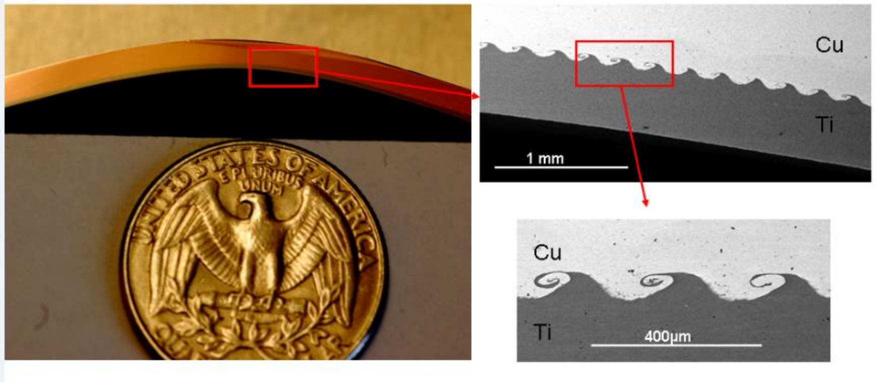
Electrically Driven Vaporization of Thin Conductors: a New Tool for Collision Welding

05/07/2013, I2FG Technical Workshop



Anupam Vivek
Post-Doctoral Researcher: Daehn Research Group

THE OHIO STATE UNIVERSITY
DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING

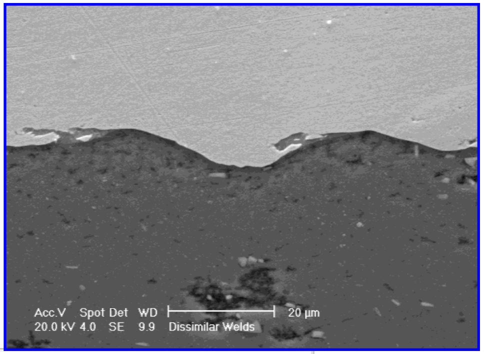
Outline

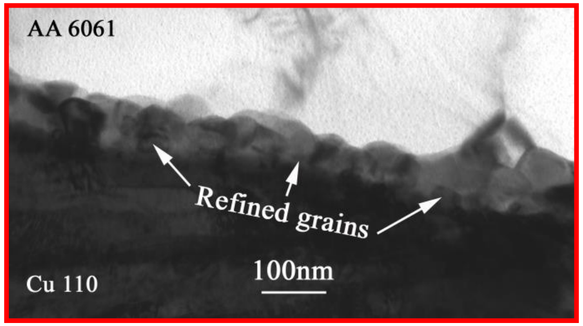
- Collision welding introduction
- Vaporizing Foil Welding
- Challenges and future work

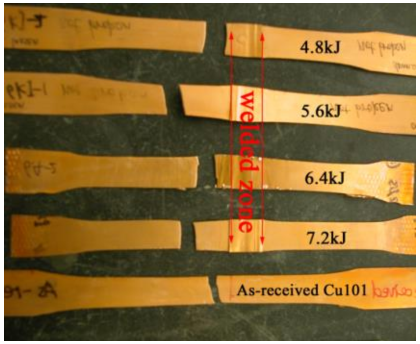
Collision Welding Introduction

Salient features

- Solid state welds with reduced intermetallic formation *(Hishashi et al, 2009; Kore et al, 2009)* or very localized melting at the interface in some cases *(Aizawa et al, 2004; Gobel et al, 2010, Zhang et al, 2010).* Welded region stronger than parent material, due to grain refinement and hardness increase *(Zhang et al, 2010),* various theories for the mechanism for impact welding *(Shribman et al, 2006; Brown, 1978),* Dissimilar metal welding possible

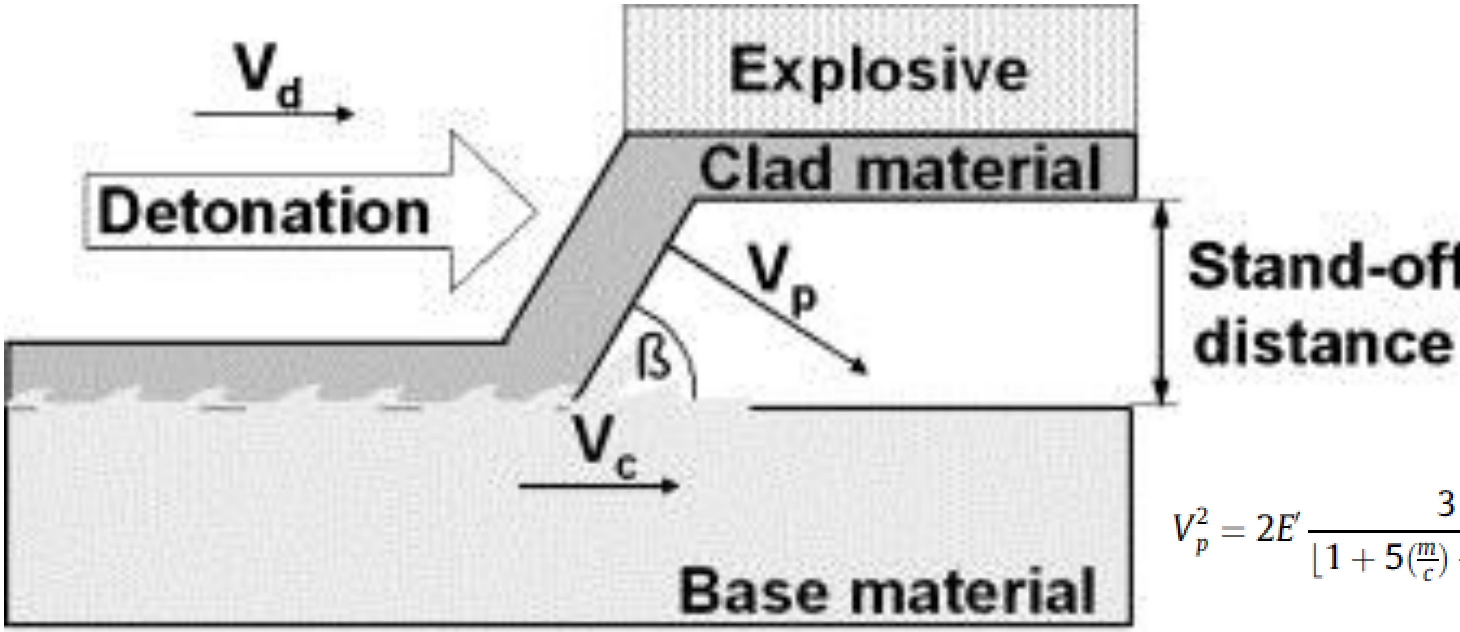






(Picture courtesy: PhD Thesis, Yuan Zhang, 2010)

Explosion Welding (EXW)



V_d: Detonation velocity
V_c: Impact point velocity
V_p: Plate collision velocity
ß : Impact angle

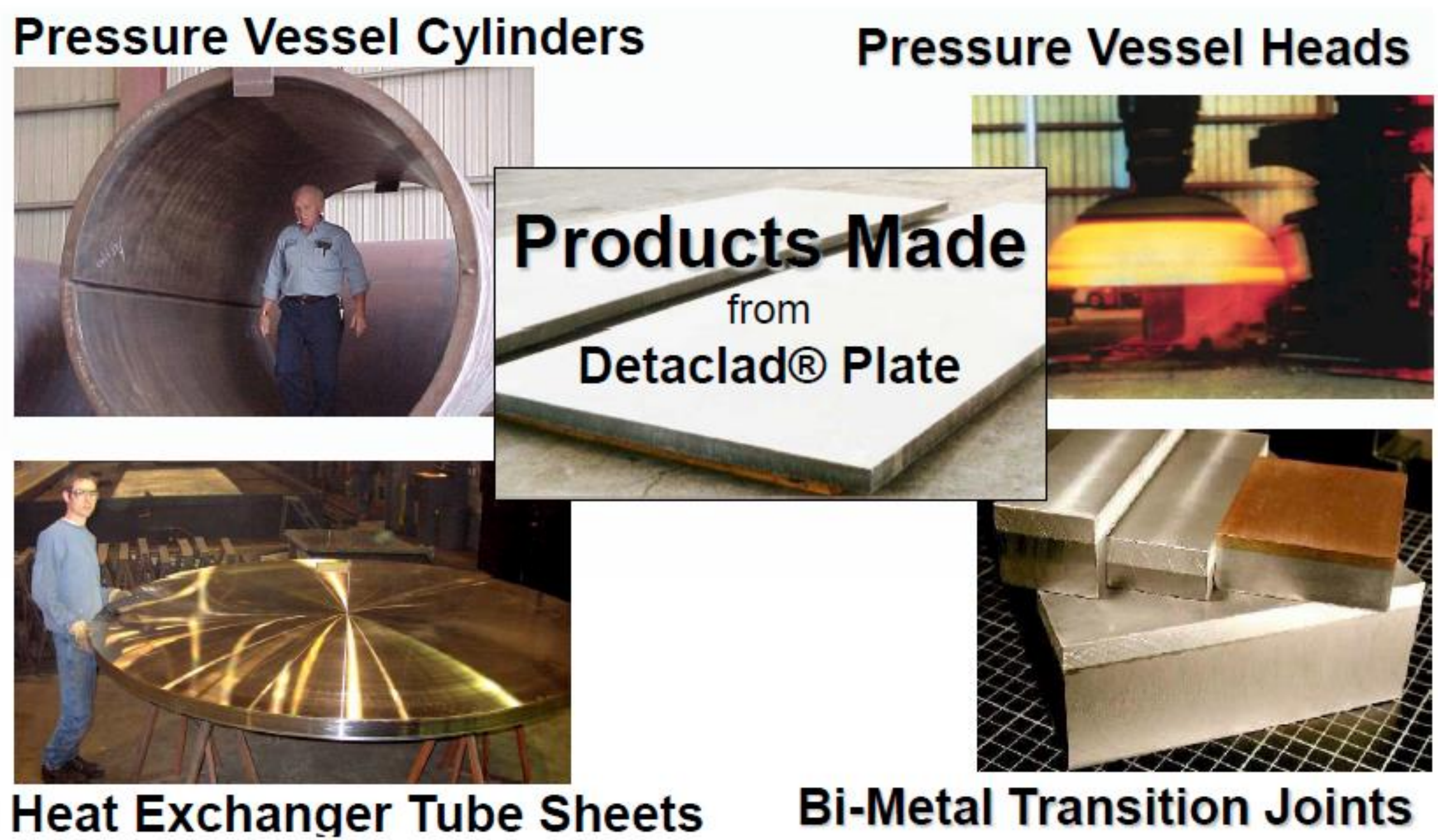
$$V_p^2 = 2E' \frac{3}{\left[1 + 5\left(\frac{m}{c}\right) + 4\left(\frac{m^2}{c^2}\right)\right]}$$

$$V_p = 2V_d \sin\left(\frac{\beta - \alpha}{2}\right)$$

$$V_c = V_p \frac{\cos\left(\frac{\beta - \alpha}{2}\right)}{\sin\beta}$$

THE OHIO STATE UNIVERSITY
DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING

