Influence of System Factors on Energy Consumption During Resistance Welding

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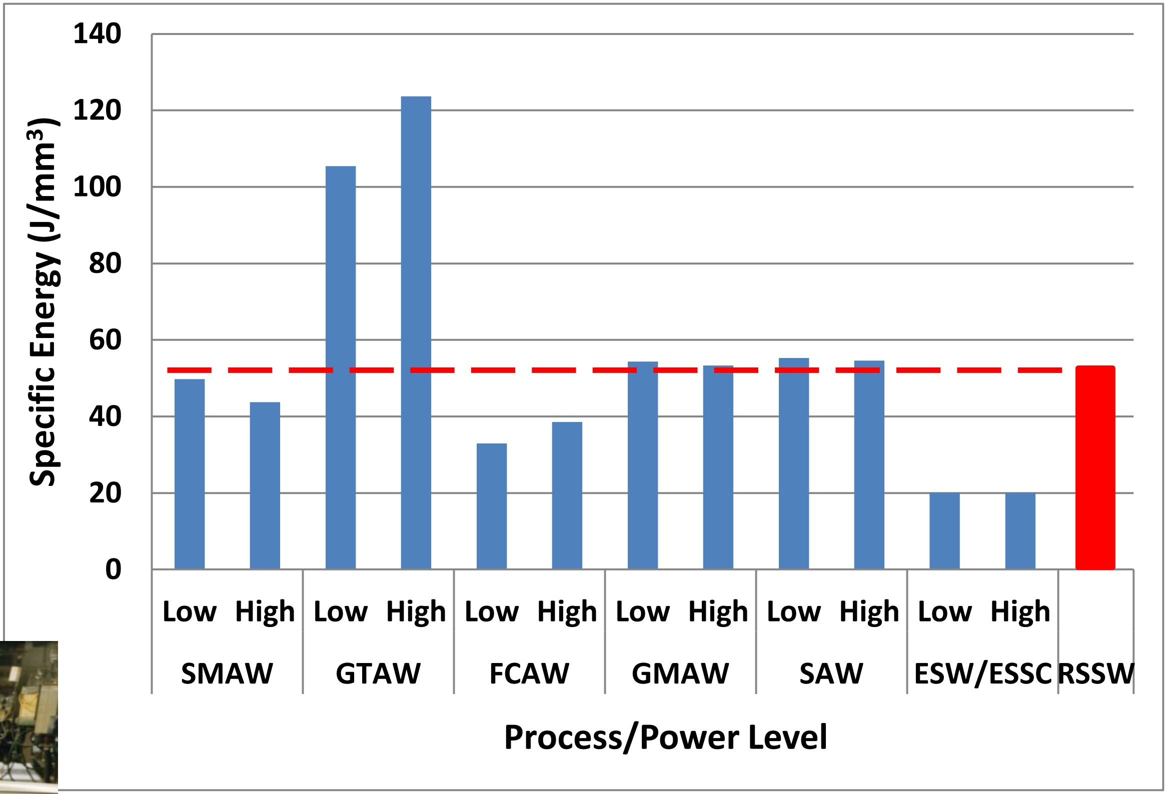
Relative Energy Consumption for Various Welding Methods

- Expectations RSW as low energy consumption
- Ontario Hydro study
- Examination of specific energies for various processes
- Counter-intuitive observations
- Focus of current discussion



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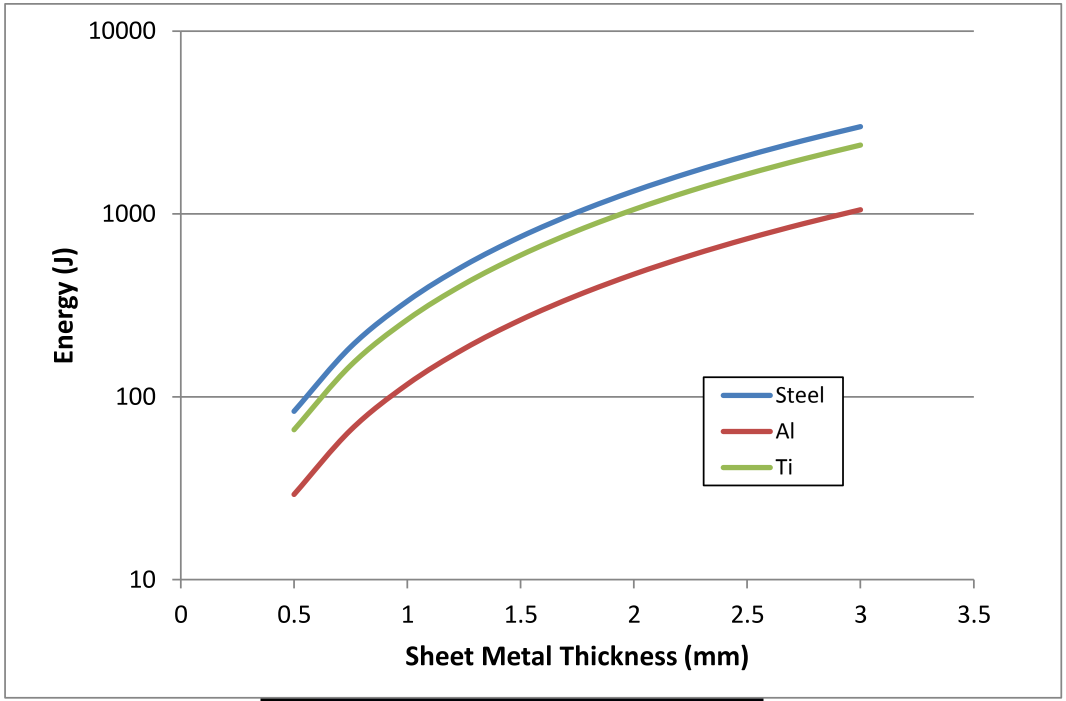
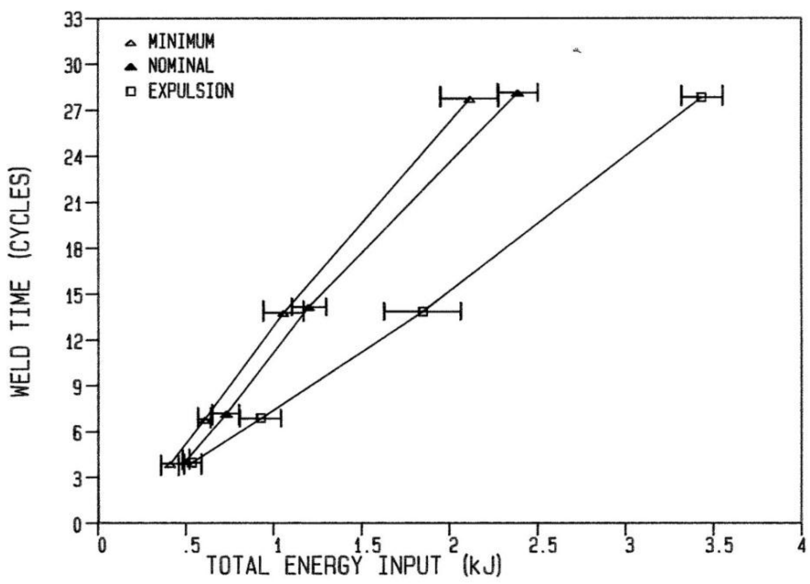
Specific energy demands to form a resistance spot weld

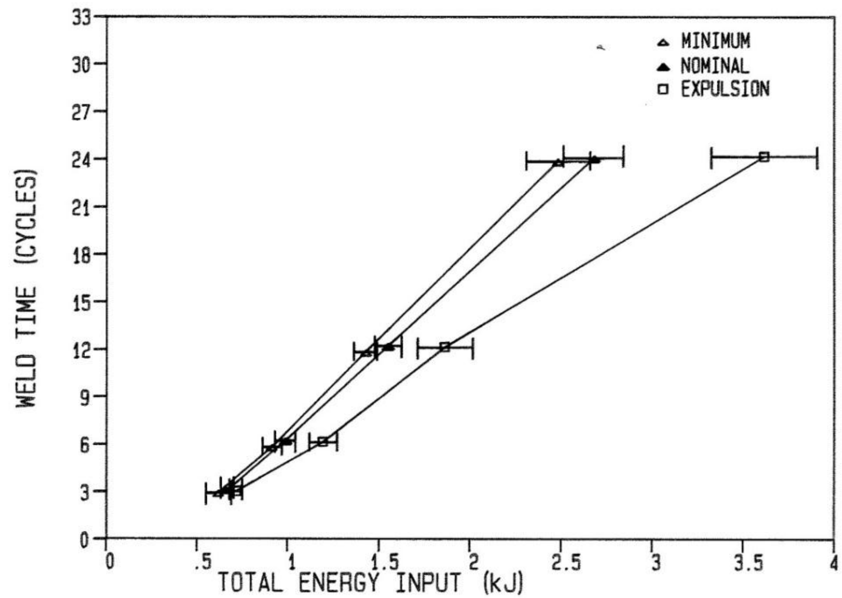
- **Theoretical calculations of energies to form spot welds**
- **Assumptions of:**
  - 6√t nugget size
  - Energy for heating up to T_m
  - Nugget melting (H_f)
- **Calculations for different:**
  - Material types
  - Sheet thicknesses
- **Energies range from a few hundred to a few thousand Joules**



Actual Energy Requirements for Steel Spot Welds made with Different Heating Times



Energy Weldability Lobe for 0.8-mm Bare Steel



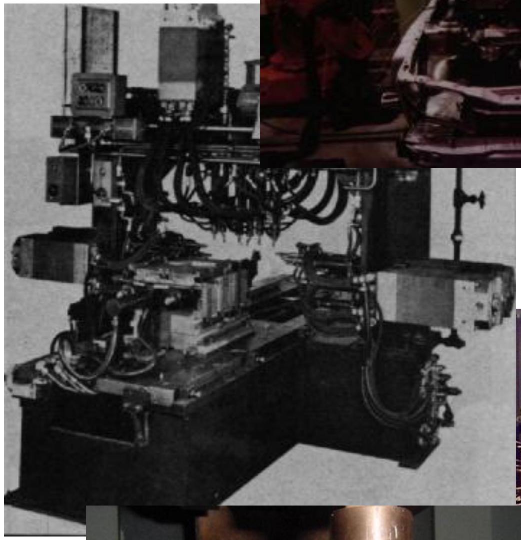
Energy Weldability Lobe for 0.8-mm HDG Steel

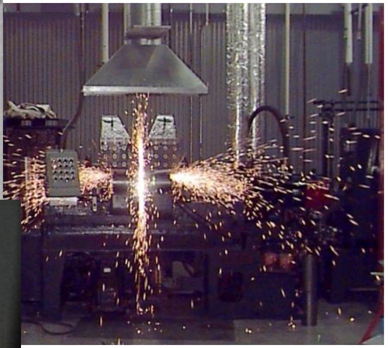
- **Energy data taken from previous work**
- **Mild and galvanized steels show similar results**
- **Energy for 0.8-mm steel ~3.5kJ at 400-ms weld time**
- **Energy required drops to 500-J at 50-ms**

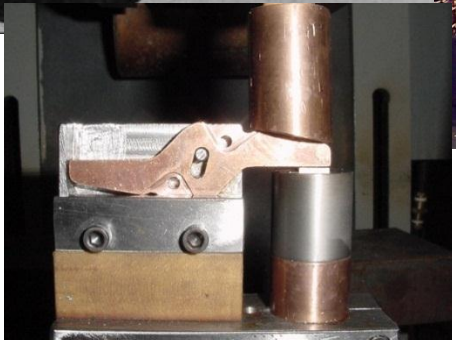
- **Energy variations due to heat loss to the electrodes**
- **Short time energies compare to heat of fusion calculations for observed nugget sizes**

Energy Consumption During Resistance Welding – Topics to Be Covered

- Thermal aspects of energy efficiency
- System aspects to energy delivery
- Characteristics of differing power supply types
- Electrical response of the various systems
- Characteristics of energy demand for differing resistance welding variants

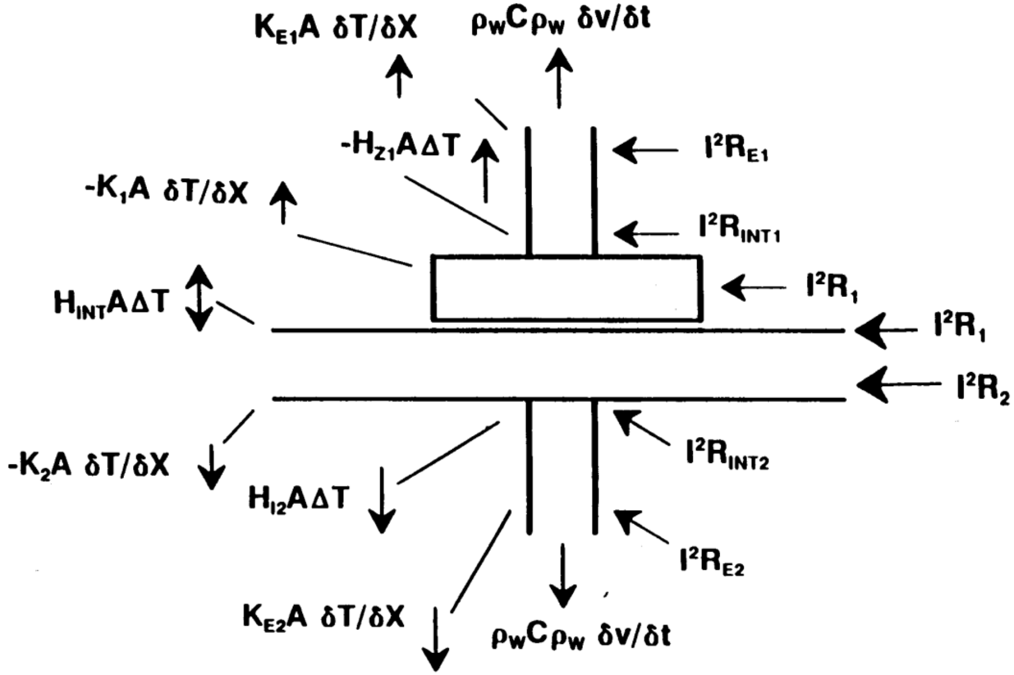






Thermal Electrical Response of Resistance Welds

- **Resistance welding a balance of**
  - Heat generation
  - Heat extraction
- **Resistance heating sources**
  - Workpieces
  - Surfaces
  - Electrodes
- **Heat extraction**
  - Electrodes
    - Thermal conductivity
    - Heat capacity
    - Cooling water
  - Environment (minor)



