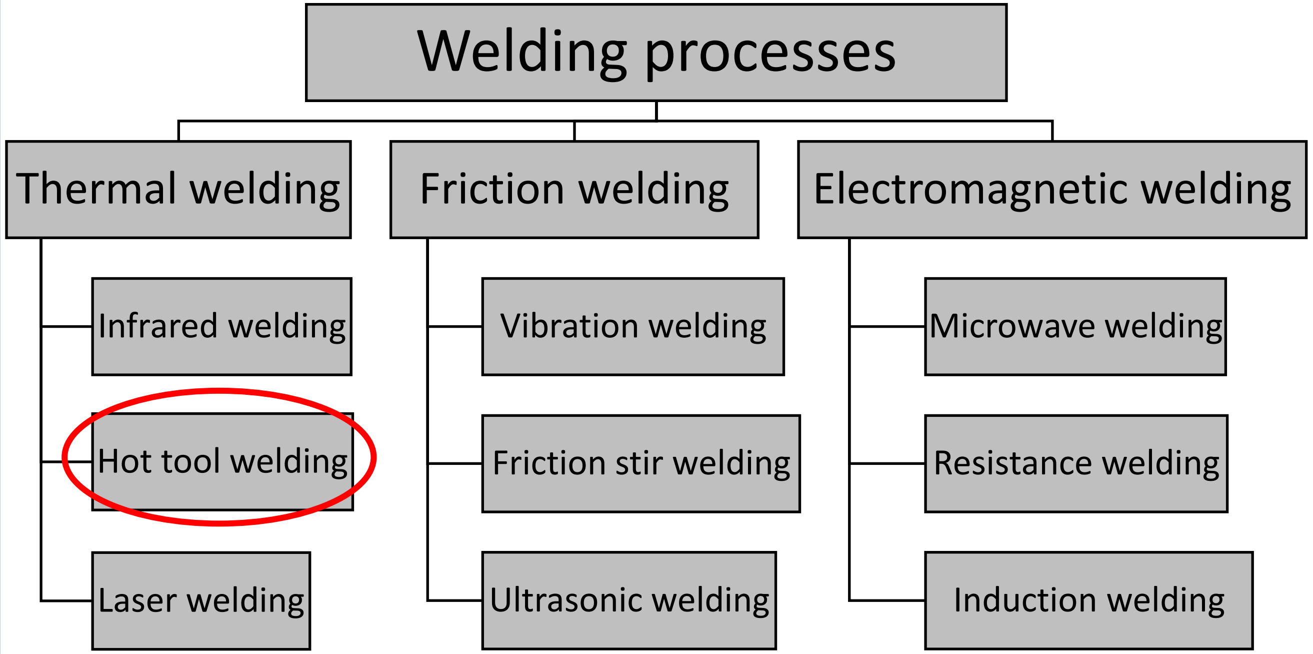
- Welding processes
  - Thermal welding
    - Infrared welding
    - Hot tool welding
    - Laser welding
  - Friction welding
    - Vibration welding
    - Friction stir welding
    - Ultrasonic welding
  - Electromagnetic welding
    - Microwave welding
    - Resistance welding
    - Induction welding

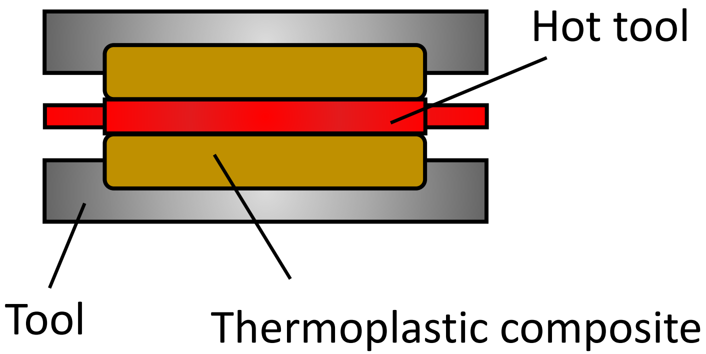


Infrared welding: Step 4

WELDING PROCESSES

Welding processes are classified based on their heat generation mechanism.

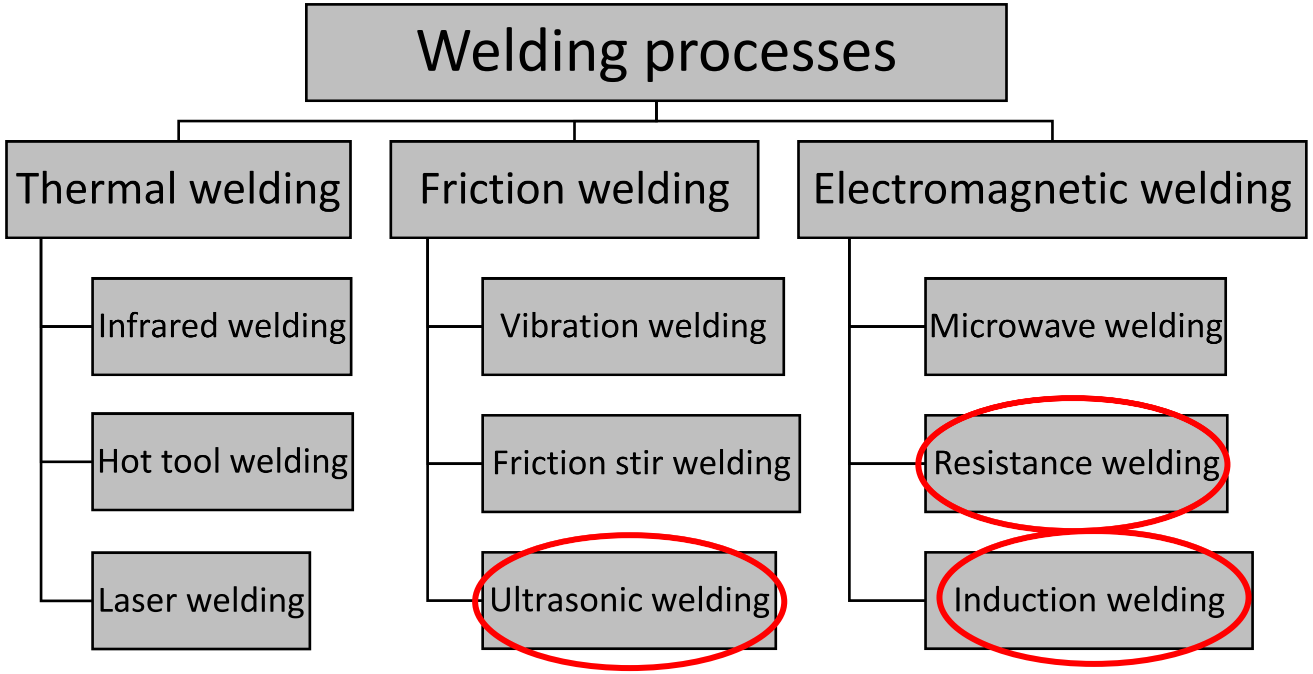




Hot tool welding

WELDING PROCESSES

Welding processes are classified based on their heat generation mechanism.



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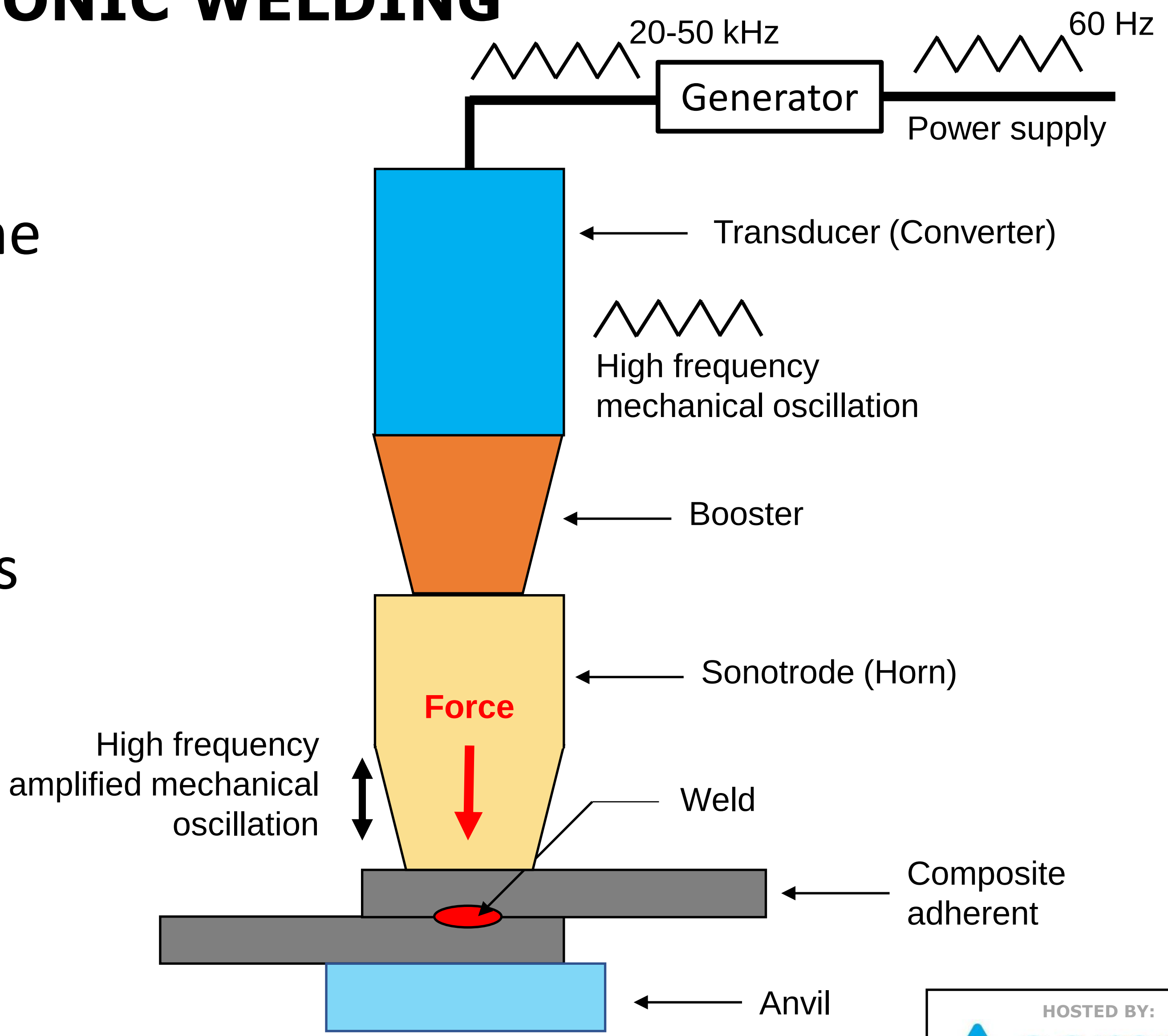
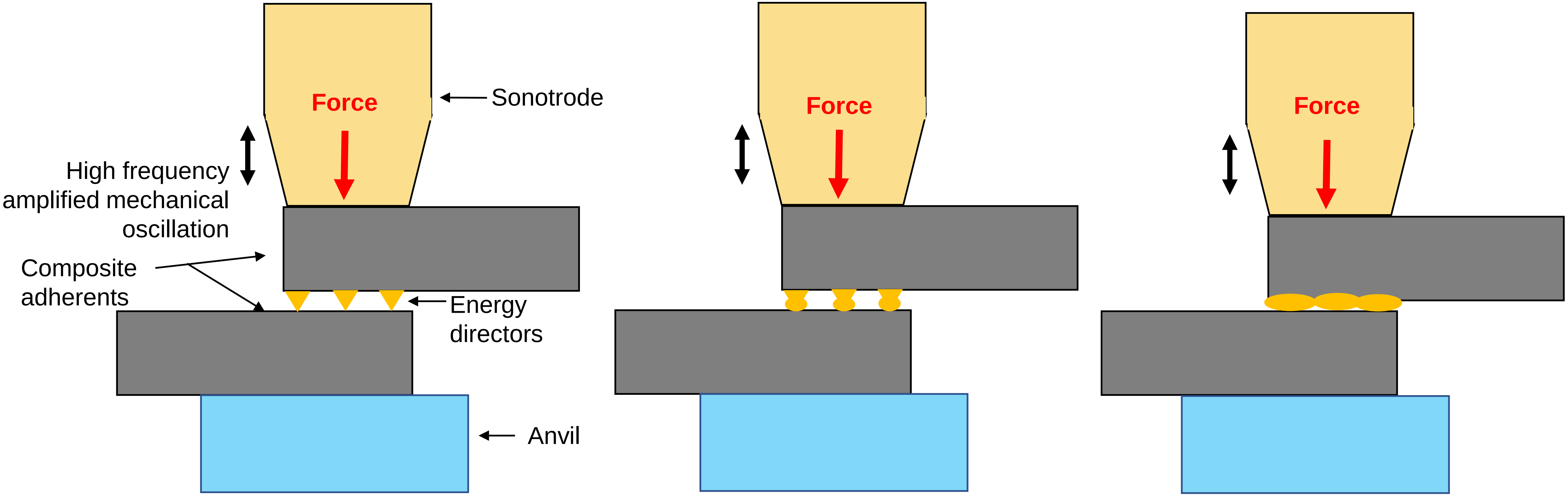
ULTRASONIC WELDING

- A high frequency mechanical oscillation is transmitted to the top composite adherent.
- The polymer located at the interface heats up and softens (or melts).