Products

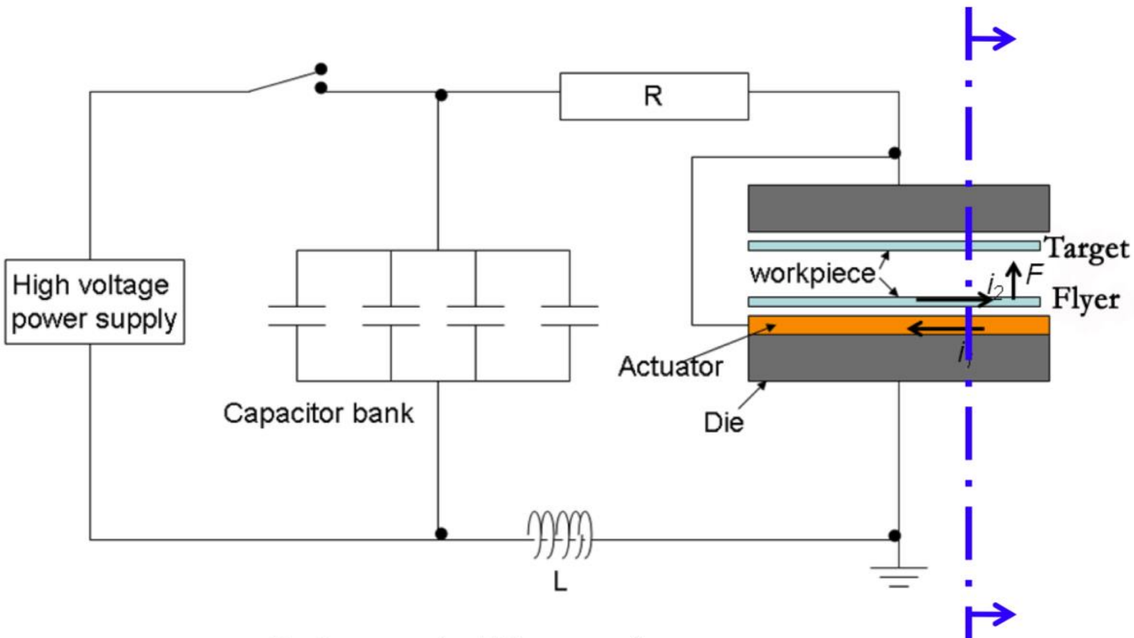

Pressure Vessel Cylinders
Pressure Vessel Heads
Products Made
from
Detaclad® Plate
Heat Exchanger Tube Sheets
Bi-Metal Transition Joints

Issues with Explosives

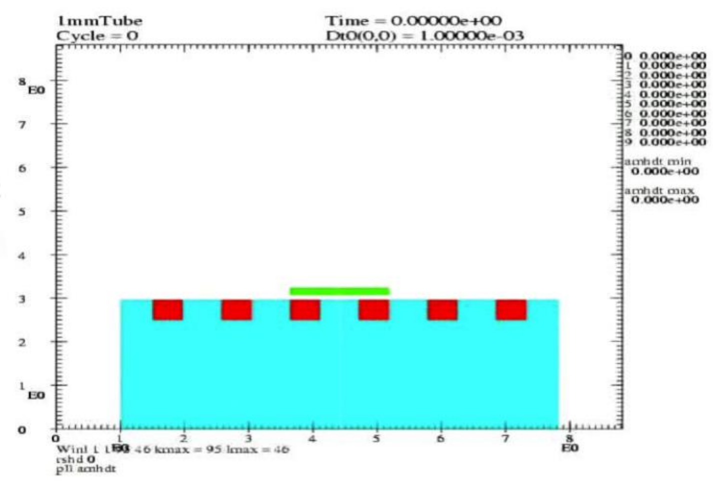
- Difficulty in handling
- Increasingly stringent regulations
- Specific training needed
- Needs big spaces for safe operation
- Critical volume: minimum physical size, a charge of a specific explosive should have to sustain its own detonation wave
- Mostly for large scale operations
- Tools must be very tough. Their life has been unpredictable

Magnetic Pulse Welding (MPW)

- Primary electromagnetic (EM) field in actuator induces secondary EM field inside of nearby metal workpiece (flyer plate).
- Primary and secondary EM fields are parallel but in opposite direction.
- Repelling force accelerates flyer plate colliding against stationary target plate to make lap joint at high impact velocity.



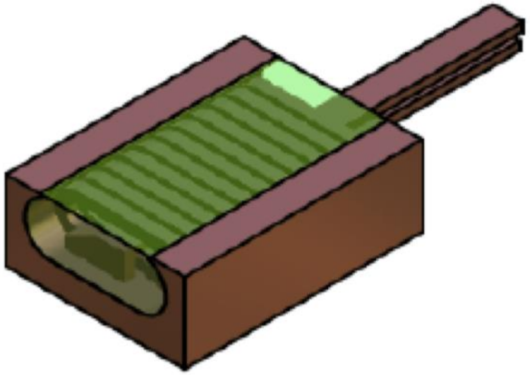
Schematic Illustration



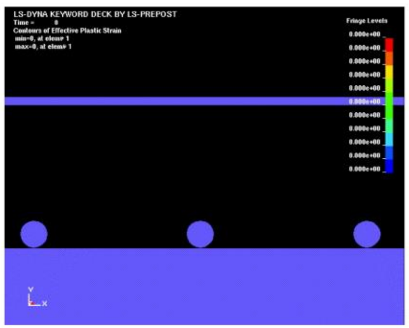
Flux Line for Electromagnetic Field*

[*Courtesy to Gregg K. Fenton, TMS 2008]

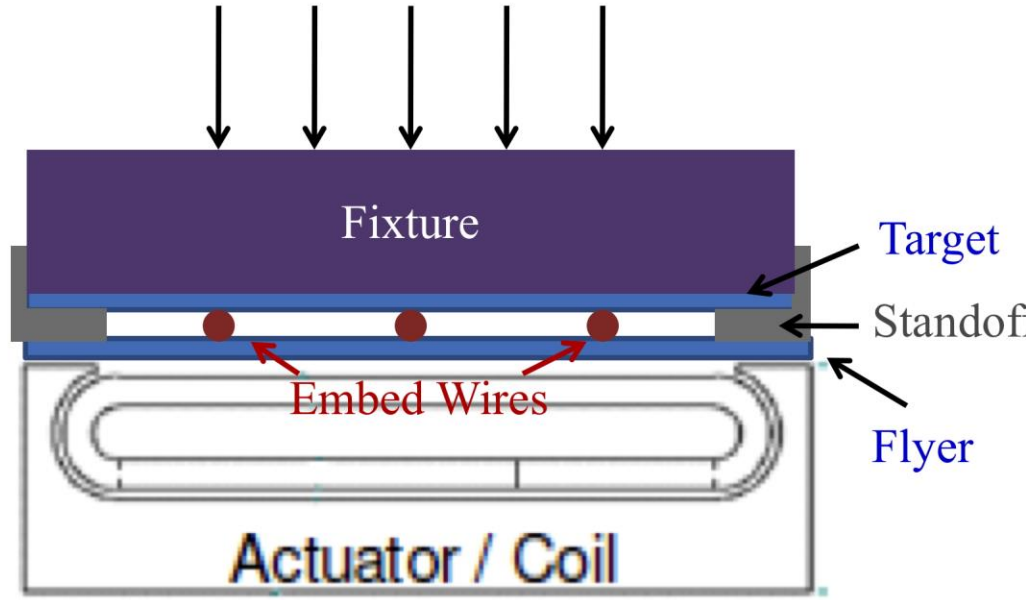
Uniform Pressure Actuator for Plate-to-Plate Welding



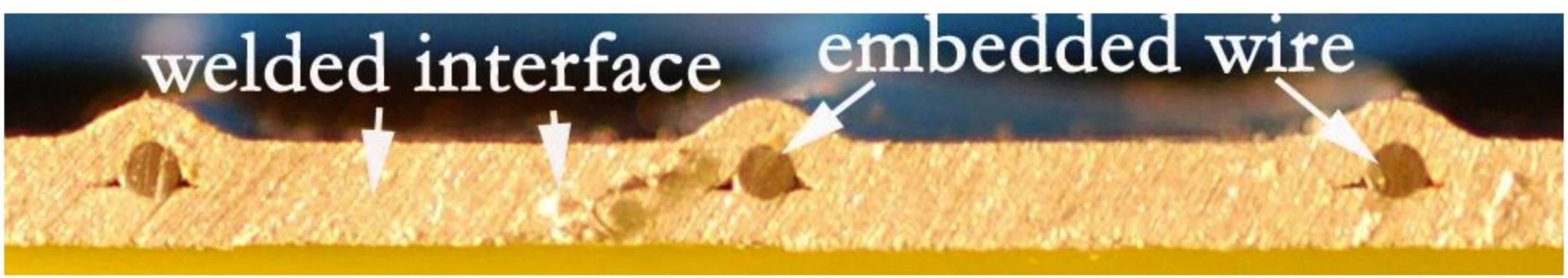
Uniform Pressure Actuator*



Clamping Force



Schematic Illustration

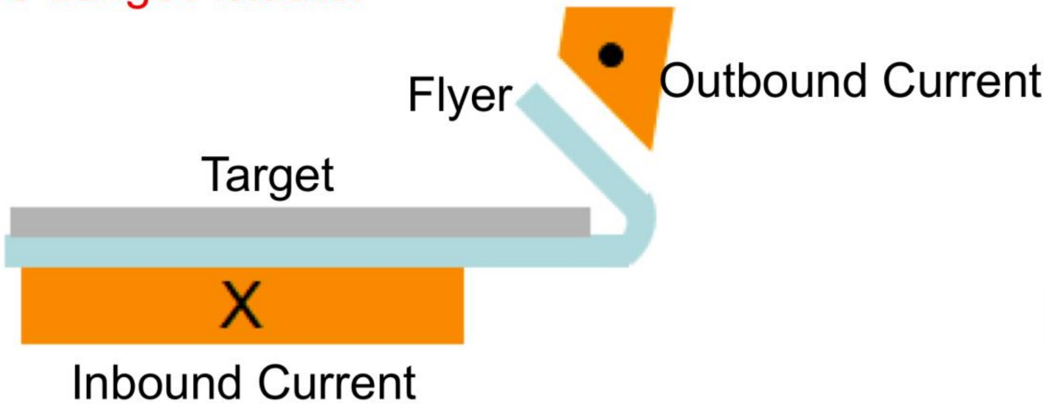


Welded Sample

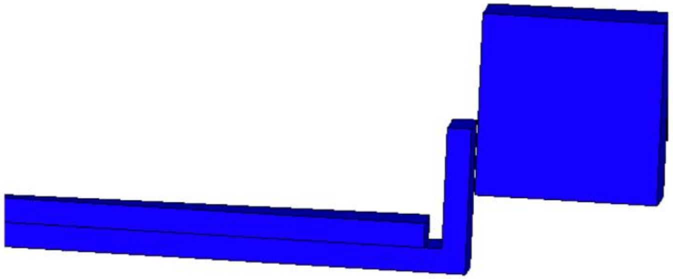
[*Banik K. Thesis, 2008 and S. Srinivasan]