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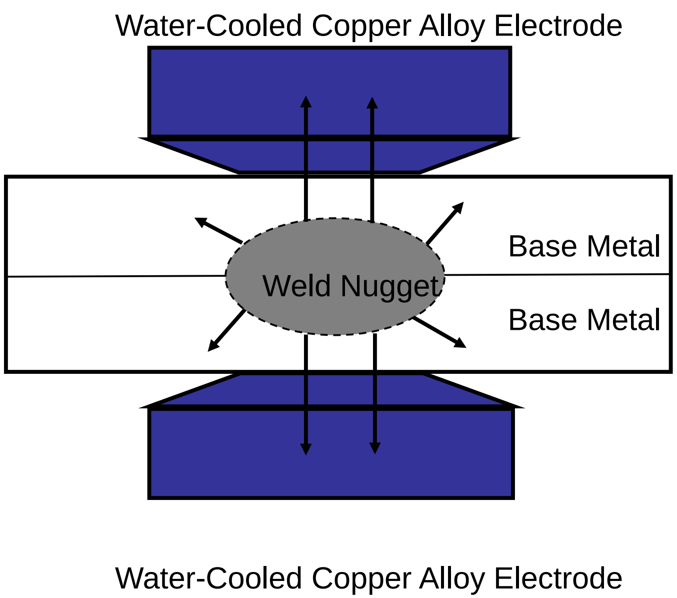
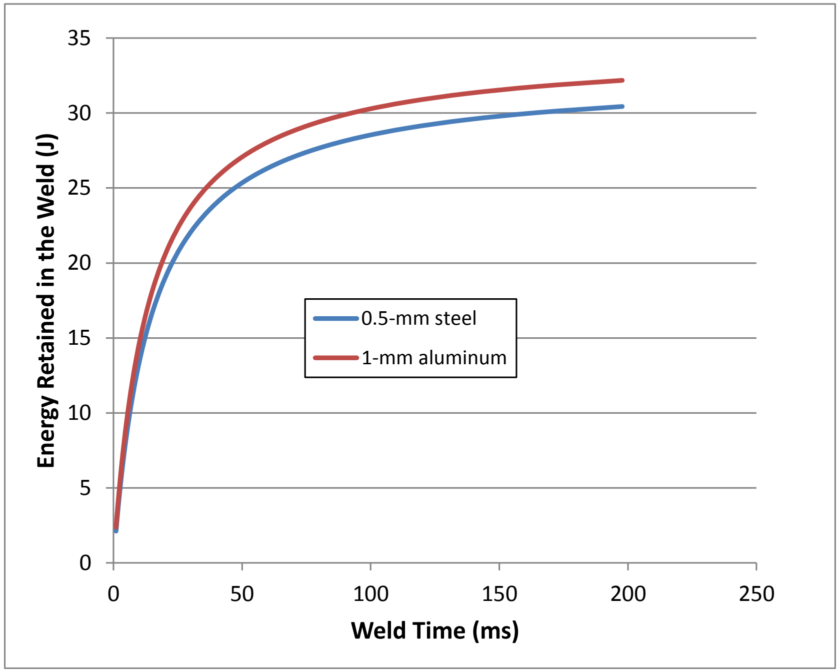
Heat Generation Characteristics of Resistance Spot Welds





- Simplified heat balance analysis of spot welds
- Effects of process conditions
- Influence of material type and geometry
- Assessments of process efficiency

$$\frac{E}{\xi C_p V} = \Delta T = \frac{I^2 \rho}{K\left(\frac{A}{\Delta x}\right)^2\left(\frac{\Delta x^2}{\alpha \Delta t}+1\right)}$$

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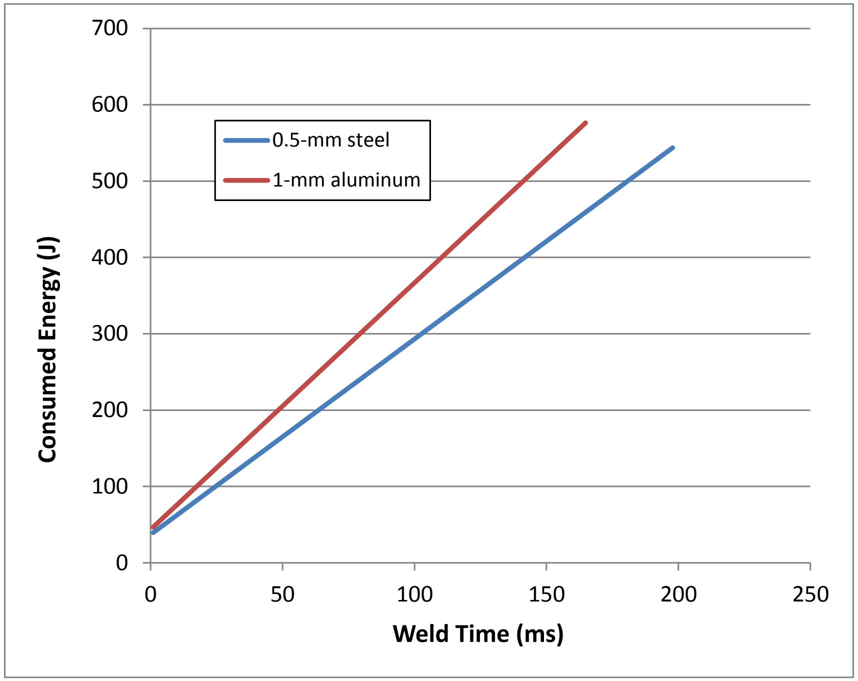
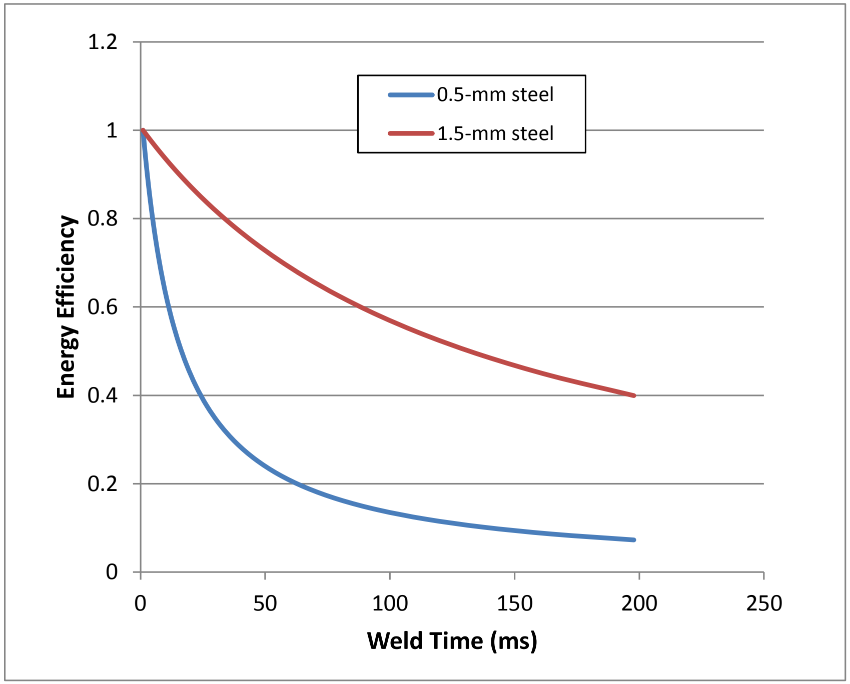
Energy and Efficiency During Resistance Spot Welding





- **Energy demand curves match those seen experimentally**
- **Linear behavior with time**
- **Material differences related:**
  - Heat capacities
  - Thermal diffusivities
  - Melting points

- **Energy efficiency a strong function of weld time**
- **Material thickness effect related to:**
  - Latent heat of workpiece
  - Heat extraction capability

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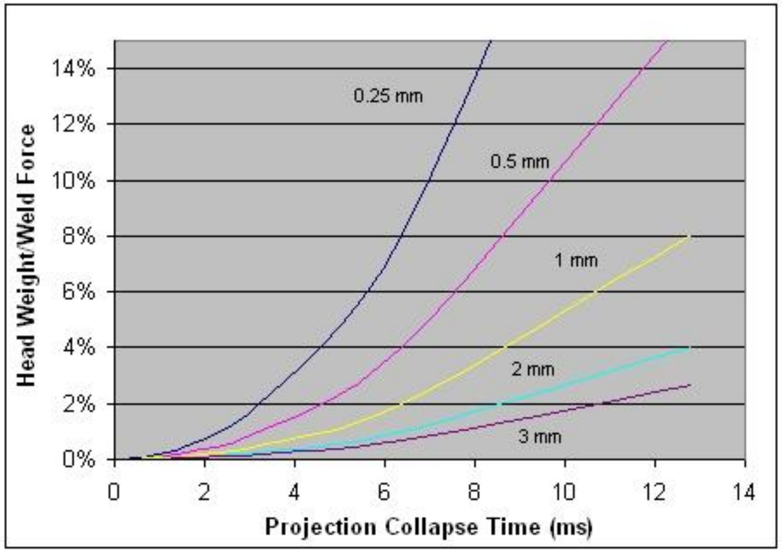
System Mechanical Dynamics

- **Stable weld forces critical to:**
  - Prevent inconsistent heat patterns
  - Avoid unstable expulsion
  - Accomplish proper forging of the projection
- **Factors affecting mechanical response requirements**
  - Weld force
  - Weld head inertia
  - Collapse distance
  - Collapse time
- **Criteria for weld head inertia based on maintaining 95% of the applied force**
- **W_{head}/F_{app} typically less than 10%**
- **Requirements for fast follow-up heads**

$$\frac{W_{head}}{F_{app}} \leq \frac{g(ft)^2}{20x}$$



Relationship between projection collapse distance, projection collapse time, and the head weight-to-weld force ratio

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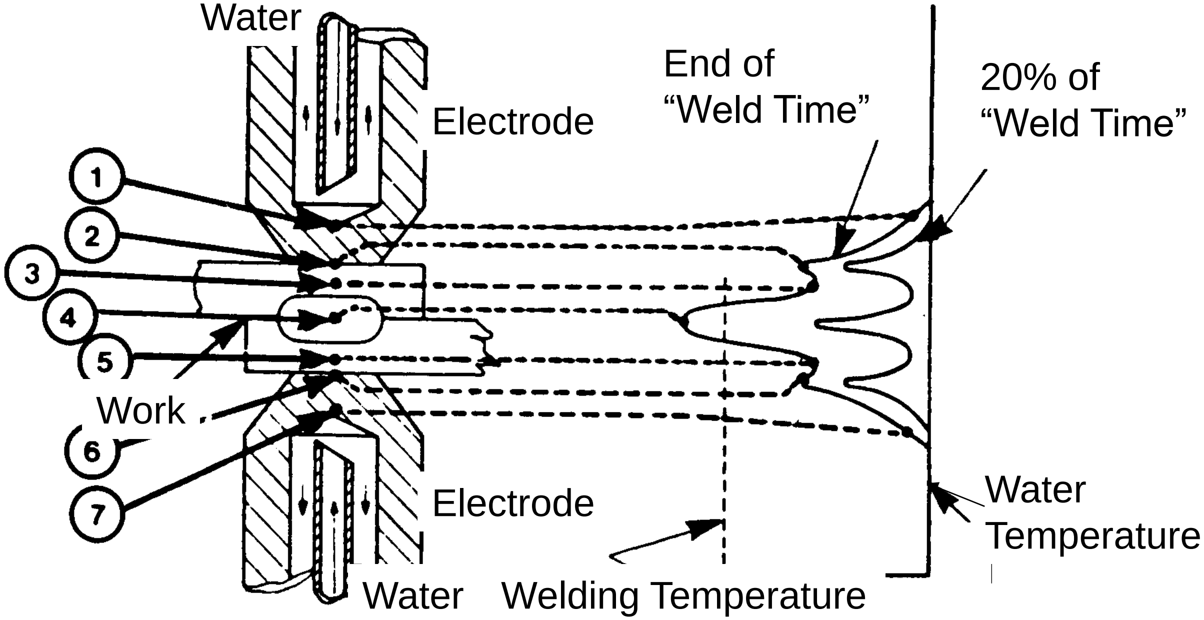
Necessity for Providing Adequate Cooling for Resistance Welding

