Induction Cure of Adhesives For Composite Repair Applications

2003 NCMS/CTMA Symposium
Salt Lake City, Utah
1 April 2003

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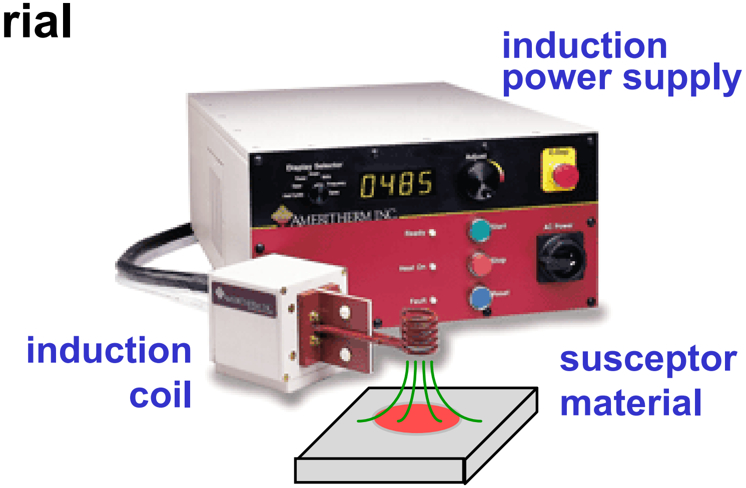
Induction Heating

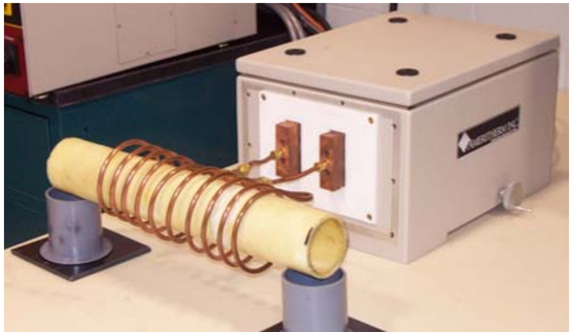
- Induction heating: high frequency electromagnetic field remotely couples power source to susceptor material
  - Typical frequencies: 0.10 - 10 MHz
    - Sub-microwave frequencies
    - Pose few risks to human exposure
  - Typical amplitudes: 50 - 500 Oe
- Field generated by passing high frequency current through water-cooled copper tubing (induction coil)
  - Spatial dispersion of field can be controlled through coil design

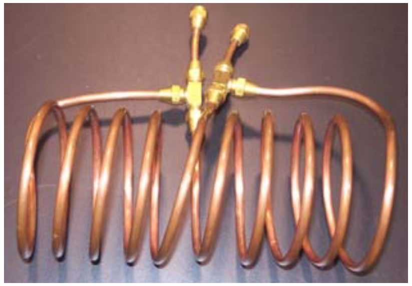


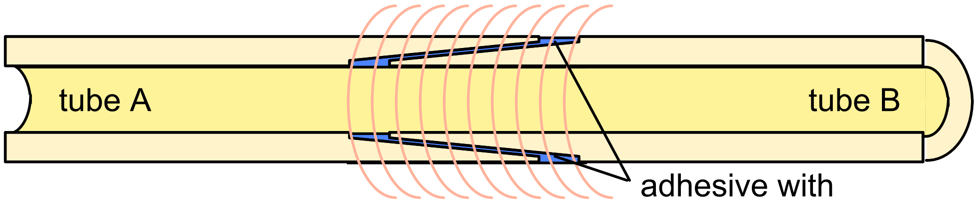
- Heat generated in susceptor material
  - Electrical conductors
    - Metals, carbon fiber composites
  - Magnetic materials
    - Magnetic metals, ceramics
- Non-susceptor materials
  - Polymers
  - Glass fiber, Kevlar fiber composites
  - Most ceramics