Bar Actuator for Flanging and Welding

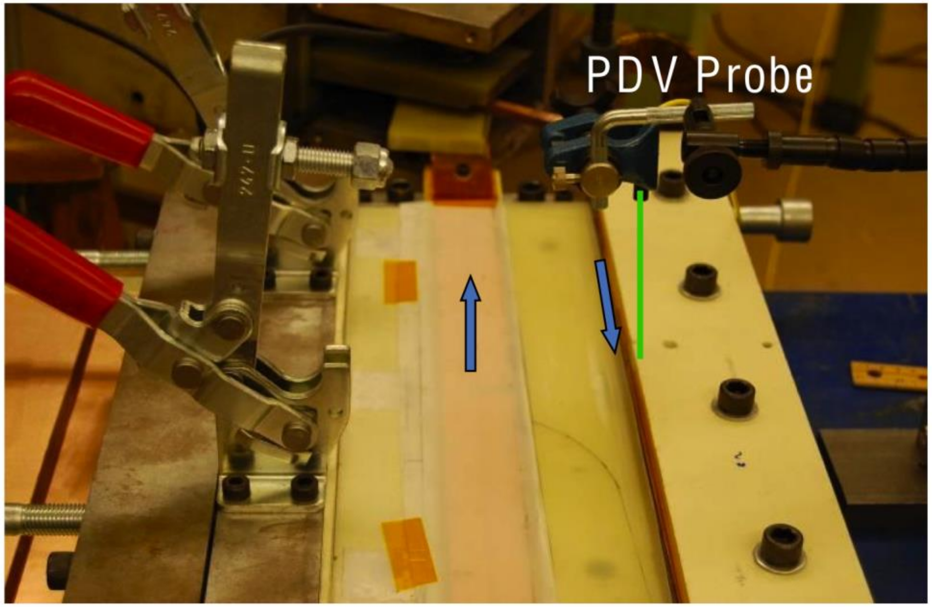
Pre-flange Actuator



Schematic Illustration



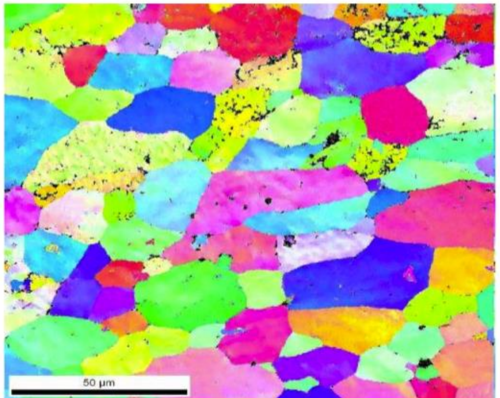
Simulated Current Density



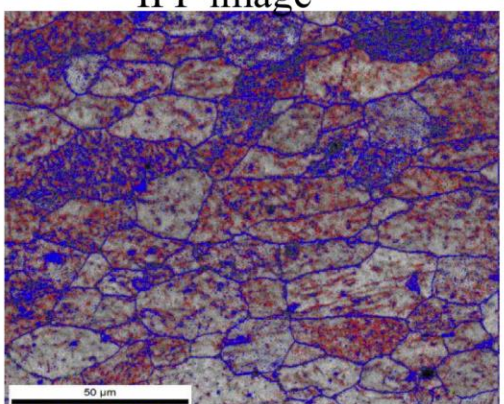
Experimental Setup

Grain Refinement Observed from EBSD

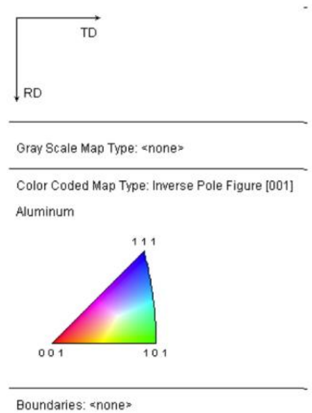
Solutionized @ 560°C 20min



IPF image



GB image

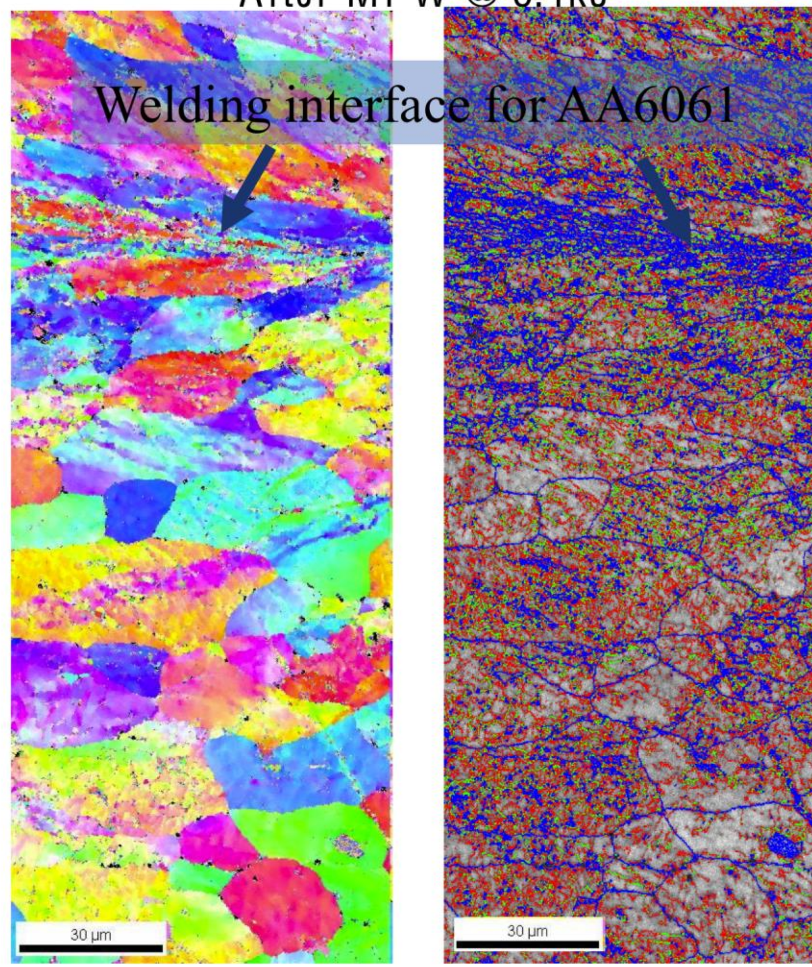


Boundaries: Rotation Angle

	Min	Max	Fraction	Number	Length
red	2°	5°	0.606	249572	2.31 cm
green	5°	15°	0.230	94613	8.74 mm
blue	15°	180°	0.165	67873	6.27 mm

*For statistics - any point pair with misorientation exceeding 2° is considered a boundary (total number = 412058, total length = 3.81 cm)

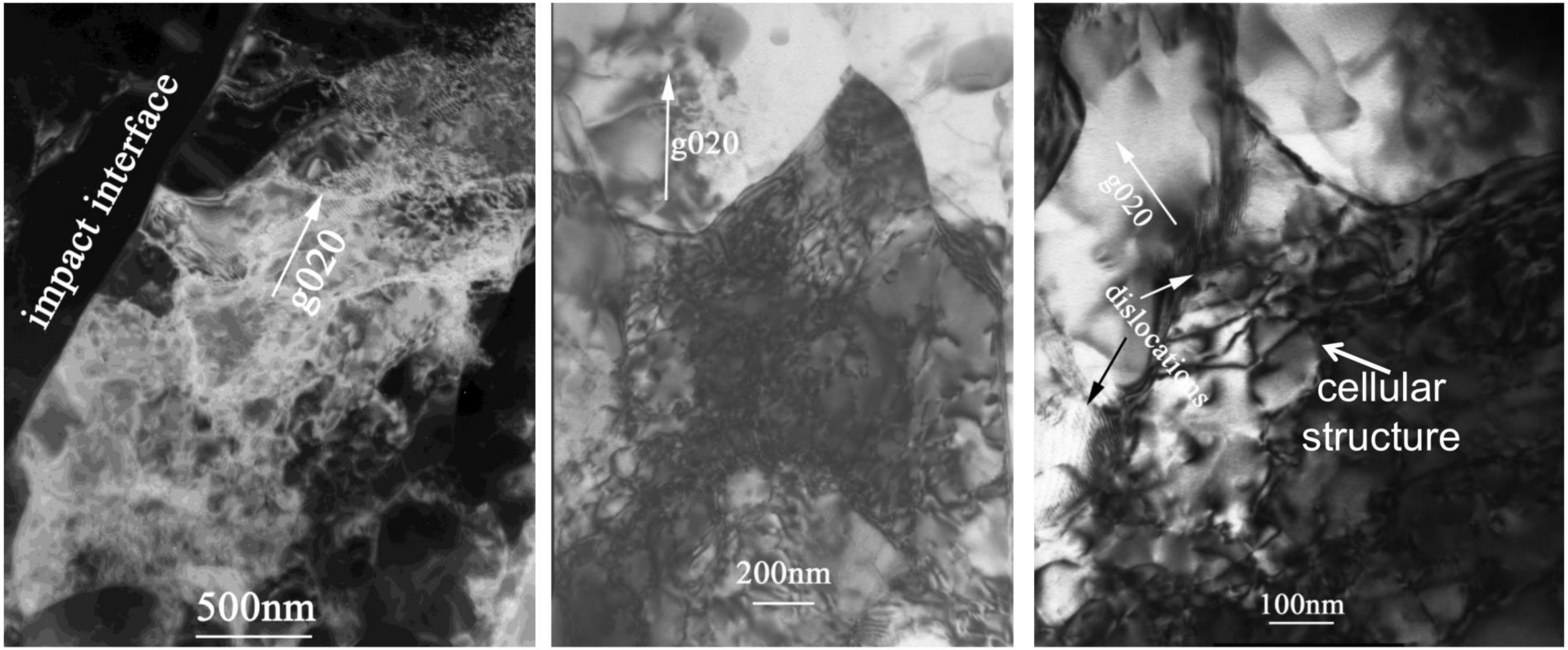
After MPW @ 6.4kJ



- Average grain size for base metal is ~40µm, with low misorientation angle (2°~5°).
- Grain size change in a continuous manner from interface to base metal.
- Grains adjacent to welded interface were elongated along impact direction.

