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Trends in Microjoining 2010

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Joining of Advanced and Specialty Materials XII

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Microjoining Landscape

- Microelectronics
  - Computers
  - Cell phones
  - Pacemakers
- MEMS (adds mechanical functions)
  - Sensors
  - Actuators
- MOEMS (adds optical functions)
  - Optical sensors
  - Optical switching
  - HDTV
- Microfluidics (adds liquid flow functions)
  - Chemlab on a chip
  - Medical implants
- Photonics (all optical)

Definition: Microjoining

- Two words, one word or hyphenated???

- JIS Z 3001 takes an operational approach and describes micro-welding as a
  - "generic term for welding processes which are applied to the sections which,owing to the object for welding being extremely small and/or fine, are affected by factors such as weldability, diffusion thickness, deformation amount and surface tension, particularly whose effect on dimensions is to be taken into account."

- K. Matsuyama chose "to treat the welding processes for components of about several millimetres or smaller as 'micro-welding'."

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Definition: Microjoining II

- **Several possible physical approaches:**
  - **Dimensions of objects being joined**
    - **One dimension, two, or all three?**
    - **One object or all objects (i.e. thin to thick)?**
    - **Filler material added (thickness/dia. or mass µg)**
    - **Thermal diffusion distance**
  - **Energy usage**
    - **µJ/pulse for spot welds**
    - **µJ/µm for seam welds**
  - **Timescale**
    - **µs**
  - **Ratio of surface tension/other significant forces ~1**
- **For our purposes, meeting *any* of the above will suffice.**

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Microjoining Processes

- Thermocompression/thermosonic/ultrasonic
  - Ball/wedge bonding
  - Flip chip (Au stud bump)
  - also TAB, beam lead
- Flip Chip reflow of solder ball arrays
- μ adhesive bonding
- μ e^--beam
- μ laser
- Focused ion beam (FIB) deposition
- μ spark (μ arc welding)
- μ resistance welding
- Exothermic nanolaminates

Microjoining Process Attributes

- Visualization of parts/process difficult (tiny dimensions)
- Handling/fixturing difficult (small, fragile, floppy)
- Control of process difficult (small energy inputs/short timescales, precise path alignment)
- Reproducibility critically dependent upon reproducible parts/fitup
- Sensitive to surface effects
  - Contamination (extreme surface/volume ratio)
  - Surface tension forces
- Difficulty inversely proportional to size!
- Poor productivity except:
  - Laser with scanner-type beam positioning
  - Ebeam with rapid magnetic lens beam control\
  - Parallel processes

Microjoining & Materials

Similar and dissimilar joints between:

- **Metals (join by all processes)**
  - **Au, Al, Cu, Si, Ni, Kovar, Stainless Steel, Elgiloy, Nitinol .....**
- **Transparent materials (not RW-US-Arc, eB difficult, LB with special techniques, FIB, At. diff.)**
  - **Sapphire, glass, SiO_2, other photonic materials**
- **Polymers (not Solder-eB-Arc)**
- **Ceramics (metallization & solder/braze, adh, FIB)**
- **Nanomaterials (carbon nanotubes, nanowires: eB, LB, FIB, solder, adh, RW + W catalyst, At. diff.)**
- **Meta-materials (negative refractive index nanocomposites, unknown durability: adh, FIB, low temp solder?)**

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Macro vs. Micro Comparison of Various Origin Stress/Force Magnitudes Acting on a Weld Pool

Force origin:	**Macro magnitude:** pressure/stress	*force*	**Micro magnitude:** pressure/stress	*force*
Thermal expansion (M) (ambient-to-molten)	6.5 GPa	*6.5 kN*	6.5 GPa	*0.65 N*
RW electrode inertial				
melting (P)		*0.02-2 N*		*0.05-0.5 N*
solidifying (P)		*0.13-13.3 N*		*0.1-10 N*
Evaporation (P)	1.5-7 kPa	*1.5-7 mN*	1.5-7 kPa	*0.15-0.7 μN*
Surface tension (M)	2 kPa	*2 mN*	200 kPa	*20 μN*
Marangoni shear (M)	70 Pa	*70 μN*	0.7 MPa	*70 μN*
Impinging droplets (P)	2.7 kPa	*12 mN*	67 kPa	*3 mN*
Lorentz vortex (P)	3.7×10^{-4} N/mm^3	*37 mN*	N. A.	

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Macro vs. Micro Comparison of Various Origin Stress/Force Magnitudes Acting on a Weld Pool II

Pool sloshing (M)		*200 mN*		*20 μN*
Stage motion, centrifugal (P)		*44 mN*		*44 nN*
Liquid viscosity shear (M)	6 Pa	*6 μN*	6 Pa	*0.6 pN*
Aerodynamic shear stress (P)	70-400 Pa	*70-400 μN*	70-400 Pa	*7-40 pN*
Aero stagnation pressure (P)	0.4-600 kPa	*0.4-600 mN*	0.4-600 kPa	*0.04-60 μN*
Lorentz GMAW pinch (P)	6 kPa	*6 mN*	N.A.	
Current carrying conductor "kick" (P)	200 N/m	*200N* *(1 m cable)*	80 mN/m	*8 mN* *(10 cm cable)*
Metallostatic head (M)	0.8 kPa	*0.8 mN*	20 Pa	*0.002 μN*
Buoyancy force (M $\Delta\rho g$):				
Autogenous[+]	2.1 kN/m³	*21 mN*	2.1 kN/m³	*2.1 μN*
Dissimilar[#]	52 kN/m³	*52 mN*	52 kN/m³	*5.2 μN*

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Ball/Wedge Bonding

- Mature technology, around since 1960's
- Incremental progress:
  - Faster bond cycle (few 10's of ms, under CNC)
  - Better placement (finer pitch)
  - Better loop height control (multilevel wire tiers)
  - Improved process yield (~25 ppm defect rate)
  - Au, Al, Cu (and other) wires
  - Broader wire diameter range, insulated wires
  - Stud bumping
  - 3D (vertically-stacked dies)

Ball Bonding

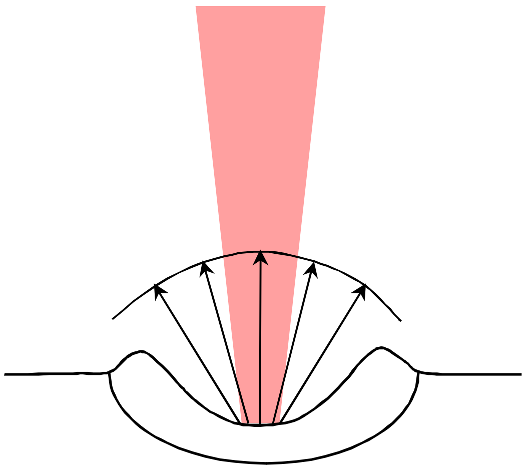
- from http://www.youtube.com/watch?v=pajE4Bi6Xts&feature=related
- search "Gold Ball Bonding"

QuickTime™ and a
decompressor
are needed to see this picture.

µ Laser Welds

- Hardware is becoming readily available
  - Near diffraction limit focused beams available from single mode fiber lasers
  - Sub-micron-resolution CNC stages
  - Rapid motion beam scanners
  - Digital optics beam splitters
- Questions:
  - Welding vs drilling at small spot sizes
  - Beam characterization at small spot sizes
  - Fixturing / handling!!!

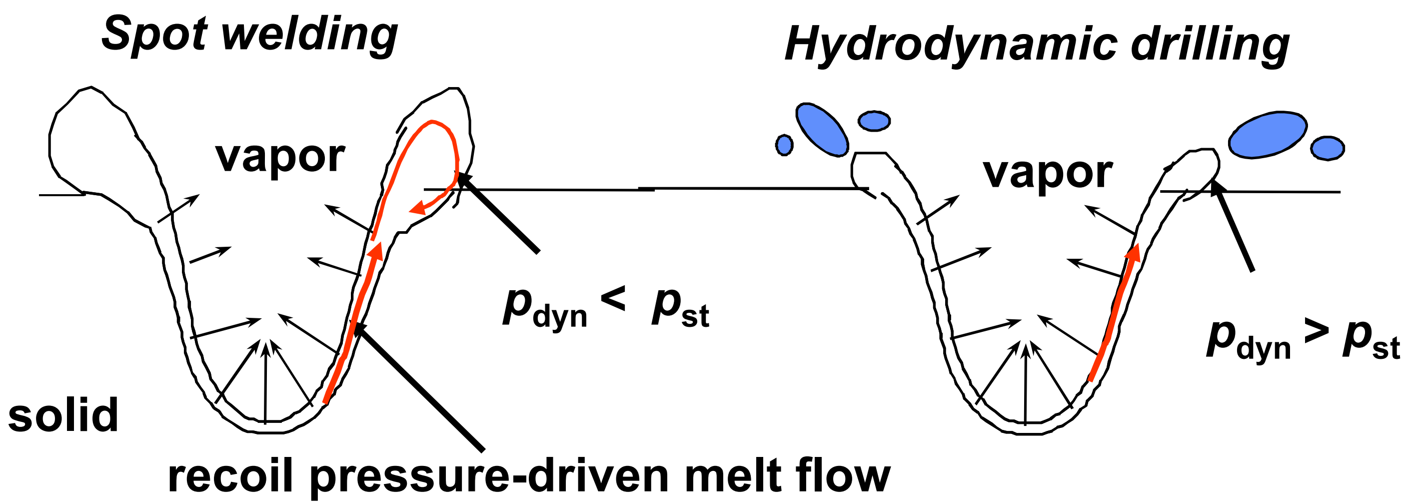
Forces Acting in Laser Welding



Evaporation:	7000 Pa
Surface tension	
Driving:	700
Resisting:	2000
Viscosity:	60
Momentum/Inertia:	0.010

Approximate values for forces acting in mm-size welds; only surface tension resisting force from capillarity changes (~1/r) with size

Welding vs Drilling



$$p_r = 0.54\ B_0(T_s)^{-1/2}\ \exp(-U/kT_s)$$

Values:
1.5 (meas.) - 7 kPa (3D calc.)