Induction Heating Equipment and Geometry

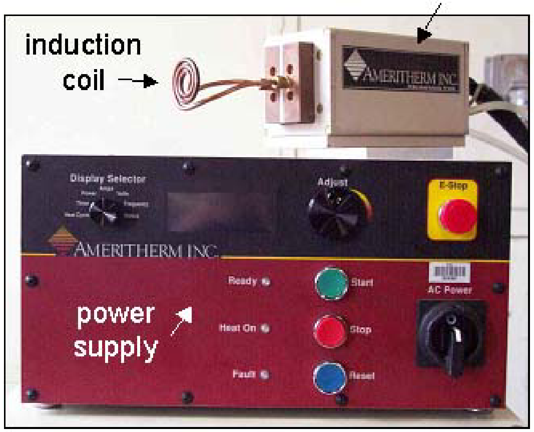
- Induction power supply
  - Ameritherm NovaStar 1M
  - Operating frequency 10-15 MHz
  - Magnetic field amplitude: "0-1500 W"
  - Self-tuning, solid state, water cooled
  - Relatively recent technology


Bench top


Coils

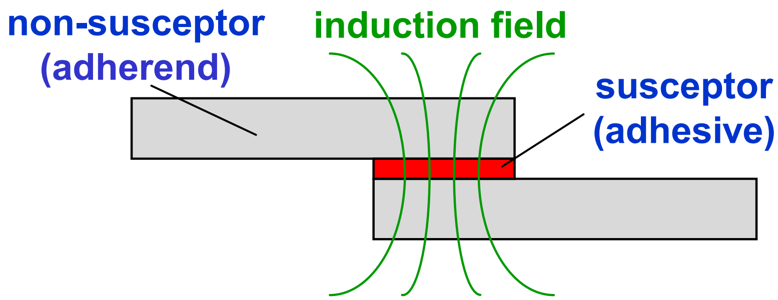



Hand held



Induction Processing of Adhesives

- Requires incorporation of susceptor material in adhesive
  – Adherend preferably a non-susceptor material

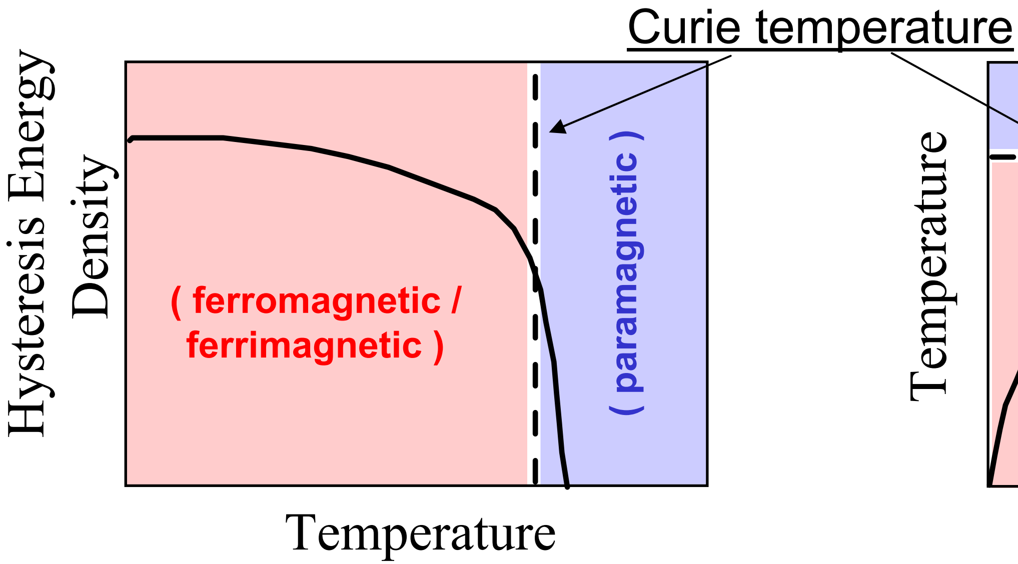


- Advantages over conventional processing (surface heating approaches, e.g., convection oven, radiant heater, heat blanket, heat gun):
  – Faster heating
  – Can heat embedded bondlines (e.g., thick-section composites)
  – Self-regulating - does not require continuous process control
- Promising susceptor material: magnetic particles
  – High energy density
  – Automatic temperature regulation
    - Ensure proper cure, minimize risk of thermal degradation

