

Advances in Welding and Joining Technologies

Swarup Bag

**Department of Mechanical Engineering
Indian Institute of Technology Guwahati**

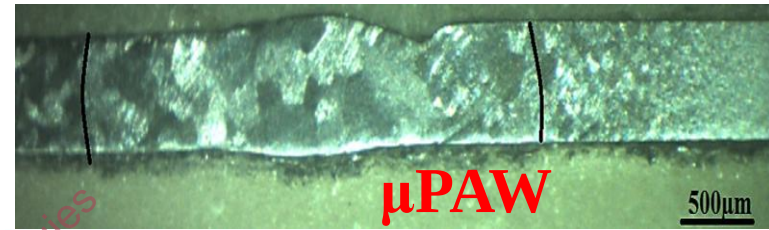
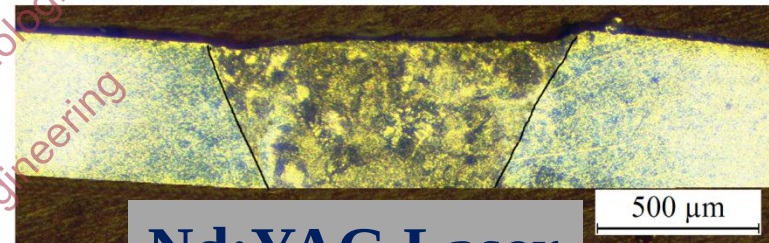
Module 5

Microjoining and Nanojoining

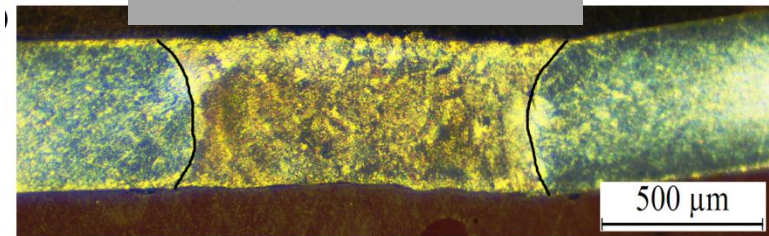
- ✓ Fundamentals of fusion microwelding
- ✓ Microelectronics wire bonding
- ✓ Bonding using nano-particles
- ✓ Laser microwelding
- ✓ Electron beam microwelding
- ✓ Resistance microwelding
- ✓ Plastics microwelding
- ✓ Microjoining of medical components and devices
- ✓ **Advances in laser and other microwelding processes**
- ✓ Development of nanojoining technologies

Introduction

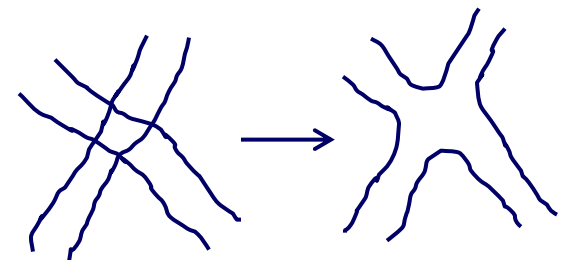
- ✓ Welding and joining of metals and non-metals in a smaller scale
- ✓ Downscaling of conventional welding processes - face challenges of ever advancing miniaturization
- ✓ Possible to develop set-up under microscope
- ✓ Precise control of heat source is required
- ✓ Even reduction in nano-scale joining is possible
- ✓ Nanoscience and nanotechnology – materials development and testing
- ✓ Emerging need to join nano-scale building blocks such as nanowires and nanotubes



Nd:YAG Laser



Ti6Al4V



Carbon nanotube

What is microjoining and nanojoining?

Joining: welding, brazing, soldering, bonding etc.

Mechanical joining: fastening, riveting, crimping etc.

Scale: Macro and nano

Microjoining:

- No strict definition of micro joining - mostly used relative to conventional welding and joining
- Characteristic dimension (sheet thickness or wire diameter) smaller than a few hundred μm but larger than 100 nm
- Effective microjoining - the most critical technical prerequisites in manufacturing at an ever-smaller scales
- However, different variants of micro joining process are used by researchers

Nanojoining: relatively new and used mostly in R&D communities

Mechanism and classification

- Two ideal solid surfaces, e.g., both perfectly clean and atomically flat - they will be drawn together spontaneously by interatomic forces
- The driving force for this joining is the reduction of Gibbs free energy of the system by reducing or replacing **high-energy free surfaces by low-energy interfaces.**
- This principle has been confirmed in tightly controlled environments, such as in direct silicon wafer bonding.
- Most **engineering surfaces are characterized as rough and contaminated with oxides**, etc. requiring some form of energy, usually heat and/or pressure, to be applied to overcome these surface impediments to make a joint.
- **Based on the physical states of the parts to be joined**
 - **Fusion welding**
 - **solid-state bonding**
 - **soldering/brazing**
 - **adhesive bonding**

Mechanism and classification

Microjoining processes can be grouped according to the traditional classification methods

Can this classification is applied to nanojoining?