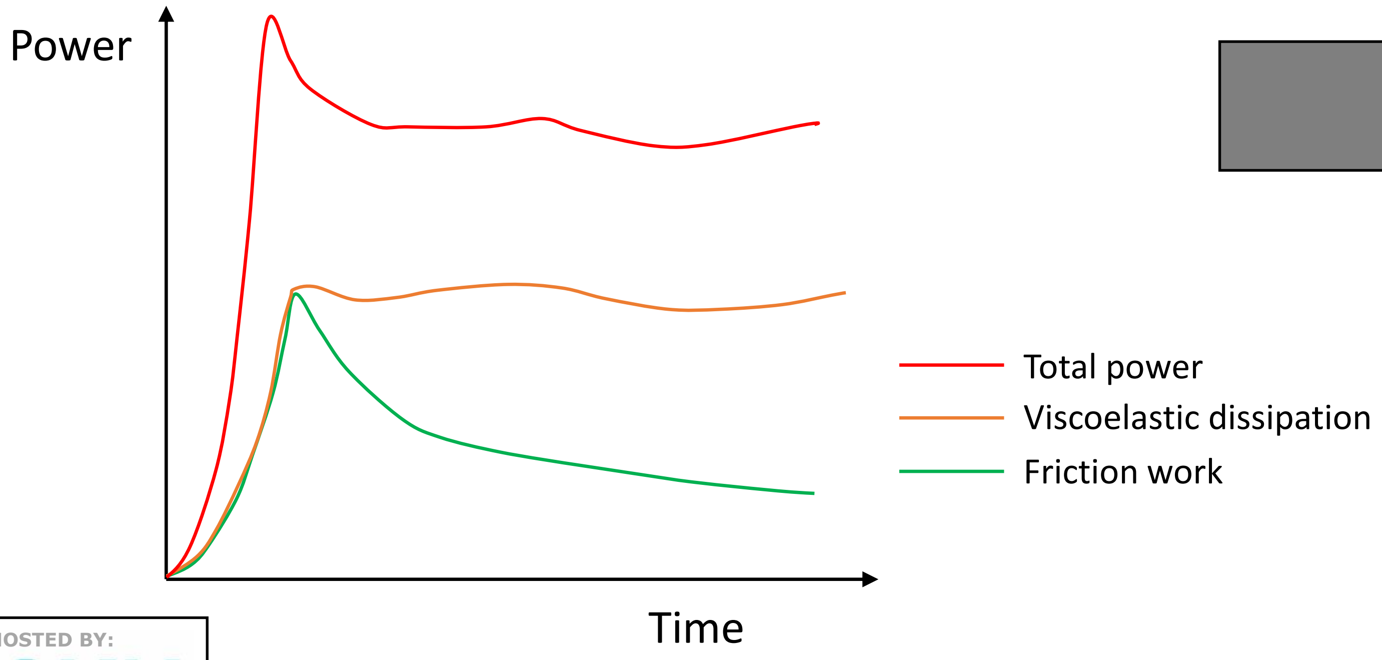
ULTRASONIC WELDING

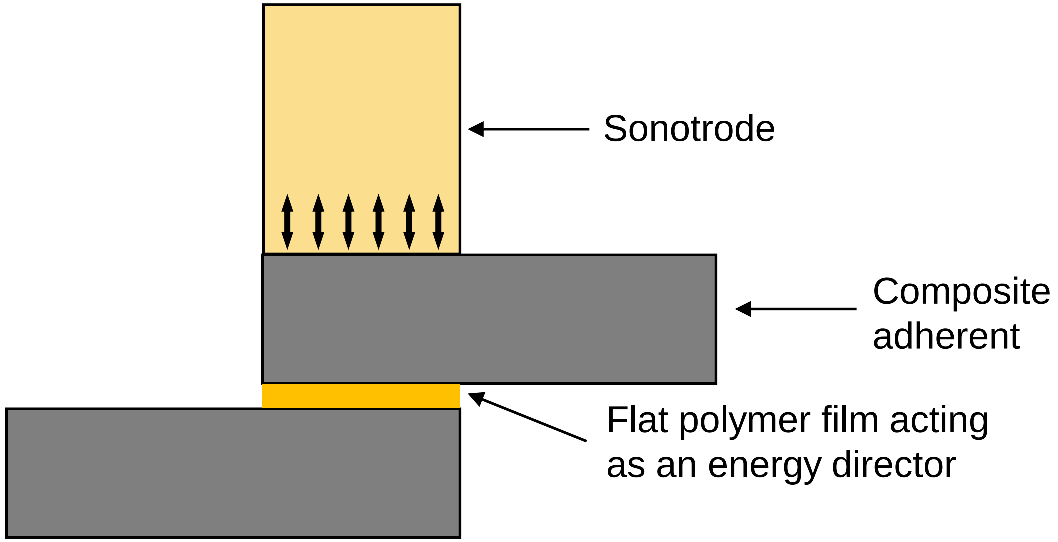
- Energy directors are man-made resin protrusions that concentrate heat production at the weld interface.



ULTRASONIC WELDING

- Heating is produced by two mechanisms:
  - Friction work (Coulomb friction)
  - Viscoelastic dissipation

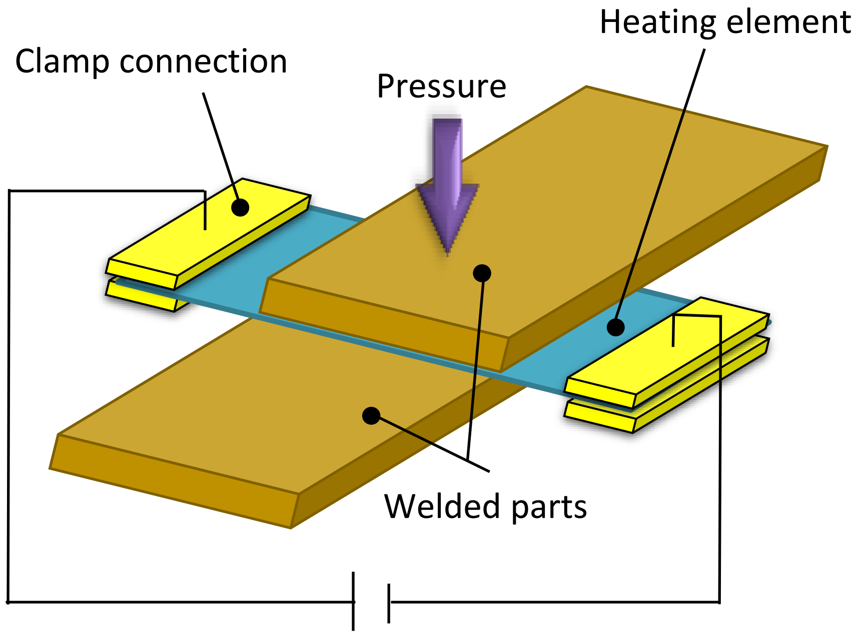


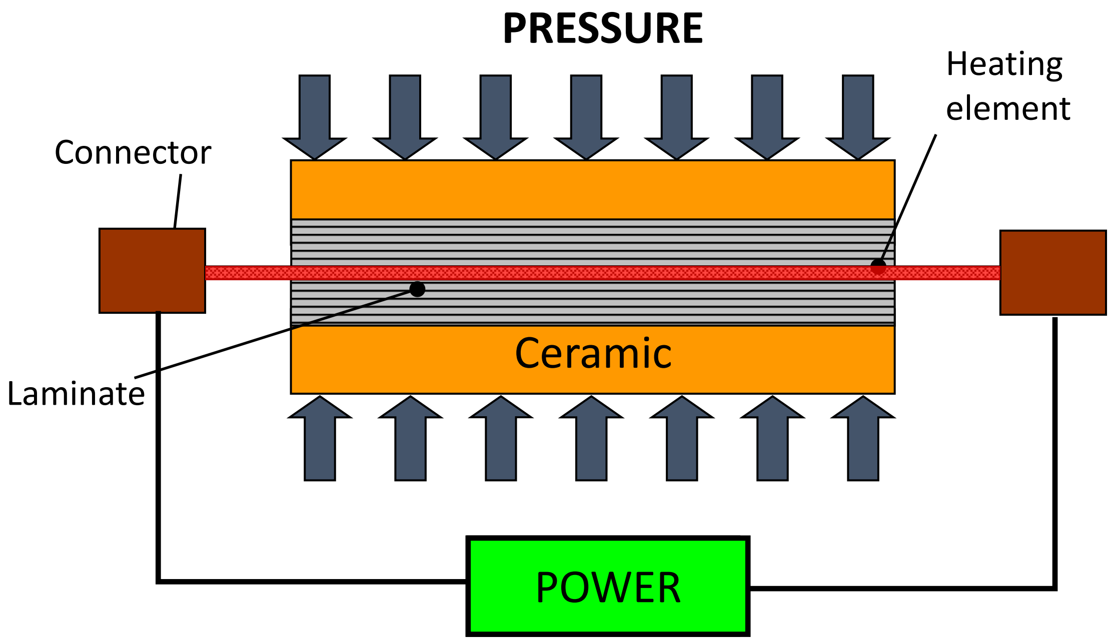


ULTRASONIC WELDING – PROS AND CONS

PROS	CONS
Very fast process	Need a physical contact between the adherent and the sonotrode (heating and pressure application)
Possibility to be made continuous	Possible non uniform heating (edge effects) due to thermal boundary conditions
Possibility to be automated	Simulation more complex than for other processes
No foreign material is left at the weld interface (energy director can be made of polymer film)	