[Y.Zhang et al. Science and technology of welding and joining, 2008]

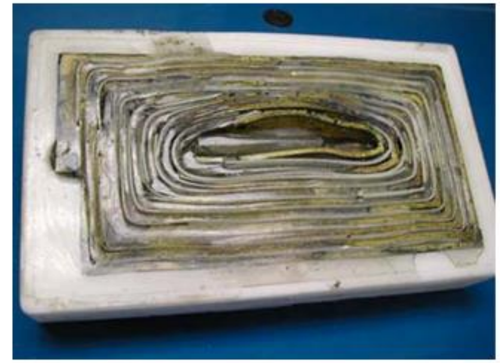
Dislocation Density Observed from TEM



- High strain rate impact induces high dislocation density.
- Dislocation rearrange into cellular structure and cell interiors were almost dislocation free.
- Parallel dislocations aligned near to the grain boundaries with very small interval.

Issues with Magnetic Pulse Technology

Deformed central turn
with increased
clearance between the
1st and 2nd turns

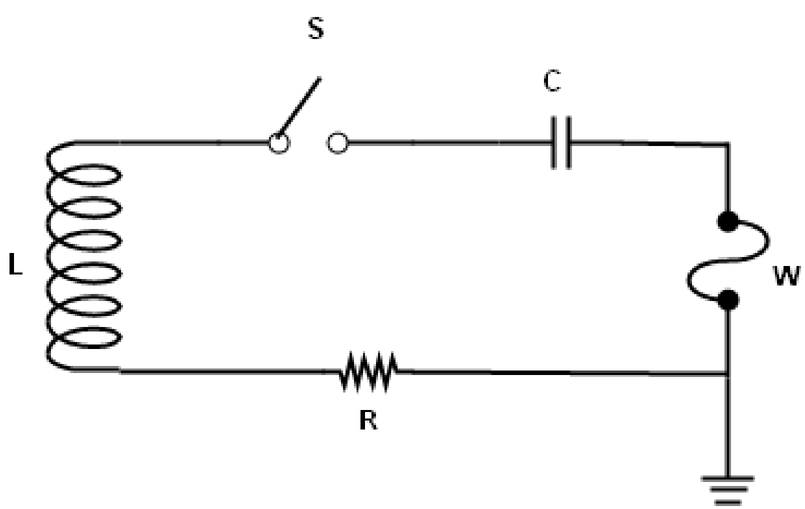


- Longevity of electromagnetic actuators at high pressure, temperature and cycle time
- Frequent inspection for cracks and voids needed to insure efficiency of the actuators
- Fabrication of coils is generally an expensive process
- Requires an electrically conductive flyer material (unless a ‘driver’ is used)

Pictures courtesy: Golovashchenko, SF., 2007, Material formability and coil design in electromagnetic forming, Journal of materials science and performance, Volume: 16 Issue: 3 Pages: 314-320 DOI: 10.1007/s11665-007-9058 7, Published: June 2007

Vaporizing Foil Welding (VFW): Technique

- What happens when a high current is passed through a thin conductor?



Basic circuit for rapid metal vaporization

W- wire/foil
C- Capacitor
L- Circuit Inductance
S- Switch
R- Circuit Resistance
V- Voltage

What happens?

- When energy deposition rate is very high then a thin conductor can be heated much above its sublimation energy due to inertial and magnetic forces

$$t_c = (\gamma_l r^3/\alpha)^{0.5}$$

$$t_{\mathrm{MHD}} = 6\left(\gamma_l r^2/H_0^2\right)^{0.5}$$

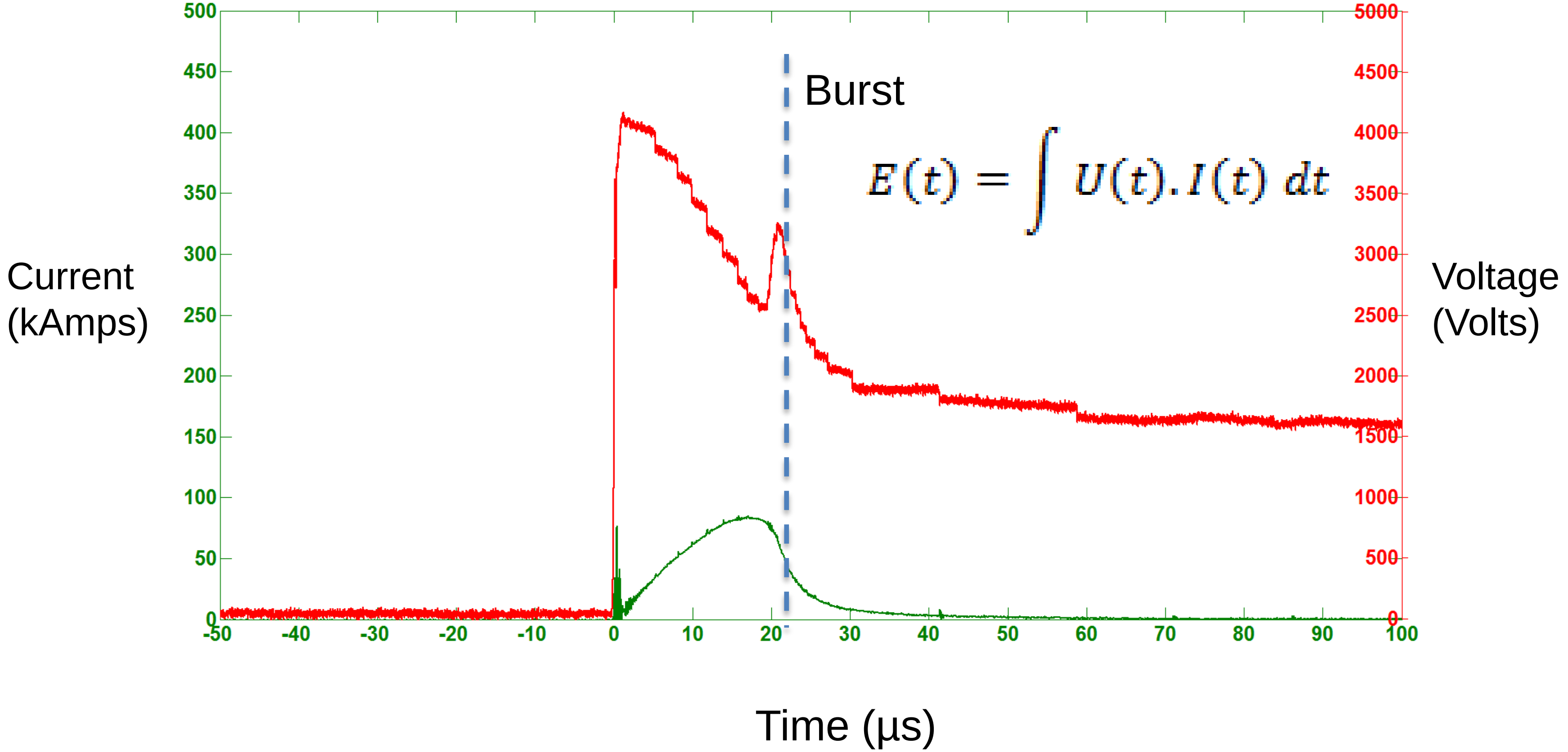
$$t_{sk} = \mu_0 r^2/\rho$$

where γ_l is the density of the liquid wire at the melting temperature, α is the coefficient of surface tension, and H_0 is the magnetic field at the wire surface; $H_0 = 5 \times 10^2 rj$ A/cm.

- When these inertial forces let go, this stored energy converts to kinetic energy of the vaporized metal and releases as a pressure pulse

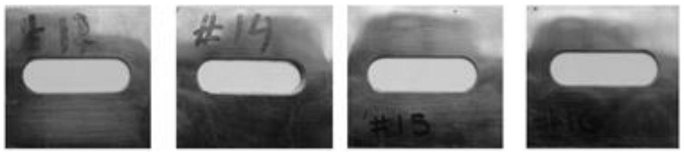
(Sedoi et al, 1999)

Data and analysis

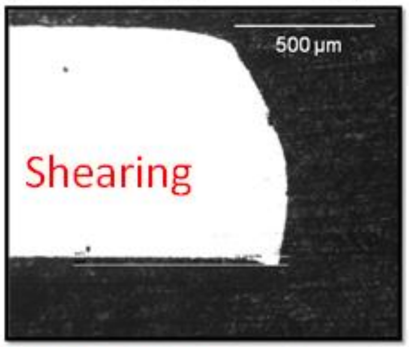


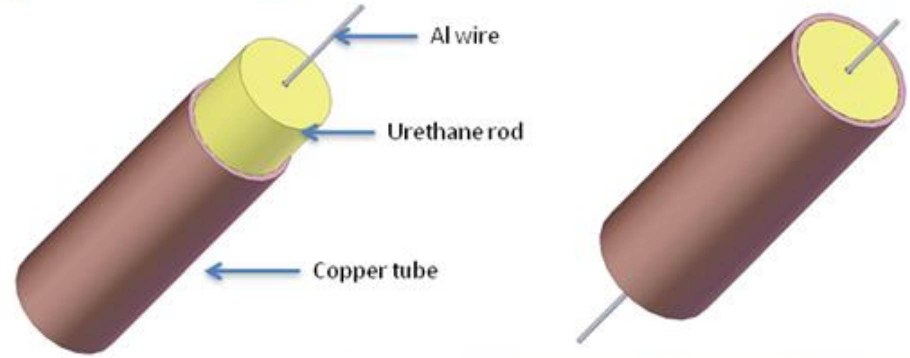
Excess energy= E(t) – H_b (0.5 kJ per 0.0254 mm of thickness)

