Le génie pour l'industrie

POLYTECHNIQUE MONTRÉAL

CONDUCTIVE NANOCOMPOSITES AS HEATING ELEMENTS FOR RESISTANCE WELDING

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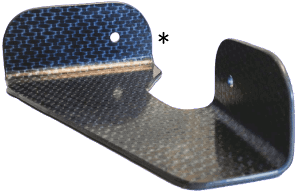
With the collaboration of
Audret Menochet, Brigitte Defoort, Guy Larnac

June 4, 2018

FROM LAMINATE TO PRODUCTS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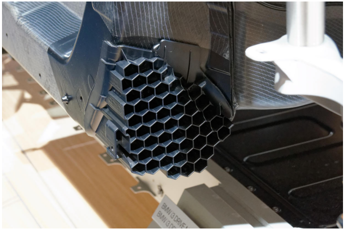
Parts

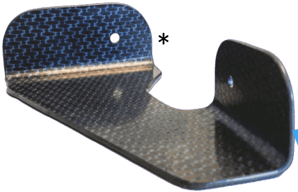
Assemblies



Products

*CompositeWorld

FROM LAMINATE TO PRODUCTS



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Parts

Assemblies

Products

Processability VS Parts complexity

*CompositeWorld

JOINING COMPOSITE PARTS

- Fasteners
- Adhesive bonding

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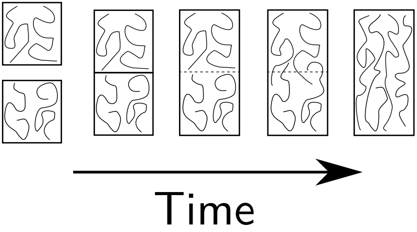
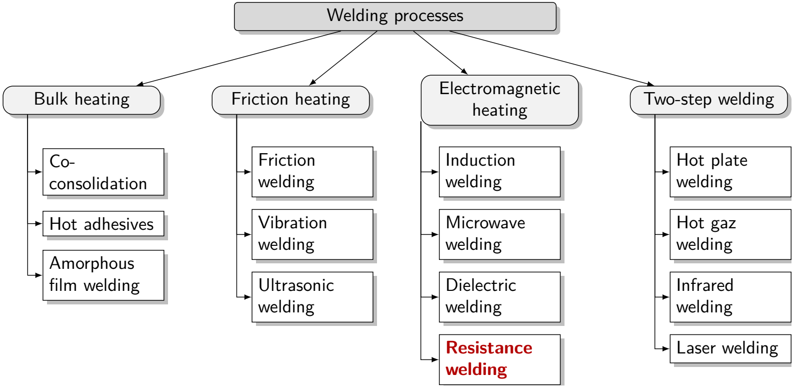
- Adhesive bonding
- **Welding**



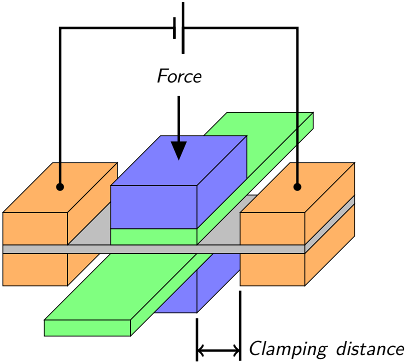
Welding

To join pieces of material by melting or softening the points that touch and pressing them together.

WELDING PROCESSES



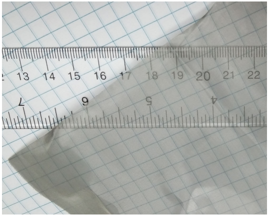
RESISTANCE WELDING



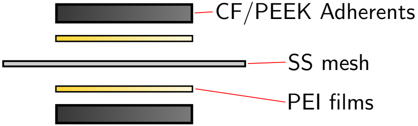
- Electrical connectors
- Adherents
- Insulator
- Porous heating element

Heating elements

- Carbon fibre (CF)
- Stainless steel (SS) mesh



Traditional welding stack



TRADITIONAL HEATING ELEMENTS

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CF heating elements

- Inconsistent results
- Poor weld uniformity
- Electrical connection issues

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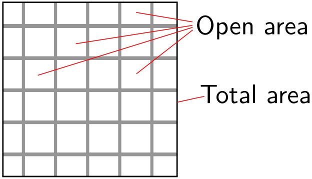

$$\frac{Open\ area}{Total\ area} = \%\ open\ area$$

Stainless steel mesh

- $\nearrow$ reliability and performances
- Poor bonding with the polymer [1–5]
- $\nearrow$ % of open area $\Rightarrow$ $\nearrow$ performance [1]
  - 100% open area $\Rightarrow$ compression-molding

WHAT MAKES A GOOD HEATING ELEMENT?