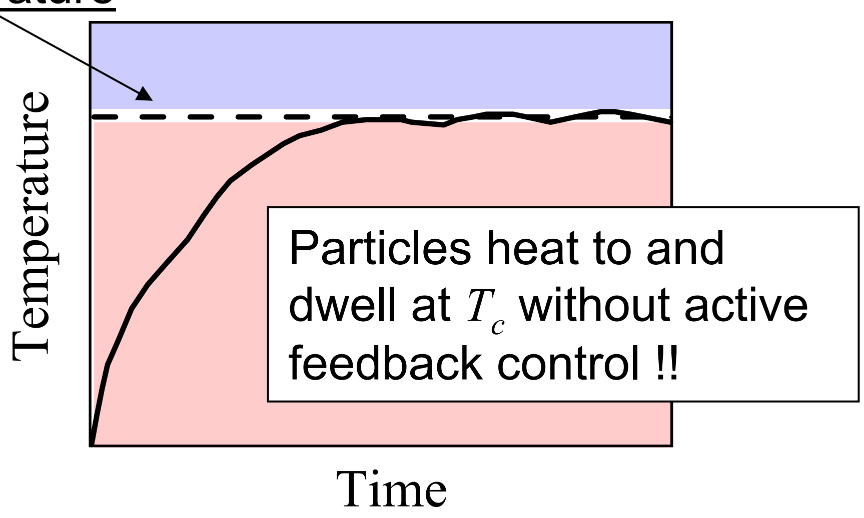
Minimize Operator Training. Minimize Operator Errors.

Magnetic Particle Susceptors

- **Heating mechanism –> magnetic hysteresis**
  - **Losses associated with magnetization / demagnetization of material**
  - **Requires high (> 1MHz) frequencies**
- **Primary advantage –> automatic temperature regulation**
  - **Hysteresis heating mechanism disappears at material Curie temperature (T_c)**



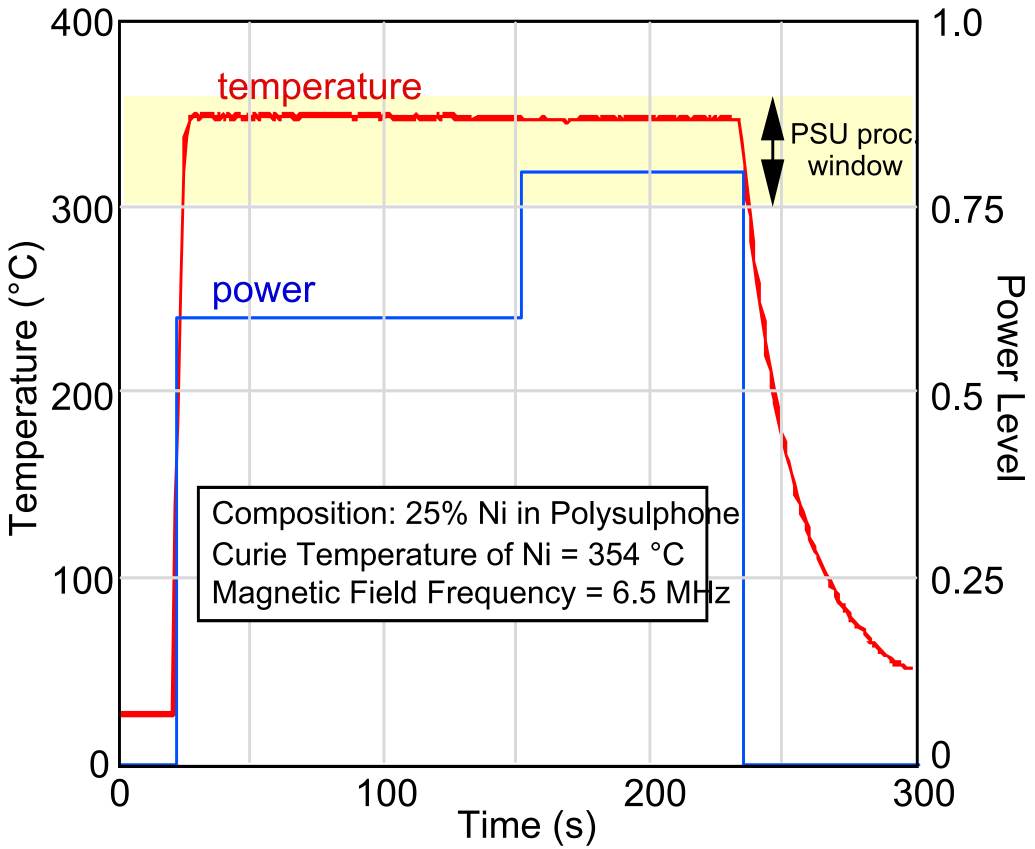
(material property measurement)