Other applications of vaporizing conductor technique

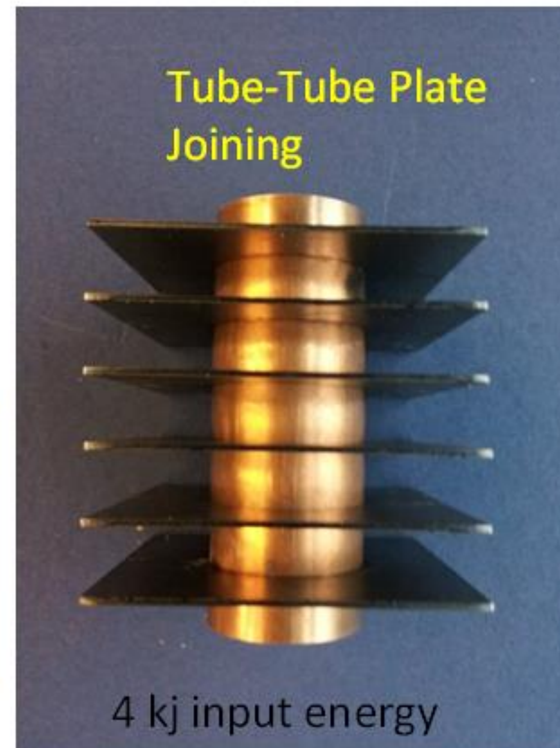


2X0.0254 mm 4.0 kJ | 2X0.0254 mm 3.2 kJ | 2X0.0254 mm 2.8 kJ | 0.0508 mm 2.4 kJ



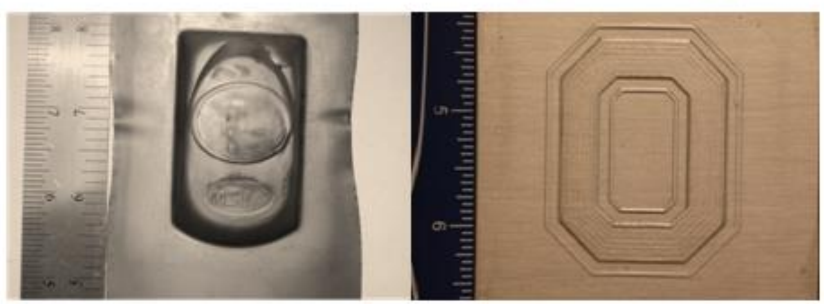


A. Vivek, G.A. Taber, J.R. Johnson, S.T. Woodward, Glenn S. Daehn, Electrically driven plasma via vaporization of metallic conductors: A tool for impulse metal working, Journal of Materials Processing Technology, Volume 213, Issue 8, August 2013, Pages 1311-1326, ISSN 0924-0136, 10.1016/j.jmatprotec.2013.02.010.



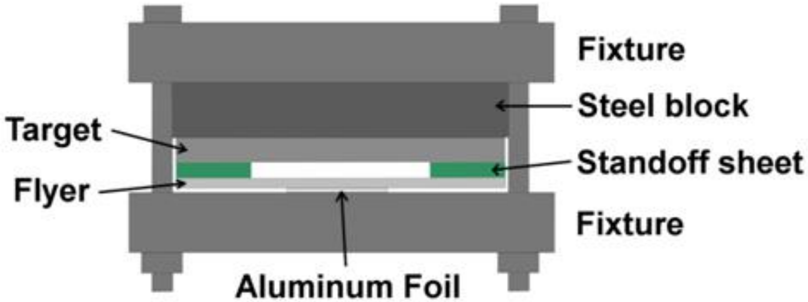
Munitions Disposal

Embossing/Forming

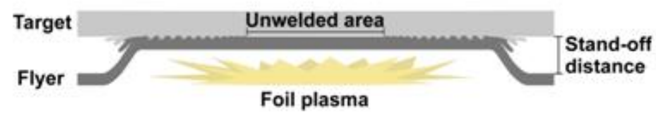


0.5 mm thick grade 2 CP titanium formed into a cellphone case die using vaporization of a 0.127 mm thick aluminum foil with input enegy of 5.6 kJ

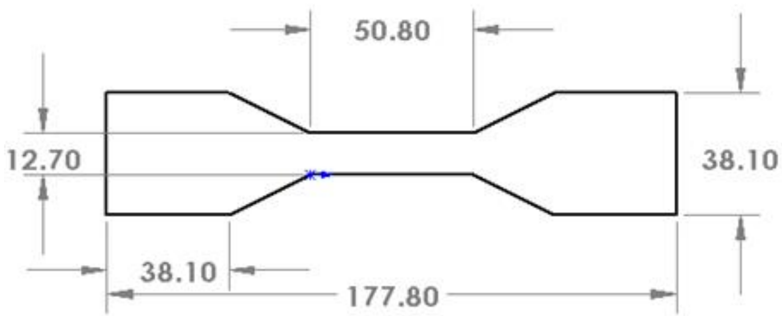
Welding: procedure



(A)



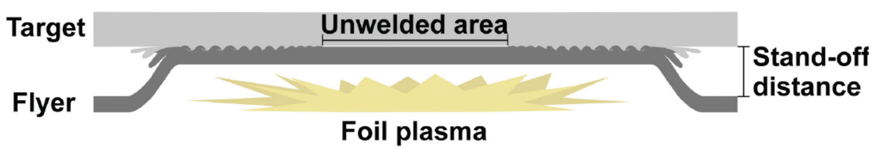
(B)

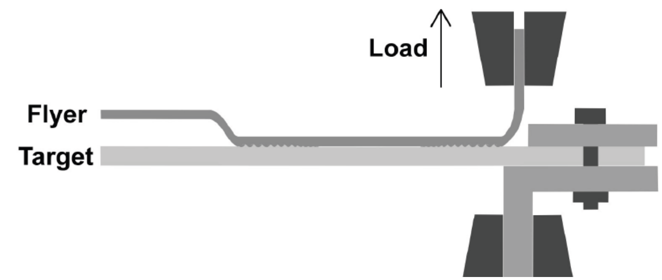


(C)

(D)

Vaporizing Foil Driven Welding

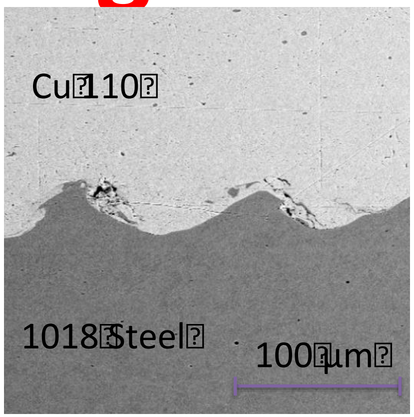


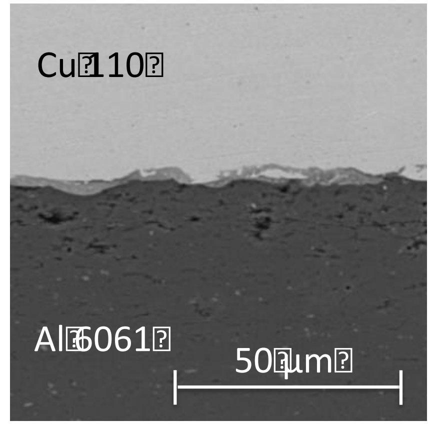


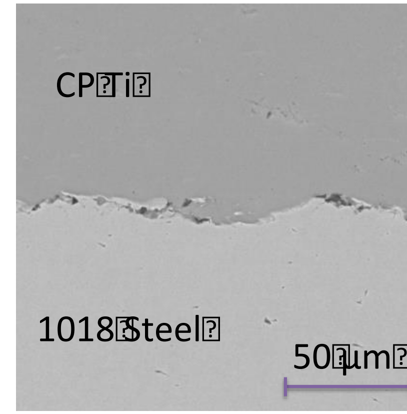
- No welding in the area just above the former position of foil-zero impact angle
- Peel test needs yields a varied spectrum of strength values

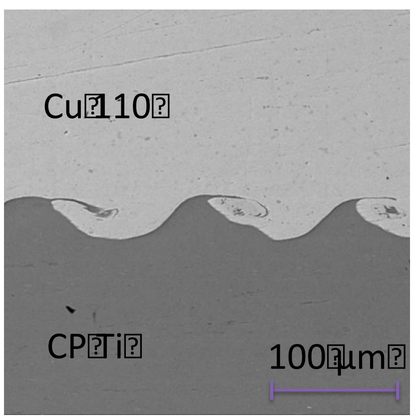
Interface morphology and **peel strength**

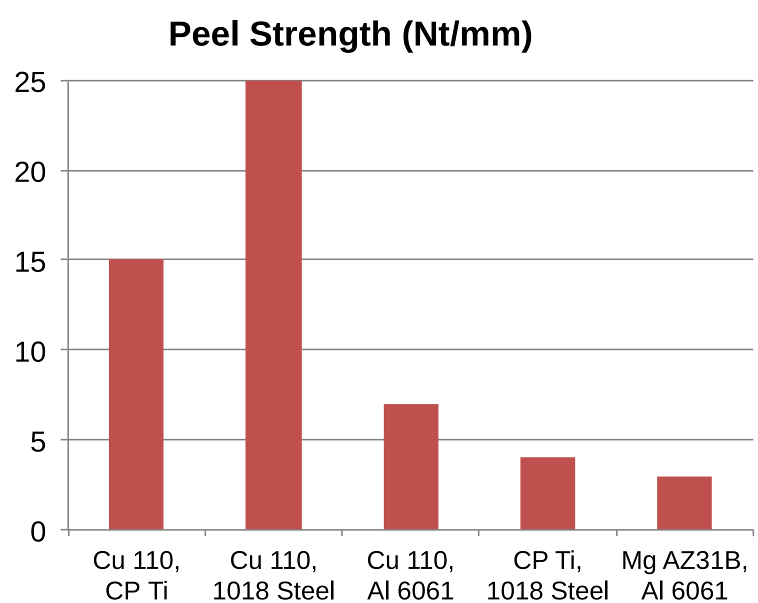
Foil actuator: Aluminum, 0.003" thick, Electrical energy: 7.2 kJ