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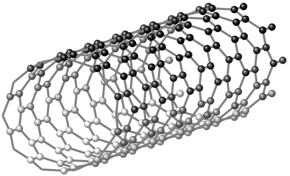
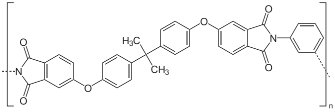
- Uniform heating in the weld

How can we achieve this?

- Miscible heating element
- High electrical conductivity

AN ALTERNATIVE HEATING ELEMENT





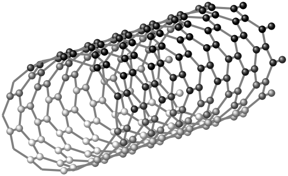
MWCNTs

- Rod like structure
- High elasticity modulus
- High mechanical strength
- **High thermal and electrical conductivity**
- Good thermal stability
- High specific surface area

Polyetherimide

- Low elastic modulus
- Low thermal and electrical conductivity
- **Miscible with PEEK**
  - Commonly used for resistance welding of CF/PEEK laminates

AN ALTERNATIVE HEATING ELEMENT



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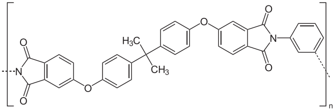


MWCNTs

- Roc
- Hig
- Hig
- **Hig elec**
- Goo
- High specific surface area

Polyetherimide

cal

f

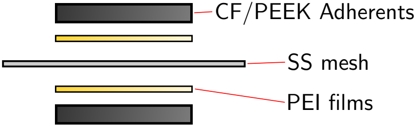
s

MWCNTs nanocomposite

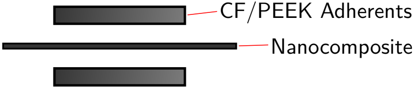
- Increased mechanical strength
- Increased thermal conductivity ($0.7\,\mathrm{W\,m^{-1}\,K^{-1}}$)
- **Increased electrical conductivity** ($0.8\,\mathrm{S\,cm^{-1}}$)
- **Isotropic properties**
- **Miscible with PEEK**

ALTERNATIVE WELDING STACK

Traditional welding stack

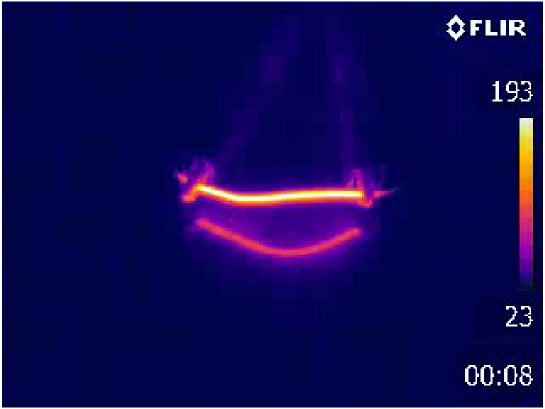


Nanocomposite welding stack



Conductive nanocomposite heating element

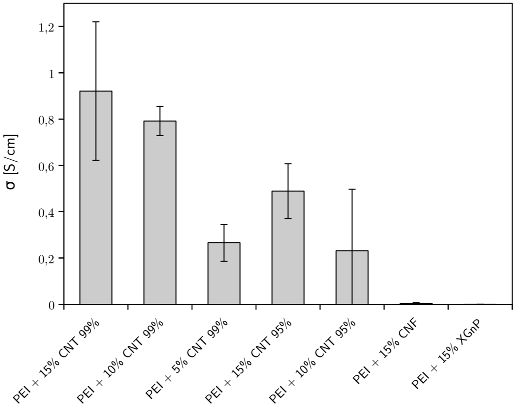
- Simplified handling
- Improved bonding



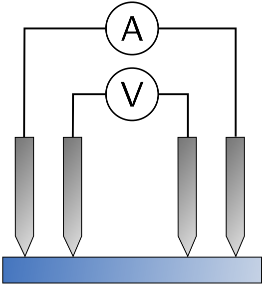
Resistive heating of a polymer based nanocomposite
PEEK + MWCNTs