(particle heating in AC magnetic field)

Temperature Control Using Curie Limit

- Curie temperature determined by <u>composition</u> of magnetic material
- Choose magnetic material with T_c = processing temperature (example, T = 354°C)
- Incorporate filler into adhesive
- Demonstrate constant heating temperature with power variation
- Demonstrate induction adhesive processing in large-scale structural applications



From Fink et al. "Ferromagnetic Nano-Particulate and Conductive Mesh Susceptors for Induction-Based Repair of Composites." Proceedings of Army Science Conference. Norfolk, VA. June 15-17 1998.

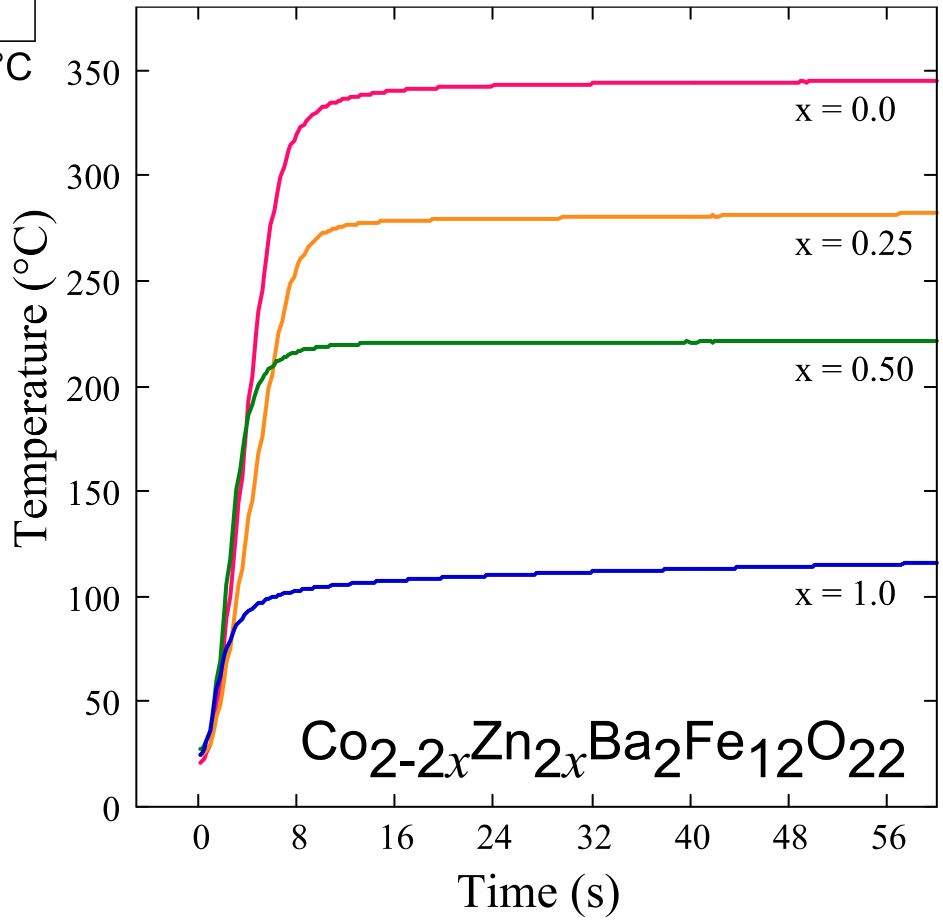
Induction Particles for Adhesive Repair

x	T_c (theory)	T_c (measured)	Dwell Temp.
0.0	340	334	346
0.25	288	281	283
0.5	236	217	222
0.75	183	164	-
1.0	130	105	117

note: all temperatures in °C

Select curie particles that meet processing requirements (limits)!

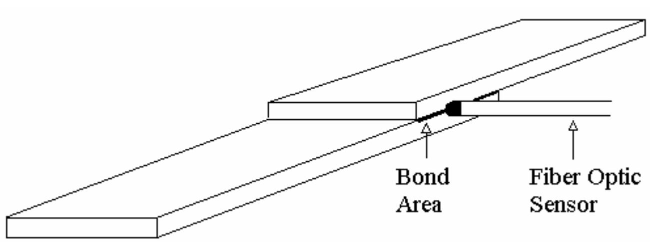
- **Heating tests performed at f = 6.28 MHz, H_a = 10 kA/m**
- **No power regulation used!**
- **Joint ARL-UD patent application in process**