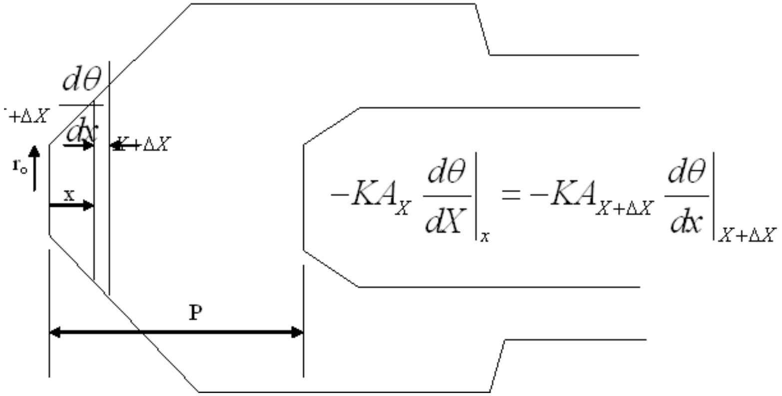


[Reference: Resistance Welding Manual, RWMA, p.1-4]

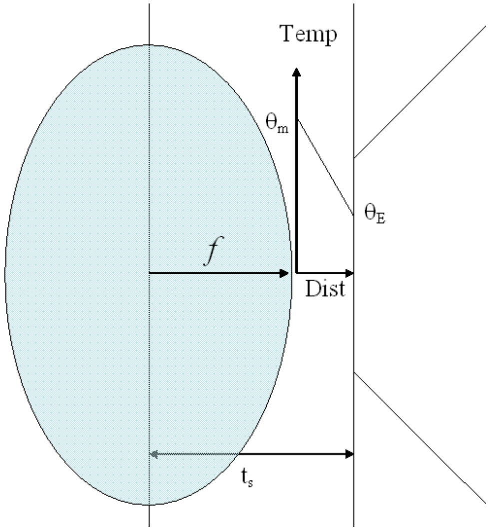
- **Functions of electrode cooling:**
  - Thermal constraint of the weld nugget
  - Mechanical stability of electrodes
- **Cooling essential for process stability**
- **Heat extraction implicit in the technology**

Modeling Tools – Temperature Profiles in Spot Weld Electrodes

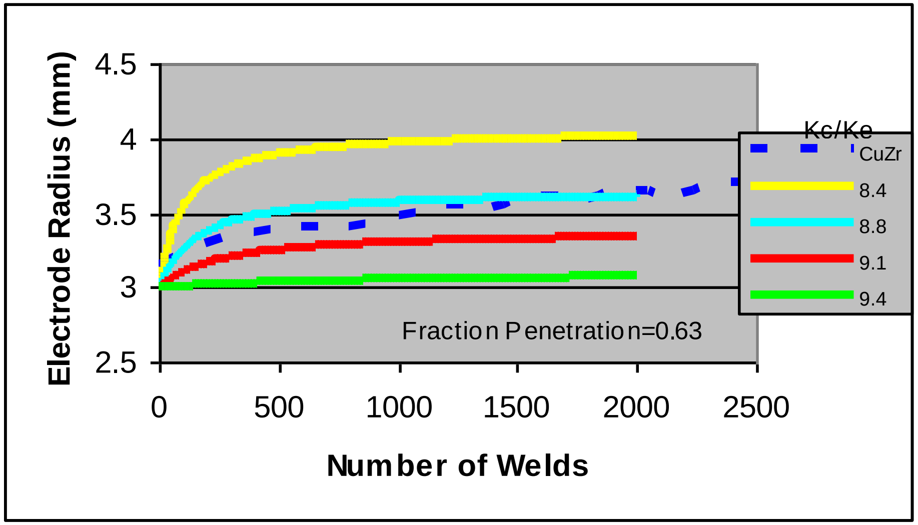
$$\theta = \theta_e - (\theta_e - \theta_o)\left(\frac{x}{p}\right)\left(\frac{r + pTan\phi}{r + xTan\phi}\right)$$

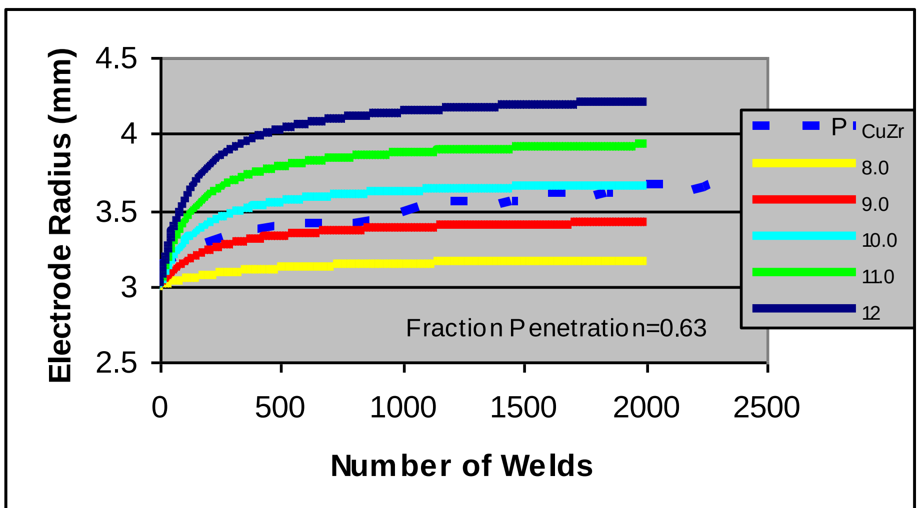


$$\theta_e = \frac{\theta_m + \left(\frac{K_c}{K_s}\right)\left(\frac{t_s}{p}\right)\left(\frac{r + pTan\phi}{r}\right)(1 - f)\theta_o}{1 + \left(\frac{K_c}{K_s}\right)\left(\frac{t_s}{p}\right)\left(\frac{r + pTan\phi}{r}\right)(1 - f)}$$



Heat Transfer Effects on the Accumulation of Electrode wear





$$XF = \frac{\left(\frac{rp}{r + PTan\phi}\right)\left(\frac{\theta_e - \theta_F}{\theta_e - \theta_o}\right)}{1 - \left(\frac{pTan\phi}{r + pTan\phi}\right)\left(\frac{\theta_e - \theta_F}{\theta_e - \theta_o}\right)}$$

$$XF' = \frac{\pi\left[\left(r + (XF)Tan\phi\right)^3 - r_o^{\ 3}\right]\left[\sigma_y(\theta_e) + \sigma_y(\theta_F)\right]}{6FTan\phi}$$

$$r_i = r_o + 2Tan\phi \sum_{i=1}^{n}\left(XF_i - XF_i^{'}\right)$$

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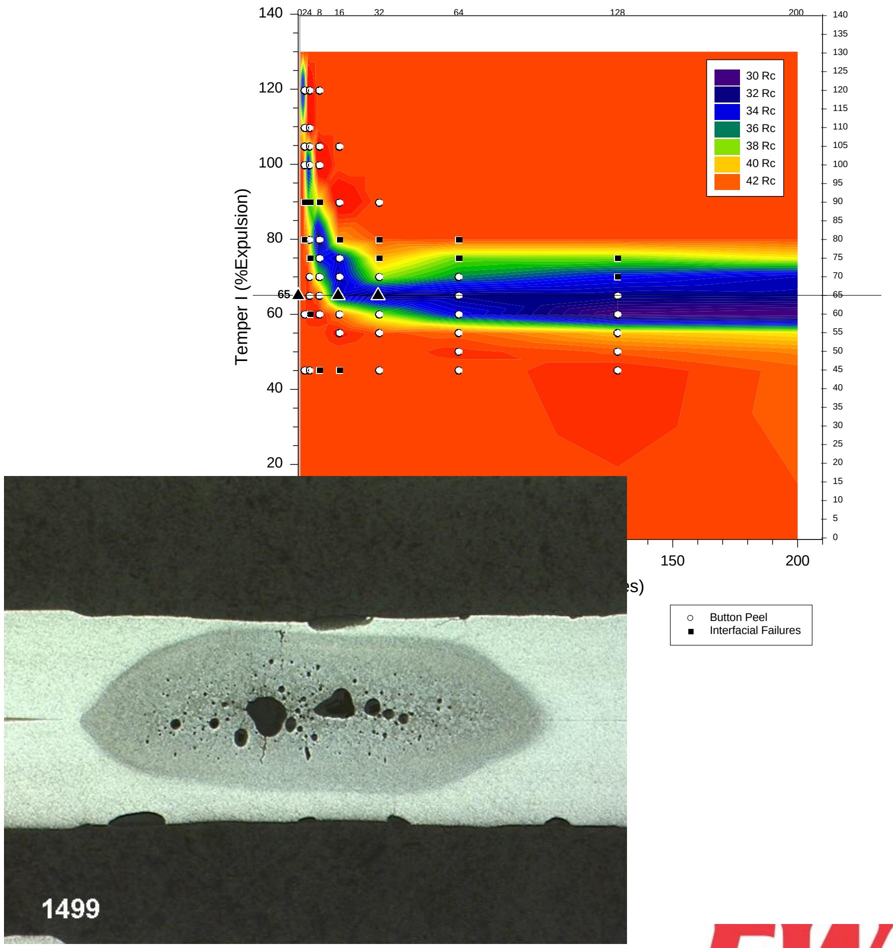
Constraints in Maximizing Thermal Efficiencies for Resistance Welding

- **Thermal efficiencies during resistance welding maximized by:**
  - Short cycle times
  - High power densities
  - Limited heat extraction
- **Influence of heating time on process stability**
- **Influence of limited heat extraction on weld and system integrity**
- **Current state of the art for spot welding ~30% thermal efficiency**



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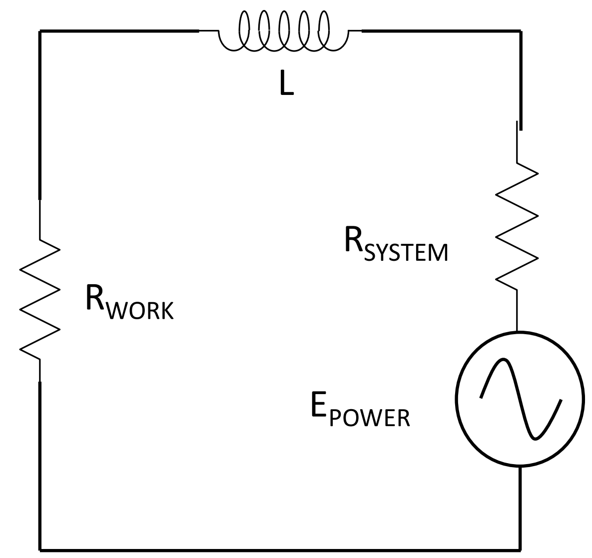
Energy Delivery during Resistance Spot Welding

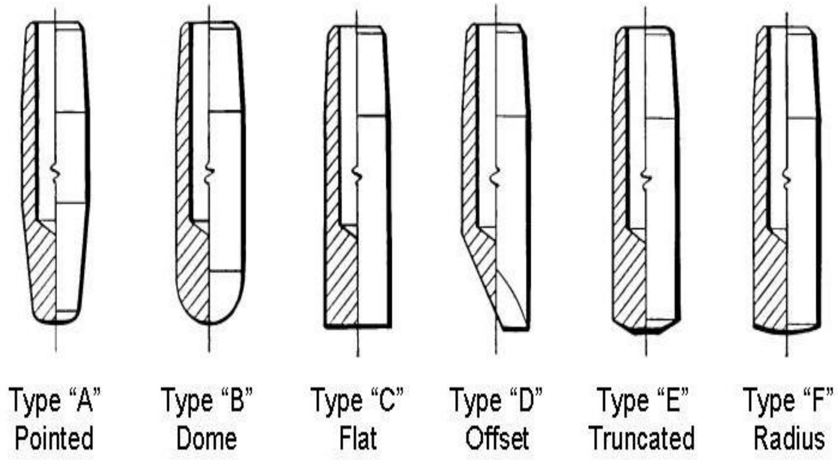
- **Secondary circuit to deliver current to the workpiece**
- **Characteristics of secondary define machine efficiency**
- **Critical characteristics of the secondary**
  - System Resistance
  - Workpiece resistance
  - System inductance
  - Power supply characteristics

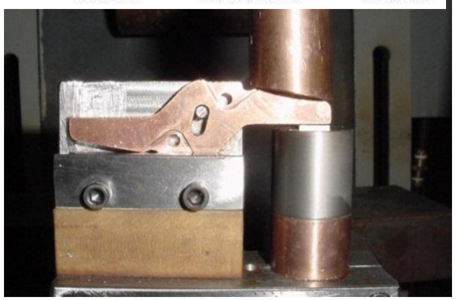


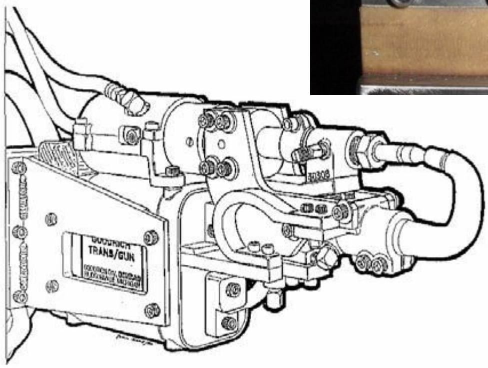
E_{POWER} = Power input type
R_{SYSTEM} = Internal machine resistance
R_{WORK} = Workpiece resistance
L = System inductance