B_0 = evaporation constant
T_s = surface temperature
U = latent heat of evaporation/atom
k = Boltzman's constant

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Welding vs Drilling Initial Model

$$t_{\mathrm{ej}} = \frac{r_{\mathrm{m}}}{< v_{\mathrm{m}} >} \leq \tau - t_{\mathrm{m}}$$

Melt displacement criterion, where:

t_{ej}	**time for melt displacement**
r_{m}	**melt pool radius**
$< v_{\mathrm{m}} >$	**melt velocity average**
τ	**laser pulse duration**
t_{m}	**time to the initiation of surface melting**

+ conservation of momentum, energy + BC's$\rightarrow$

calculated displacement thresholds implied:

Small diameter pulses should drill immediately upon surface melting, particularly for longer τ **!**

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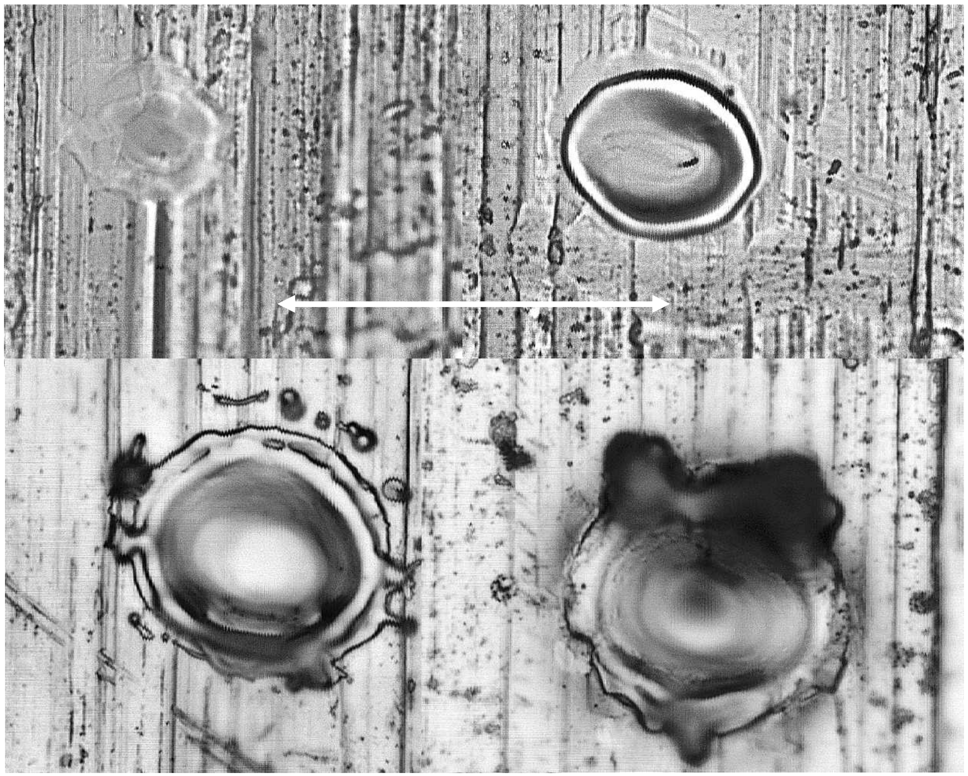
Weld vs Drill Experimental Results



Ni 200

pulsed Nd:YAG laser

5 ms pulse

20 μm radius beam

Results showed it is possible to make small welds without drilling and that a progression from flat to concave to drilled occurs with increasing energy

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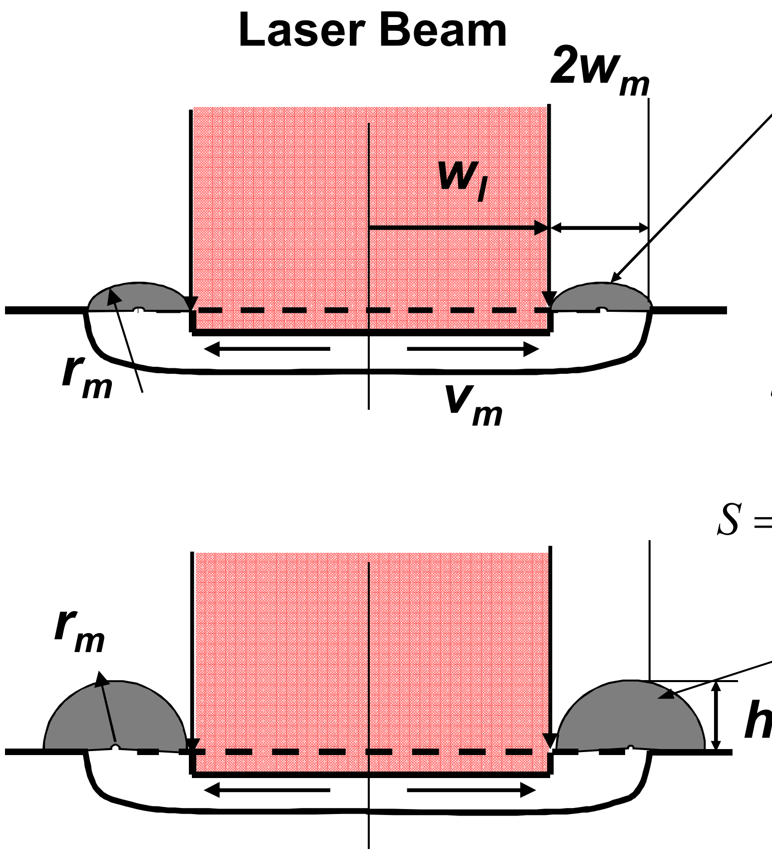
Improved Model: Including Surface Tension



$$S = 2w_{\mathrm{m}} \int_{o}^{t} v_{\mathrm{m}} dt$$

$$h = r_{\mathrm{m}} - \sqrt{r_{\mathrm{m}}^2 - w_{\mathrm{m}}^2}$$

$$l \approx \sqrt{2w_{\mathrm{m}}^2 + \frac{16}{3} h^2}$$

$$S = 0.5\left[l r_{\mathrm{m}} - 2w_{\mathrm{m}}\left(r_{\mathrm{m}} - h\right)\right]$$

$$S = 0.5 \pi r_{\mathrm{m}}^2$$

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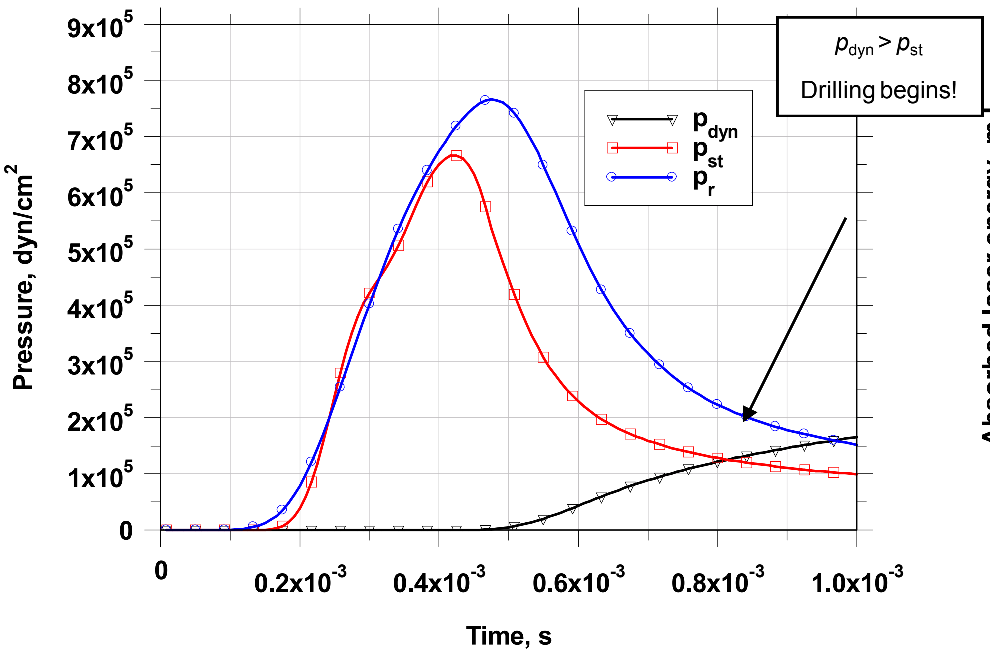
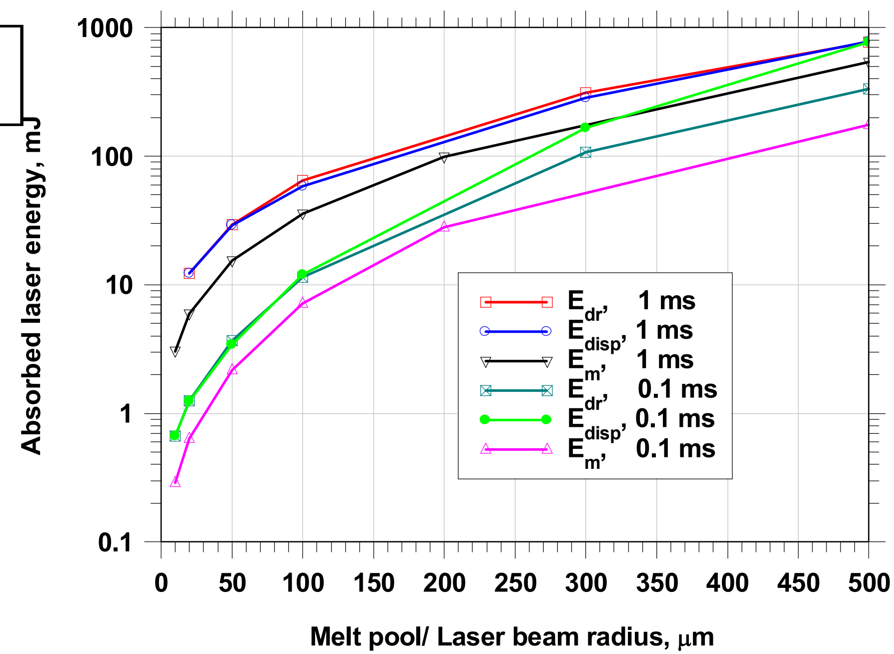
Results

