New Areas of Automotive NDE: Li-ion Batteries and Composite Materials

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Houston, TX
OBAMA ADMINISTRATION Fuel Economy Standards

In the year 2025

The fleet-wide average will be 54.5 MPG.

Consumers will have saved $1.7 TRILLION at the pump over the life of the program.

A family that purchases a new vehicle in 2025 will save $8,200 in fuel costs when compared with a similar vehicle in 2010.

Over the life of the program, the standards will:

- Save 12 billion barrels of oil.
- Eliminate 6 billion metric tons of carbon dioxide pollution.

This program, together with standards already put into place by this administration for Model Years 2011-2016, will result in significant cost savings for consumers at the pump, dramatically reduce oil consumption, cut pollution and create jobs.
**Future of Automotive Manufacturing**

**Improving Transportation**

The President has invested in making America a leader in the future of electric vehicles.

**Forecasted Cost of a Typical Electric-Vehicle Battery**

- **$33,333**
- **$16,667**
- **$10,000**
- **$5,000**
- **$3,333**

- By 2013, advanced battery costs are expected to drop by half.
- By 2015, American companies will go from producing 2% of the world's advanced batteries to 40%.

The biggest cost of electric cars are their batteries.

**Goal:** 1 million advanced technology vehicles on the road by 2015.

Which would reduce oil consumption of about 750 million barrels through 2030.
"The 2011 Chevrolet Volt is in the vanguard of the auto industry’s shift from the petroleum-based model...to the electrified model. With its new Voltec propulsion system, GM...brings a unique approach...” [SAE, 2011]
Voltec Powertrain
The hart of Voltec powertrain: Li-ion Battery
Voltec Battery Design

Battery Pack – Basic Construction

>200 Cells

Modules

Pack

Forward

Battery Management System
Automotive Li-ion Battery “Cell”

Courtesy MIT TechReview
Battery Assembly: Stacking Operation
Installation of Interconnects
Ultrasonic Welding Is Used for Battery Assembly

Photo courtesy of EWI
Voltec Battery Joints

Four parts (three cell tabs and a common bus) per joint, three interfaces, dissimilar metals: aluminum and copper.
Each battery = 200 welds, multiple automated welding stations, high production rate.
Each interface has to be good!
Novel NDE Techniques Developed In-House

- **Active and Passive Flash Thermography NDE**
- **Shearographic NDE with Vibration Excitation**
  - Automated “pick test”;
  - Good in finding concealed defects; can detect the extend of weld fused area
- **High-precision electrical resistance NDE:**
  - Tests functionality of the weld *and* its strength
  - A large number of welds can be measured quickly (~0.2 sec per measurement) and conveniently with one fixture
Flash Thermography NDE

**Energy** (flash light, etc.)

IR camera

Copper Common Bus

Signal to the IR camera: *temperature* $T$ as a function of time $t$: $T=f(t)$

Cell tabs

Energy
Thermal model

\[
\begin{align*}
\frac{\partial T}{\partial t} &= \frac{\partial^2 T}{\partial x^2} \\
T(x,0) &= 0 \\
\frac{\partial T}{\partial x}(x,0) &= \begin{cases} 
\frac{q}{k} & 0 \leq t \leq t_0 \\
0 & t_0 \leq t 
\end{cases} \\
\frac{\partial T}{\partial x}(x,\infty) &= 0
\end{align*}
\]

\[t_0 = 5\text{ms}\]
\[q = 5\times10^7 \text{ J/m}^2\]
Thickness: 1mm
Material: Copper
How to detect the fused area

The temperature rise is more rapid in the fused area.
Post-processing: differentiating with respect to time in each point (pixel) to find total fused area.
Weld strength correlates with the size of the “nugget” ...unless the joint fails elsewhere.

Shear strength of nuggets

\(~28.2\text{N/mm}^2 = 28.2\text{MPa}\)
What is a shearographic camera?
Formation of a shearographic pattern

Two superimposed images are formed: a *sheared* image(s) of the object and the superimposed image of the fringes containing information about surface strains.
When vibration is applied to an assembly, a pattern of (elastic) strains forms around the weld.