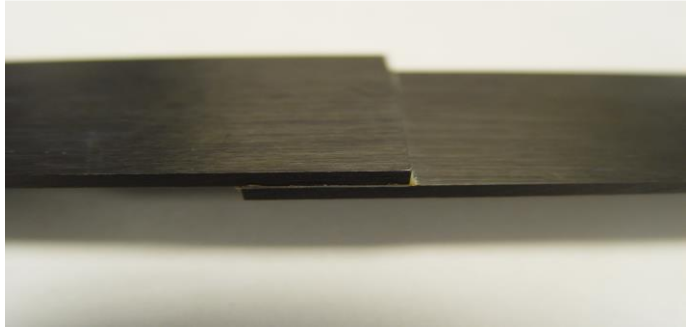
RESISTANCE WELDING



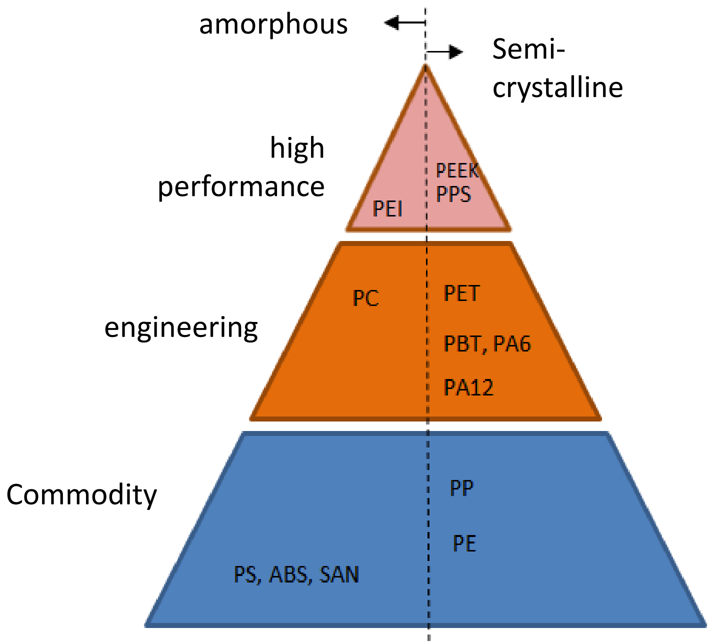


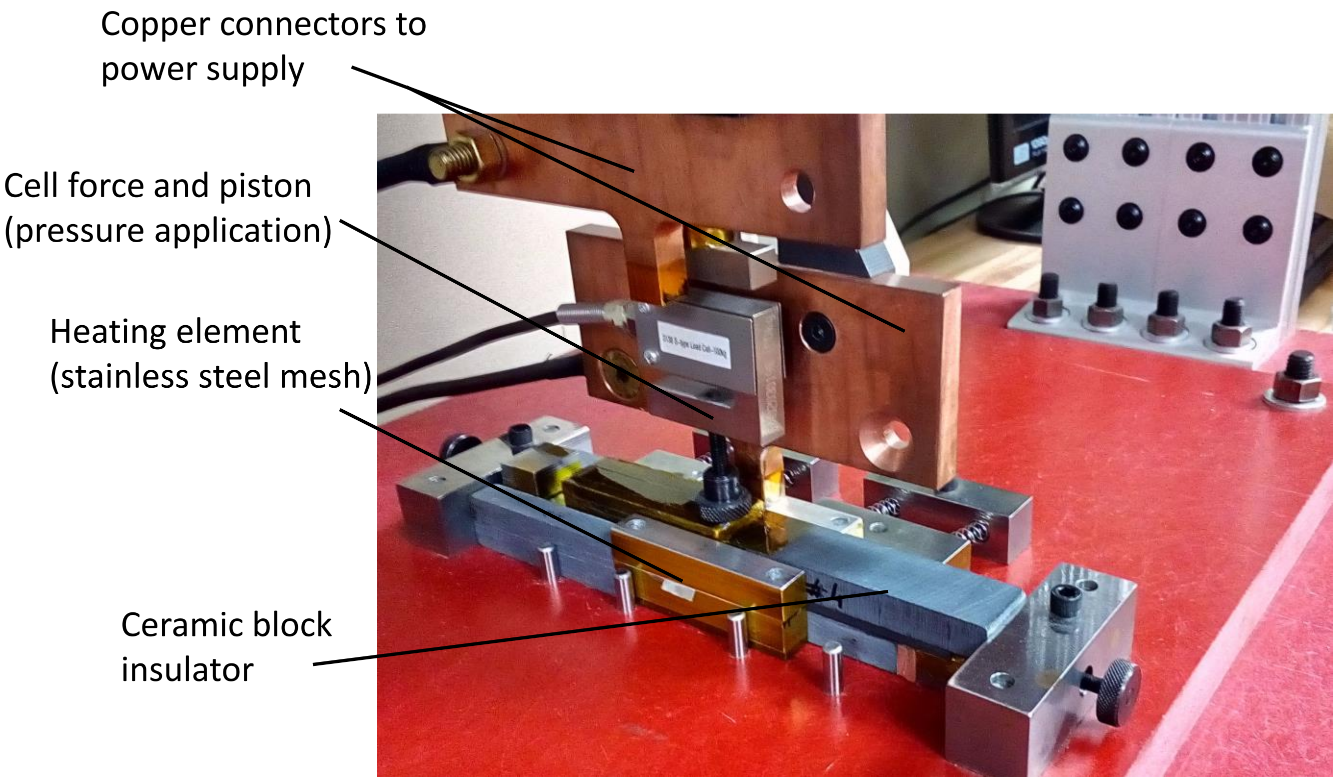
Vincent Rohart, ÉTS, 2020

RESISTANCE WELDING



CF/PEEK lap shear joint made by resistance welding





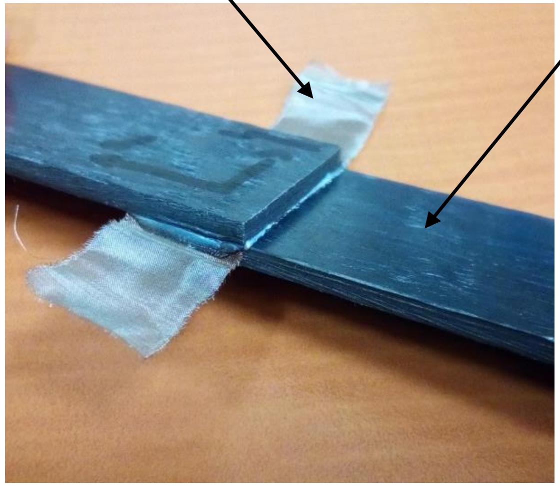
Resistance welding set-up (static)