330 mJ,1ms, 300μm radius drilling pulse



Surface tension retards the displacement/drilling threshold to > melting



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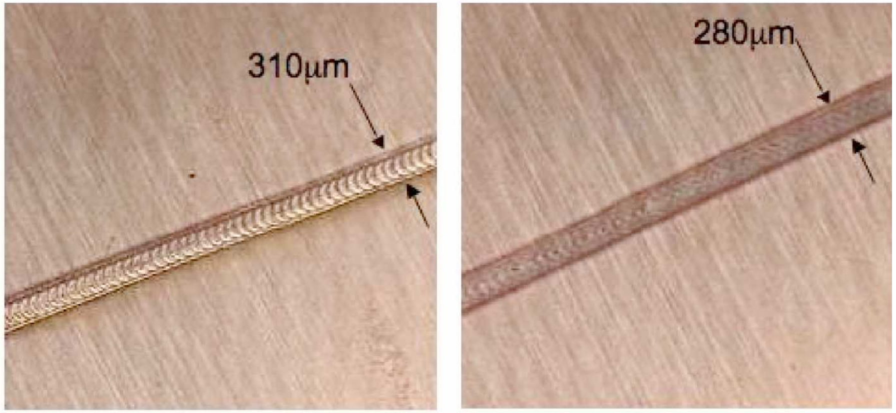
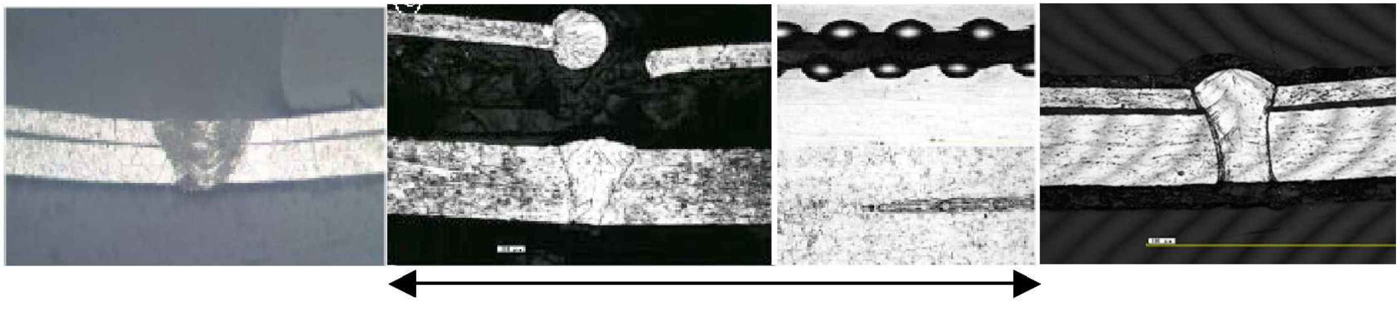
Examples of µLBW



Top surface   Bottom surface

Cu, SHG Nd:YAG, courtesy of Miyachi Technos



(a)   (b)   (c)

Single mode fiber laser: 10 µm spot size, stainless steel foil lap welds
(a): 20µm/30µm, 25W @ 1m/s, (b): 10µm/30µm, 30µm gap not bridged,
(c): same as b, with no gap

Miyamoto, Park, Seo-heong, Ooie, Proc. 4th LPM

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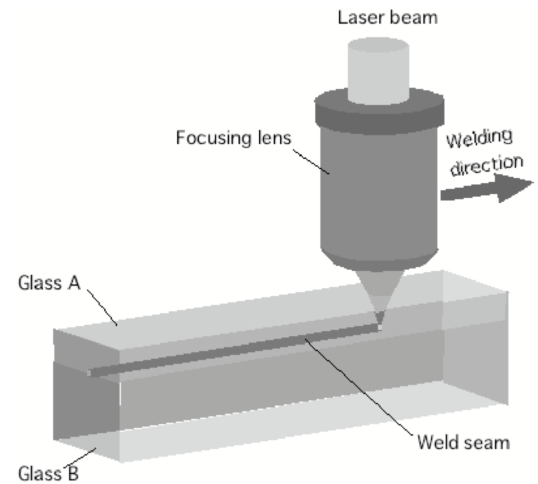
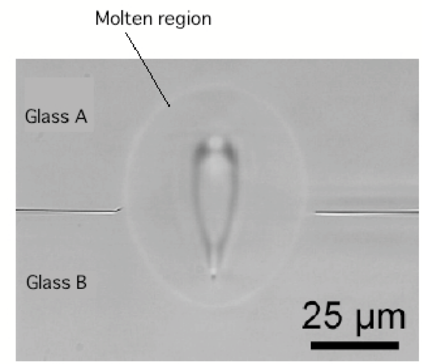
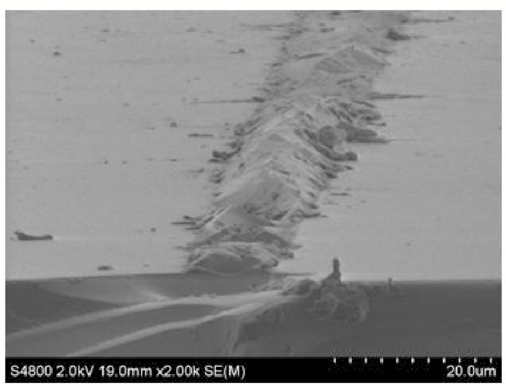
Example of µLBW: Glass
from Miyamoto & Herrman Proc LPM2007

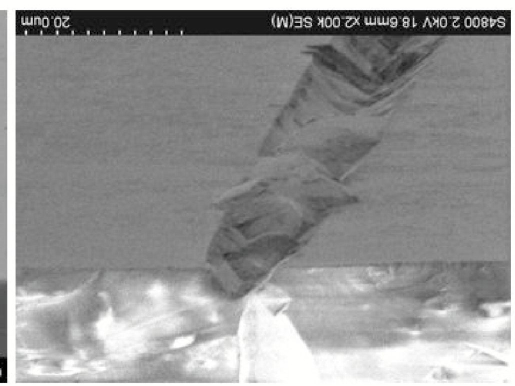


(a)



(b)