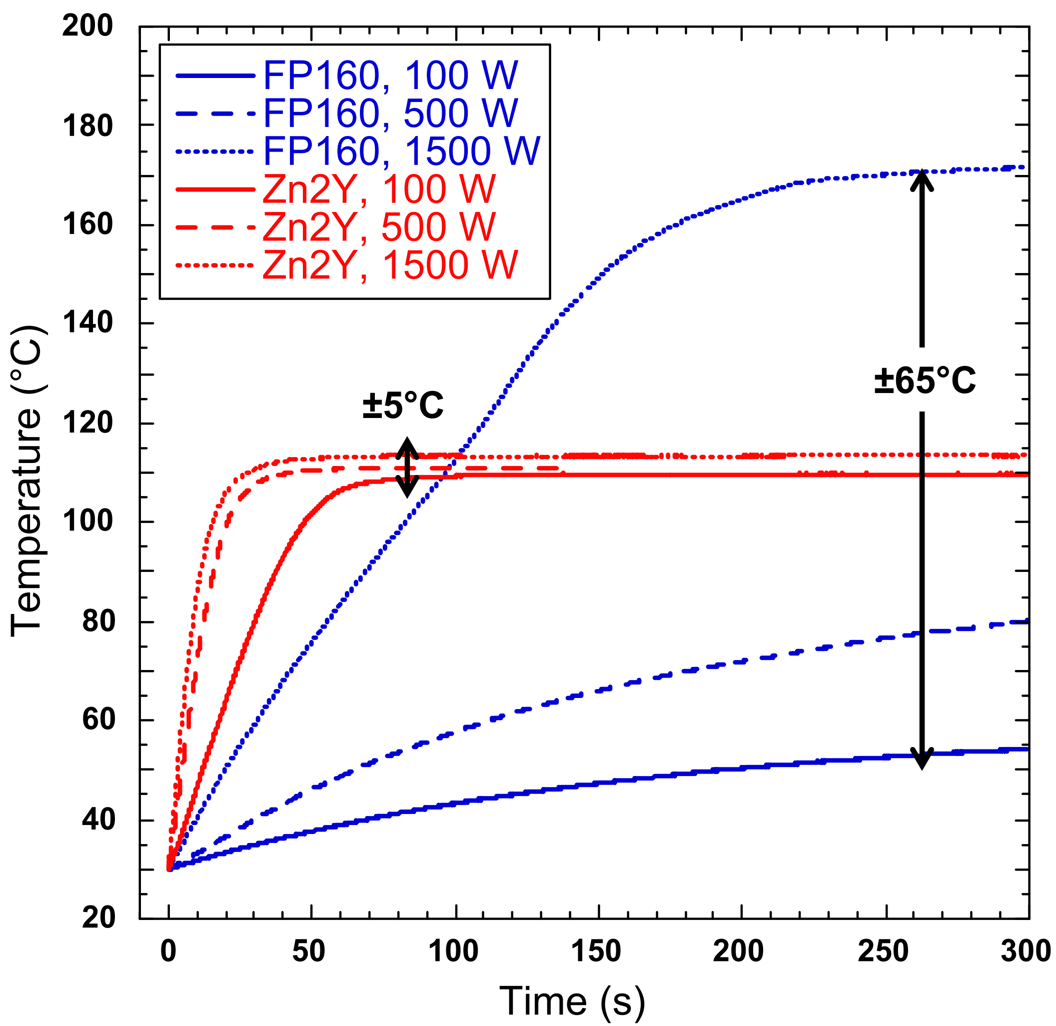


Induction Particle Susceptors

- Commercial particle susceptors (FP160) demonstrate variability in heating uniformity
- Historic reason for limited usefulness of technology
- Not ideal for controlled bonding

- Synthetic particle susceptors (Zn2Y) demonstrate *ideal* heating behavior
- Ideal for operator independent performance