Vincent Rohart, ÉTS, 2020

RESISTANCE WELDING

Stainless steel mesh heating element

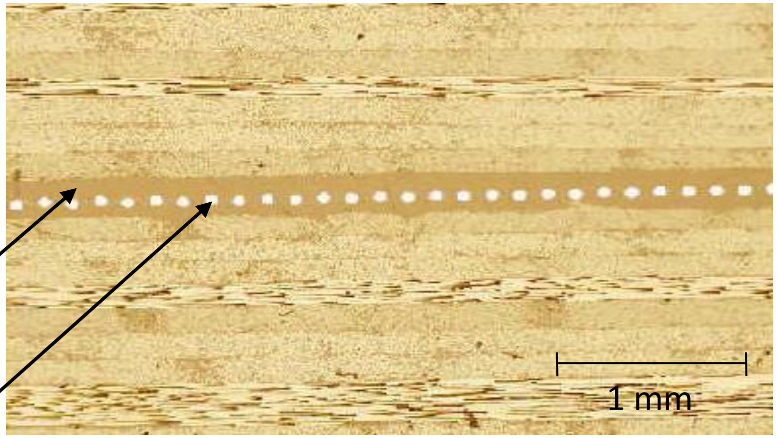
Thermoplastic composite adherent



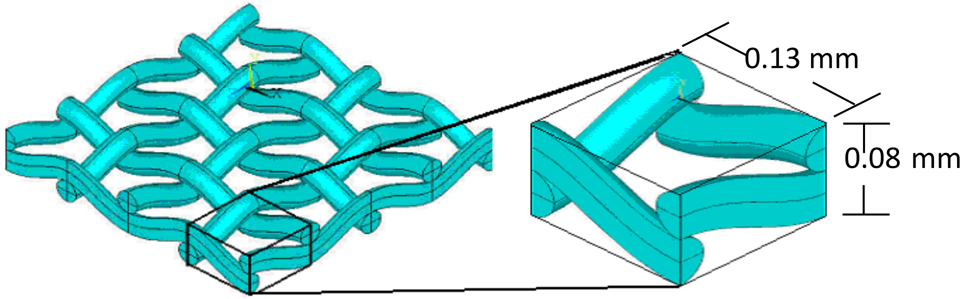
Thermoplastic composite welded joint

PEEK polymer

Heating element

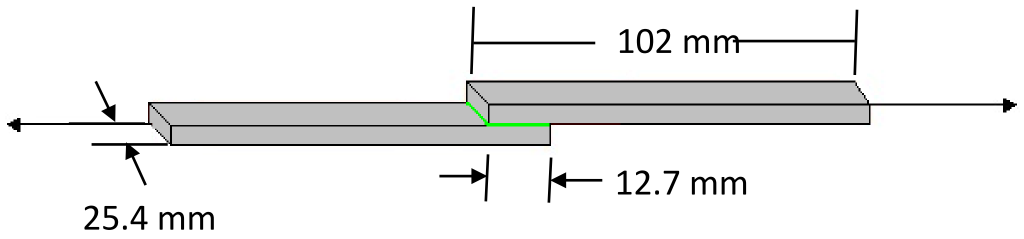


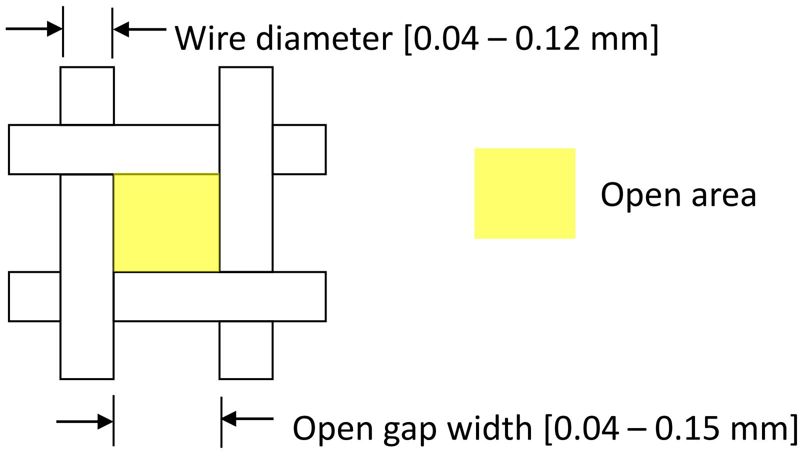
Weld interface of a CF/PEEK specimen

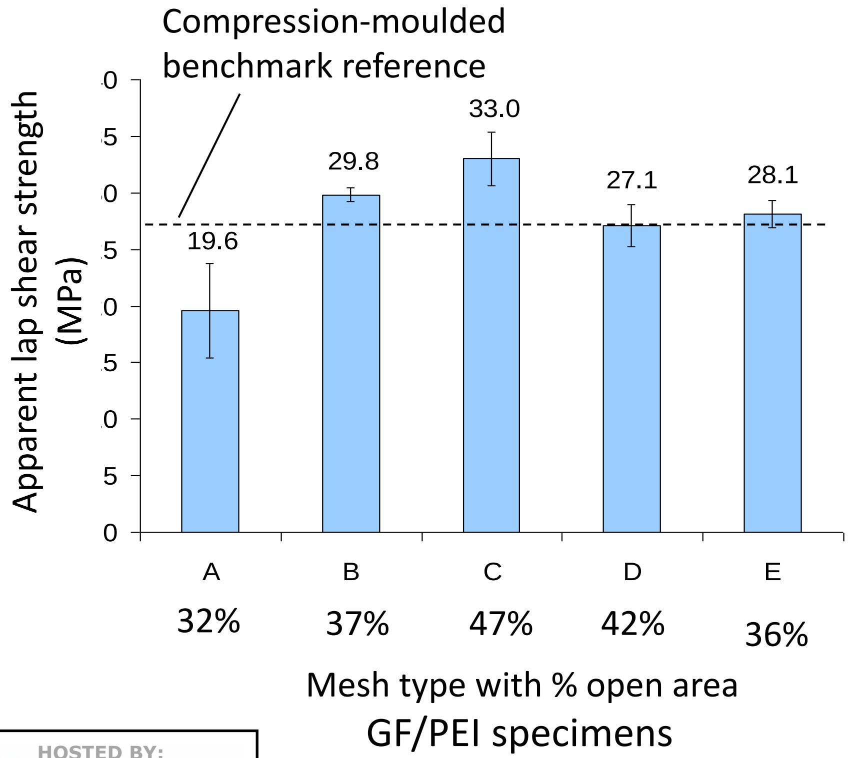


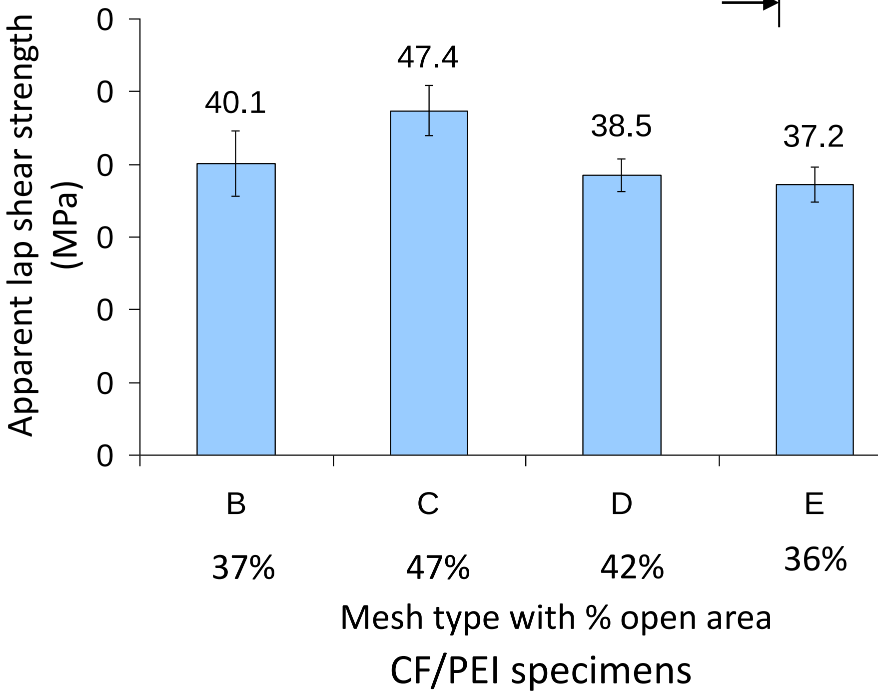
Heating element typical dimensions

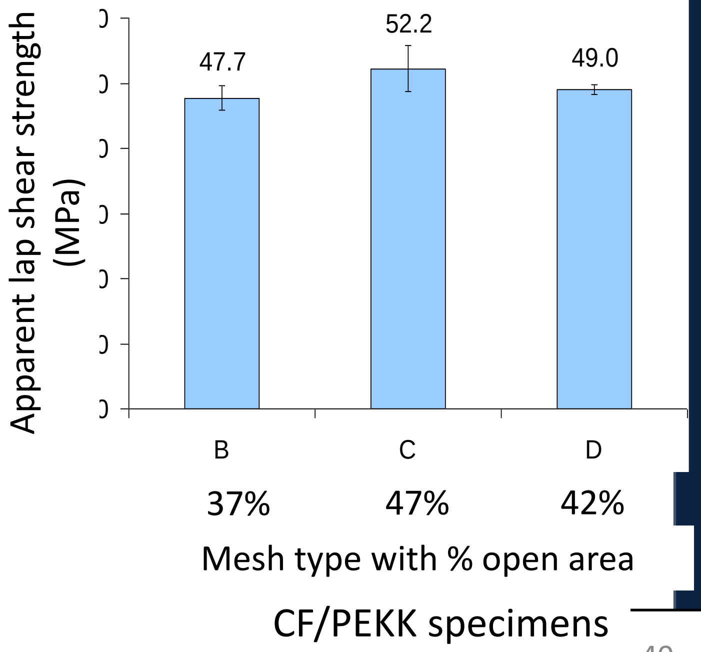
RESISTANCE WELDING



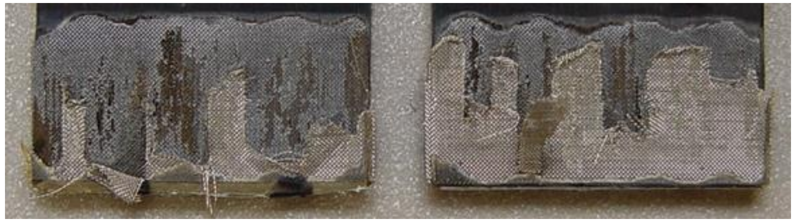








RESISTANCE WELDING – EDGE EFFECTS



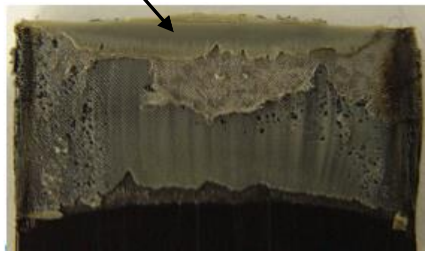
Better temperature homogeneity and better mechanical performance

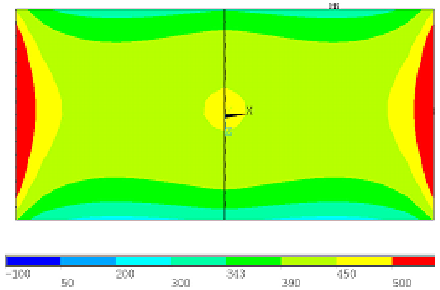
Facture surfaces of a lap shear CF/PEKK specimen

A full glass fibre ply was removed from one adherent during lap shear test

Example of a fracture surface of a GF/PEI specimen

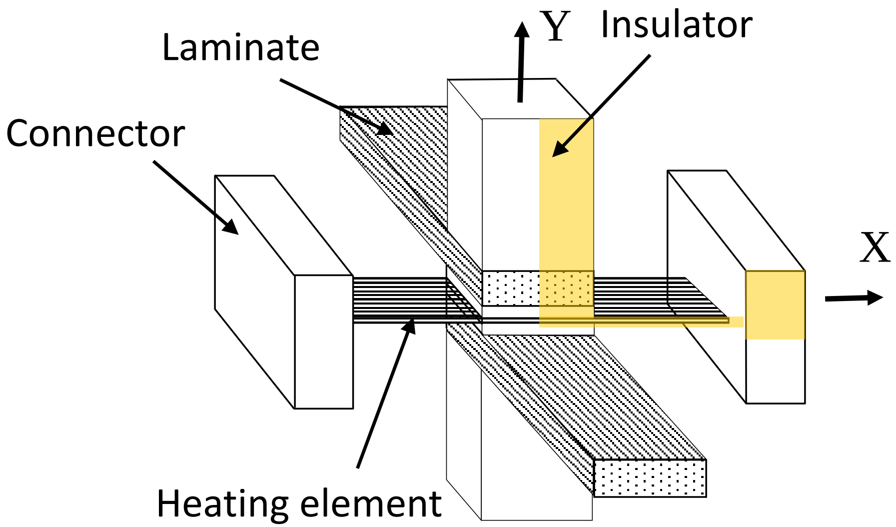
Un-melted polymer





Non uniform heating and poor welding

Example of edge effect: Facture surfaces of a lap shear CF/PEEK specimen



Schematic of a resistance welding set-up

Talbot et al., 2013

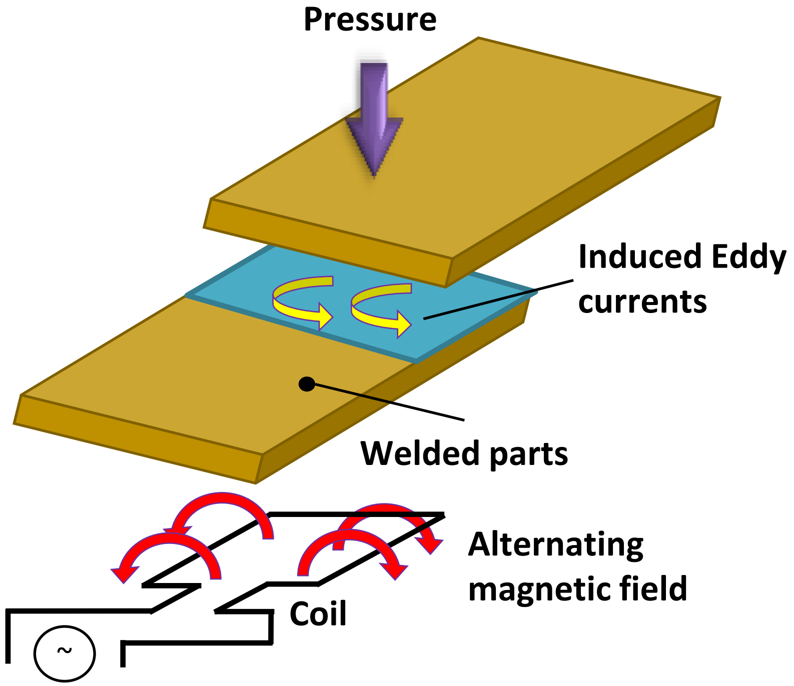
RESISTANCE WELDING – PROS AND CONS

PROS	CONS
Fast and simple process	Implant (heating element) remains at the weld interface
Possibility to be made continuous	Need a physical contact between the heating element and the power supply
Possibility to be automated	Possible non uniform heating (edge effects) due to heat transfer boundary conditions

INDUCTION WELDING

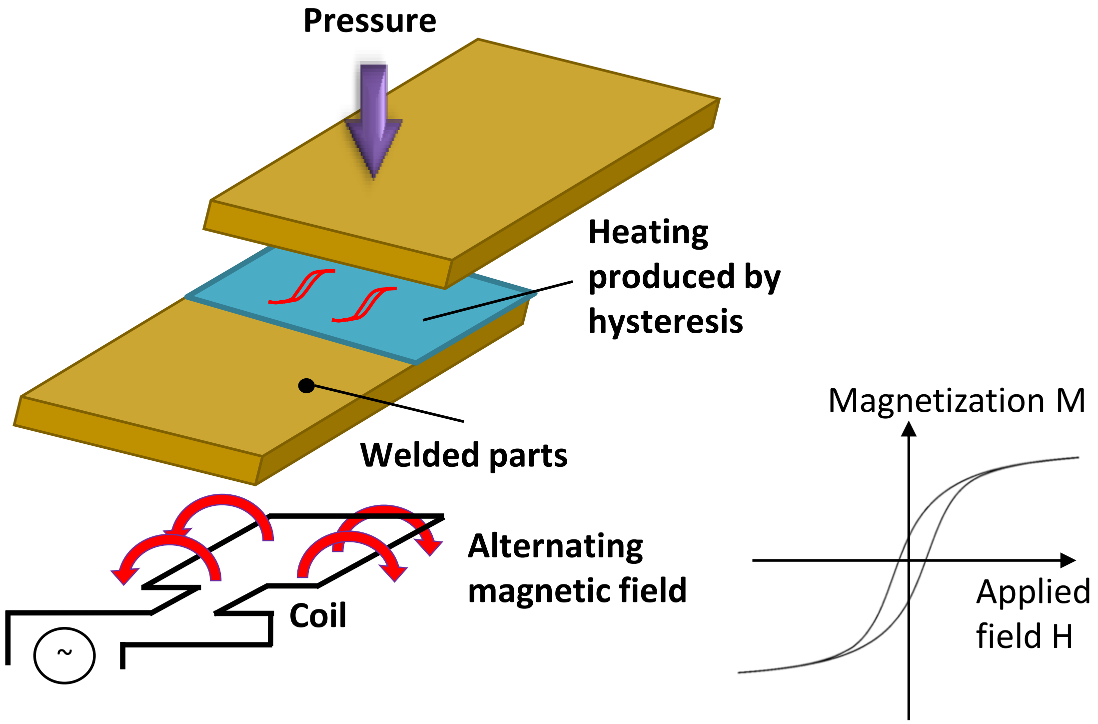
Heat is generated by an alternating magnetic field produced by a coil. Heat can be generated by two mechanisms: Eddy currents and Hysteresis.