NANOCOMPOSITE COMPOSITION

Electrical conductivity of PEI mixed with conductive particles

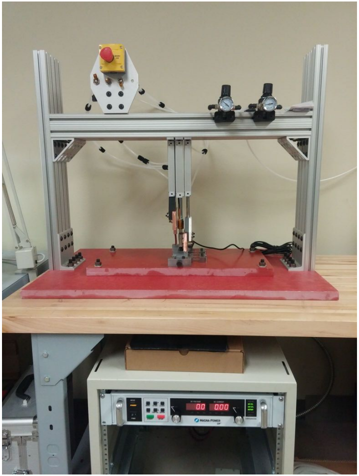


- Mixed with a twin-screw micro-compounder
- **PEI** from Sigma-Aldrich
- **MWCNTs** from Raymor industries
- **XGnP** from XG Sciences Inc.
- **CNF** from Pyrograf Products Inc.

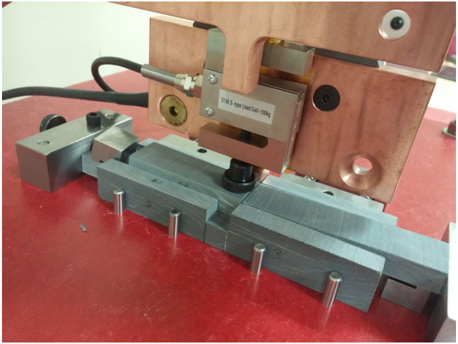


Four-point probe technique

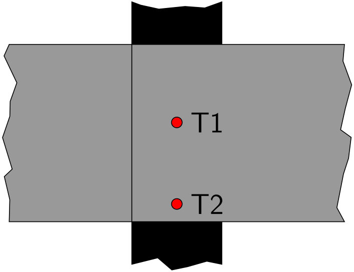
WELDING SETUP



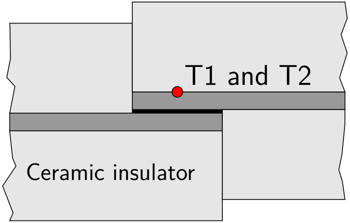
- Computer controlled welding jig
- Temperature monitoring (not shown)
- Programmable DC power source
- Pneumatic actuators
- Force sensor



TEMPERATURE MONITORING



Top view without the ceramic insulators



Side view with the ceramic insulators

WELDED SPECIMEN

- PEI nanocomposite
- 10% weight fraction MWCNTs
- 0.5 mm initial thickness
- $\sigma = 0.79\,\mathrm{S\,cm^{-1}}$
- Pressure over the weld 1 MPa

WELDING CONDITIONS

Constant voltage operation

- Initial experiments
- 60, 62.5 and 65 V
- 60 s
- Inconsistent results (power variations)

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Constant voltage operation

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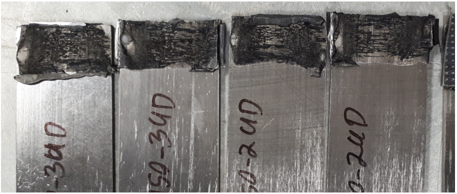
Constant power operation

- 350 kW m^{-2}
- 60, 70, 90 and 120 s
- Repeatable results
- Clamping distance 0, 1 and 1.5 mm



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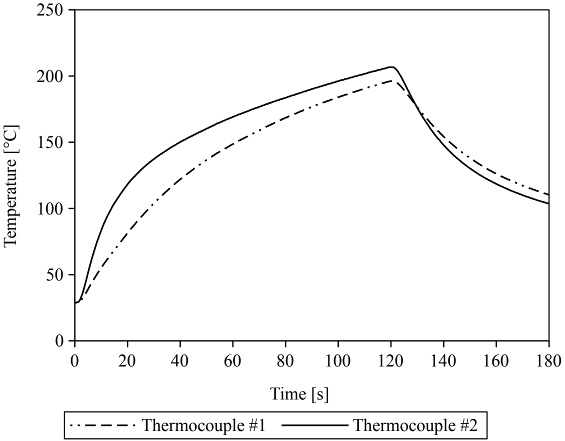


- $350\,kW\,m^{-2}$
- 120 s
- Pressure on the weld 1 MPa
- Clamping distance 1.5 mm

SINGLE LAP SHEAR RESULTS

ASTM D5868 - 01(2014)