Sources of Resistance in Welding Secondaries

- **Two elements of resistance in welding secondaries**
  - System resistance
  - Workpiece resistance
- **System resistance defined by conductor characteristics:**
  - Length
  - Cross-sections
  - Materials
- **Workpiece resistance defined by:**
  - Materials
  - Geometries
  - Surfaces
- **Typical secondary resistance range from 10's to 1000's of μΩ**
- **Series summation of resistances**







Analysis of the Secondary Circuit for Resistance Welding Systems

$$L = \frac{\mu P}{4} f(k)$$

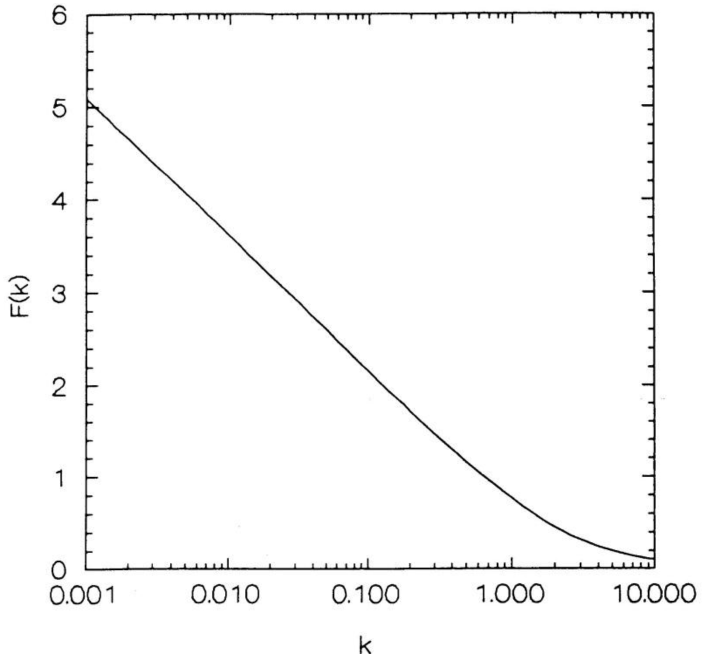
$$k = \frac{\pi w_c}{P}$$

$$f(k) = \frac{2}{\pi} ln\left(\frac{8}{k}\right)$$

$$\mathrm{L} = \frac{\mu P}{2\pi} ln\left(\frac{8}{k}\right)$$

L = secondary inductance
μ = magnetic permeability of air
P = periphery of the conductor

k = shape factor
w_c = conductor width



Relationship Between the Shape Factor k and the Function f(k)

- **Weld throat analysis taken from previous work**
- **Maxwell equations used to define relationship between geometry and inductance**
- ***F(k)* logrithmic with *P/w_c* a wide range of values**
- **Estimates of inductance can be used to calculate current response**
- **Typical inductances on the order of 1's to 10's of μH**

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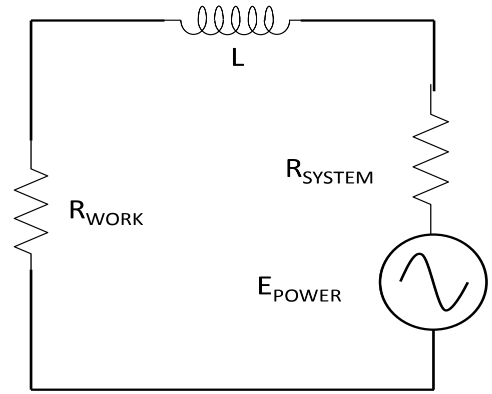
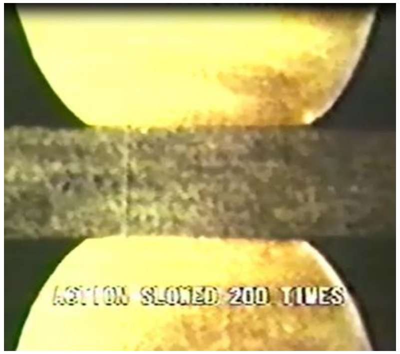
Characteristics of Alternating Current Power Supplies

- **Most traditional form of resistance welding power supplies**
- **Constant frequency (50-Hz – 60-Hz)**
- **Power losses associated with both resistive and inductive loading**
- **Estimations of system impedance through resistive and reactive loading**
- **Estimates of power delivery efficiencies**





$$I = \frac{V}{Z} \qquad Z = \sqrt{\left(R_{Work} + R_{Syd}\right)^2 + {X_L}^2}$$

$$X_L = 2\pi f L \qquad \mathrm{L} = \frac{\mu P}{2\pi} ln\left(\frac{8}{k}\right) \qquad k = \frac{\pi w_c}{P}$$

$$eff = \left(\frac{R_{Work}}{Z}\right)^2$$

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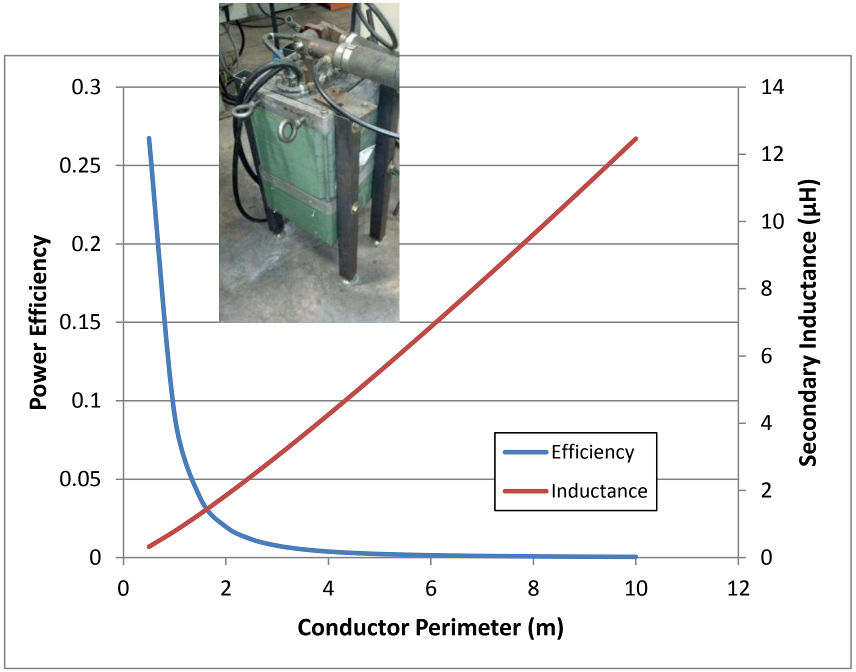
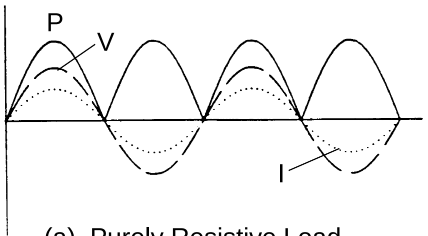
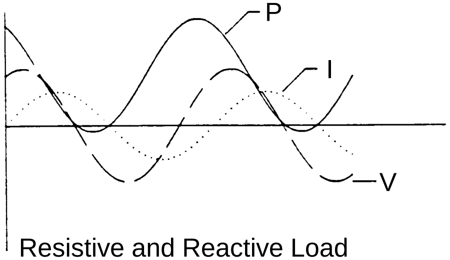
Influence of Secondary Design on Efficiency of the AC Power Delivery

- **Changes in inductance for different loop sizes**
- **Design assumptions:**
  - Conductor Dia ~50-mm
  - Workpiece resistance ~100-µΩ
  - System resistance ~50-µΩ
- **Rapid increase in system inductance with loop perimeter**
- **Power factor increase**
- **Rapid reduction in deliverable power**



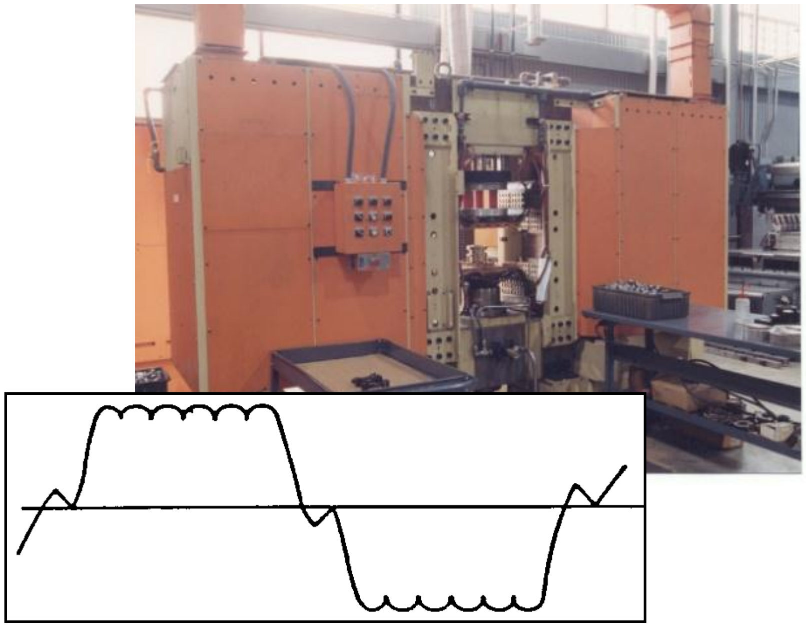


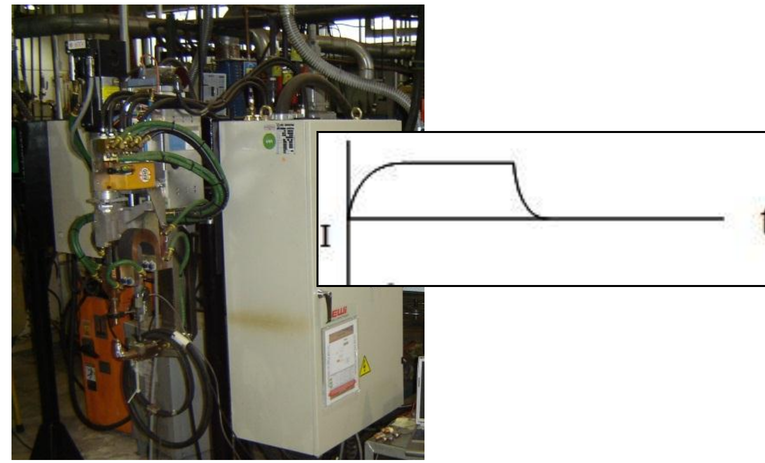
(a) Purely Resistive Load

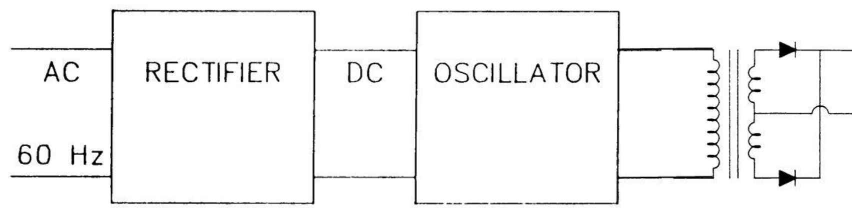


Resistive and Reactive Load

Types of DC Power Supplies for Resistance Welding





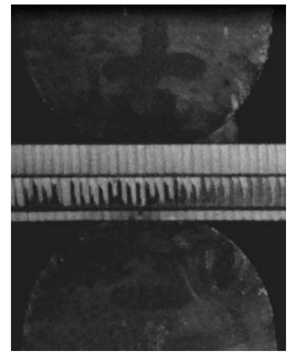


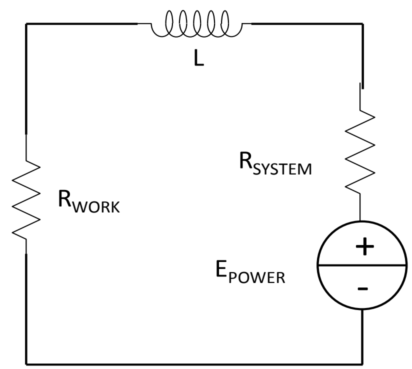
- **DC systems – Direct current in secondary**
- **Frequency converter systems – DC pulses into transformer**

- **MFDC – MF power into transformer with rectification on secondary**
- **Reduced influence to system inductance**

Characteristics of DC Resistance Welding Power Supplies

- **LR circuit DC response**
- **Current and energy estimations from secondary circuit analysis**
- **Limited influence of system inductance**
- **Minimal power factor influence**
- **Large secondary diodes**
- **Influence of diode impedance**