Eddy currents



Heat is produced by **Eddy currents** induced in an **electrically conductive heating element**

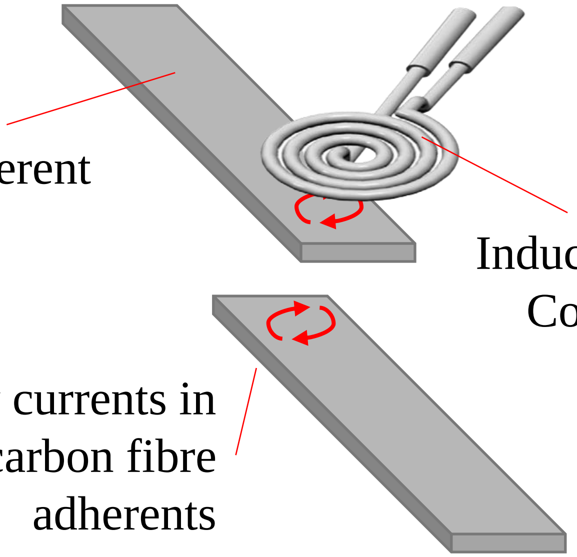
Hysteresis



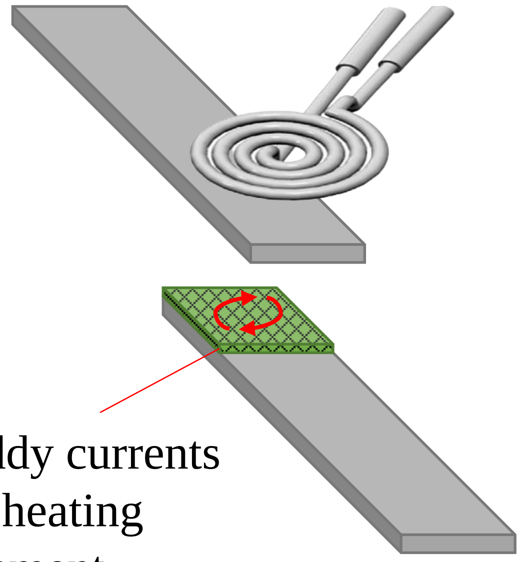
Heat is produced by **hysteresis** in an **electromagnetic susceptor**

INDUCTION WELDING

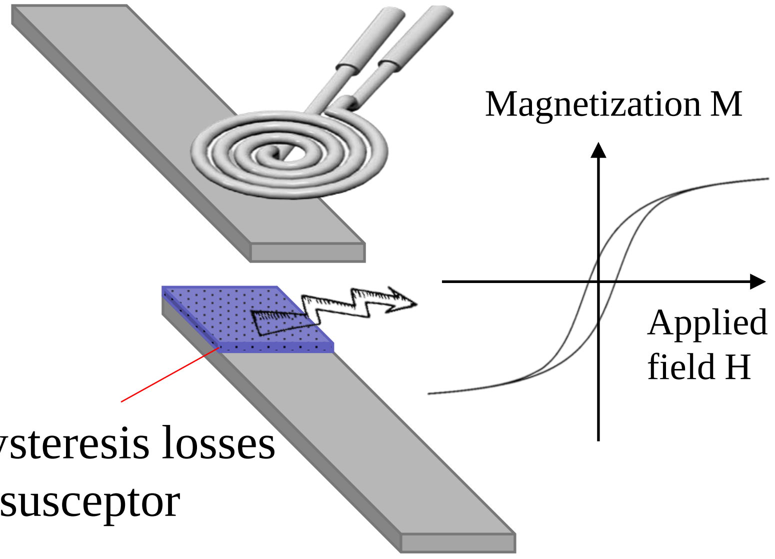
- Eddy currents in the carbon fibre adherents



- Eddy currents in an electrically-conductive heating element



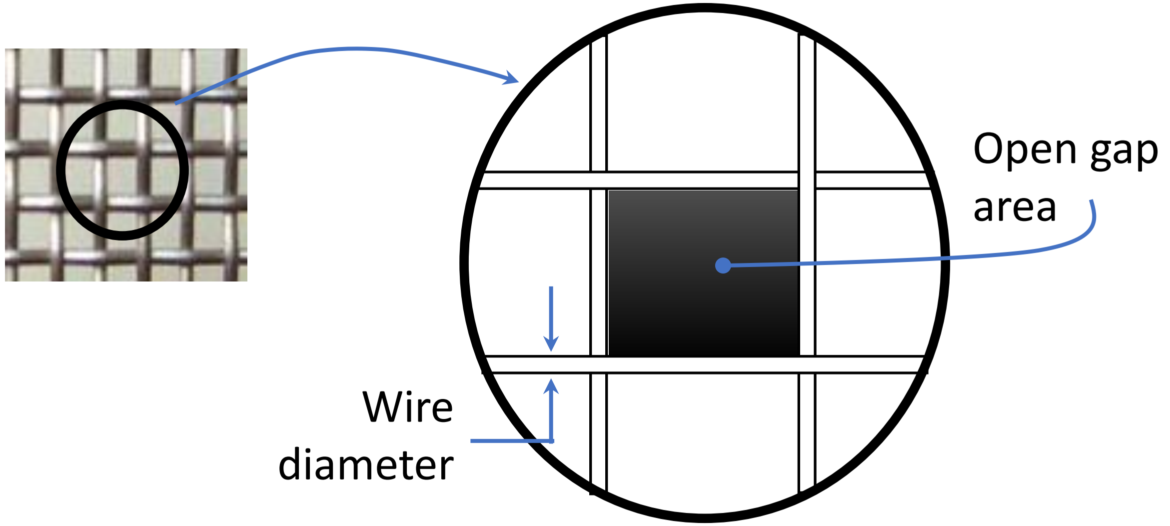
- Hysteresis losses in a magnetic susceptor



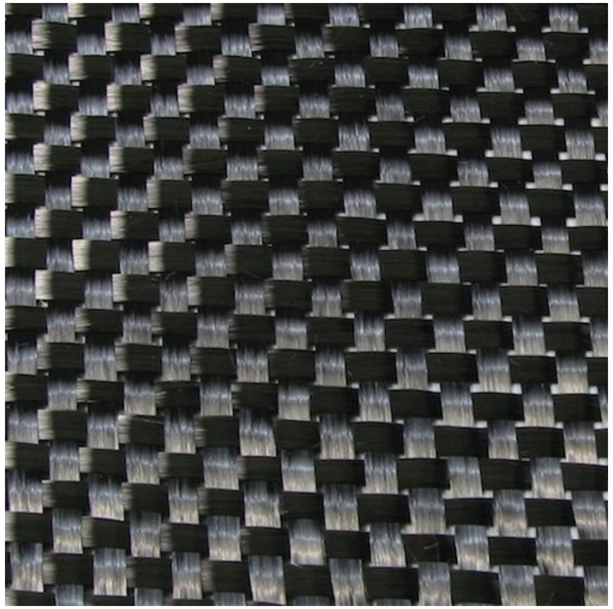
Romain Martin, ÉTS, 2022

INDUCTION WELDING

Heating based on induced Eddy currents



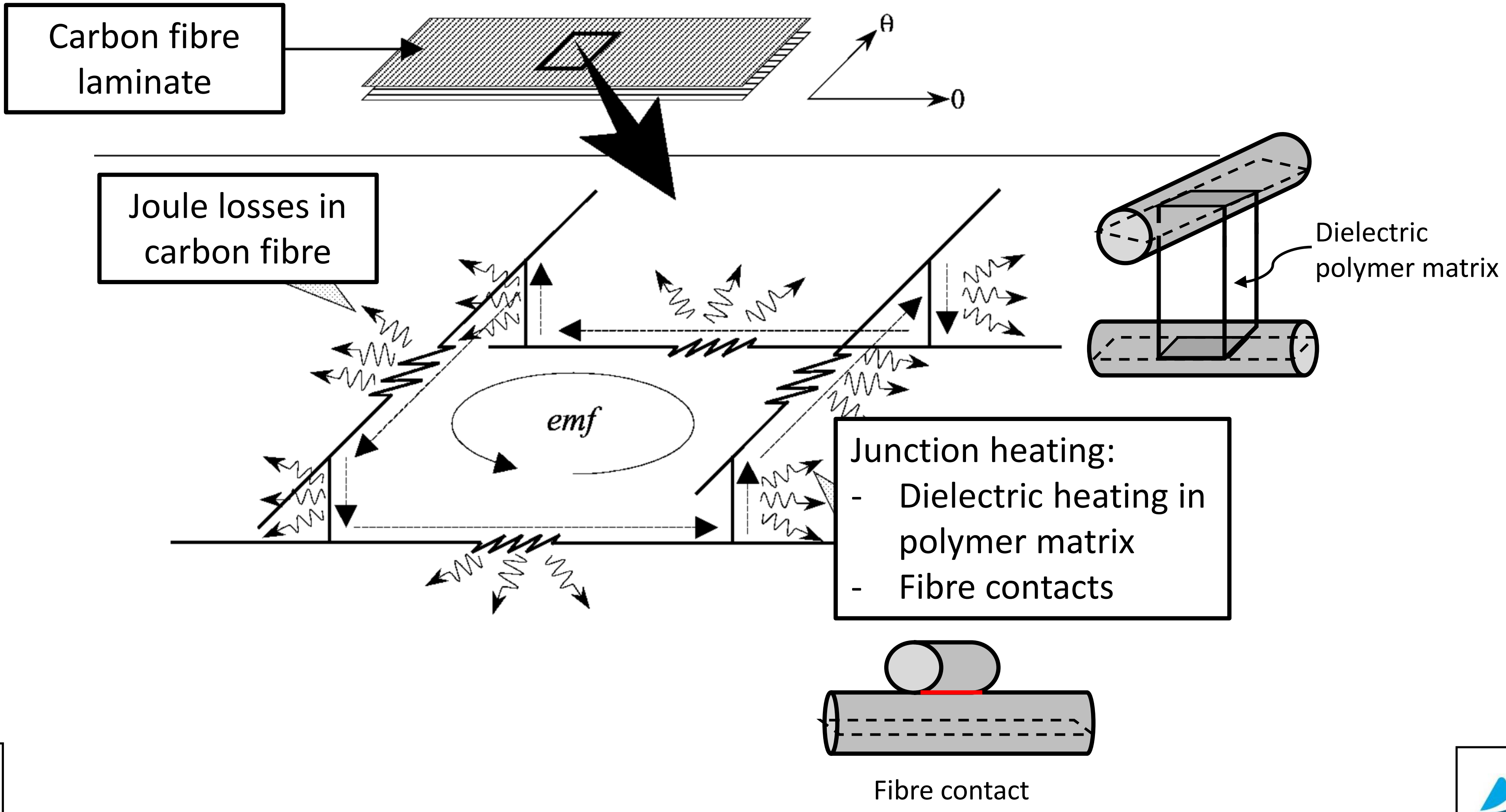
Heating element made of an electrically-conductive metal mesh



Carbon fibre ply (Composite adherent)

INDUCTION WELDING

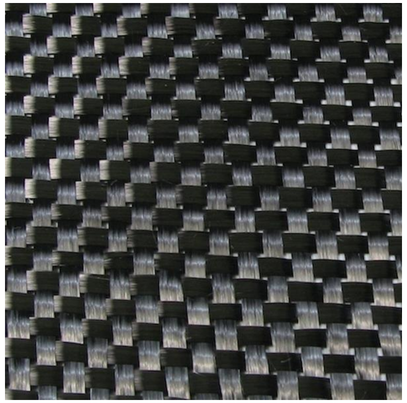
Heating based on induced Eddy currents



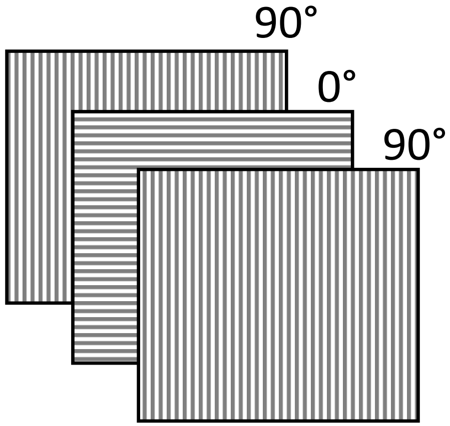
INDUCTION WELDING

Eddy currents generation

A carbon fibre fabric (e.g. plain weave) is ideal for eddy currents generation



Eddy currents can also be induced in a laminate composed of UD CF plies, provided a proper plies stacking sequence