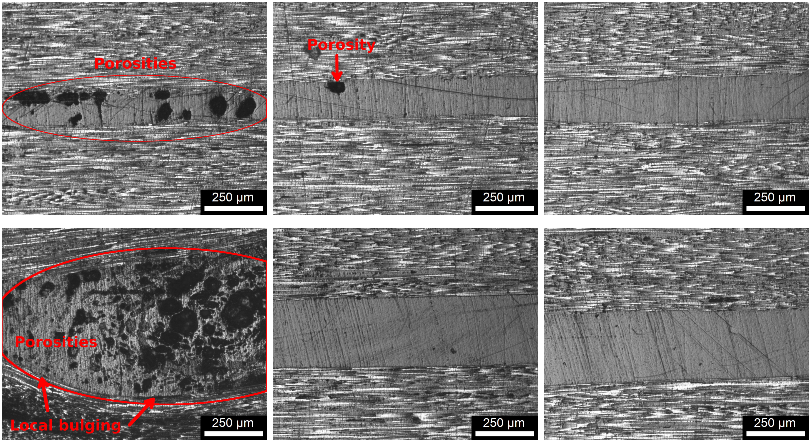
Clamping distance [mm]	Time [s]			
	60	70	90	120
0				14.5 ± 1.3
1				13.0 ± 4.4
1.5	16.4 ± 7.8	18.6 ± 2.0	15.5 ± 3.8	**19.6 ± 3.5**

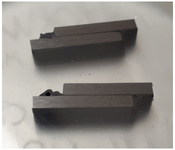
Average shear strength in MPa ± Standard deviation

MICROGRAPHY ANALYSIS

A

B





$290\,\mathrm{kW\,m^{-2}}$, $600\,\mathrm{s}$, $1\,\mathrm{MPa}$ welding pressure and $0\,\mathrm{mm}$ Clamping distance

CURRENT LIMITATIONS OF THE PROCESS

- Lower electrical conductivity of the heating element requires higher operating voltage

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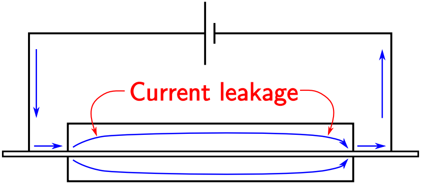
  - The process is more prone to current leakage



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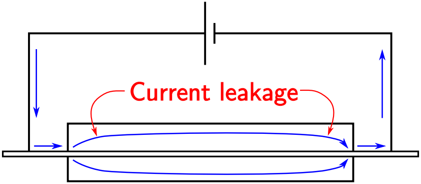
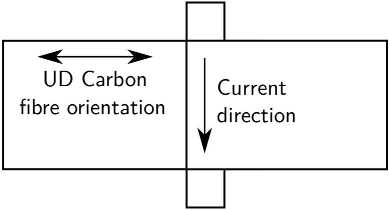
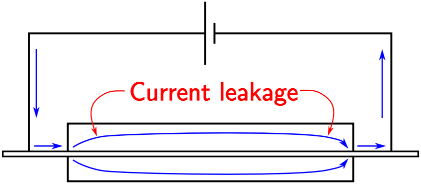
  - UD laminates as a solution
  - Thicker nanocomposite film

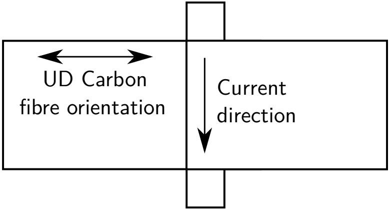




CURRENT LIMITATIONS OF THE PROCESS

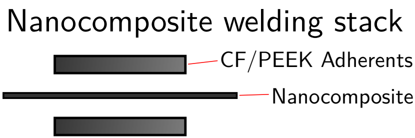
- Lower electrical conductivity of the heating element requires higher operating voltage
  - The process is more prone to current leakage
  - UD laminates as a solution
  - Thicker nanocomposite film
- Brittle cohesive failure within the heating element is the main failure mode
  - Increasing its toughness





CONCLUSION

- Investigation of
  - alternative welding parameters
  - the parameters leading to the creation of porosity
- A nanocomposite heating element is a viable alternative for resistance welding of CF/PEEK composites



ACKNOWLEDGEMENTS

arianeGROUP

CREPEC

Centre de recherche
sur les systèmes polymères et
composites à haute performance

BIBLIOGRAPHY

[1] M. Dube, P. Hubert, J. N. Gallet, D. Stavrov, H. E. Bersee, and A. Yousefpour. Metal mesh heating element size effect in resistance welding of thermoplastic composites. *J. Compos. Mater.*, 46:911–919, 2012.