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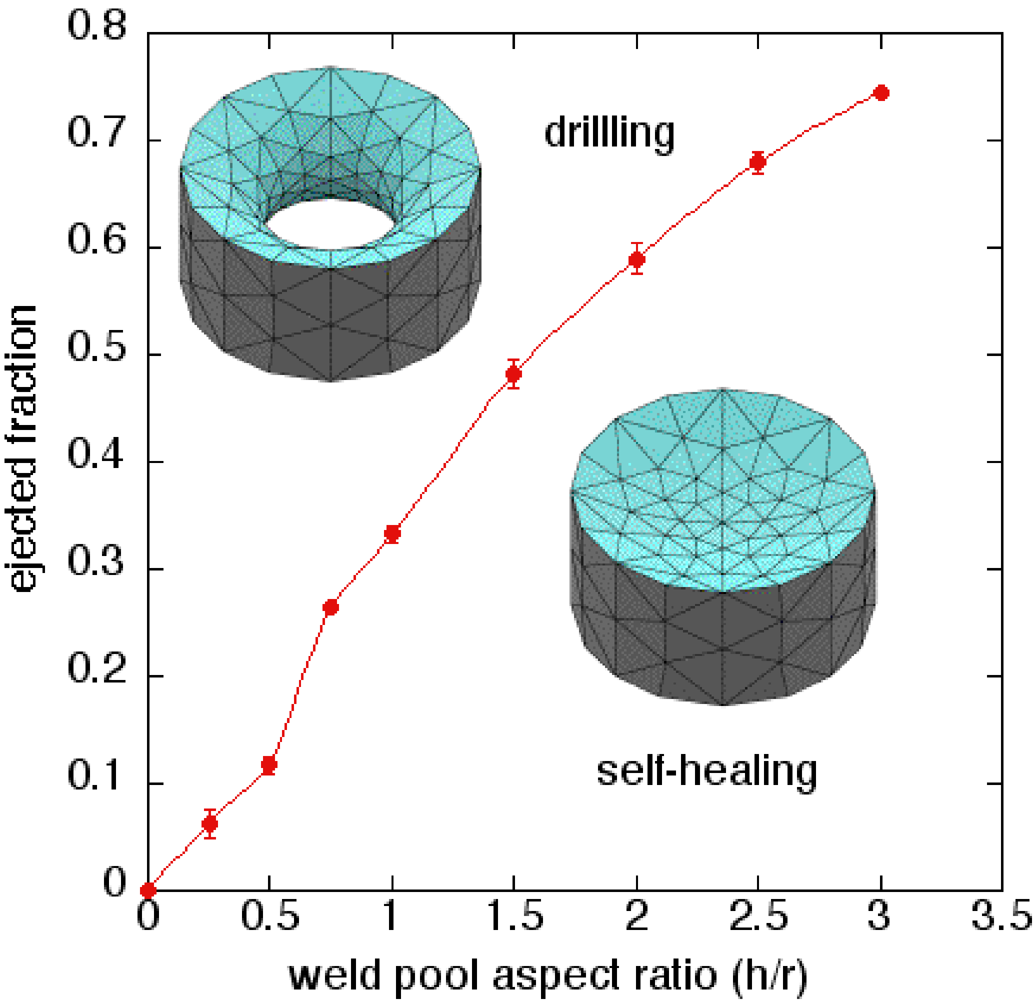
Surface Energy Considerations

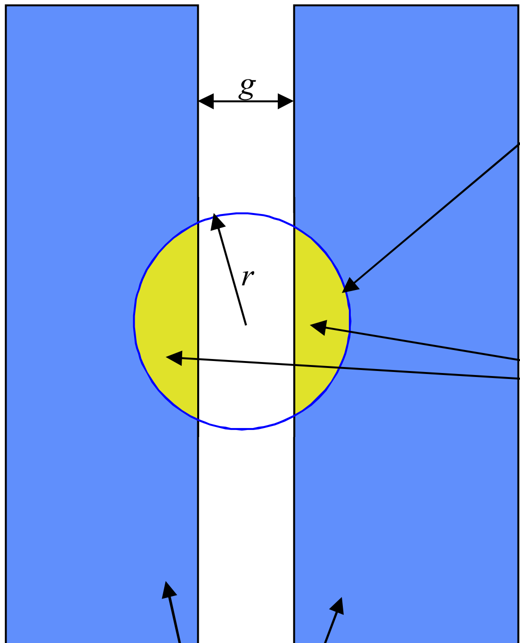


Scenario:
Perform lap spot weld in thin sheets where metal ejection occurs.

How much can be lost without leaving a hole?

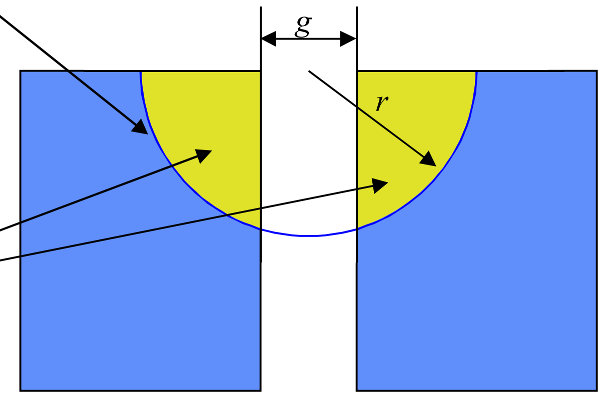
Brakke, K.E., The Surface Evolver, available from www.susqu.edu/facstaff/b/brakke/evolver/

Surface Energy Consideration II



laser/e⁻-beam hot zone

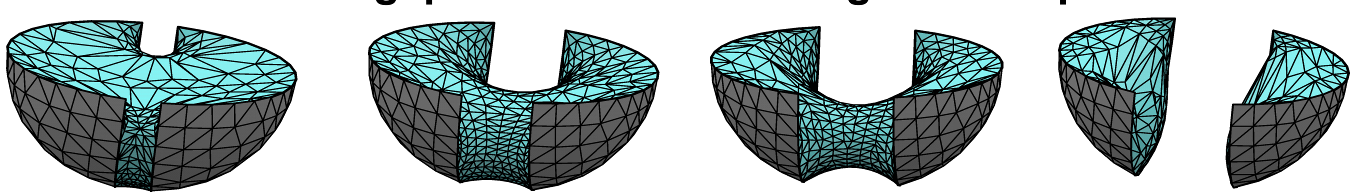
hemispherical $r = 1$
Material inside hot zone melts; remainder stays solid



liquid (melt zone):
total volume, $v = (\pi/3)(2r+g)(r-g)^2$
contact angle $\theta = 10°$
We begin with liquid contiguous across the gap. Total liquid volume remains constant as pool shape evolves.

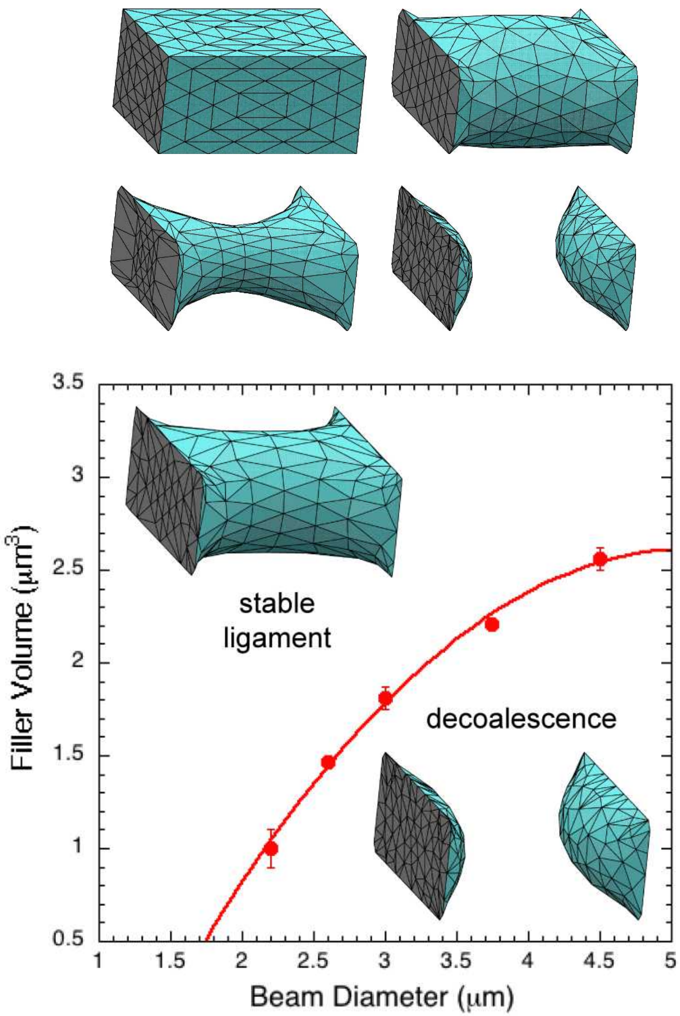
material thickness > r

At a critical gap-to-width ratio the ligament separates:

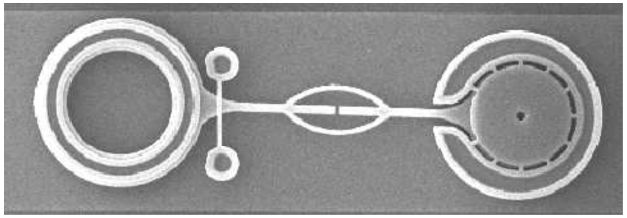


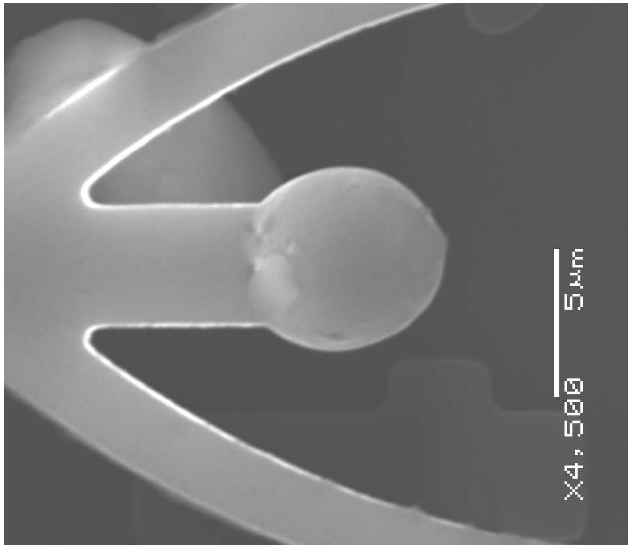
g/r = 0.125 | 0.25 | 0.33 | 0.345

Surface Energy Considerations III



Minimum melt volume needed to bridge gap





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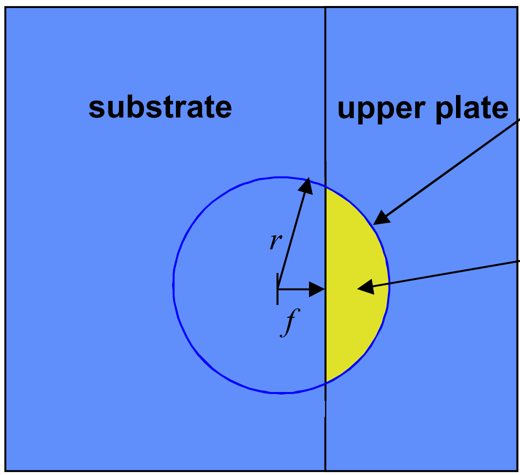
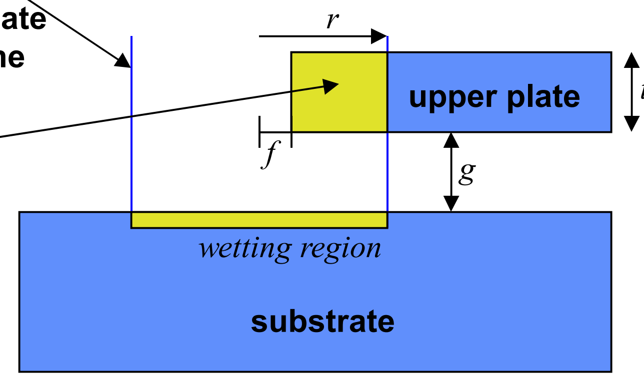
Surface Energy Considerations IV



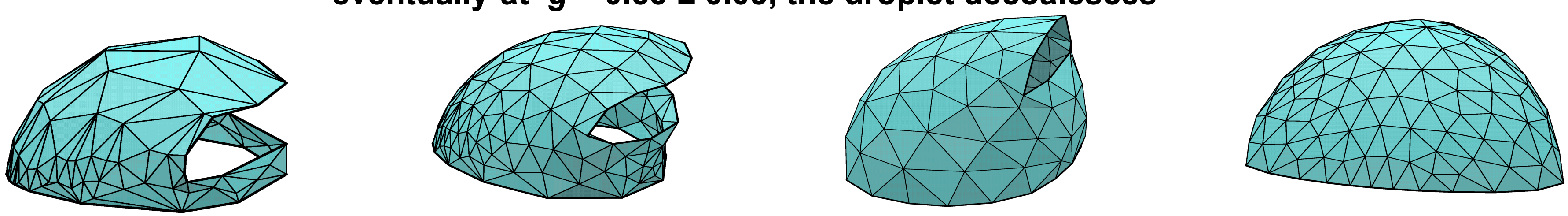
hot zone

circular with radius $r = 1$
may be offset from center
Material inside the spot in the upper plate melts; that outside the spot and on the substrate remains solid.

liquid (melt zone):
total volume, $v = t\,(r^2/2)(\varphi - \sin\varphi)$
where $\varphi = 2\cos^{-1}(f/r)$
Contact angle varies. The total liquid volume remains constant as the liquid pool shape evolves. Liquid wets the substrate hot spot and the upper plate's hot edge only.



As the gap becomes larger, contact area with the upper plate decreases; eventually at $g \sim 0.53 \pm 0.03$, the droplet decoalesces



gap width = 0.125 | 0.25 | 0.5 | 0.5625

Notes: For this system, spot radius = 1, upper plate thickness = 0.25, contact angle = 90° offset = 0. Only the liquid is shown. Total volume of liquid is constant.

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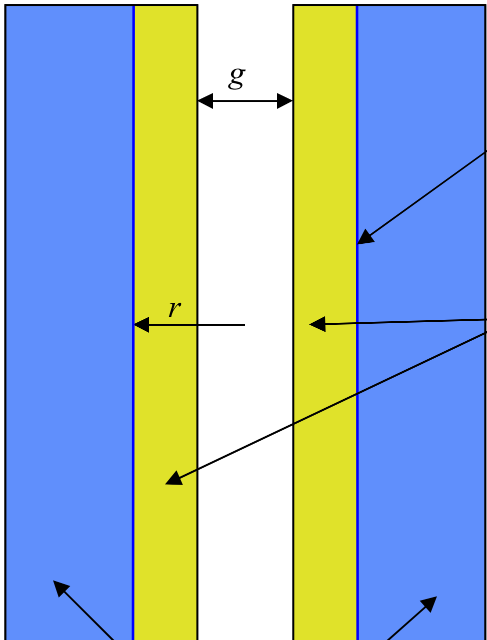
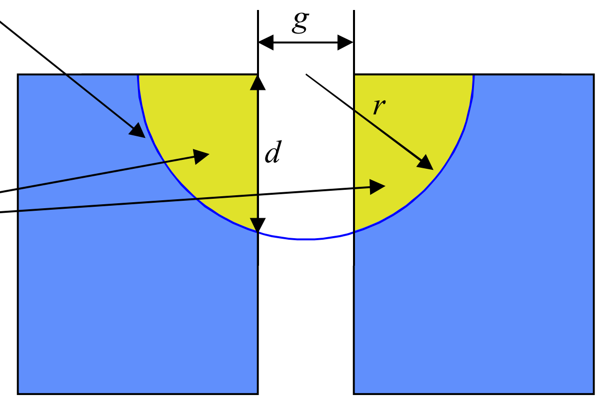
Surface Energy Considerations VI



weld line (hot zone):
hemicylindrical with radius $r = 1$
centered between the bars
Metal inside the hot zone melts; metal outside the hot zone remains solid.
The maximum depth of the weld pool
$d = (r^2 - g^2/4)^{1/2}$

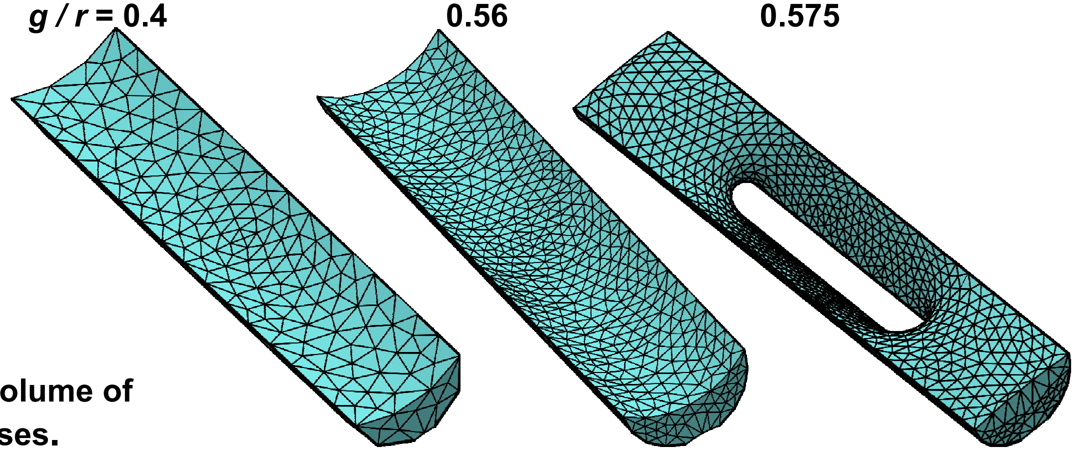


liquid (melt zone):
total volume, $v = (\pi r^2 l/2)-(dgl/2)-[r^2 l \arcsin(g/2r)]$
liquid/solid contact angle, $\theta = 10°$
We begin with liquid contiguous across the gap. The total volume of liquid remains constant as the pool shape evolves.

metal plates:
thickness is greater than the maximum melt zone depth, *r*
width of gap *g* varies
length *l* >> *r*

When gap-to-width ratio is low, the weld is contiguous;
For gap-to-width ratio greater than about 0.57, the weld tears.

g / *r* = 0.4   0.56   0.575



Notes: Only liquid is shown. Total volume of liquid decreases as gap increases.

Beam Intensity: Electron Beams vs Lasers

	Beam Dia.	Beam Current	Accel. Voltage	Power	Intensity (*kW / mm²*)
Laser μ welder:	15 μm	n.a.	n.a.	20 W	*~100*
Standard eB welder:	~0.5 mm	~25 mA	~150 kV	~4 kW	*~20*
SEM: (*analysis*)	600 nm	1 μA	30 kV	~30 mW	*~100 **
SEM: (*imaging*)	60 nm	1 pA	30 kV	30 μW	*~10 **
Tweaked SEM:	5 μm	~25 μA	30 kV	~750 mW	*~40 **