HOSTED BY: CKN Composites Knowledge Network

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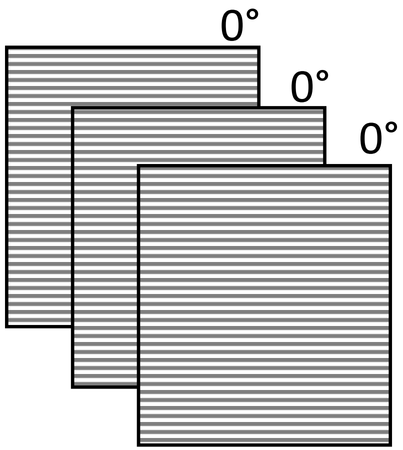
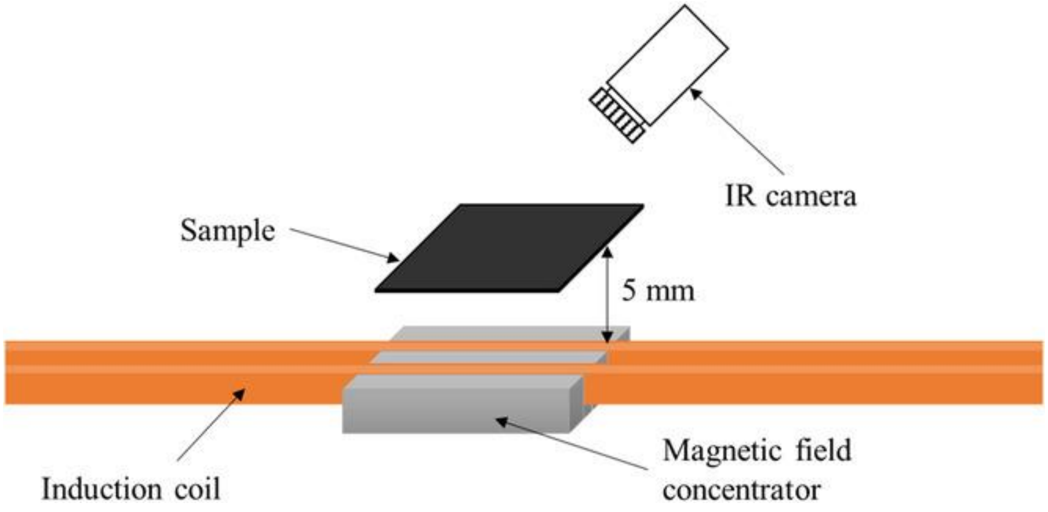
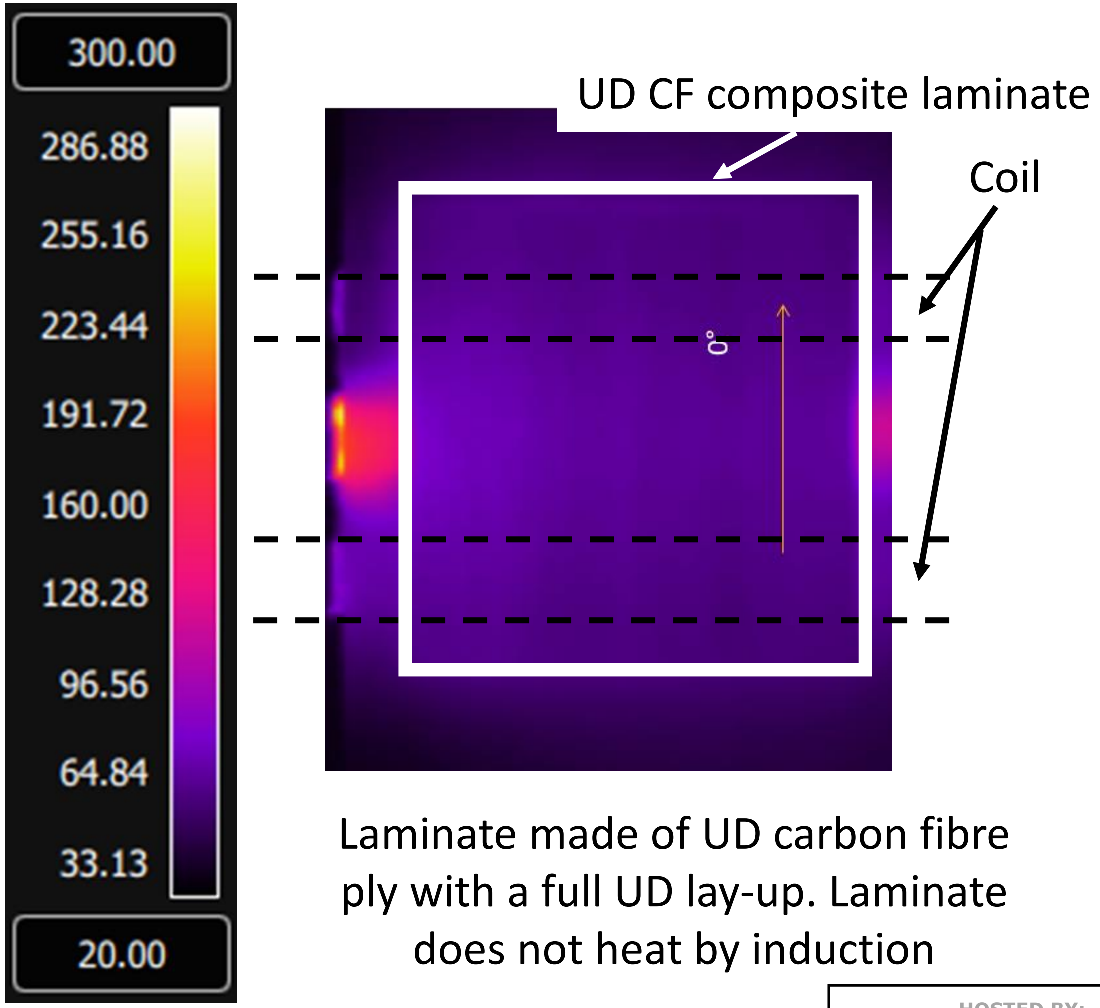
INDUCTION WELDING

Eddy currents generation

Eddy currents will not be induced in a fully UD laminate and heat will not be generated



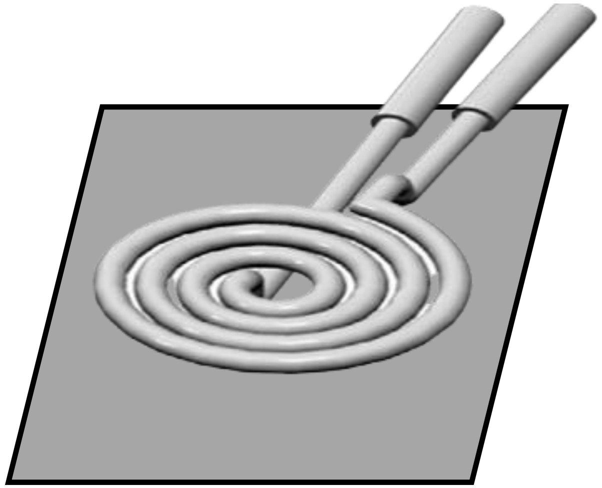




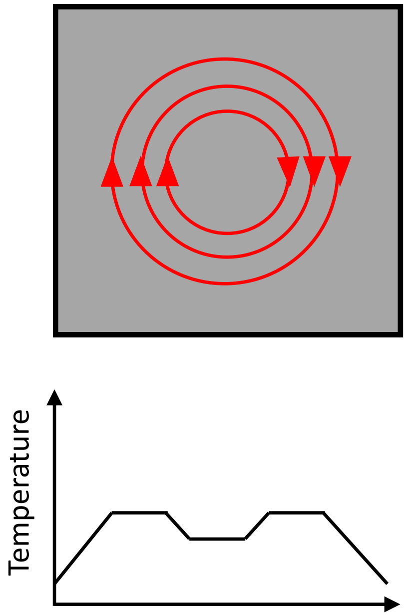
Laminate made of UD carbon fibre ply with a full UD lay-up. Laminate does not heat by induction

Romain Martin, ÉTS, 2022

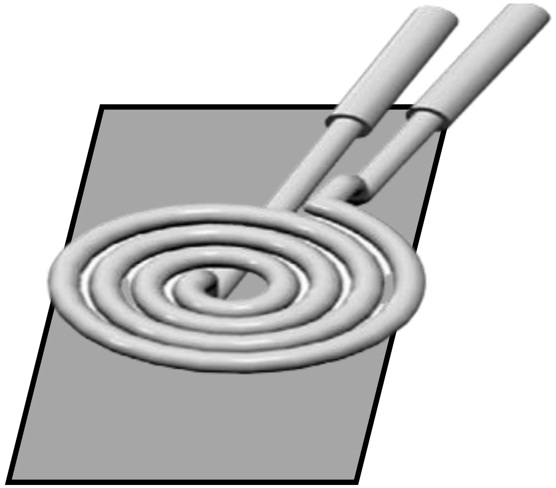
INDUCTION WELDING – EDGE EFFECTS



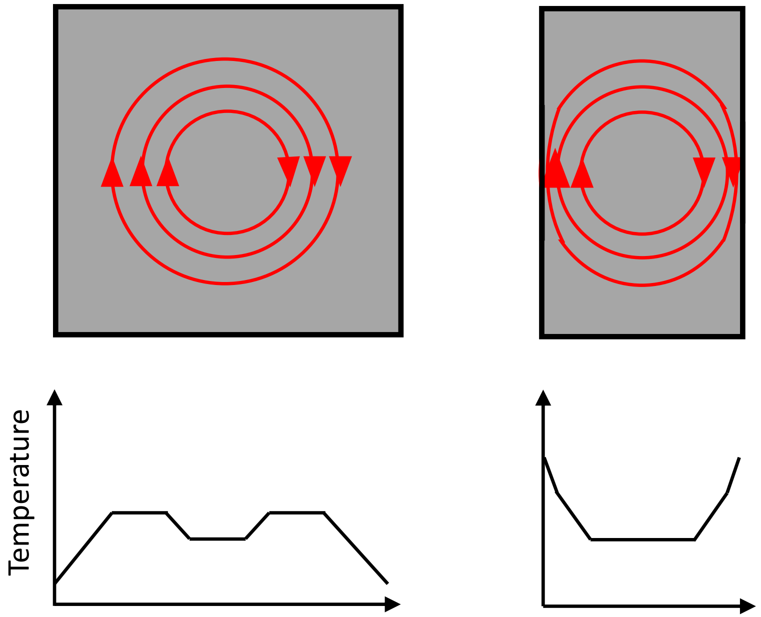
Induction heating of a carbon fibre laminate



INDUCTION WELDING – EDGE EFFECTS

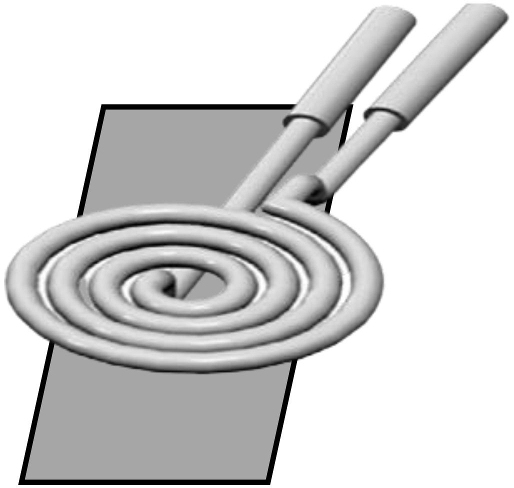


Induction heating of a carbon fibre laminate

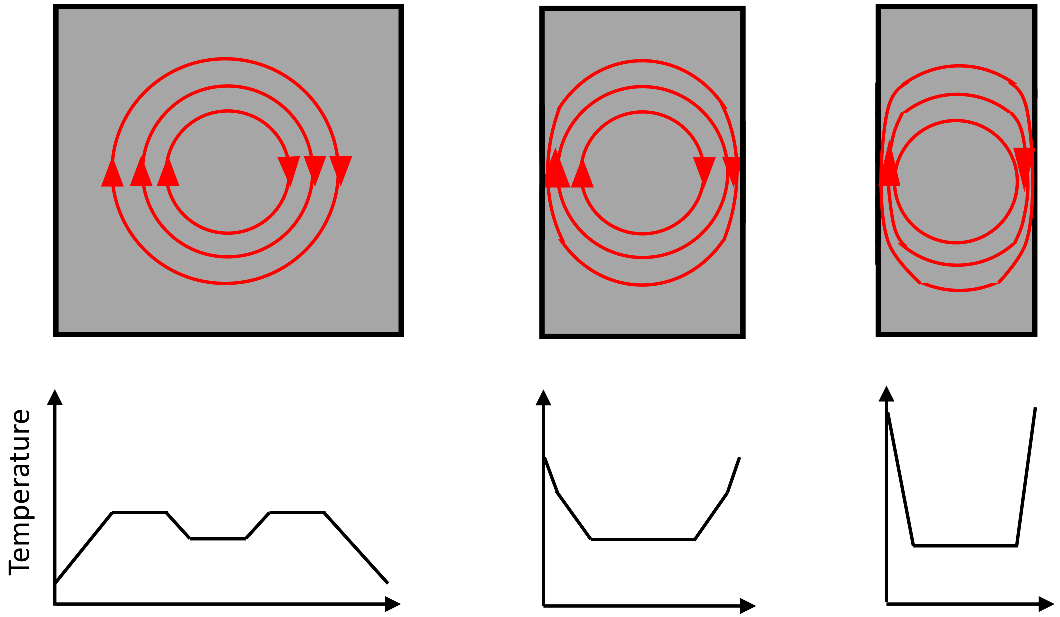


Edge effect affecting the eddy currents paths and distribution in the carbon fibre laminate