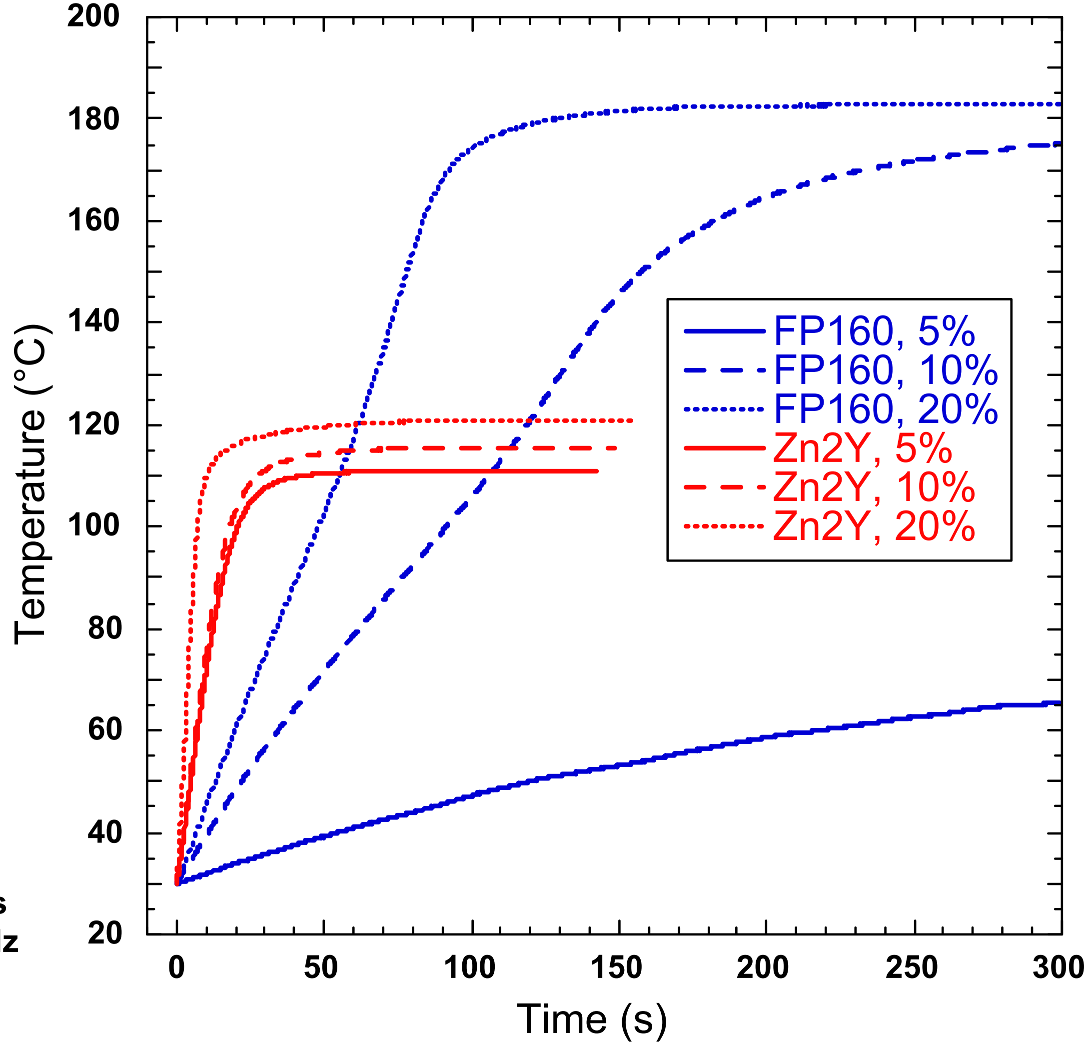




Dilution Effect on Curie Temperature

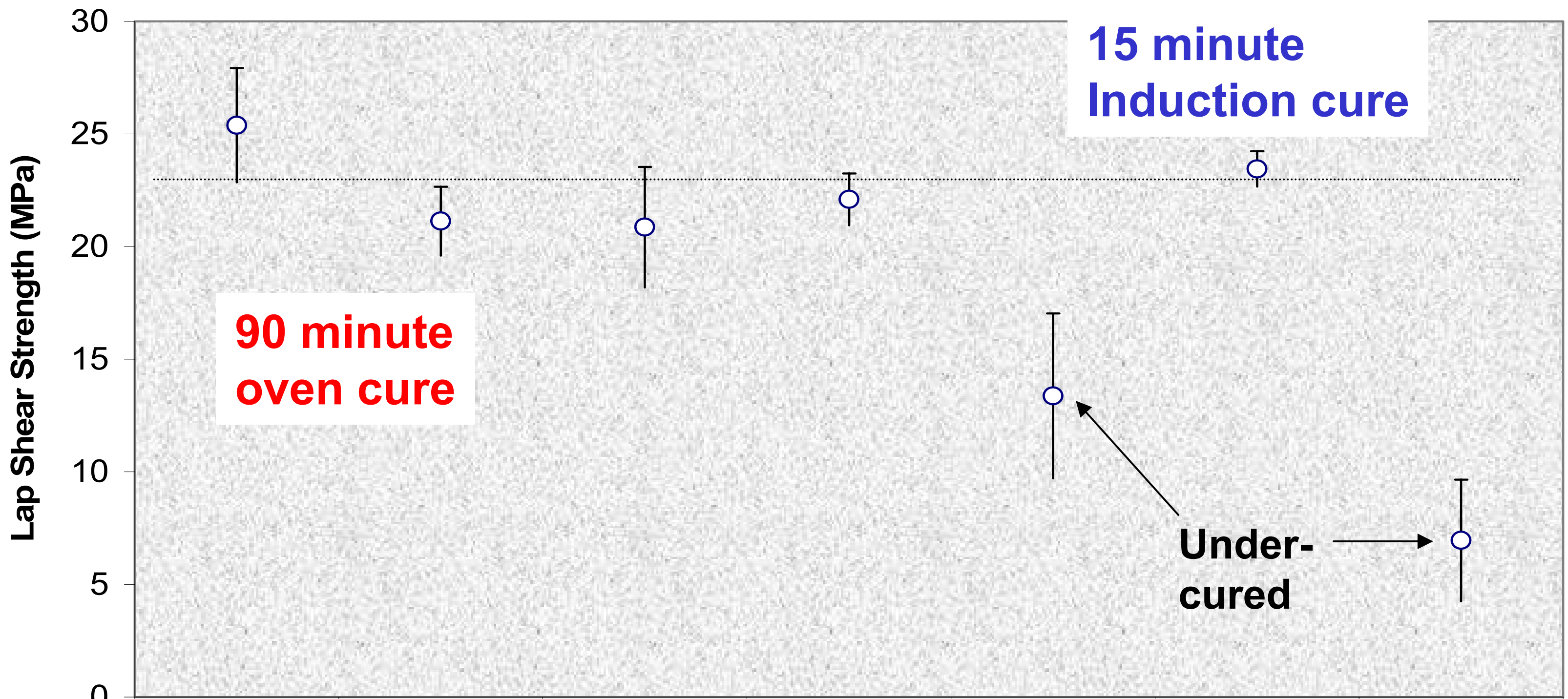
- Dilution effect is significant
- Cure rate and cure temperature are poorly controlled