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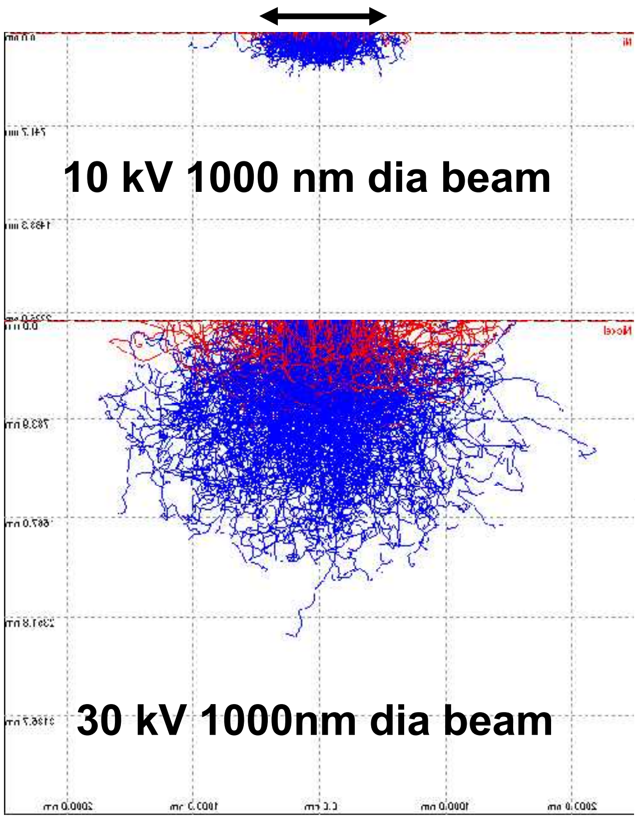
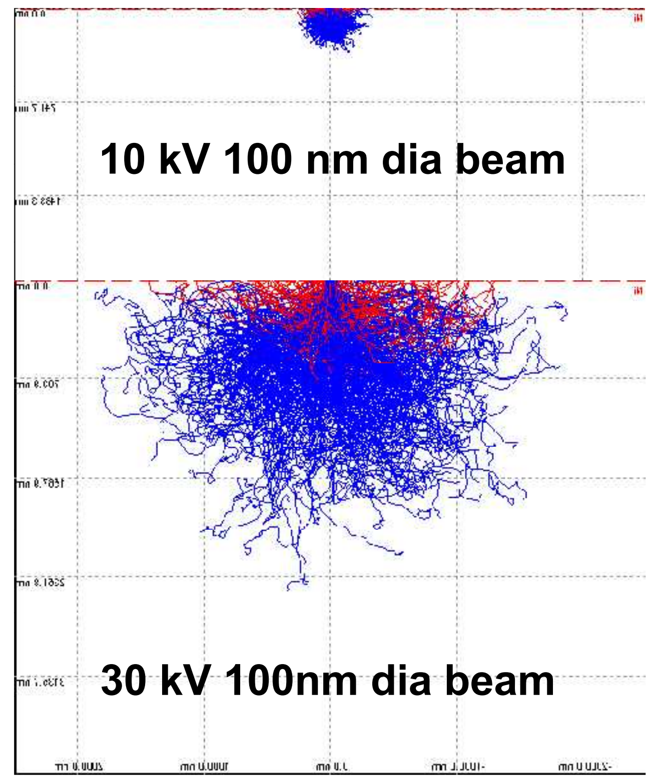
e⁻-Beam Intensity

When an SEM builder says, ".......the beam is X nm in diameter......", What does that really mean for energy deposition?





Can't directly compare lasers vs electron beam surface intensities

Beam Comparison: Laser vs e^--Beam

Equation for radiation absorption by a medium:

$$I = I_0 \exp[-\mu z]$$

Energy Absorbed vs depth /Area:

$$E(z) = \int_0^z I_0 \exp[-\mu z]\, dz$$

Assume laser and E beam have same power and beam size:

$$E_{laser} = \int_0^\infty I_{laser} \exp[-\mu_{laser} z]\, dz = E_{eb} = \int_0^\infty I_{eb} \exp[-\mu_{eb} z]\, dz$$

which can be reduced to:

$$I_{laser} / I_{eb} = \mu_{laser} / \mu_{eb}$$

For Ni, $\mu_{laser} = 50\ \mu m^{-1}$, $\mu_{eb} = 2\ \mu m^{-1}$ @ 30 keV

thus, the E beam's surface intensity is effectively 25x lower than an equivalent laser beam

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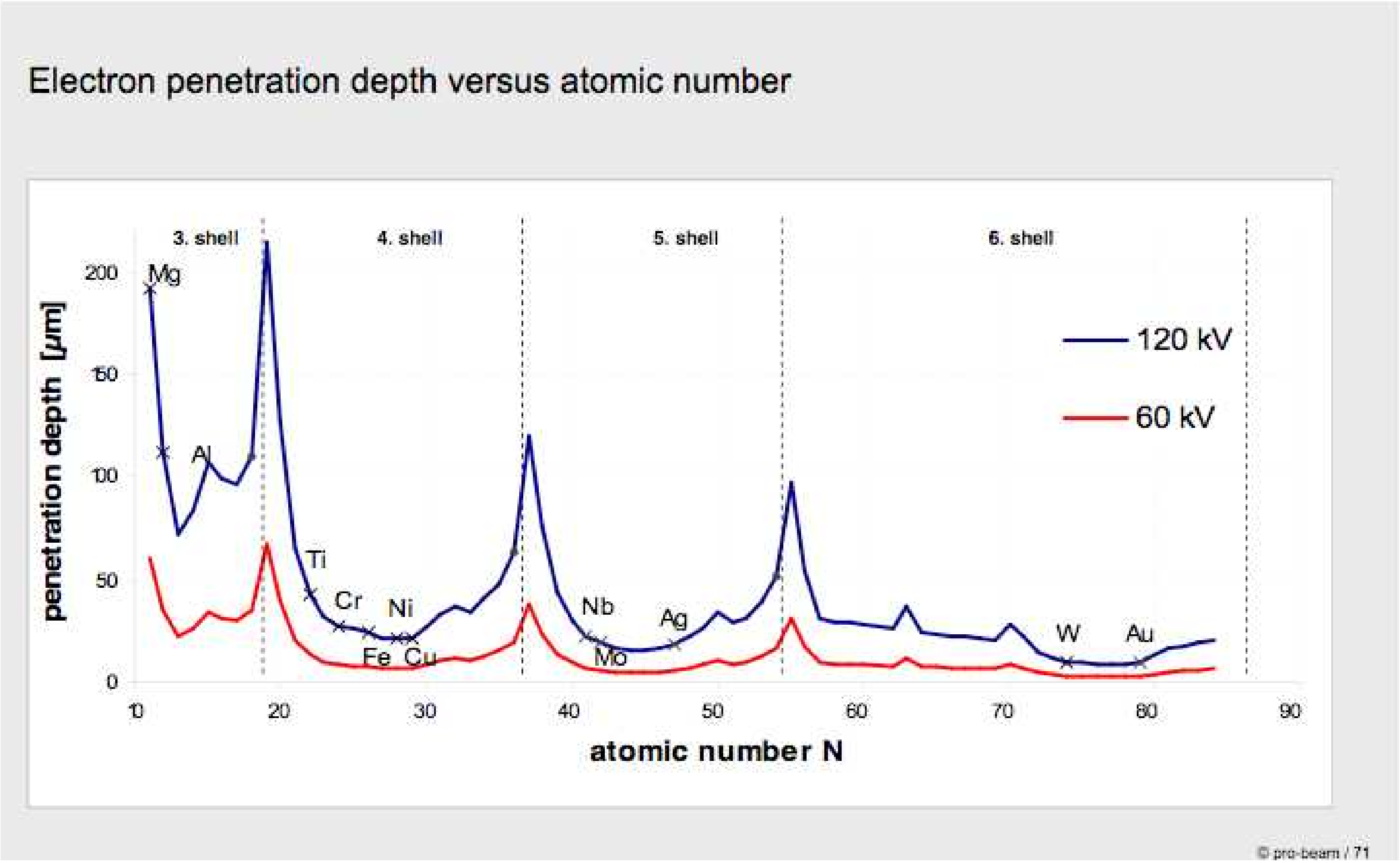
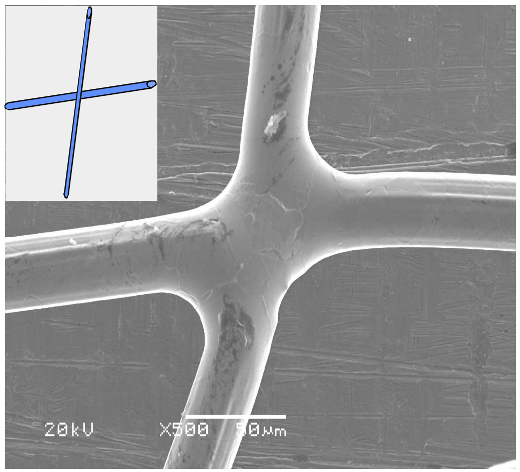
Material / e⁻-Beam Interaction