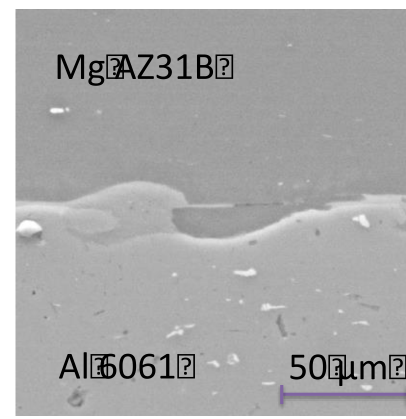






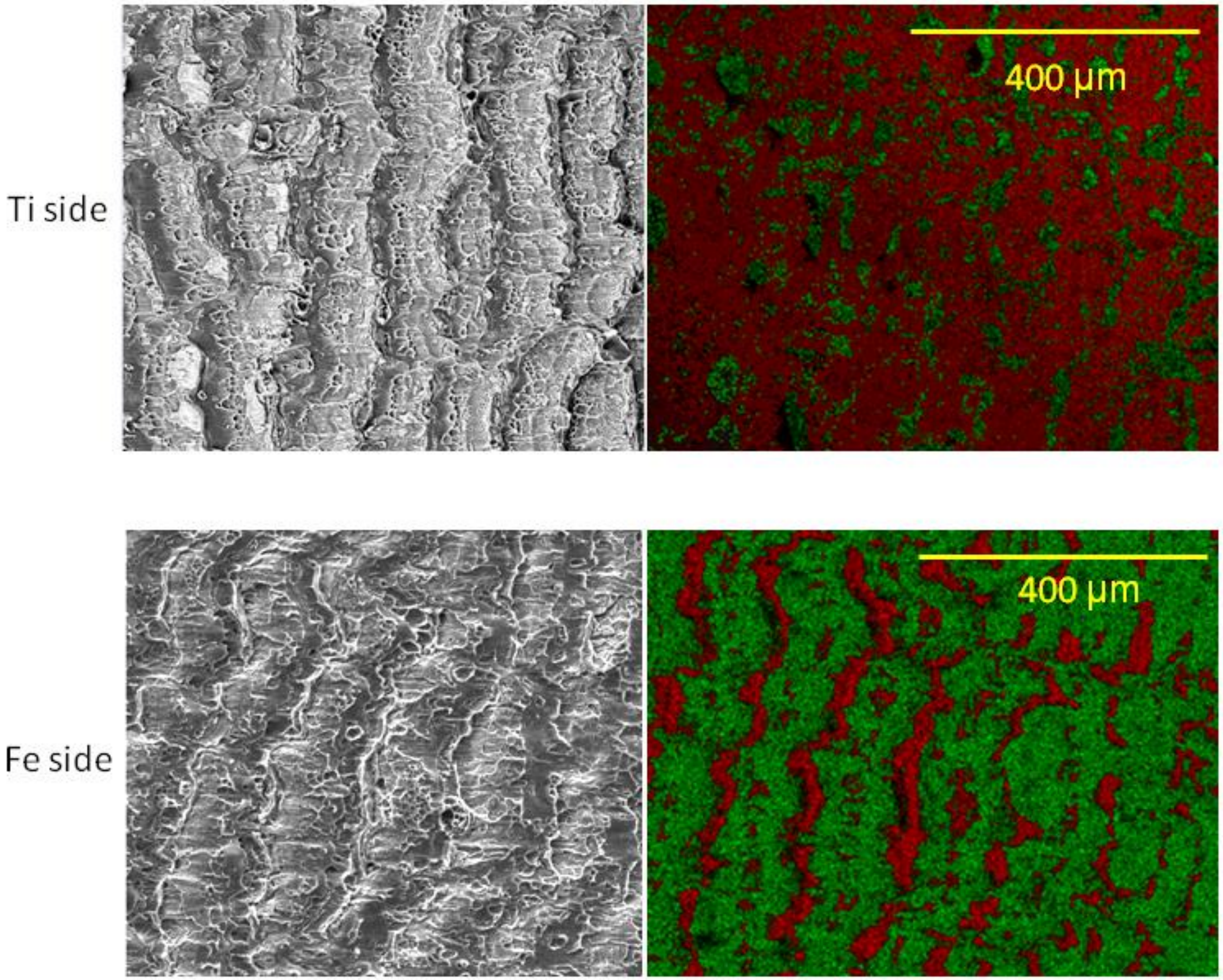




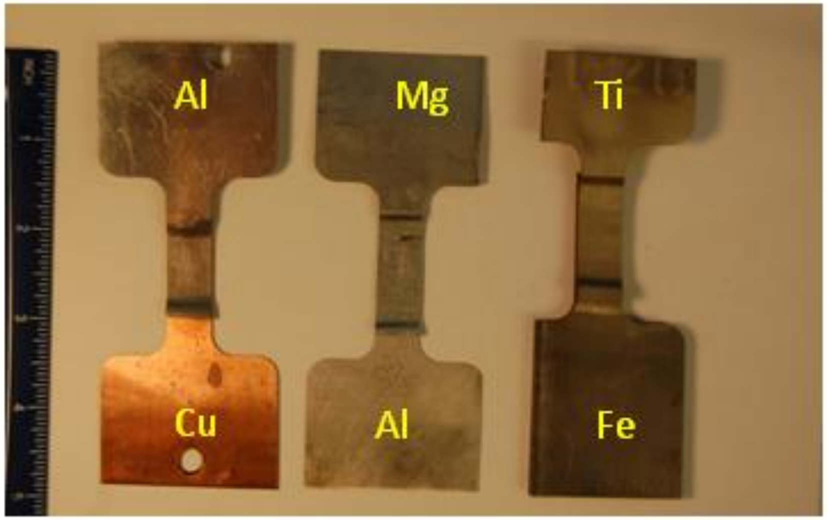


THE OHIO STATE UNIVERSITY
DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING

Material exchange

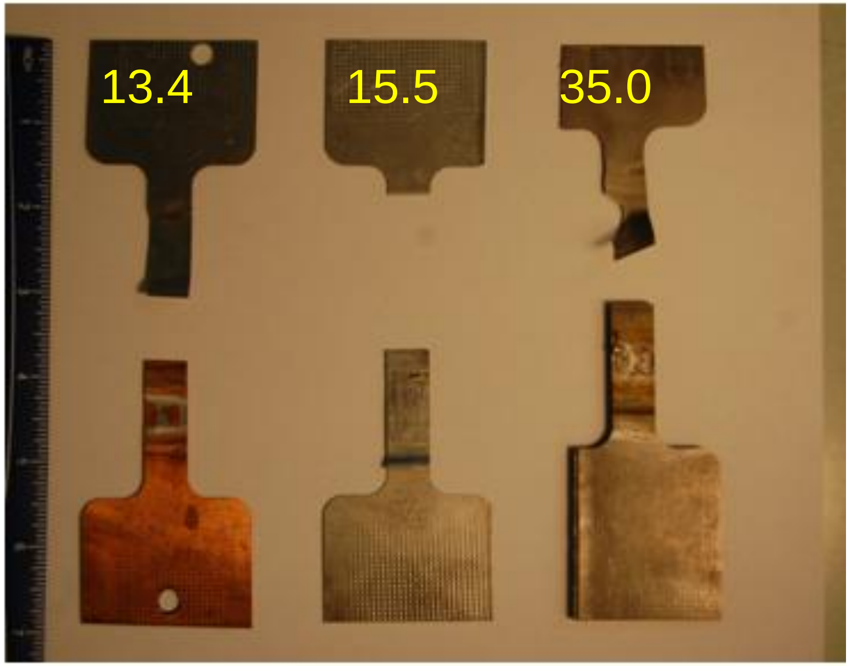


Lap shear test



(A)

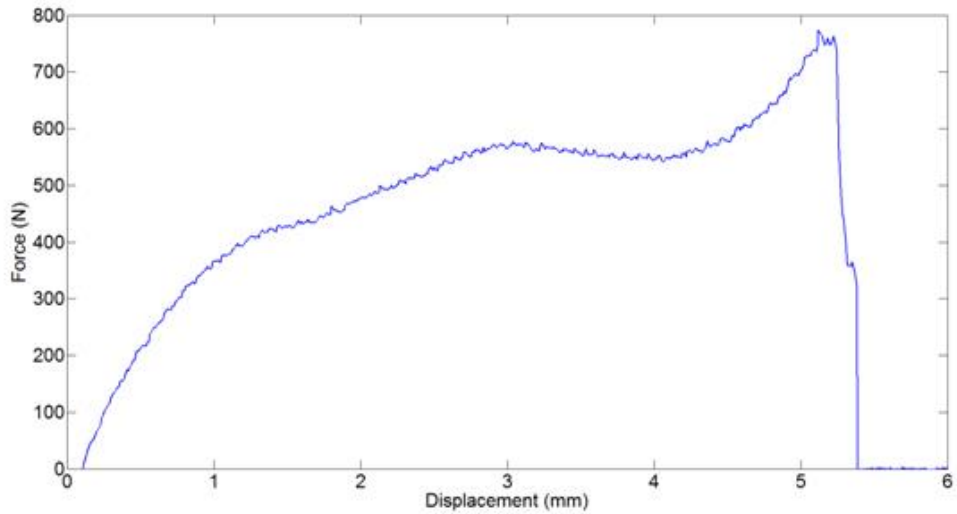
Sustained shear strength (MPa)



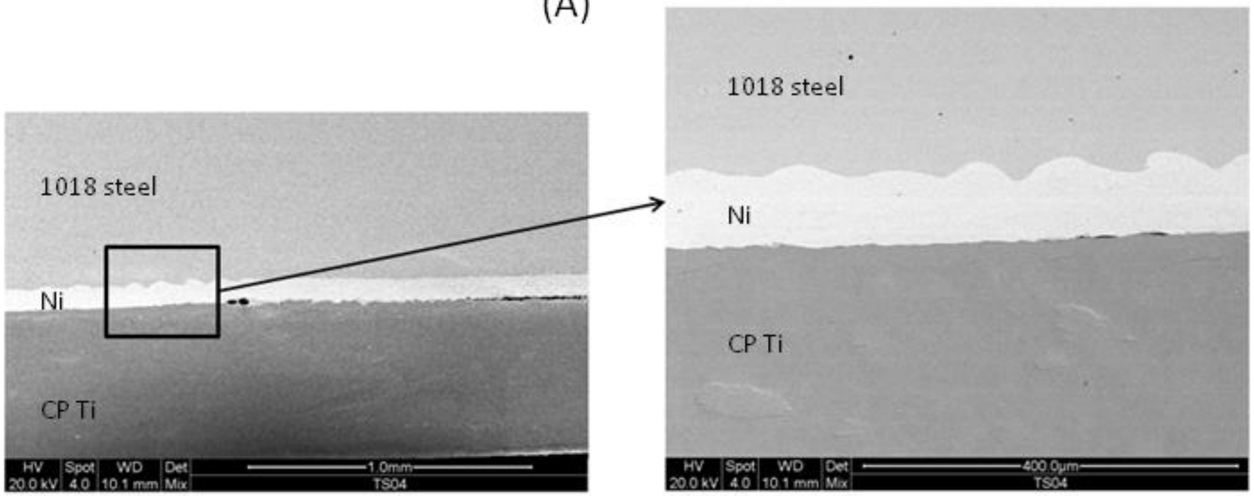
(B)

Interlayer for creating stronger interfaces

- Nickel interlayer: compatible with both sides and acts as a diffusion barrier
- Single shot with 7.2 kJ input energy
- Much higher peel strength value