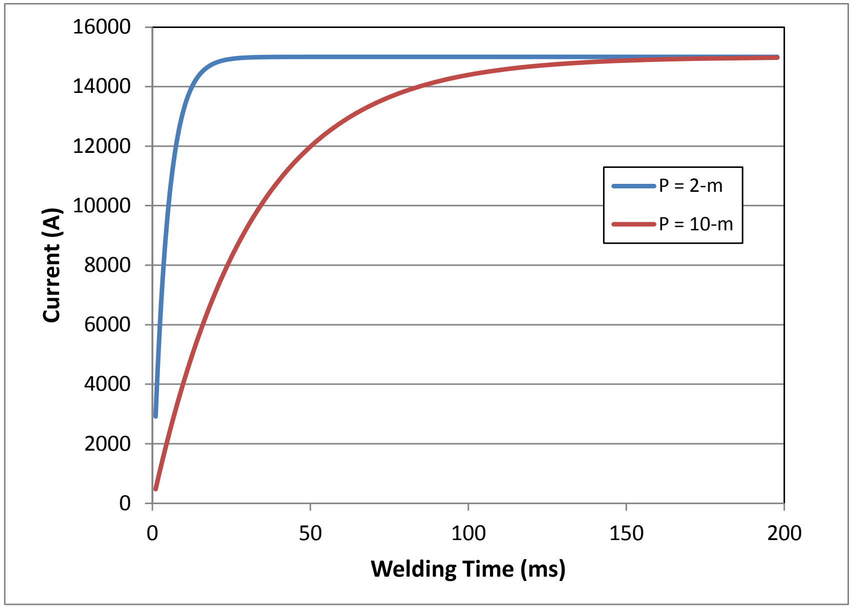




$$I = \frac{V}{R_{Work} + R_{Sys}}\left(1 - e^{-(R_{Work}+R_{Sys})t/L}\right)$$

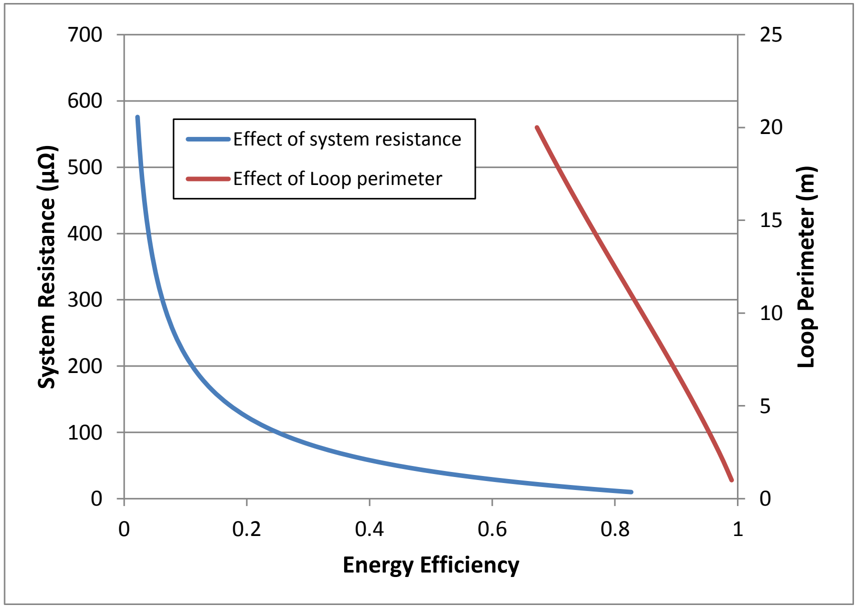
$$E = \frac{V^2}{R_{work} + R_{sys}}\left(t + \frac{L}{R}\left(e^{\frac{-(R_{work}+R_{sys})t}{L}} - 1\right)\right)$$

Influence of Secondary Design on the Efficiency of DC Power Delivery



Estimated current response from a typical MFDC spot welding system and influence of perimeter loop size

- Inductance influences system rise time
- Changes in rise time affect total delivered energy
- Changes in rise time affect process response



Energy efficiency variations associated with changes in system resistance and secondary loop size.

- Order of magnitude loop sizes affect efficiencies only minorly
- MFDC Efficiencies dominated by diode resistances

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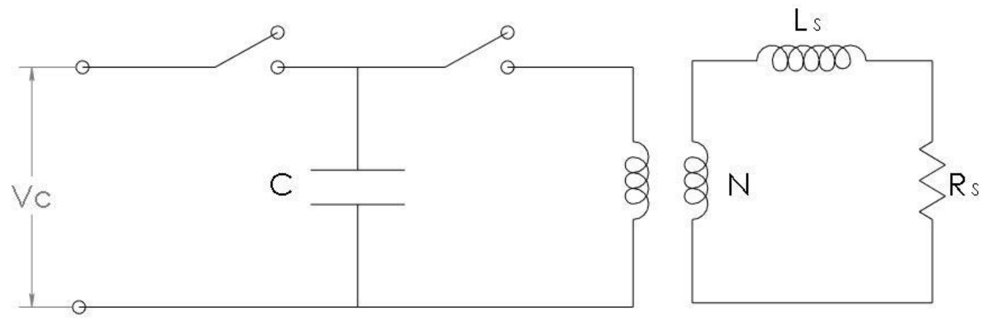
Characteristics of Alternating Current Power Supplies

- **Capacitor based energy storage**
- **Standard systems:**
  - High charge voltages
  - Low system capacitances
- **Transformer for energy conversion**
- **System can be modeled as an LRC circuit**
- **Analysis based on high current flow in welding secondary**
- **Current characteristics**
  - Rise times
  - Peak values



Schematic representation of the power circuit for a CD projection welding system

$$I_s(t) \approx V_c \sqrt{\frac{C}{L_s}} e^{-\zeta \varpi t} \sin(\omega t)$$

$$\omega = \frac{1}{N} \sqrt{\frac{1}{L_s C}} \qquad \zeta = \frac{NR_s}{2} \sqrt{\frac{C}{L_s}}$$

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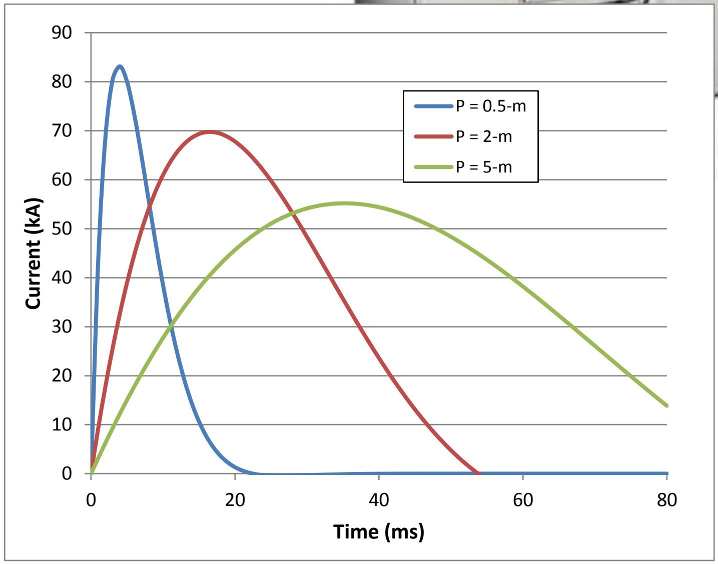
Some Aspects of System Design on Process Efficiency

- **CD welding largely associated with projection welding**
- **Some typical CD system parameters**
  - Capacitances up to 70-kJ
  - Charge voltages >3000-V
  - Capacitances of 1000’s of μF
- **System responses**
  - Currents in excess of 100-kA
  - Rise times <10-ms
- **Influence of secondary configuration**
- **Increasing throat sizes affect rise times and peak currents**
- **Dominance of rise times on projection weld quality**
- **Increases in energy demand based on rise times**



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Characteristics of New Generation Resistance Welding Processes

- **Summary of system factors affecting efficiency**
  - Efficiency compared to other processes
  - Thermal effects
  - Inductance losses
  - Resistance losses
- **Balance between system utility and energy efficiency**
- **Examples from new generation processes**
  - Resistance seam cladding
  - Flash-butt wedge repair
  - Translationally assisted upset welding
  - Supercapacitor power supplies
  - Electro-spark deposition
  - Indirect resistance heating processes

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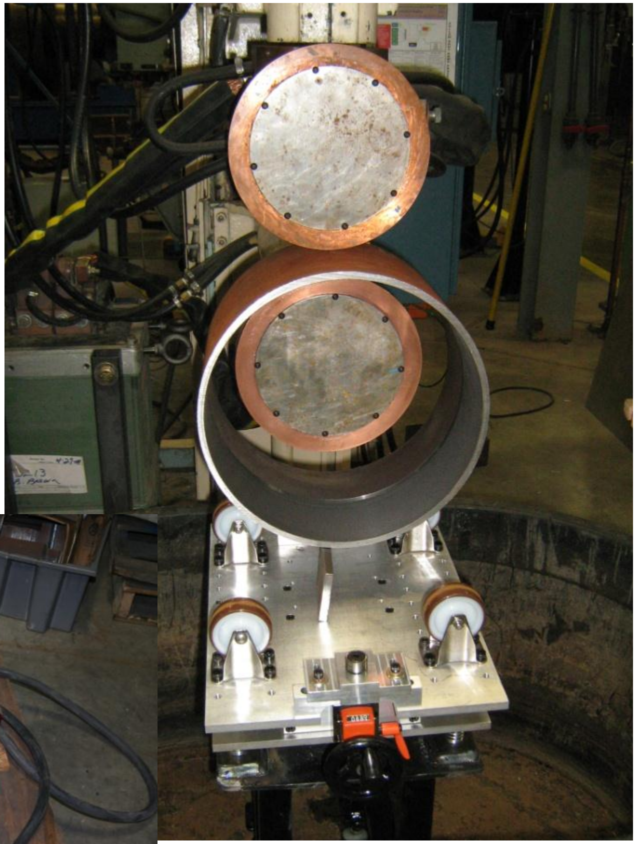
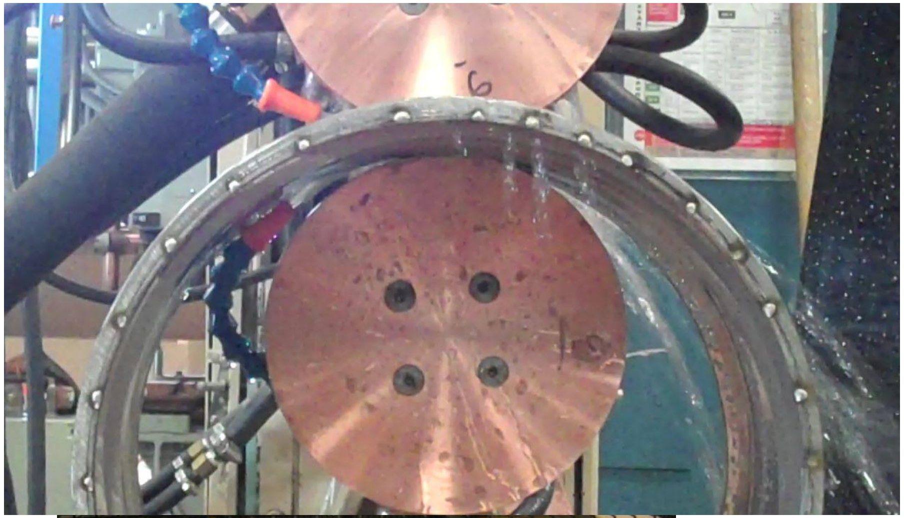
Resistance Seam Cladding for Linepipe

- **CRA pipe**
  - 316SS or High Ni alloys
- **CRA is becoming critical**
  - Gas applications with CO_2 and Cl ions
  - Fluid applications with H_2S
- **Steel pipe ~10-mm wall X 350-mm diameter**
- **Inconel 625 liner rolled from sheet stock ~2-mm thick**



Application and Advantages of Resistance Welding for Pipe Cladding

- **Clad tube inserted into steel pipe**
- **Weld wheels pass current through the sheet stack to be bonded**
- **Weld made between CRA and substrate**
- **Expanded area by progressive overlapped seams**
- **Localized energy application**
- **Thermal control**
  - Surface protection
  - Retention of base metal properties



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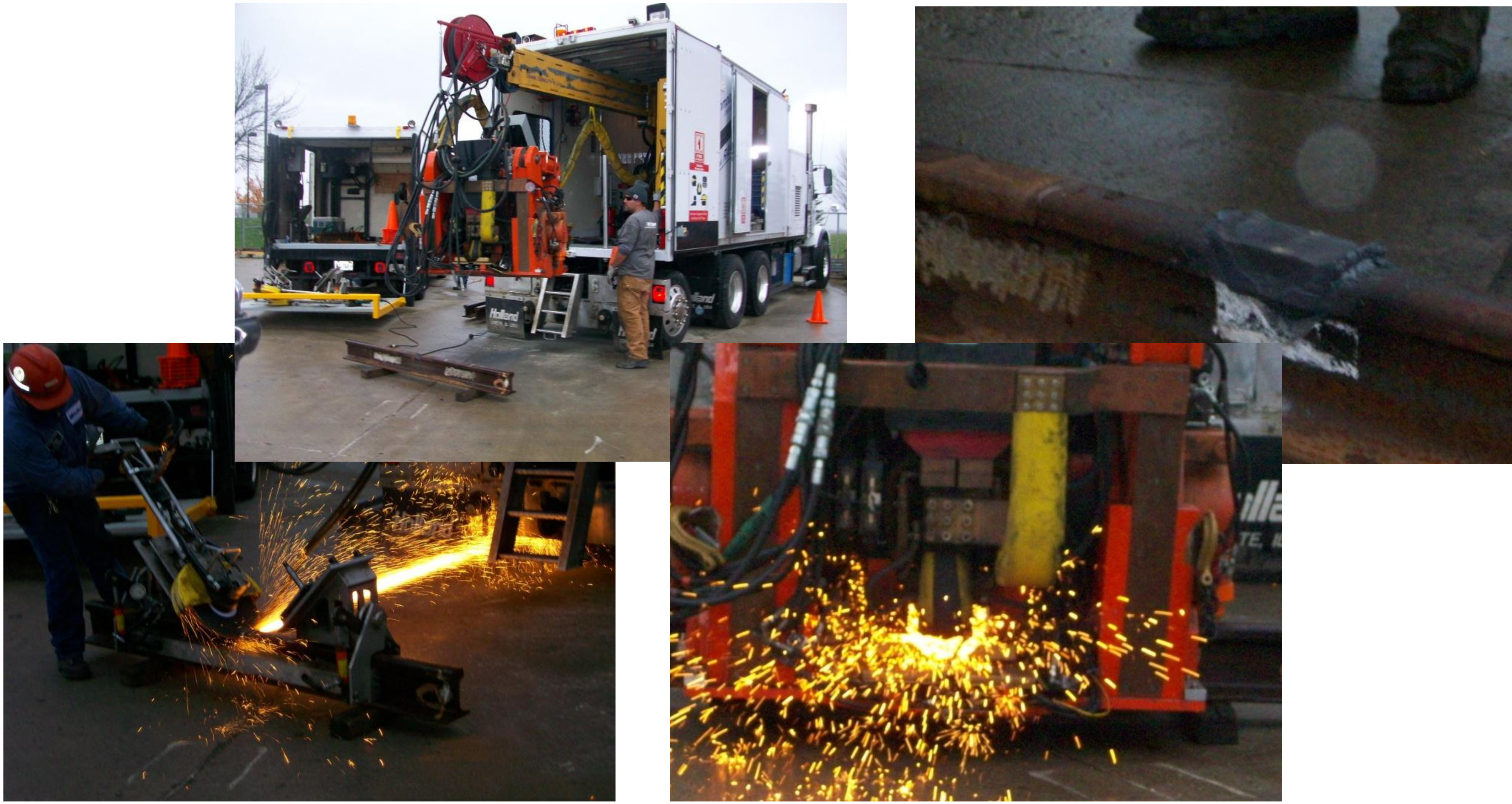
Flash-Butt Wedge Repair of Rails