Thanks to Thorsten Löwer, ProBeam AG & Co

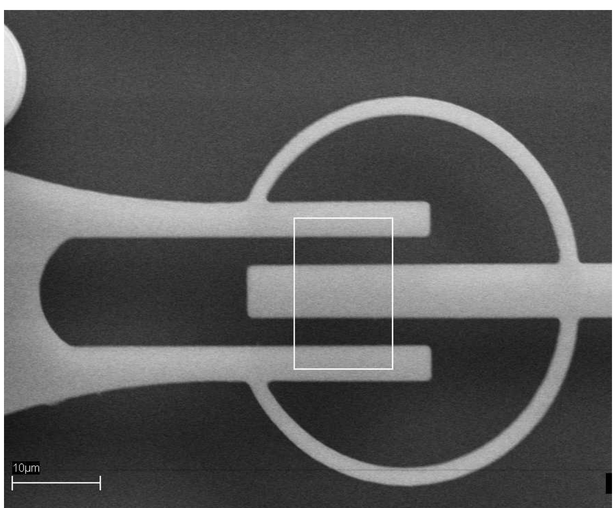
Examples

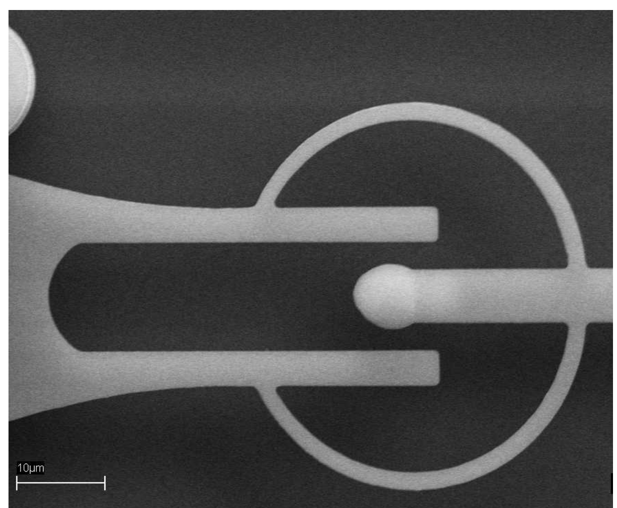


Cross-wire weld

Tophet C

30 μm diameter





Unsuccessful weld of poly-Si MEMS device; did not bridge gap

Thermal Considerations

- If heat sink is nearby
  - Temperature distribution rapidly achieves steady-state
  - Thermal influence distance: TID ~ $(\alpha\ t)^{1/2}$
    - Pick α ~ 0.1 $cm^2/s = 10^7\ \mu^2/s$ (value for steel)
    - TID of 100 µm implies t ~ 1 ms
    - TID of 10 µm implies t ~ 10 µs
  - Considerable heat input needed if material being welded is a good conductor.
- If no heat sink is nearby
  - System acts like adiabatic block
  - Temperature rises very quickly and uniformly.
  - $7.2 nJ/(\mu m)^3$ raises Si from ambient to melt. An "adiabatic" MEMS feature 100µm x 10µm x 1µm, needs only 7.2 mJ, applied in ~10 ms by tweaked SEM.

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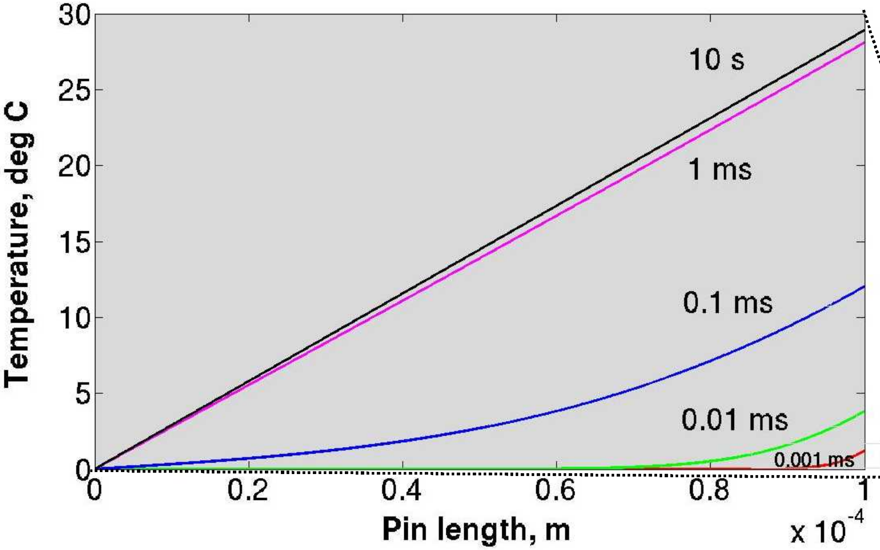
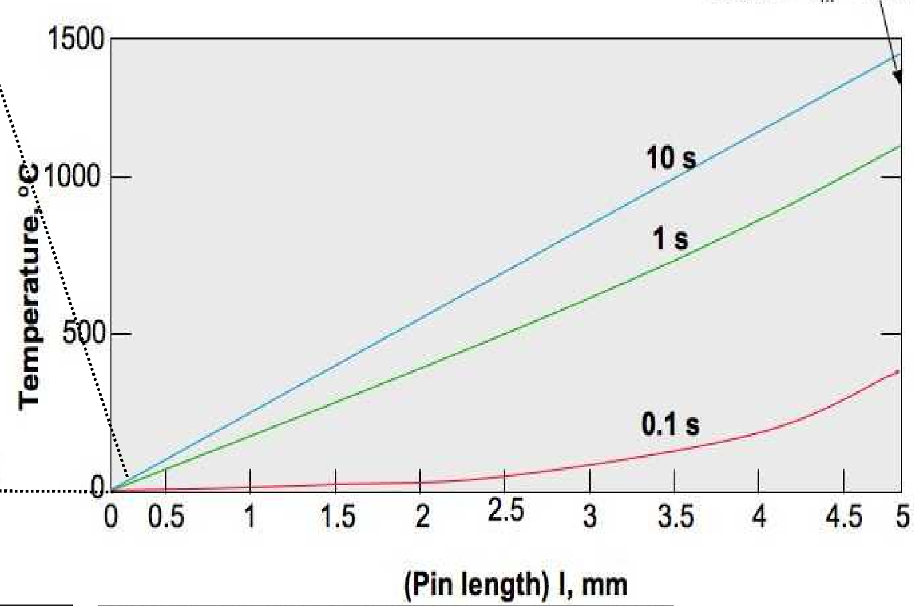
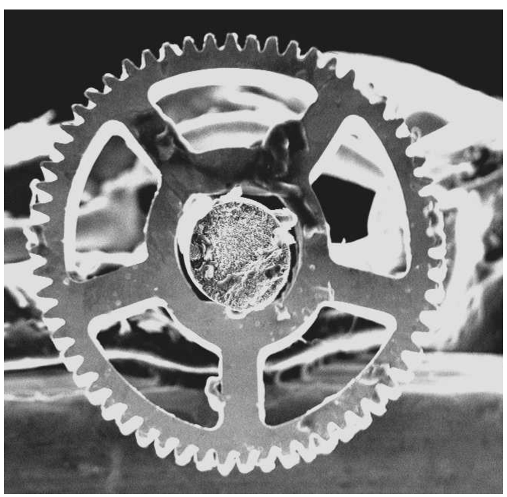
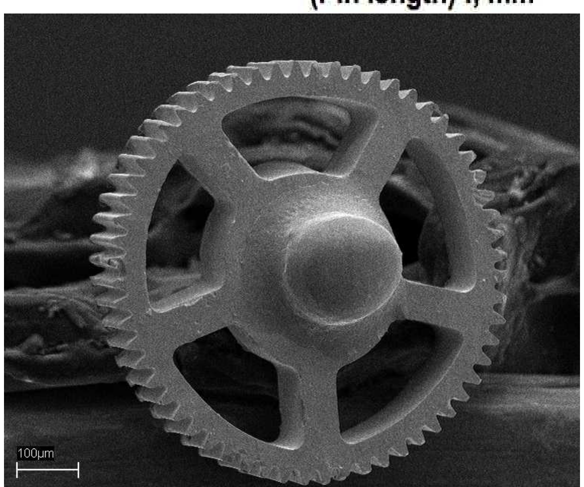
Thermal Considerations: Heat Sink

Scenario: Const heat flux at one end of bar; const Temp at other









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No Heat Sink

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Examples of μe^--Beam welds

from U. Reisgen, T. Dorfmüller, ISF Aachen Univ.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Axial butt and cross wire welds (175 µm dia. Ck101)

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Fillet and butt welds (Al)

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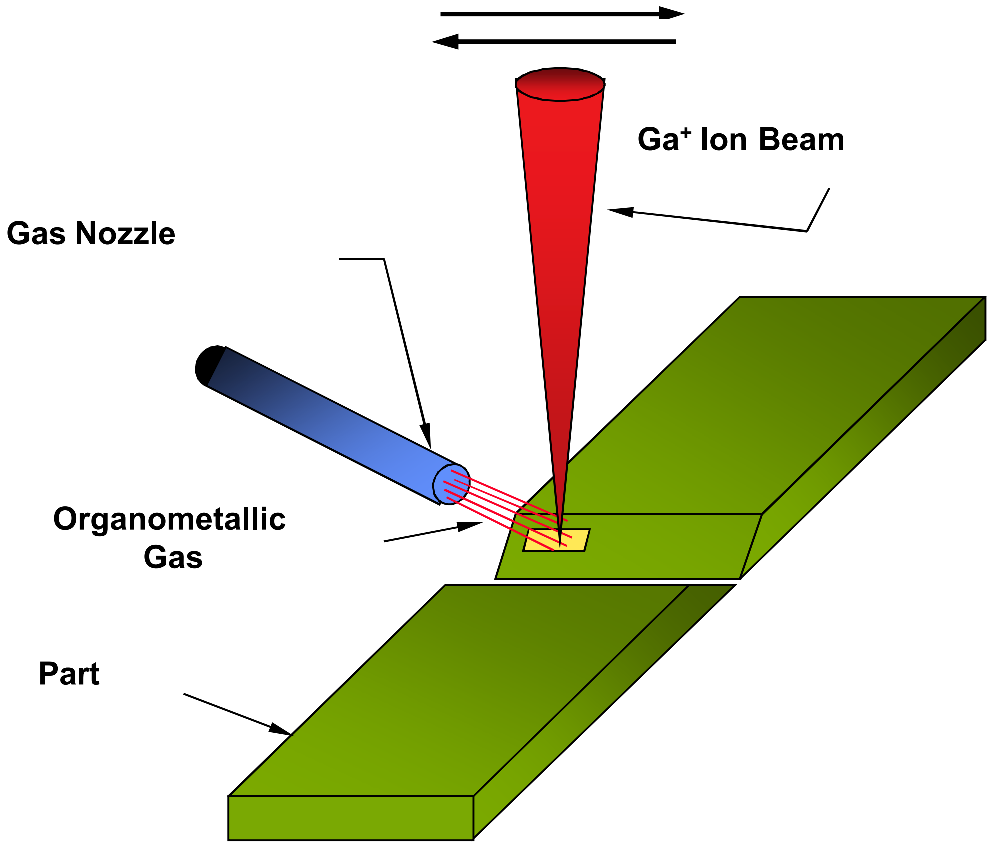
Focused Ion Beam Joining