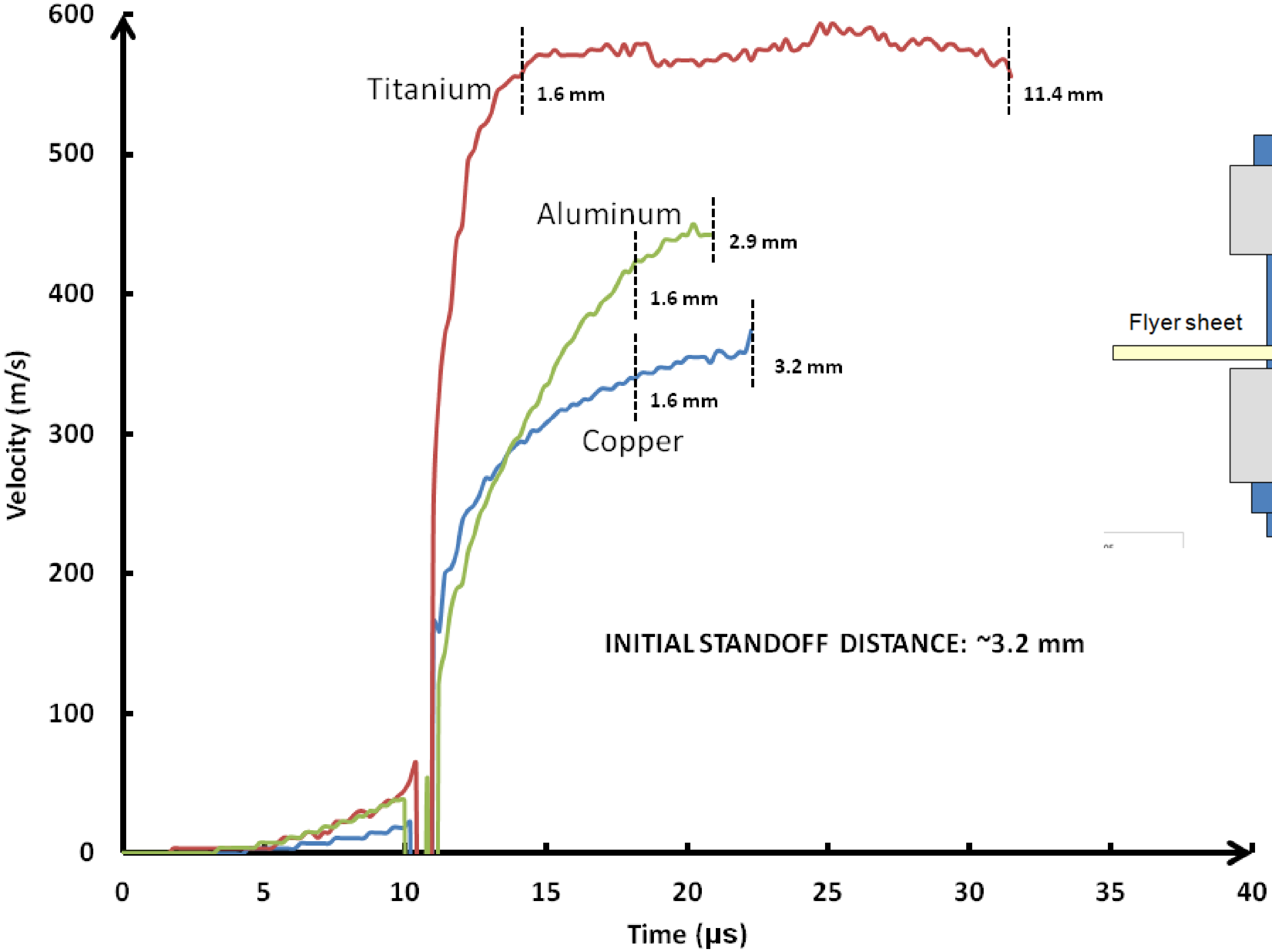


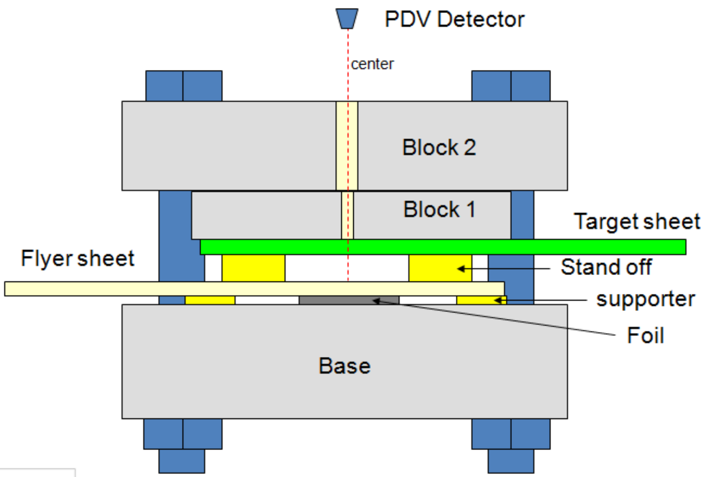
(A)



(B)

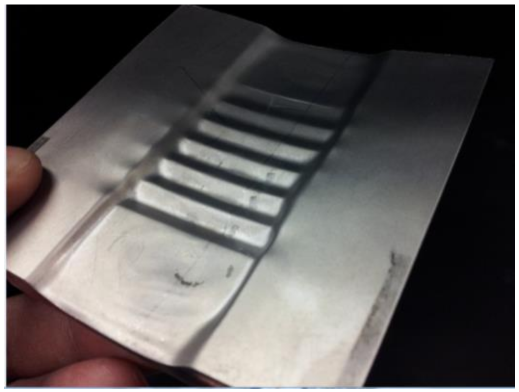
Photonic Doppler Velocimetry

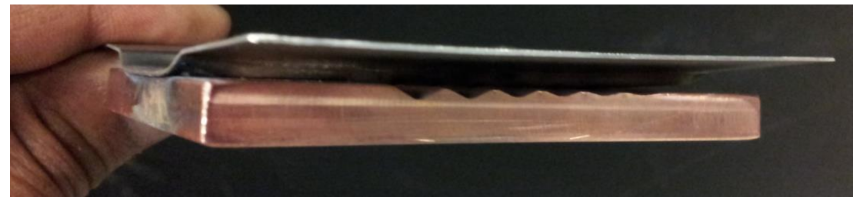


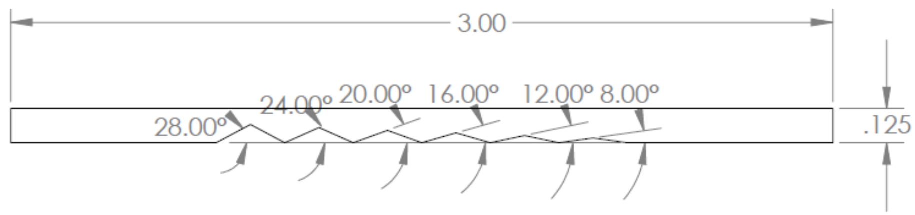


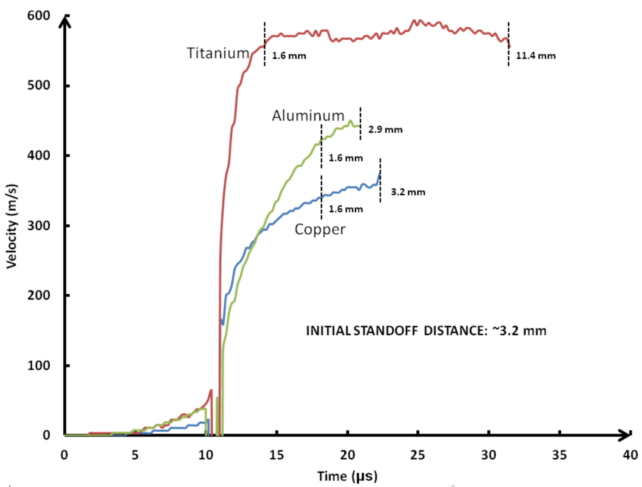
MATERIALS SCIENCE AND ENGINEERING

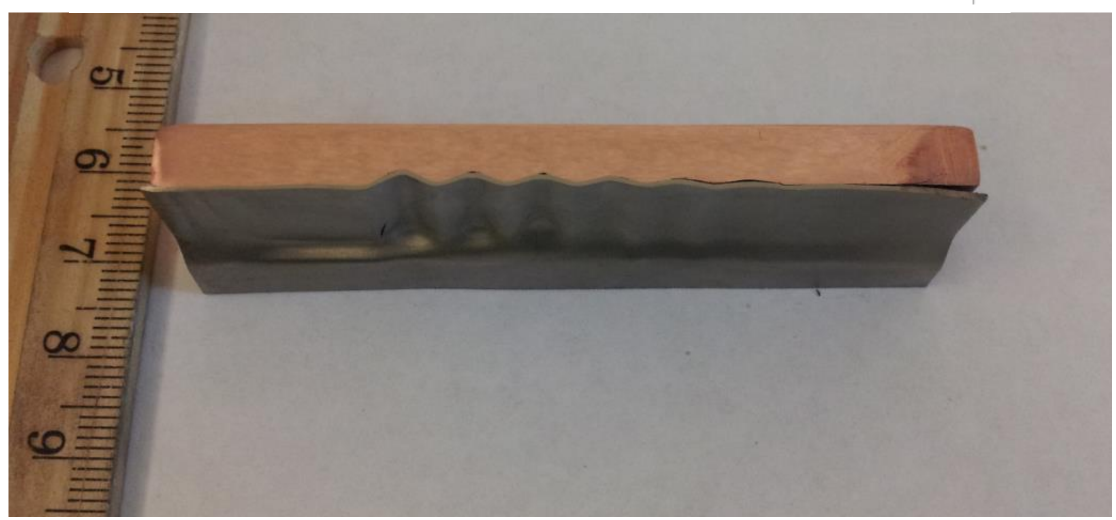
Groovy Experiment: welding window estimation