- Rapidly reach dwell temperature
- Minimal thermal gradient in bondline



Induction heating behavior of various volume fractions of magnetic powders dispersed in alumina powder, in 14 MHz field at amplitude of 500 W

Induction Cured Adhesive Performance



	Oven, unfilled	Oven, filled	500 W, 15 min	500 W, 30 min	1 kW, 5 min	1 kW, 15 min	1.5 kW, 3 min
Avg (MPa)	25.392	21.132	20.863	22.103	13.375	23.451	6.9547

- **No time-dependence on adhesive toughness**
- **Performance is not sensitive to rapid cure**

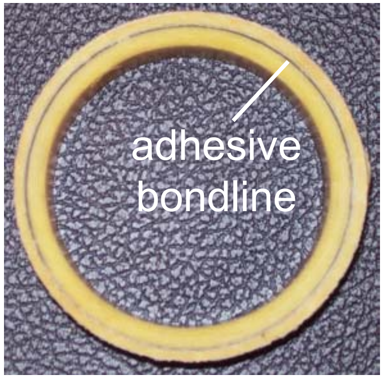
SUCCESSFUL DEMONSTRATION

Importance of Induction Control

- Minimize impact of “heat sinks”
- Applicable to rapid cure of thick sections
- Effective for use in repair around honeycomb
- Uniformity of thermal cure in induction field
- Adhesive development necessary to take advantage of technology
- Increase cure rate == Decrease repair time == Decrease turnaround time
- Potential to improve mission readiness of aircraft and ground vehicle structures

Tube Bonding Example

- **Tubes fully bonded in 15 minutes!**



mechanical testing at NUWC

Summary

- Significant developments in induction processing of adhesives
  - Development of advanced magnetic filler materials
    - High energy density -> rapid heating rates and consistent dwell temperature at low filler contents
    - Curie temperatures from 130°C - 380°C
    - High purity -> consistent dwell temperature
  - Commercial availability of high frequency induction processing equipment
- Induction is a non-contact heating mechanism suitable for use in composite repairs
- Adhesives designed to be insensitive to RAPID induction cure conditions
- Demonstrates ability to increase rate of repair and decrease down-time over room temperature cured adhesives
- Materials can be selectively designed to meet repair performance requirements allowing rapid non-contact curing of adhesives

Where to go from Here?

- Commercial development of curie limiting particles
- Commercial development of adhesives or commercial implementation of induction technique in current adhesives
- Establish "limits" for induction technology
  - Electronic interferences
  - Thermal heating in composite laminates
- Demonstrate advantages to repair applications