Thermal and Energy Management of the Flash-Butt Wedge Repair process

- **In-process pre-heating**
- **Cooling rate monitoring using IR Thermal**
- **Process optimization to:**
  - Minimize any residual bond line decarburization
  - Reduce any far HAZ softening
- **Over-harden wedge prior to welding process**
  - allow in-process heating to temper back wedge
- **Portable power supplies**
- **Transportability**
- **Thermal management key**

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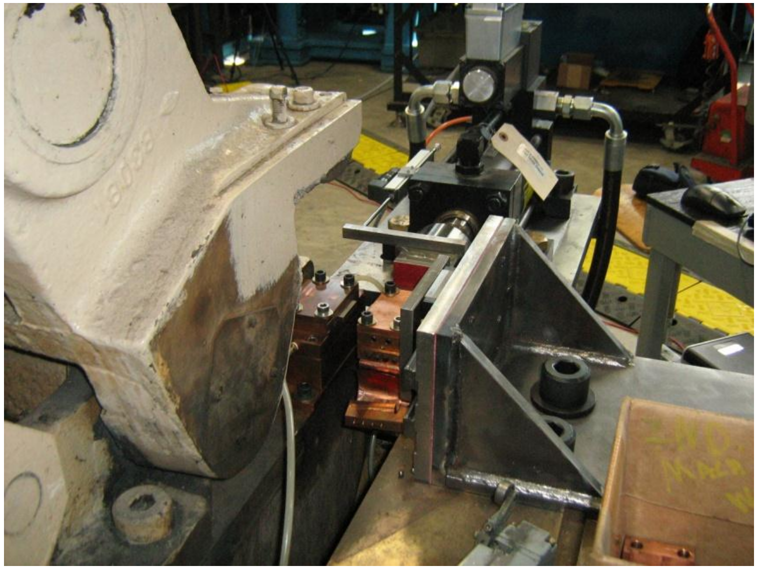
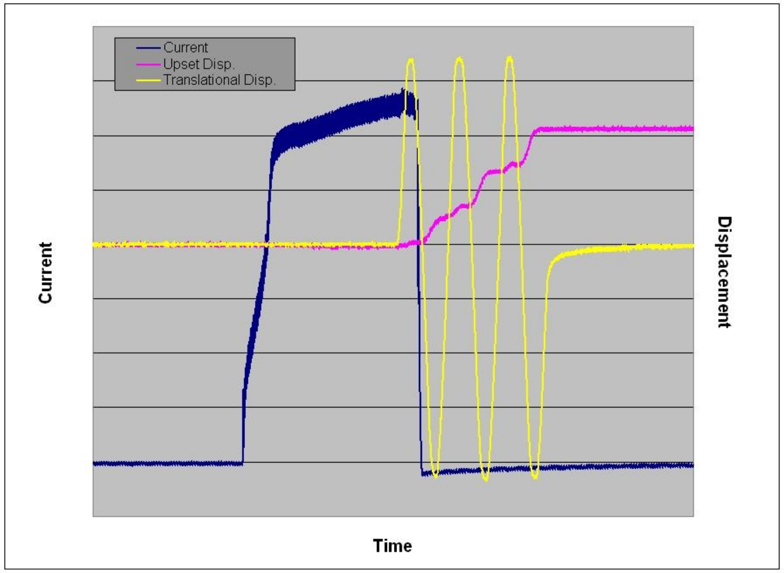
Translationally Assisted Upset Welding (TAUW) – New Generation Solid State Welding





- **Technology based on resistance butt welding**
- **Translational action to improve bond line strains**
- **Independent forging and scrubbing cylinders**

- **Independent action of**
  - Current pulse
  - Translational action
  - Upset action
- **Independent control of surface strains and heat content**

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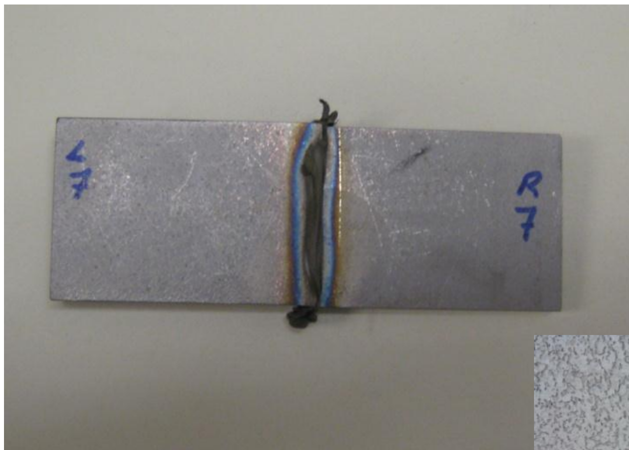
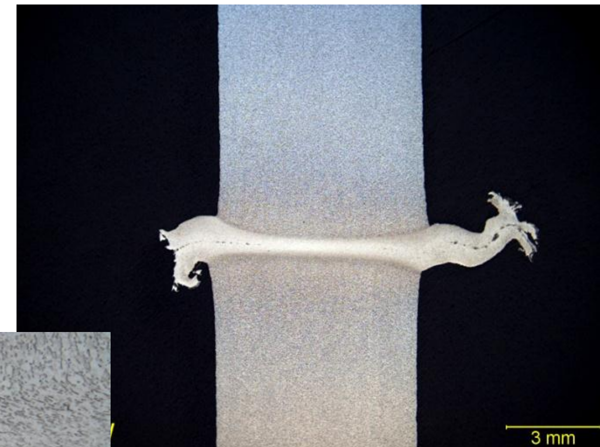
Translationally Assisted Upset Welding - Characteristics



As Welded Specimen
Showing Minimal
Flash Curl

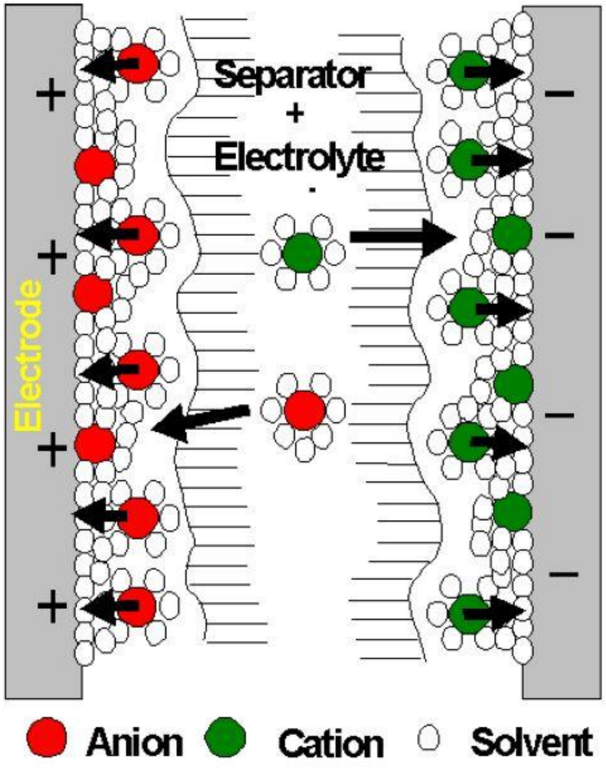
Details of the Bond Line Showing
Re-Solutionized Microstructure



Bond Line Macrograph
Showing Flash Curl
and Bond Line Profile

Supercapacitors Applied as Resistance Welding Power Sources

- **Conventional dry capacitors**
  - Layered electrodes
  - Dielectric separator
  - Capacitance through static charge attraction
  - Capacitance limited by breakdown voltage of separator
  - Limited capacitance values
- **Construction of supercapacitors**
  - Double wound capacitor
  - Incorporates carbon electrodes
  - Electrodes wound with a permeable separator
  - Charge stored through ionic separation
  - Separate charge surfaces at each electrode
  - Micro-scale separators
  - High surface to separation ratios
  - High achievable capacitances



Supercapacitor Functionality, taken from Green and Jehoulet, 2002

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Advantages of Supercapacitor based for Spot Welding Systems

- **Supercapacitors as a candidate alternate power supply**
- **CD power supplies established for RPW**
- **Supercapacitors as an alternative to conventional capacitors**
  - Low operating voltage (<5V)
  - High specific capacitance (kF)
  - High specific energy (kJ)
  - Rapid charge and discharge cycles
  - High output currents
  - Long life (10^6 cycles)
- **Potential for welding without transformers**
  - Weight reduction
- **Cost reduction potential**

Maxwell K2 Series Supercapacitors


Nippon Chemi Con DLCAP Series Supercapacitors

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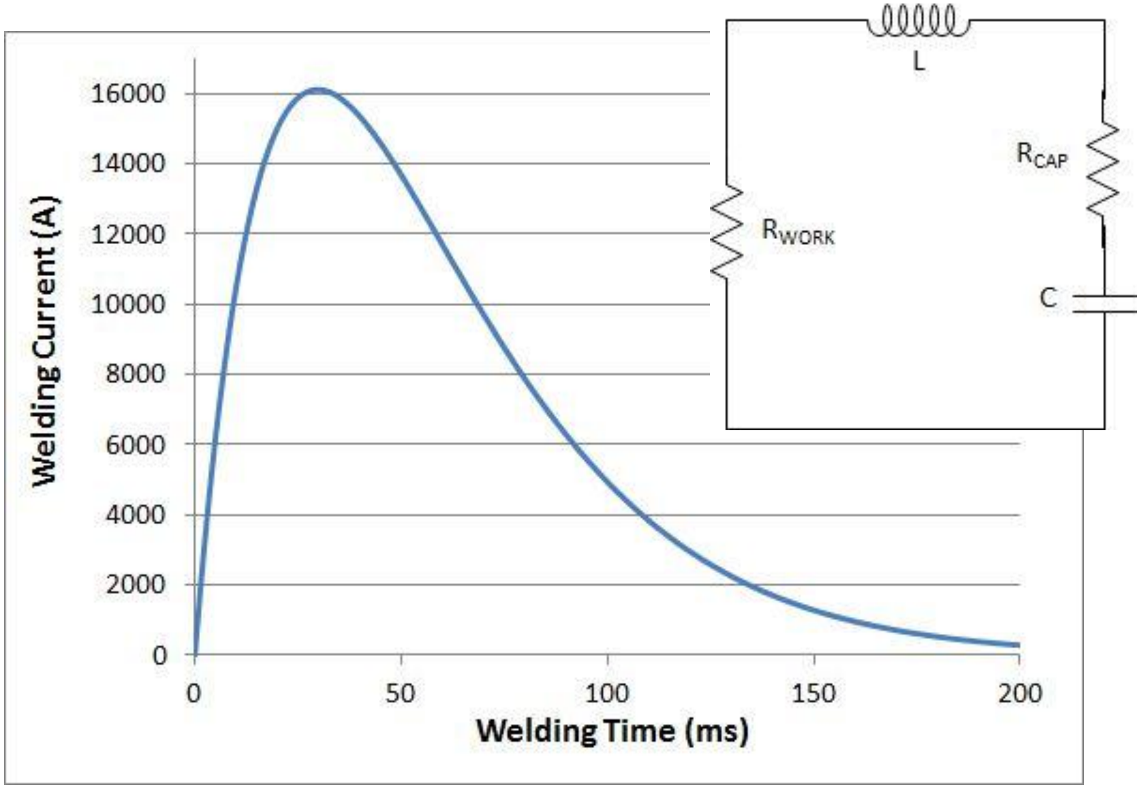
Electrical Analysis of a Supercapacitor Driven Spot Welding Secondary

$$I(t) = V_c\sqrt{\frac{n_{caps}C}{L}}\, e^{-\zeta\omega t} sin(\omega t)$$

$$\zeta = \frac{1}{2}\left(R_{work} + \frac{R_{caps}}{n_{caps}}\right)\sqrt{\frac{n_{caps}C}{L}}$$

$$\omega = \sqrt{\frac{1}{n_{caps}LC}}$$

C = System capacitance
R_{cap} = Internal capacitor resistance
R_{work} = Workpiece resistance
V_c = Charging voltage
N_{caps} = Number of capacitors in parallel



Predicted Response from a Supercapacitor Based Welding Gun. Analysis is based on 2.7-V, 3000F capacitors with a 0.29-mΩ internal resistance, four caps in parallel, and a gun loop perimeter of 2-m.