Pattern of strains \( \varepsilon \) (generally, a 3D field, becomes 2D on the surface)

A schematic of a spot weld, loaded with loads \( L \)

Size of the weld nugget

Image recognition is used to detect weld defects. FEM model is used to determine the size of the fused area from the strain pattern (“inverse problem”).
Sample with three welds, illuminated by a laser
Good weld. Excitation frequency is 9.3KHz.

3 good welds.
Defective weld. Excitation frequency is 2.5KHz

No weld nugget
Defective weld. Excitation frequency is 5KHz
High-precision electrical resistance NDE

Electrical Resistance $R$ and Strength $S$ of a Weld:
- area $A$
- Resistivity $\rho$
- Interface “length” $L$
- Interface ultimate strength $\sigma_u$

$S = \sigma_u A$

$R = \rho \frac{L}{A}$

Therefore: $S \propto R^{-1}$
The real weld is more complicated...

Electrical current I

Common bus

- c3 b3 a3
- c2 b2 a2
- c1 b1 a1
Correlation: Strength v Resistance

Strength testing of welded samples

Shear strength v El. resist., Al welds

Shear strength v El. resist., Al welds

Tearing through the weld

Strength S v El. Resist., Cu welds

Strength S v El. Resist., Cu welds

S = 16.766R^{-0.289}

S = 0.2334R^{-0.169}
## Comparison of the developed NDE methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermography</strong></td>
<td>The only method to measure the size of the fused area of multi-ply welds</td>
<td>Requires high-power energy input → needs protection on production floor.</td>
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<tr>
<td></td>
<td>Non-contact</td>
<td></td>
</tr>
<tr>
<td><strong>Shearography</strong></td>
<td>Measures the true extent of a fused area; may uncover concealed defects</td>
<td>Requires:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• high-resolution shearographic cameras</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• sophisticated image analysis and software</td>
</tr>
<tr>
<td><strong>Precision Electrical</strong></td>
<td>Measures the main functional parameter of the weld.</td>
<td>Requires contact fixture; needs a reliable contact with joints</td>
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<tr>
<td>Resistance NDE</td>
<td>Can monitor welds throughout the battery life.</td>
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Automotive NDE Needs

- **Traditional NDE areas:**
  - NDE of safety-critical lightweight automotive components
  - NDE of welding and joining
  - NDE of adhesive joints
  - NDE of spot welds (in selective applications)

- **New NDE applications:**
  - NDE of Li-ion batteries and cells, in production and throughout the life
  - Inexpensive NDE methods for composite materials
  - NDE of joints of dissimilar materials, composites
  - Life monitoring of composite structures.

- **Production process control**
THANK YOU FOR YOUR ATTENTION!
Automotive NDE Needs

- **Traditional NDE areas:**
  - NDE of safety-critical lightweight automotive components
  - NDE of welding and joining, particular of dissimilar materials and composites
  - NDE of adhesive joints

- **New NDE applications:**
  - NDE of Li-ion batteries and cells, in production and throughout the life
  - Inexpensive NDE methods for composite materials
    - Infrared, shearography, vibro-thermography, x-ray, CT, ultrasonic, eddy current; combination, new NDE techniques
  - Life monitoring of composite structures.
    - Fluorescent dyes/penetrants
    - Electrical methods
  - Process control in production
The electrical resistance of the weld depends on how the current is applied.

\[ S = \sigma_u A \]

\[ R = \rho \frac{L}{A} \]

Therefore: \( S \propto R^{-1} \)
Explanation of lower power

\[ S = aR^{-0.351} \]

\[ S = R^{-1} \]

\[ S = \text{const} \]

<table>
<thead>
<tr>
<th>0</th>
<th>0.02</th>
<th>0.04</th>
<th>0.06</th>
<th>0.08</th>
<th>0.1</th>
<th>0.12</th>
<th>0.14</th>
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<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td></td>
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</tr>
</tbody>
</table>

- Combination of inverse and const
- Inverse dependence
- A constant
- Power (combination of inverse and const)
- Power (Inverse dependence)
- Exponent (A constant)
The signal can be digitized (made 0 or 1) and counted

- Done with Matlab
- Each pixel is a square with dimensions (approximately):
  - 100µ X 100µ, with area A=10^{-2} mm^2
The entire module can fit in the field of view of IR camera...

...but heat can be applied one joint at a time