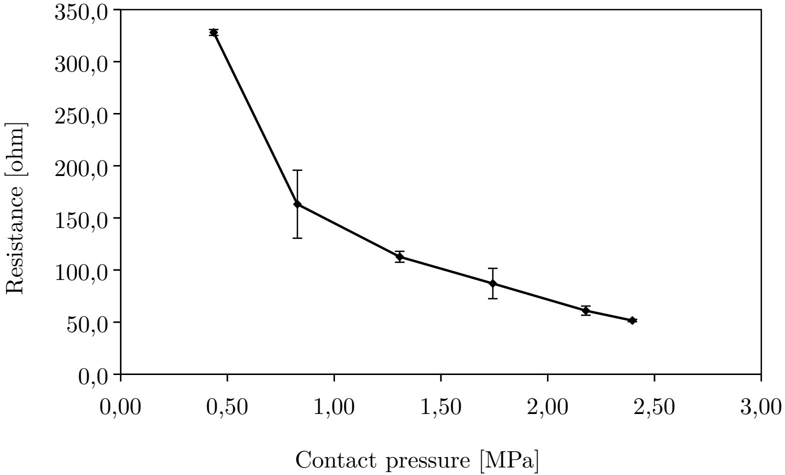
[2] M. Dubé, P. Hubert, a. Yousefpour, and J. Denault. Resistance welding of thermoplastic composites skin/stringer joints. *Compos. Part A Appl. Sci. Manuf.*, 38:2541–2552, 2007.

[3] Martine Dubé, Pascal Hubert, Jan N a H Gallet, Darko Stavrov, Harald E N Bersee, and Ali Yousefpour. Fatigue performance characterisation of resistance-welded thermoplastic composites. *Compos. Sci. Technol.*, 68:1759–1765, 2008.

[4] Huajie Shi. *Resistance welding of thermoplastic composites: Process and performance*. PhD thesis, TU Delft, Delft University of Technology, 2014.

[5] Huajie Shi, Irene Fernandez Villegas, Marc-André Octeau, Harald E.N. Bersee, and Ali Yousefpour. Continuous resistance welding of thermoplastic composites: Modelling of heat generation and heat transfer. *Compos. Part A Appl. Sci. Manuf.*, 70:16–26, 2015.

CONTACT RESISTANCE

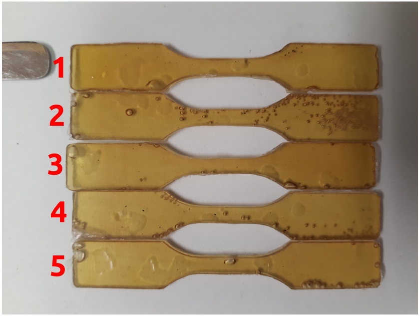


1.6 mm thick sample

ANALYSIS OF POROSITY

Virgin PEI $1.25 \pm 0.02\,\mathrm{g\,cm^{-3}}$

Sample number	M_{air} [g]	M_w [g]	Density [$\mathrm{g\,cm^{-3}}$]	Porosity
1	1.01	0.22	1.28	-0.4%
2	0.93	0.18	1.24	2.6%
3	0.98	0.21	1.27	0.0%
4	0.98	0.20	1.25	1.3%
5	0.91	0.17	1.23	3.4%



Nanocomposite $1.32 \pm 0.01\,\mathrm{g\,cm^{-3}}$

Sample number	M_{air} [g]	M_w [g]	Density [$\mathrm{g\,cm^{-3}}$]	Porosity
1	1.15	0.28	1,32	-0.1%
2	1.09	0.28	1,34	-1.9%
3	1.00	0.25	1,33	-0.9%
4	1.06	0.26	1,32	-0.3%
5	1.07	0.26	1,32	0.0%
6	1.01	0.24	1,31	0.7%
7	1.06	0.26	1,32	-0.3%

- ASTM D792 - 13
- ρ_{PEI} $1.27\,\mathrm{g\,cm^{-3}}$
- ρ_{CNT} $2\,\mathrm{g\,cm^{-3}}$
- $\rho_{nanocomposite}$ $1.32\,\mathrm{g\,cm^{-3}}$ (law of mixture)