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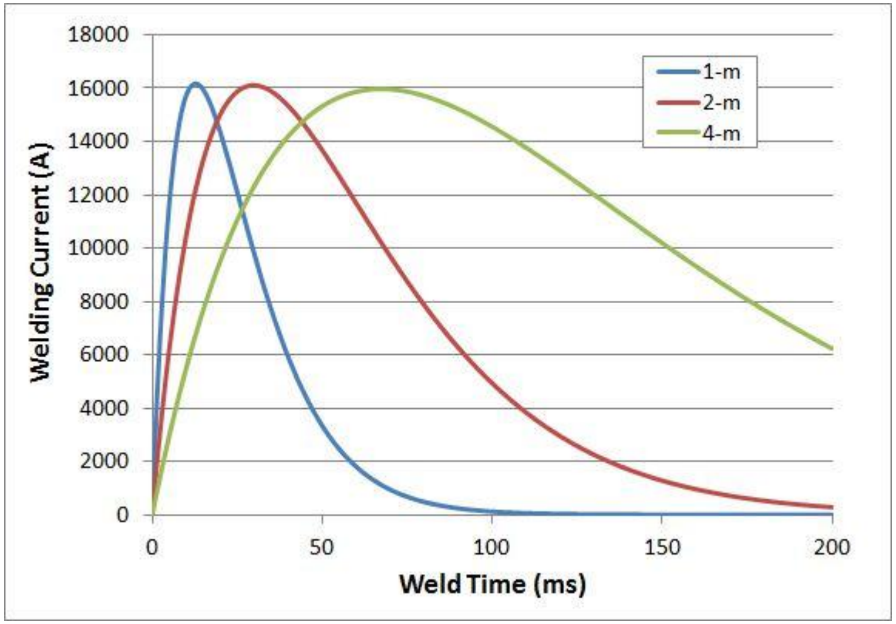
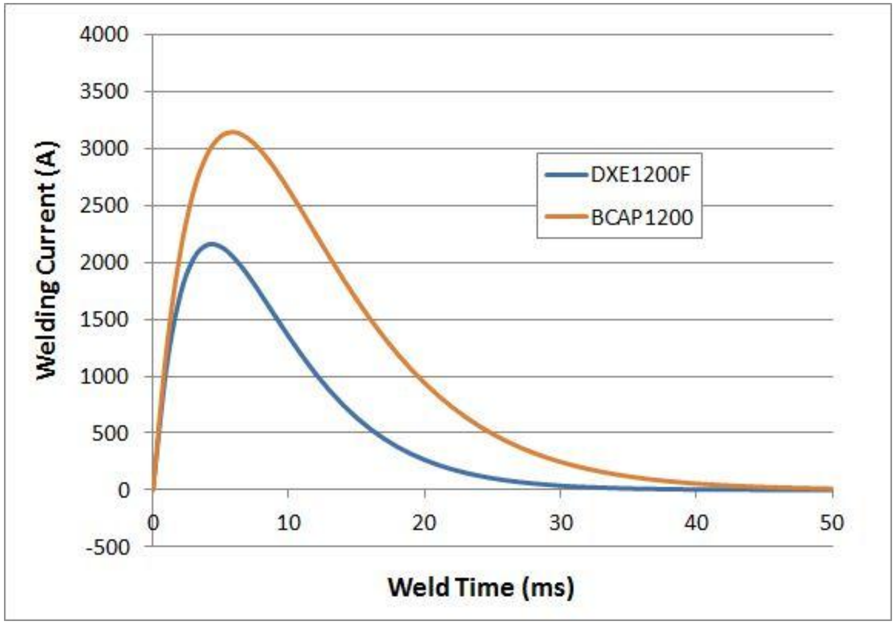
Influence of Electrical Circuit Factors on Deliverable Currents



The Influence of Gun Throat Size on the Current Response from a Supercapacitor Based Spot Welding System. Calculations are done for four parallel 2.7V, 3000-F Maxwell supercapacitors.



The Influence of Charge Voltage on the Current Response from a Supercapacitor Based Spot Welding System. Calculations are done for four parallel 2.7V, 3000-F Maxwell supercapacitors and a 2-m perimeter gun secondary.

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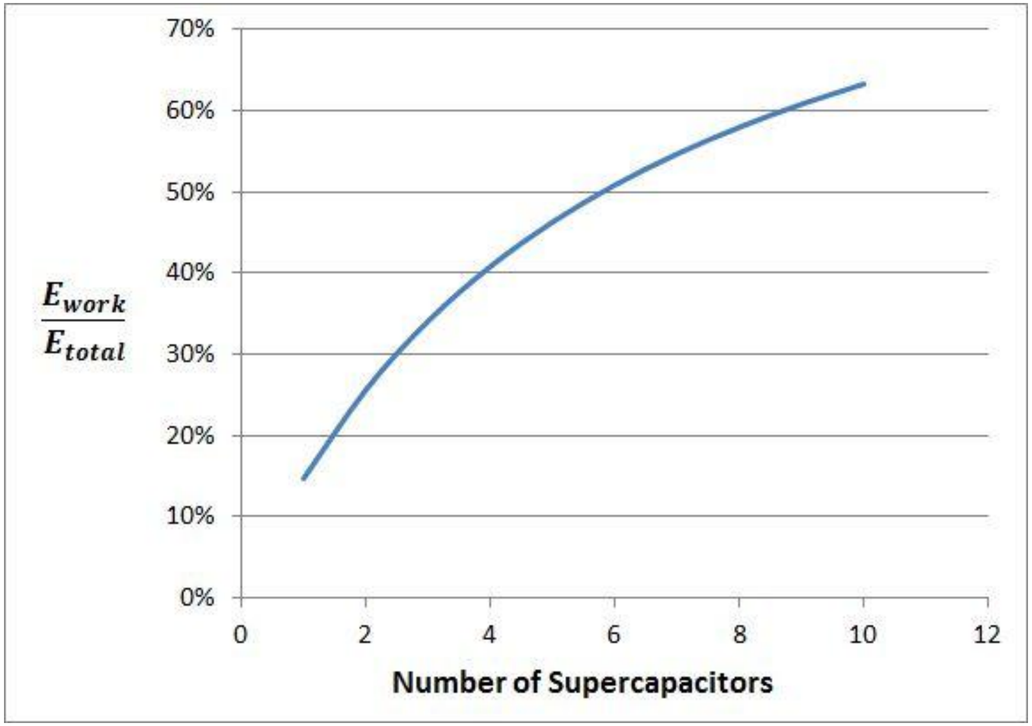
Influence of the Numbers of Parallel Caps on the Electrical Efficiency of the Process

The Influence of the Number of Parallel Caps on the Fraction Energy Delivered to the Workpiece. Calculations are done using 2.7V, 3000-F Maxwell supercapacitors and a 2-m perimeter gun secondary, calculating energy at the workpiece compared to that of the total system.



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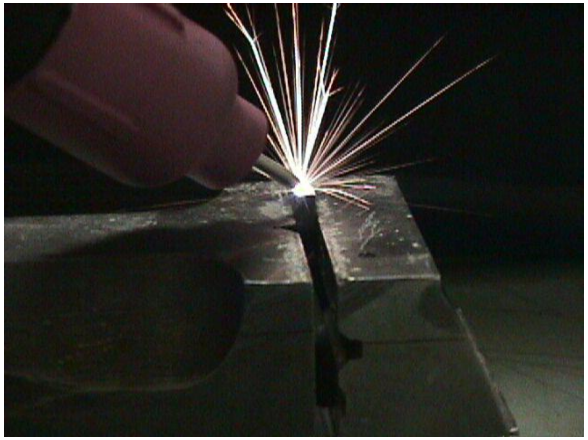
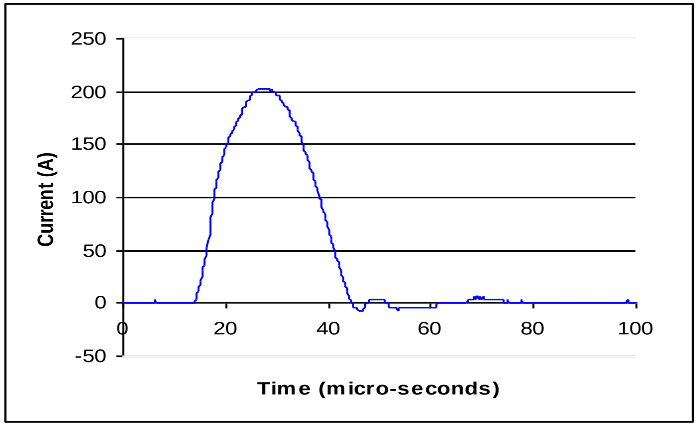
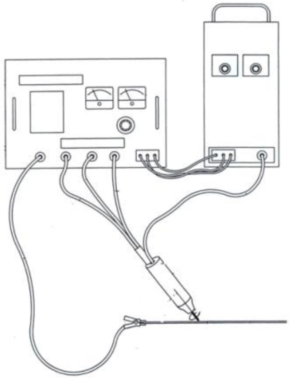
Electro-Spark Deposition – A Localized Resistance Repair Process

- **Local surface buildup for cosmetic repair**
- **Deposits without cracking or distortion**
- **Process sensitive to a range of factors:**
  - Power supply
  - Torch
  - Mechanical Setup



Spark emission during manual ESA deposition





Three primary components

- Power supply
- ESA torch
- Motion control

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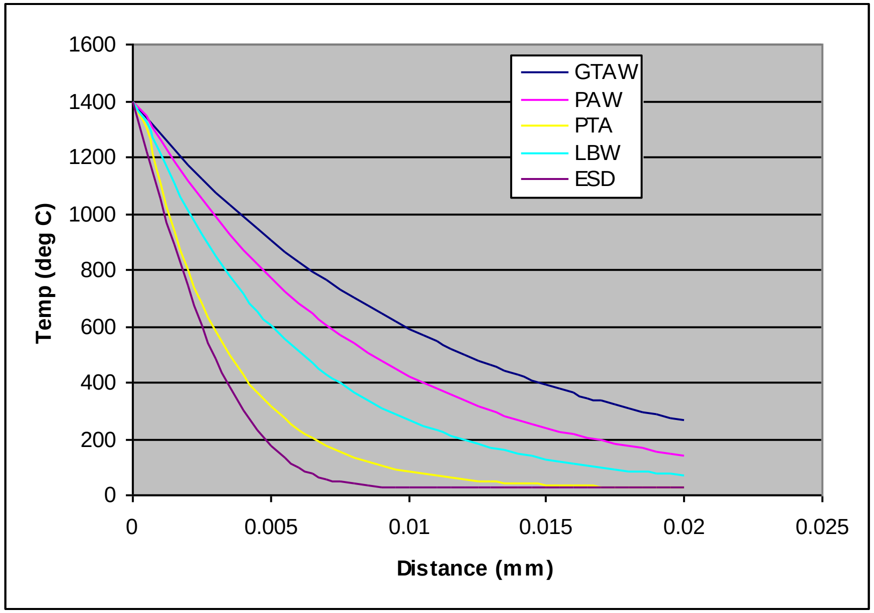
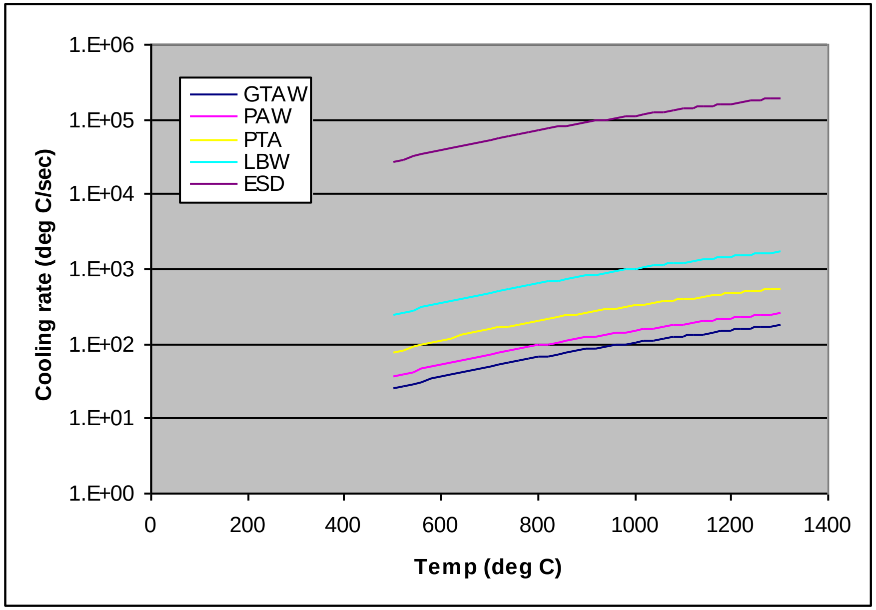
Thermal Analysis of Various Localized Deposition Processes