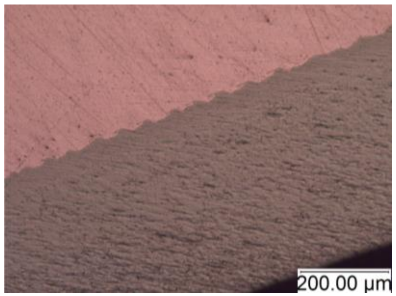


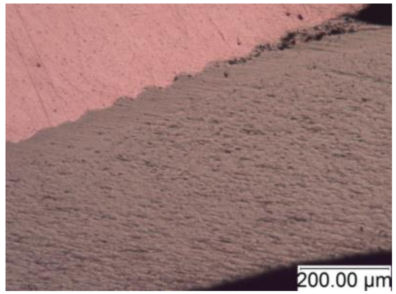


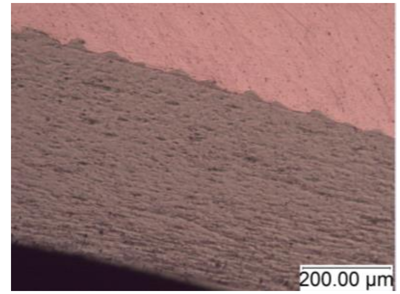


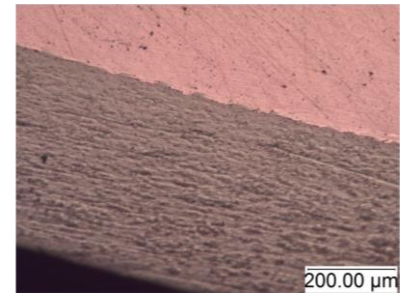
DEPARTMENT OF
MATERIALS SCIENCE
AND ENGINEERING

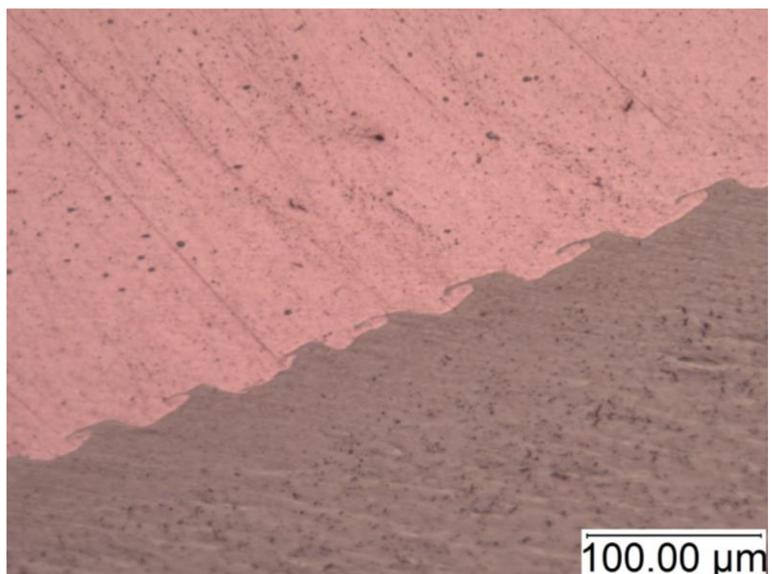
20°







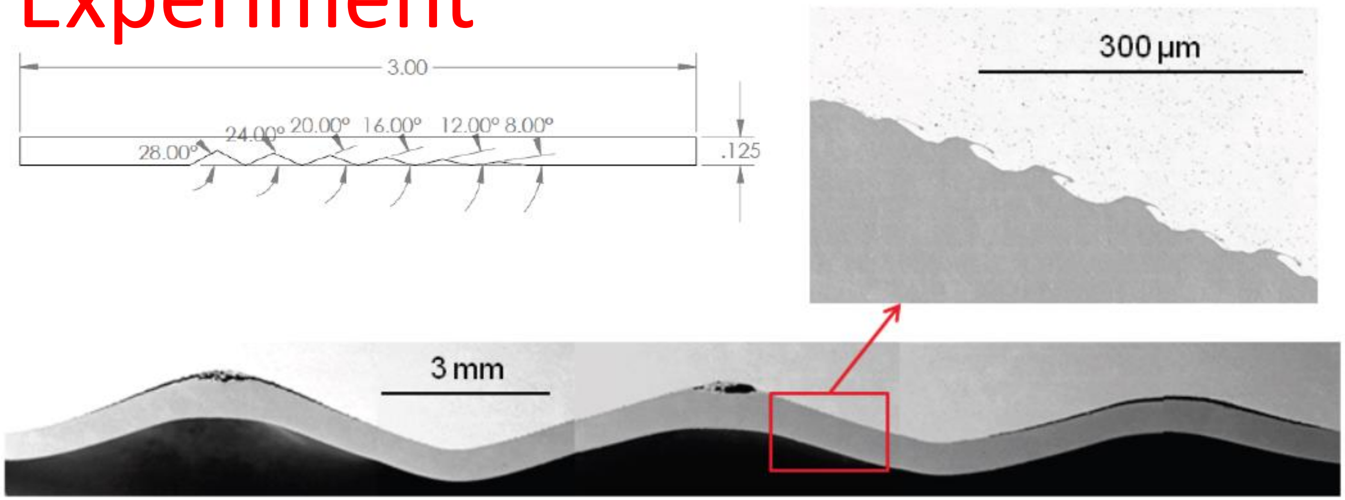




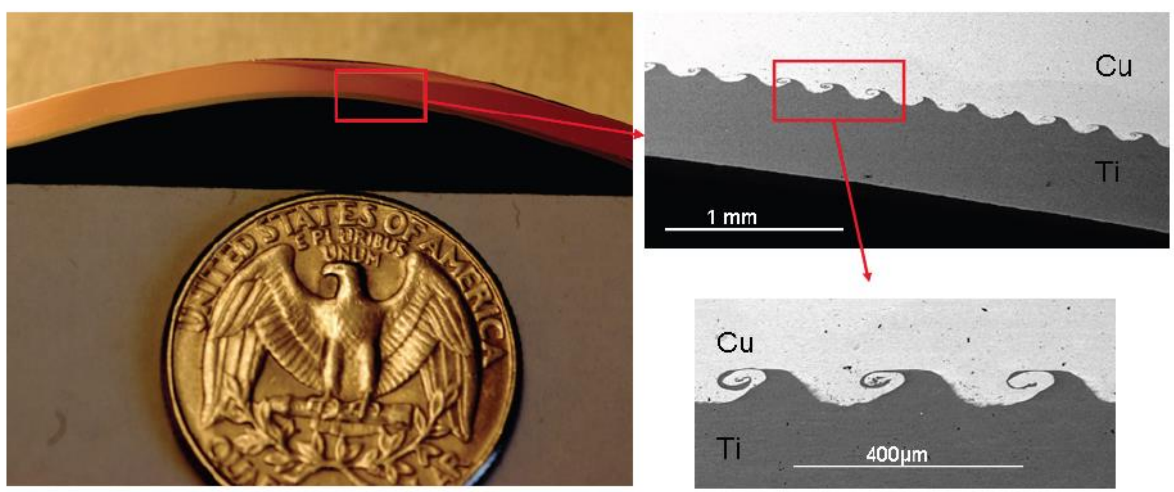
Groovy Experiment

(A)

(B)



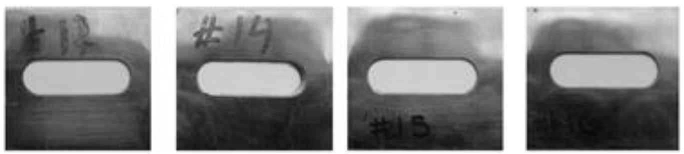
(C)



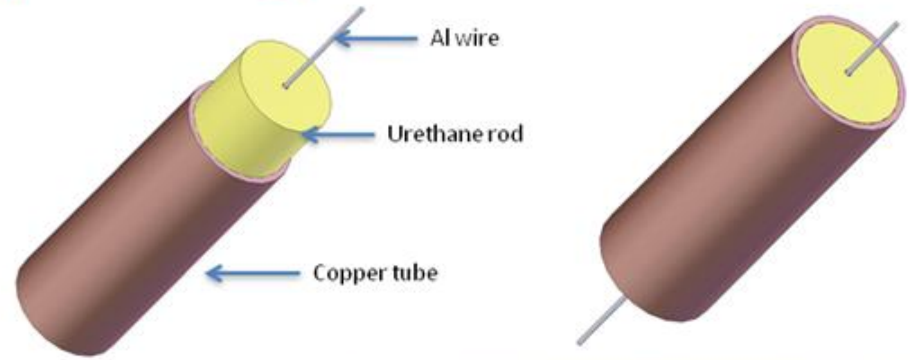
VFW: Summary

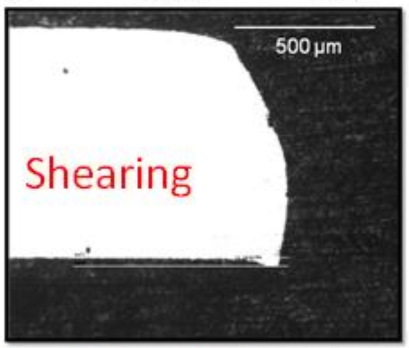
- Developed at OSU. A variation of explosion welding - in safe laboratory environment. Unlike MPW, does not require an electrically conductive flyer material
- Dissimilar materials welded with varying strength and interface structure
- Strong welds associated with wavy interfaces free of intermetallics whereas weaker welds were riddled with defects
- Peel test is more discriminating in terms of strength of the welds
- Velocities upto 560 m/s observed using PDV
- Can be used for quick determination of welding windows for any weldable couple
- Welds created over lengths of upto 50 mm

Other applications of vaporizing conductor technique



2X0.0254 mm 4.0 kJ | 2X0.0254 mm 3.2 kJ | 2X0.0254 mm 2.8 kJ | 0.0508 mm 2.4 kJ

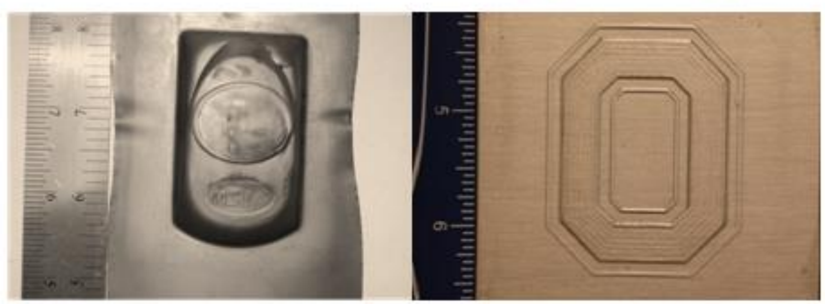




A. Vivek, G.A. Taber, J.R. Johnson, S.T. Woodward, Glenn S. Daehn, Electrically driven plasma via vaporization of metallic conductors: A tool for impulse metal working, Journal of Materials Processing Technology, Volume 213, Issue 8, August 2013, Pages 1311-1326, ISSN 0924-0136, 10.1016/j.jmatprotec.2013.02.010.

Munitions Disposal

Embossing/Forming



0.5 mm thick grade 2 CP titanium formed into a cellphone case die using vaporization of a 0.127 mm thick aluminum foil with input enegy of 5.6 kJ

Challenges and future work

- Simulation work: ideal gas assumption
- Foil shape effects
- Options for insulation material
- Die-less forming
- Industrial adaptation
- Development of standardized peel testing for metal-to-metal welds
- ?