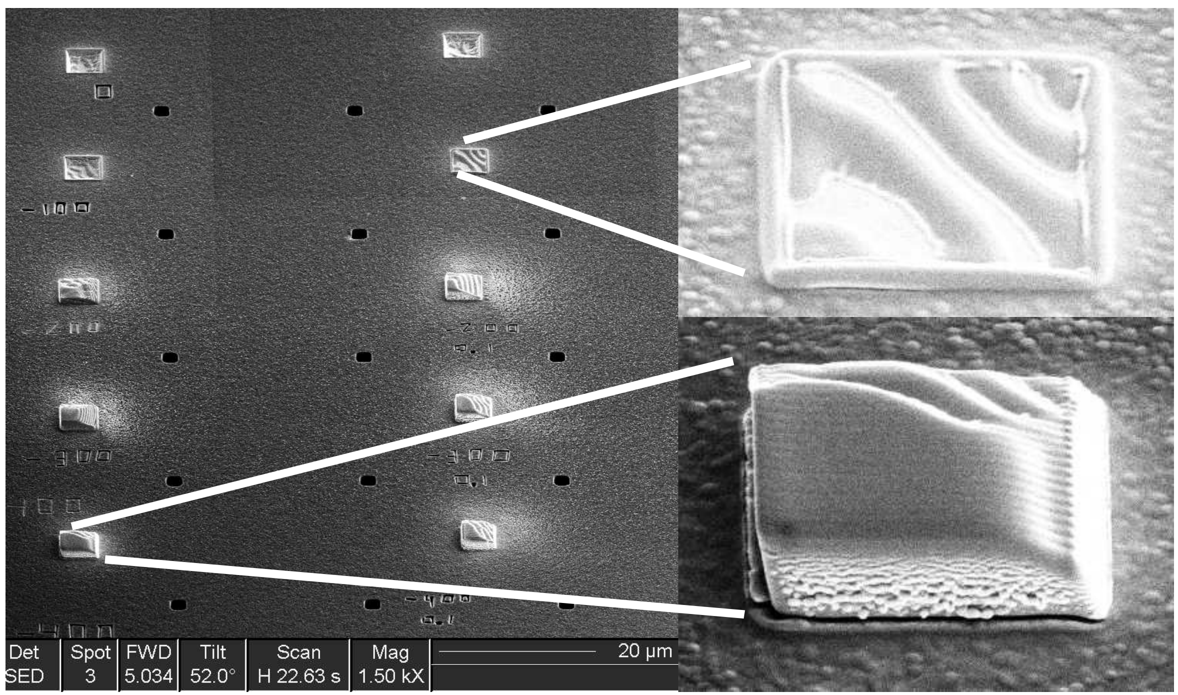


Ion beam "cracks" organometallic gas which has adsorbed onto surface

Can also be done with electron beam, but slower.

Characterizing the FIB process

FIB deposit as function of ion beam parameters: dwell and overlap
Observe gas flow eddies



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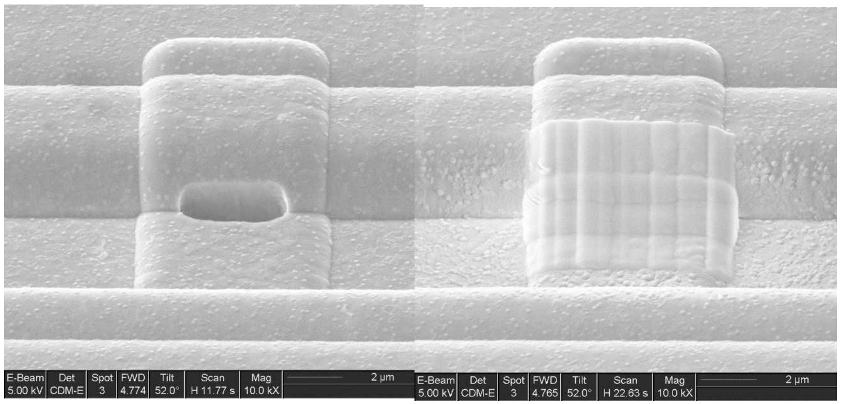
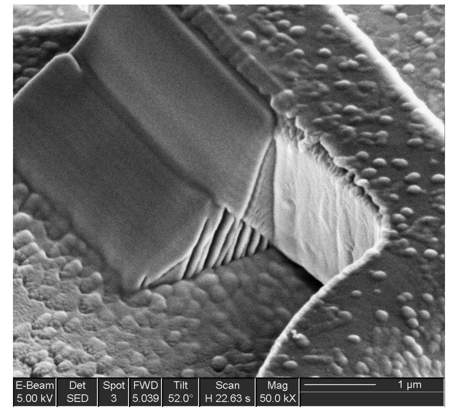
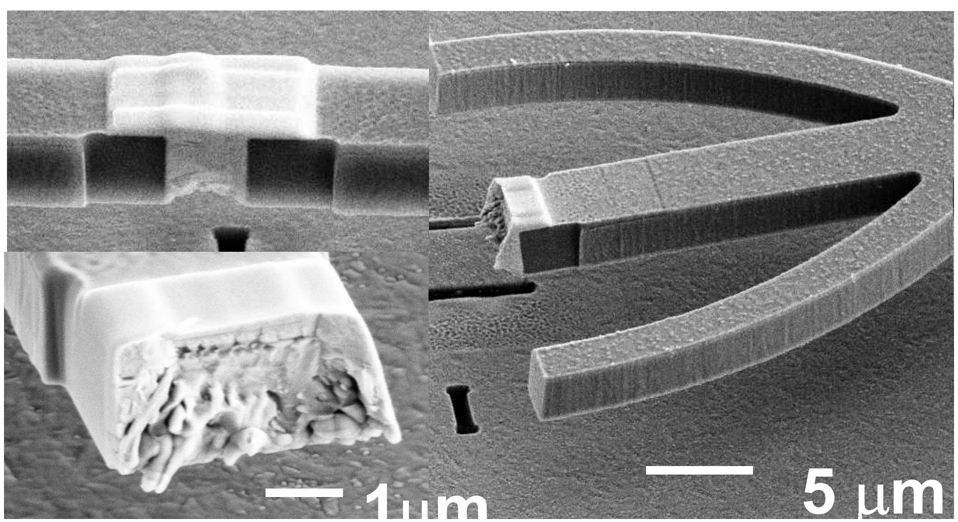
Example Joints



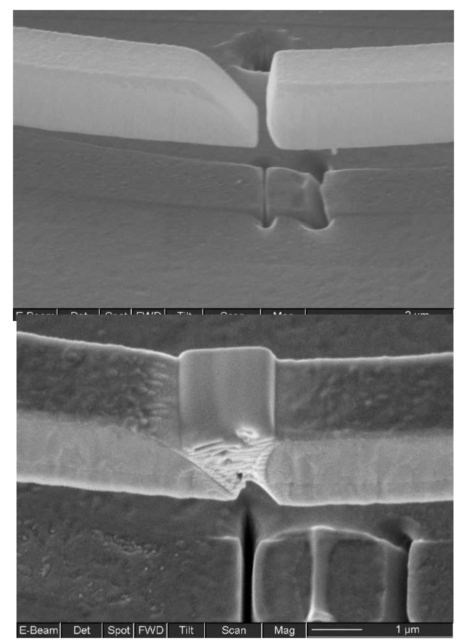
Etch hole patch in MEMS pump



Fillet joint in MEMS test bar



"wide gap" joint in MEMS test bar



"cut and rejoin narrow gap" joint in MEMS test bar

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Exothermic Nano Laminates

Technique uses nanoengineered foil comprised of many thin alternating layers of materials with exothermic heat of mixing (e.g. Al-Ni) to provide controllable in-situ intense heat source.

re.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

from:

T Rude, D Van Heerden, TP Weihs, OM Knio, Reactive NanoTechnologies, Inc.

MT Powers, CD Enns, Agilent Technologies

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Summary

- The small size and delicate nature of microparts makes process observation and handling major difficulties.
- Success requires careful attention to: energy input (amount and location), part fitup, fixturing and surface effects (especially for fusion processes).
- Nevertheless, many processes can be used to create successful microjoints, in both spot and seam geometries (though spot welds are predominant, by far)

Future Developments?

- Self-assembling molecules making microjoining a wet-chemical massively parallel process (already used to produce coatings for tribological control)

- Tailored nano-particles that aggregate and react at preferred locations

- Joining of nanotubes/nanowires will become important in microdevices

- Photon (or other energy form) stimulated bonding reactions (like today's UV-cured adhesives)

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