Arc and Laser Processes: $$T = \frac{\dot{Q}}{2\pi KR} e^{-\frac{V(R-x)}{2\alpha}} + T_o$$

Arc and Laser Processes: $$\frac{dT}{dt} = 2\pi K \frac{V}{\dot{Q}} (T - T_o)^2$$

ESD: $$T = T_m - (T_m - T_o) erf\left[\left(\frac{x}{x_{sp}}\right)\left(\frac{C_p (T_m - T_o)}{H_m}\right)\left(\frac{1}{\sqrt{\pi}}\right)\right]$$

ESD: $$\frac{dT}{dt} = \frac{2\alpha C_p}{\pi x_{sp}^2 H_m} (T_m - T_o)^2$$

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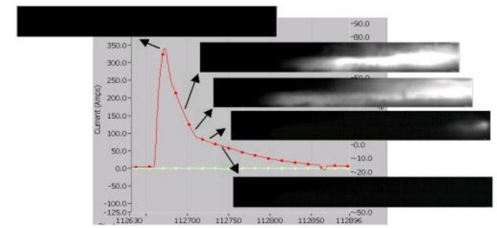
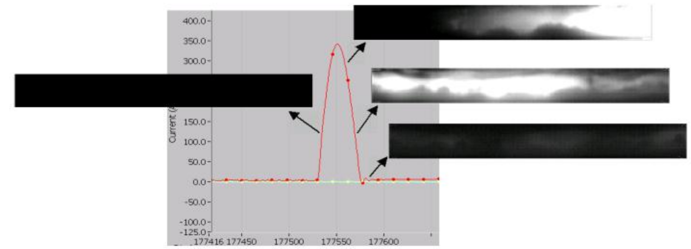
High-Speed Video Studies for Electro-Spark Alloying

- Video Imaging done at 62,500 frames per second
- CMOS camera technology – full frames in a single 16-μs exposure
- Power-sparking sequencing
- Details of the sparking event
- Current waveform effects



Current waveform and synchronized video images for electro-spark alloying using a Sheldon power supply



Current waveform and synchronized video images for electro-spark alloying using an ASAP power supply

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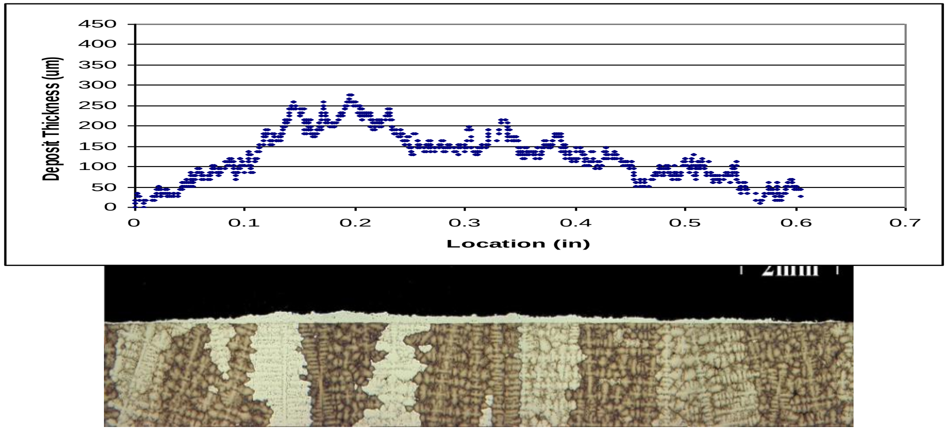
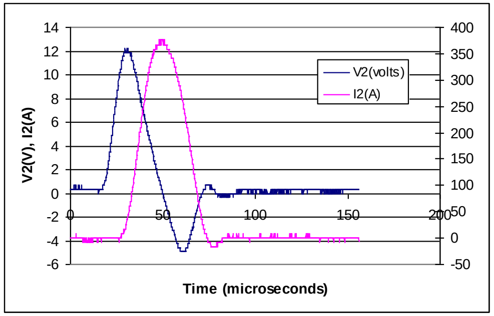
Characteristics of Electro-Spark Deposits

- **Splat thicknesses on the order of microns**
- **Deposition rates on the order of 100's of microns/sec**
- **Splat quenching**
- **Buildups of un-weldable alloys**
- **Cooling rates observed in access of 10^6 °C/s**
- **Adaptable to dissimilar metals combinations**



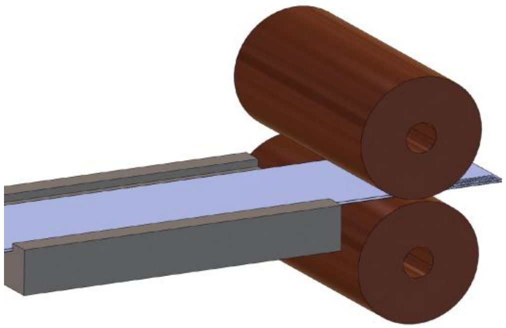
Coating microstructure and associated variation in thickness taken using quantitative microscopy



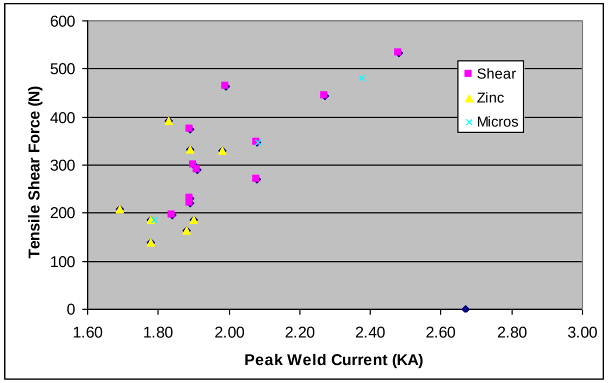
Voltage and current waveforms taken at the torch for the ASAP power supply

Use of Thermal Constructs for Preliminary Cost Scaling of New Technologies

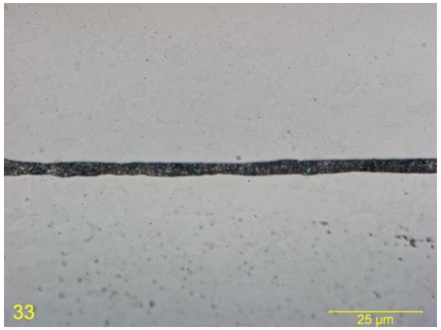
- **Application: High speed indirect resistance brazing of internally reinforced panels**
  - Thin gauge construction
  - Automotive customer
- **Development of roll brazing technology**
  - Resistively heated rolls
  - Flood cooling to control overall thermal cycle
- **Integration of low cost materials**
  - Mild and AHSS steels
  - Galvanized coating as the braze alloy
- **Preliminary trials on resistance brazing using the galvanized coating**
  - Reflow with single point resistance heating
  - Joint strengths ~50% that of full spot welds



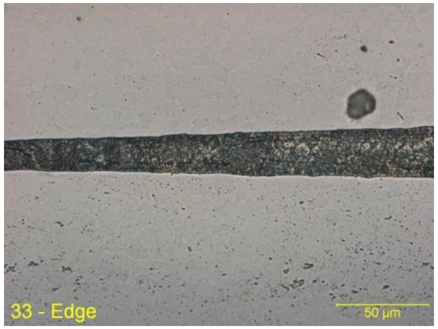
Schematic Representation of a Roll Brazing System for Low Cost Honeycomb Panel Construction (Courtesy CellTech Metals)



Strengths for Joints made at Increasing Currents Showing the Transitino from Brazing to Welding (Courtesy CellTech Metals)



Zinc re-flow at the center of a braze joint at best practice conditions (Courtesy CellTech Metals)



Zinc re-flow at the edge of a braze joint at best practice conditions (Courtesy CellTech Metals)

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Preliminary Assessments of the High Speed Manufacturing System for Automotive Panel

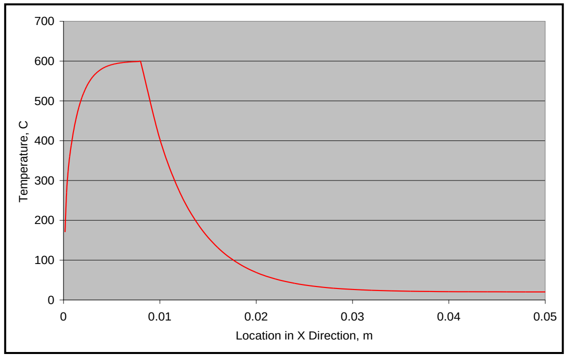
- **Thermal analyses for predicting strip heating and cooling**
  - Closed form solutions
  - Geometric and material property effects
  - Estimates of heating and cooling dynamics
  - Temperature-time relationships at each interface
- **Estimates of processing requirements**
  - Total thermal cycles on the order of 10s of milliseconds
  - Speeds in the range of m/min
  - Influence of panel design
  - Estimates of currents and voltages
- **Demonstration trials underway**

$$\theta = \theta_w - \frac{4\theta_w}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\exp\left(-\frac{\alpha(2n+1)^2\pi^2}{4(\xi_1+\xi_2)^2}\frac{x}{v}\right)$$

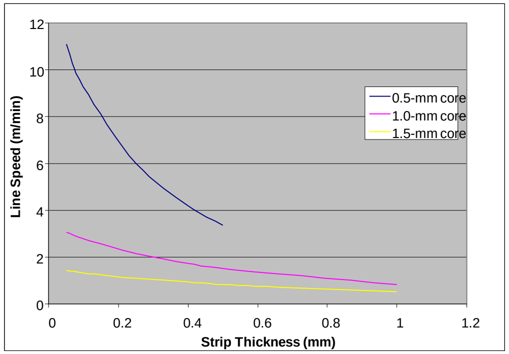
Equation Defining Conductive Heating Associated with the Hot Roll Technology (Courtesy CellTech Metals)

$$\theta = \theta_0 + (\theta_h - \theta_0)\exp\left[\left(\frac{v}{2\alpha} - \sqrt{\left(\frac{v}{2\alpha}\right)^2 + \frac{H}{K_1(\xi_1+\xi_2\bar{R})}}\right)x\right]$$

Equation Defining Cooling Associated with the Hot Roll Technology (Courtesy CellTech Metals)



Heating and Cooling Profile for a 1.5-mm Thick Panel During Resistance Roll Brazing (Courtesy CellTech Metals)



Relationships Between Panel Geometry Factors and Line Speed for Resistance Roll Brazing (Courtesy CellTech Metals)

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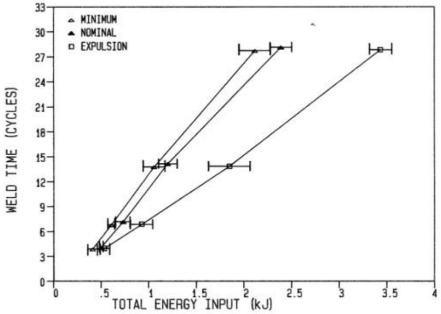
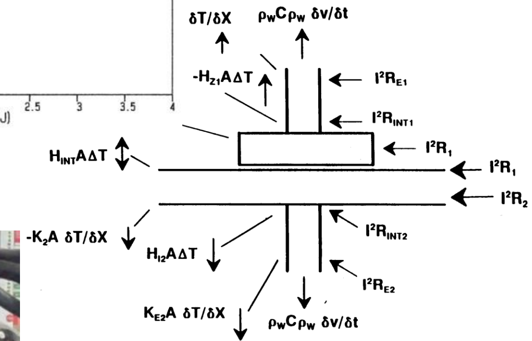
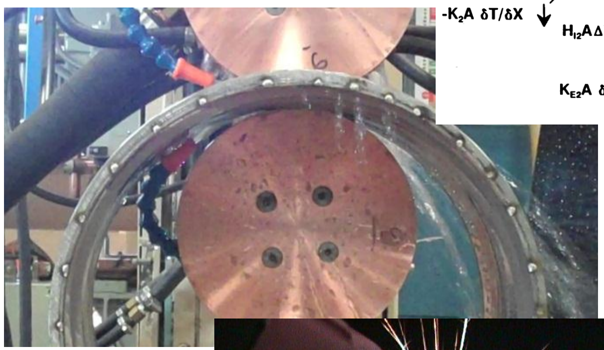
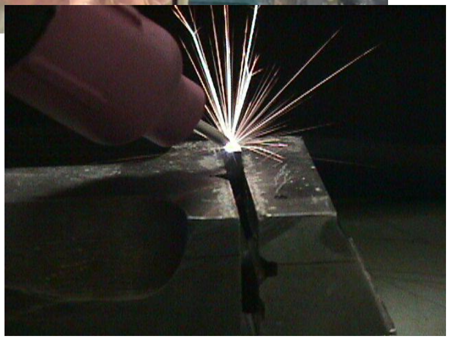
Influence of System Factors on Energy Consumption During RW – Summary

- **Energy consumption compared to other welding technologies**
- **Thermal effects**
- **Electrical effects**
  - Influence of power systems
- **Tradeoffs between efficiency and performance**
- **Examples from emerging RW technologies**
  - Resistance seam cladding
  - Flash-butt wedge repair
  - Translationally assisted upset welding
  - Supercapacitor power supplies
  - Electro-spark deposition
  - Indirect resistance heating









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Additive Manufacturing Consortium
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EWI Nuclear Fabrication Center

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