INDUCTION WELDING – EDGE EFFECTS

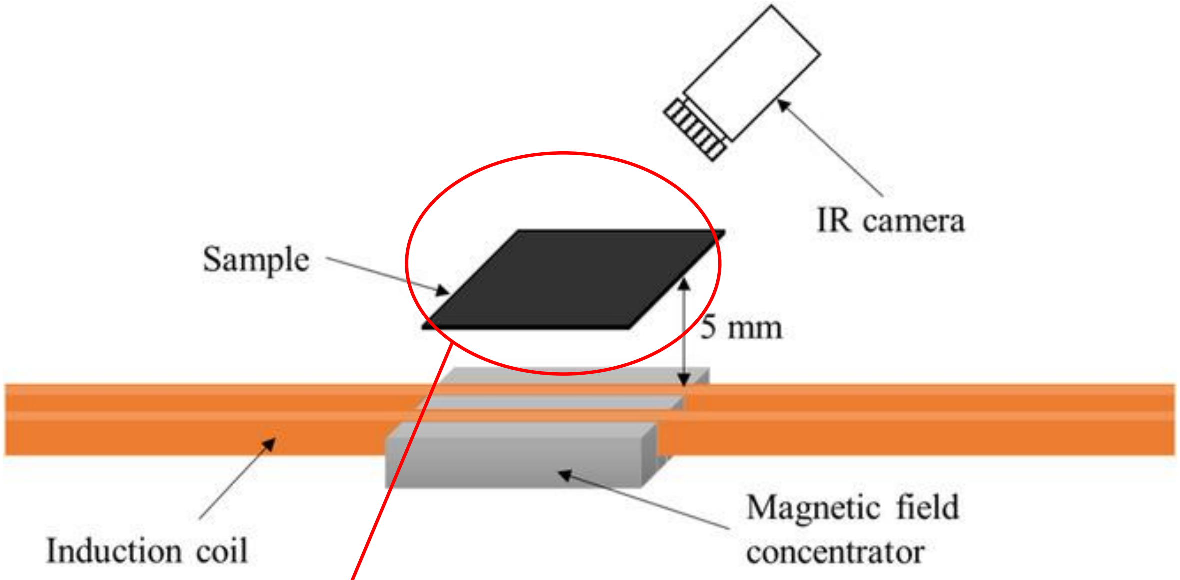


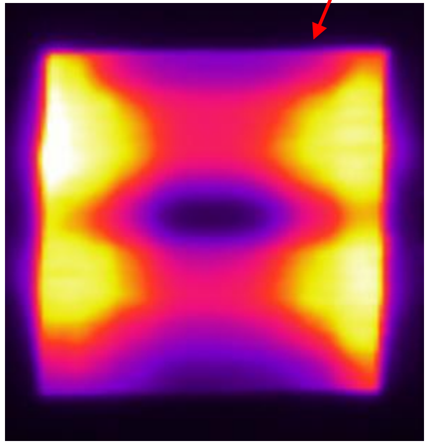
Induction heating of a carbon fibre laminate



Edge effect affecting the eddy currents paths and distribution in the carbon fibre laminate

INDUCTION WELDING – EDGE EFFECTS

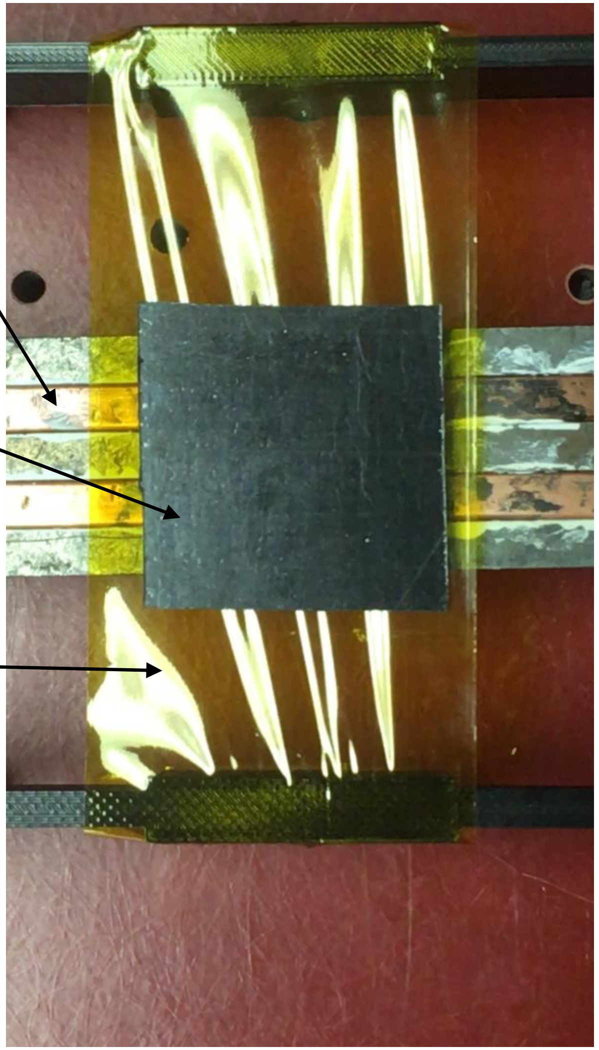




Coil

Carbon fibre laminate made of UD plies with a $(0/90)_{ns}$ lay-up

Film to hold the laminate in place



Edge effect visible during induction heating of a carbon fibre laminate. Here the laminate deconsolidates upon heating over the polymer melting temperature due to the absence of applied pressure.

Romain Martin, ÉTS, 2022

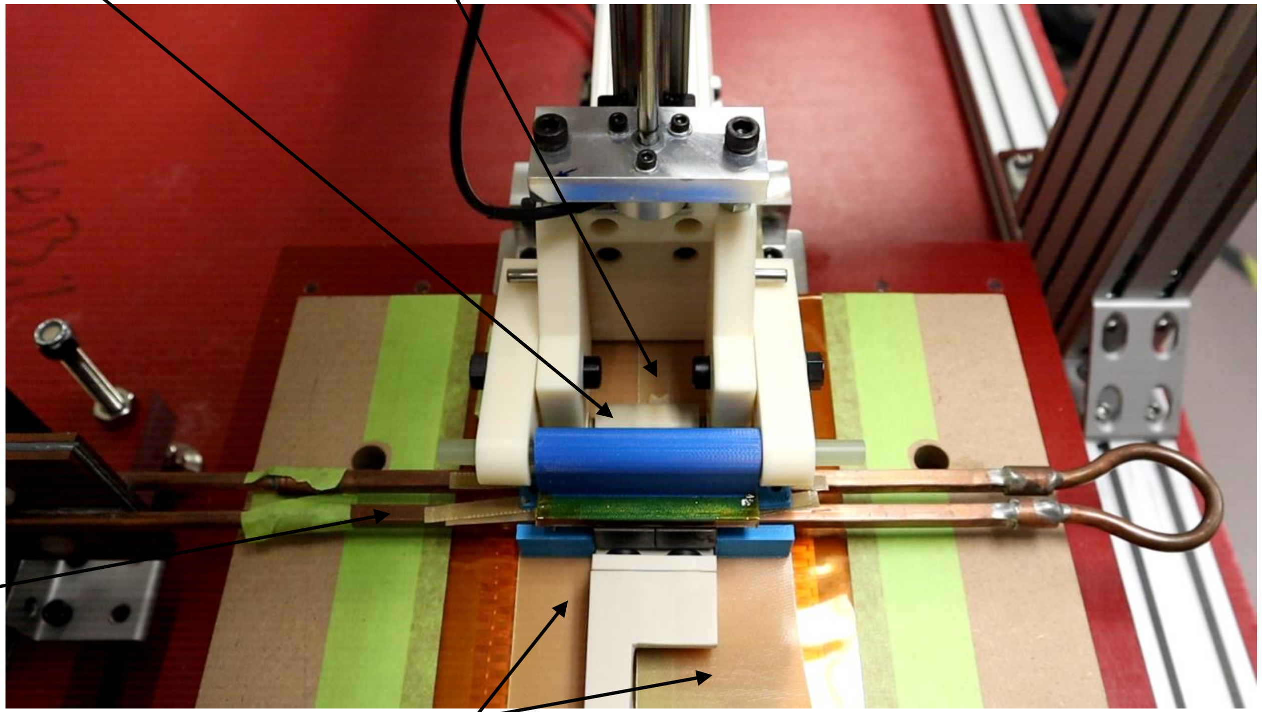
INDUCTION WELDING

Eddy currents in a conductive heating element

Continuous induction welding of a glass fibre/poly-ether-imide (GF/PEI) composite

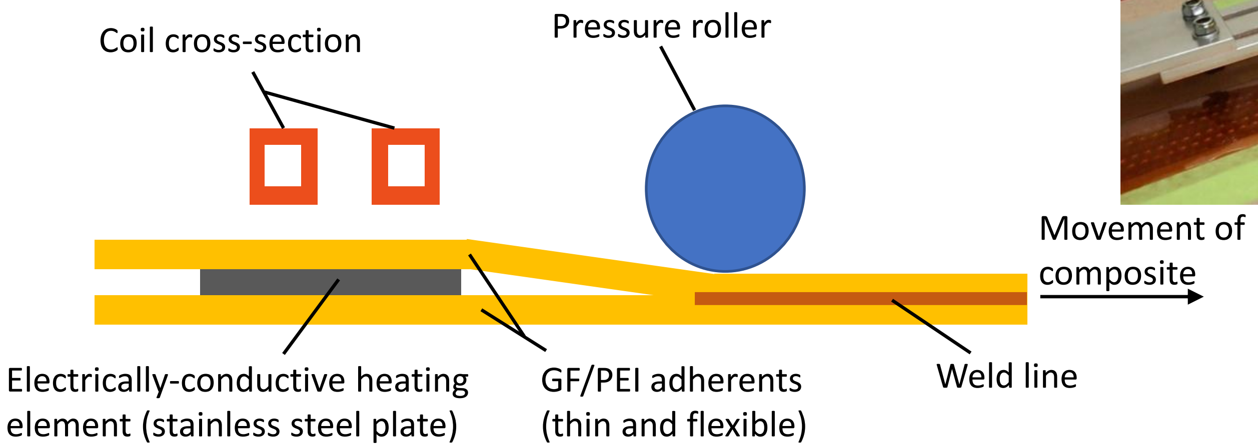
Single turn coil (hairpin shape)

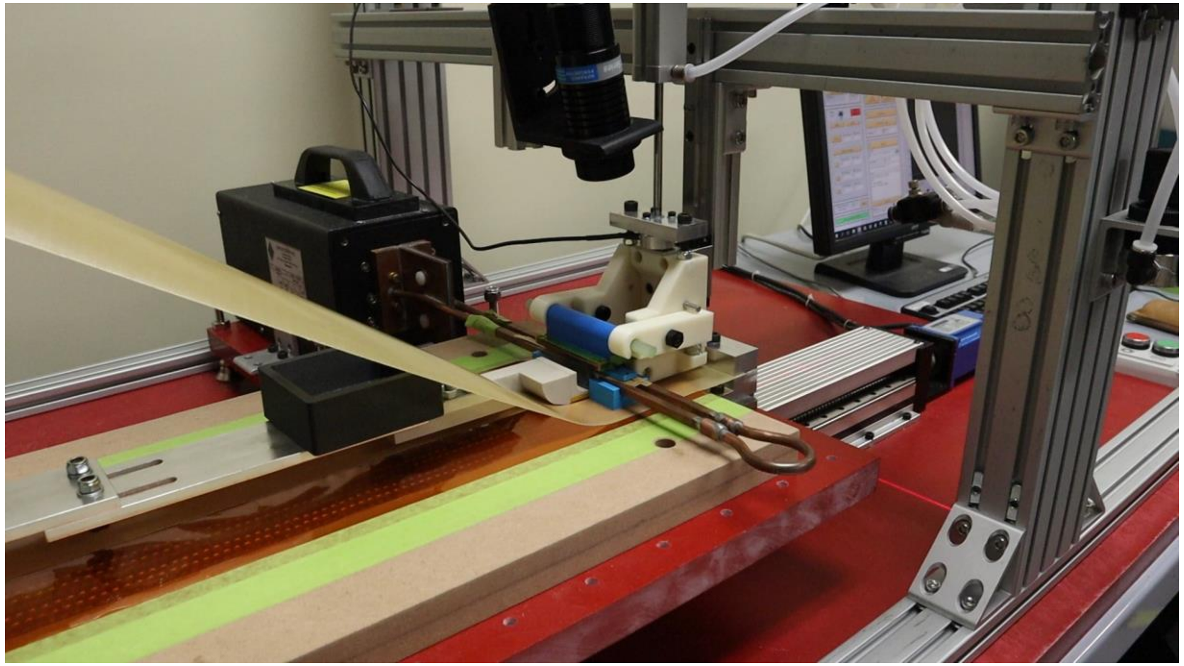
Application of pressure by a roller



INDUCTION WELDING – Application to glass fibre composites

Because the adherents are non conductive, a heating element or susceptor has to be used here. But because the adherents are very thin and flexible, the heating element slides between the two adherents as they are welded. Therefore, no foreign material remains at the weld interface following the welding process.





Continuous induction welding of a glass fibre/poly-ether-imide (GF/PEI) composite

Corentin Bobet, ÉTS, 2021

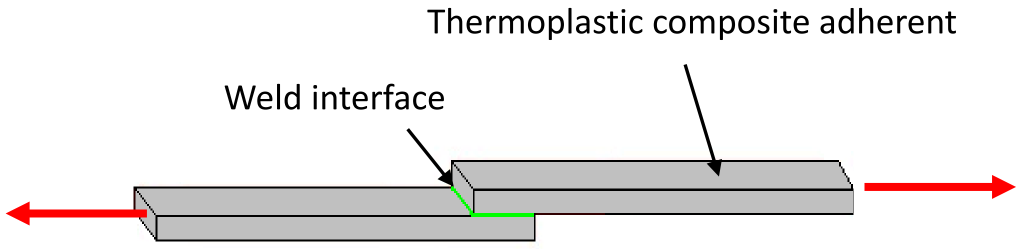
INDUCTION WELDING – PROS AND CONS

PROS	CONS
Fast process	Coil geometry needs to be designed for each application
No contact between coil and part	Simulation more complex than for other processes
Can be made continuous	Non uniform heating (edge effects)
Can be automated	Even if coil does not touch the part, need to apply pressure
Possible to avoid a foreign material at weld interface	

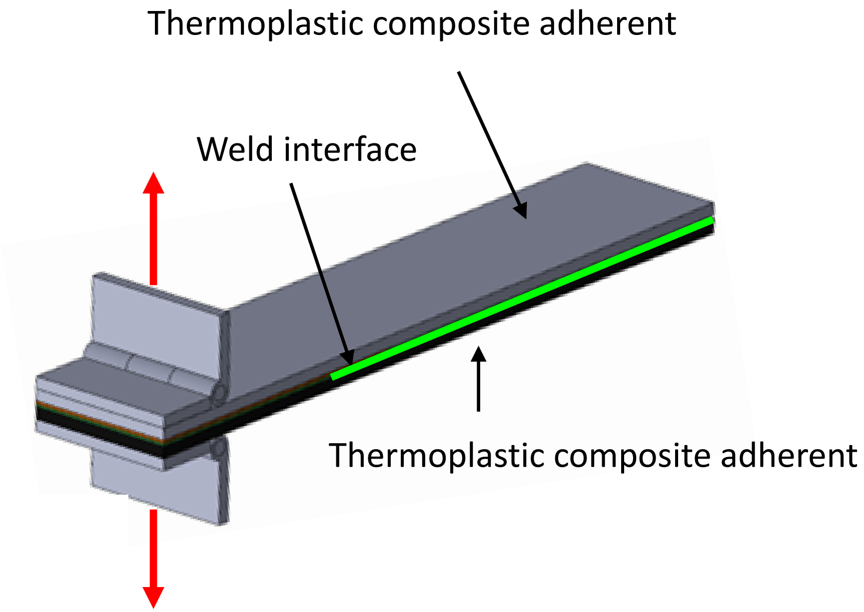
Characteristics of welding processes

	Ultrasonic welding	Resistance welding	Induction welding
Heat generation mechanism	Friction work	Joule heating	Joule heating / magnetic hysteresis
External material at weld interface?	No (but extra polymer may be needed)	Yes (heating element)	Yes or No (but extra polymer may be needed)
Can be made continuous	Yes	Yes	Yes
Pressure application	Sonotrode	Piston/roller	Piston/roller
Speed	Very high speed	High speed	High speed
Edge effect	Due to thermal boundary conditions	Due to thermal boundary conditions	Due to thermal boundary conditions and concentration of eddy currents at the edges of the part

MECHANICAL CHARACTERIZATION OF JOINTS



Single lap shear specimen



Double cantilever beam specimen

MECHANICAL CHARACTERIZATION OF JOINTS

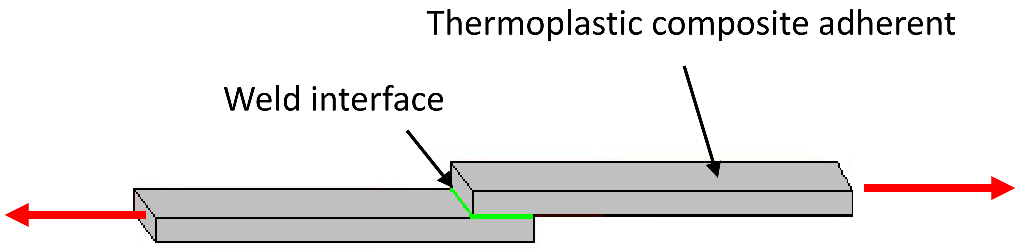
Single lap shear test

- Most commonly-used mechanical test
- Based on ASTM standard D5868 (designed for bonded joints)
- Useful to test various adhesives or see the effects of welding parameters (power, time, pressure, etc) on the mechanical performance
- Indicates the « apparent lap shear strength » (LSS)

$$LSS = \frac{P_{max}}{A}$$

P_{max}: Maximum tensile load obtained during the test

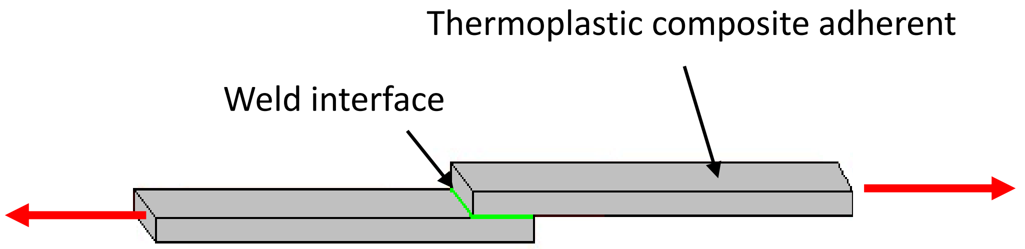
A: Joint area (length X width)



Single lap shear specimen

MECHANICAL CHARACTERIZATION OF JOINTS

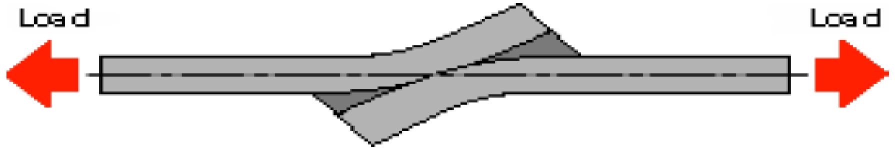
Single lap shear test

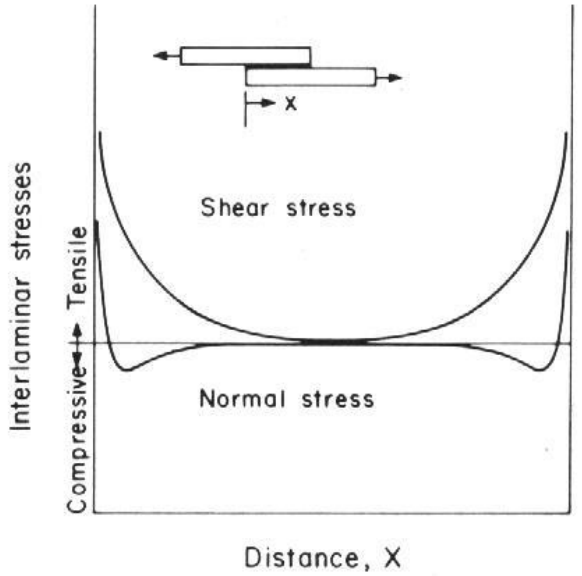


Single lap shear specimen

LSS gives an indication of the weld strength but is not to be used for design purposes.

LSS depends on a number of factors :
- Adherents material
- Adherent thickness, lay-up
- Weld/adhesive nature and thickness

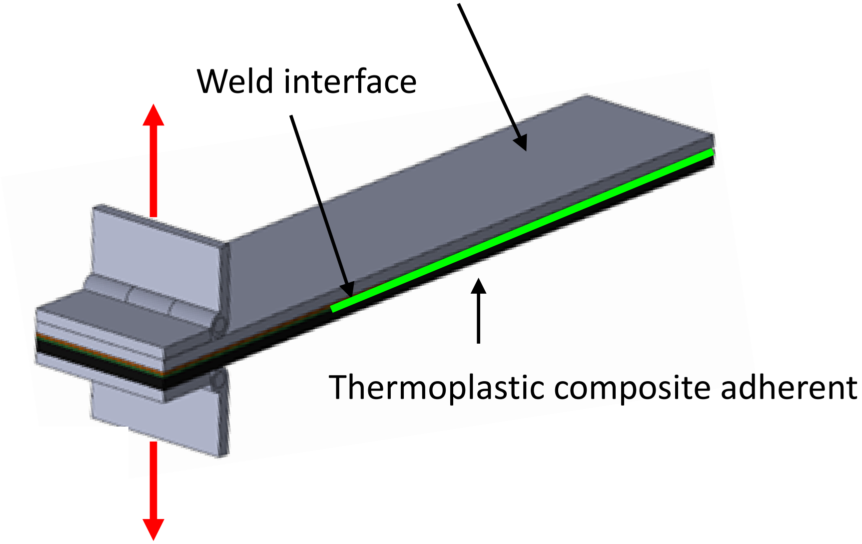




MECHANICAL CHARACTERIZATION OF JOINTS

Double cantilever beam test

- Test usually conducted to characterize the toughness of a composite material
- Can be adapted to test welded or adhesively-bonded joints
- Indicates the Mode I toughness of the joint



Double cantilever beam specimen

CONCLUSION

- Welding is well adapted to joining of thermoplastic composites, having many advantages over mechanical fastening, adhesive bonding
- Fast process that can be automated
- Not very sensitive to surface preparation (unlike adhesive bonding) – could help in certifying joints for aerospace industry
- Potential to be further developed and used to repair damaged structures

Thank you for joining us!

Questions?

Keep an eye out for upcoming AIM events:

Case Study: Optimizing a Press Moulding Process
Dr. Casey Keulen, July 27, 2022

And don't forget to visit the KPC for more information:

https://compositeskn.org/KPC

Today's Webinar will be posted at:
https://compositeskn.org/KPC/A323