Typical microjoining and nanojoining processes

	Microjoining	Nanojoining
Solid-state bonding	Wafer, Diffusion, Ultrasonic wire bonding, Cold, Explosive, Friction stir, Friction welding	Electron beam welding, Diffusion bonding, Ultrasonic welding , Cold welding
Soldering/ Brazing	Diffusion, Furnace, Induction, Laser reflow, Resistance, Eutectic soldering/brazing; Dip, Wave, Vapour phase, Fluxless soldering; Active brazing; Flip chip bonding; etc.	Liquid-phase reflow soldering, Resistance soldering, Active brazing, Laser brazing
Fusion welding	Electron & Laser beam, Percussive, Plasma, Gas tungsten, Resistance welding; Glass sealing; etc.	Laser beam welding, Resistance welding
Adhesive bonding	Adhesive die attachment, Adhesive flip chip bonding, Adhesive sealing, etc.	Adhesive bonding

Ref: Y. Zhou and A. Hu, From Microjoining to Nanojoining, The Open Surface Science Journal, 2011, 3, 32-41.

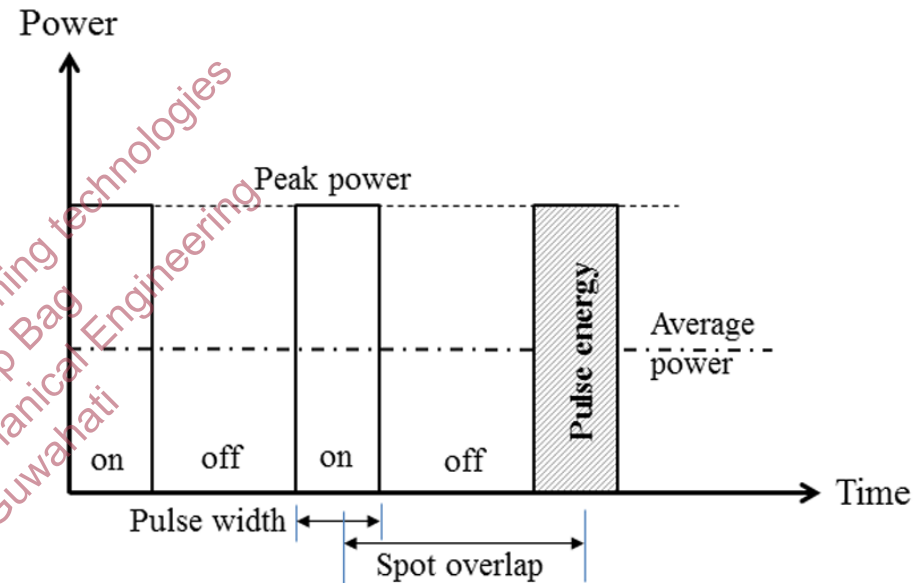
Fundamentals of Fusion Microwelding

❑ Techniques for microwelding

- with similarly controlled variables such as voltage, current and travel speed

❑ Continuous or pulse mode of energy release

❑ Processes divided dependent upon how the heat is applied and the effect of the heat

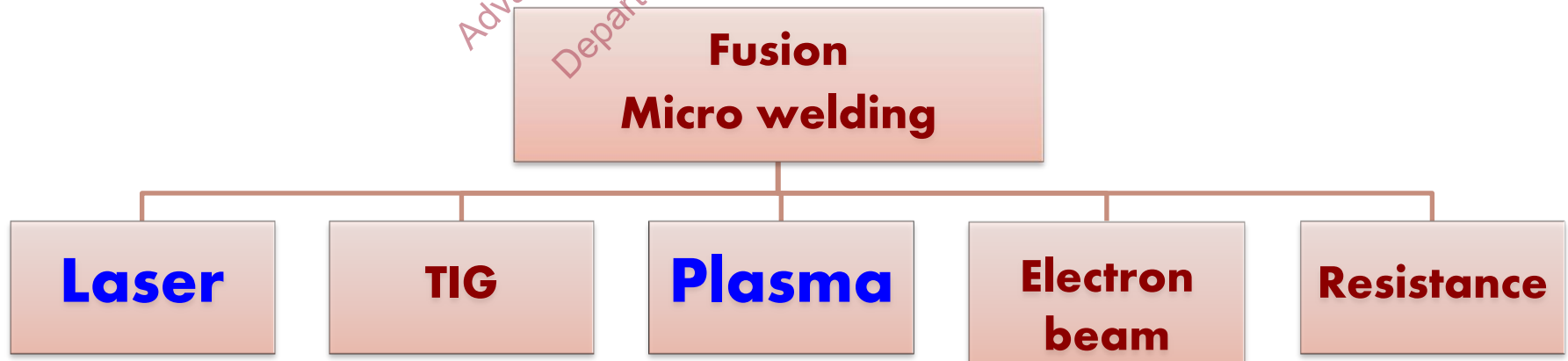


Resistance, arc (TIG, MIG and plasma) and laser

Also electron beam welding could be considered for miniature welding

Fusion Microwelding

- Welding by fusion of sheet materials of less than 0.5 mm in thickness, or tubular materials of less than 1 mm in diameter
- The basic phenomenon that interact in the formation of a fusion joint:
 - Thermal aspects
 - Mechanical aspects
 - Geometry aspects



Application area of microjoining

- ✓ **Microelectronics, medical, aerospace and defense industries**
- ✓ **Packaging and interconnecting in MEMS**

MEMS: also called microsystems or micromechanics where individual electrical, mechanical, fluidic and optical components need to be connected and coupled to the macroscopic external environment

Tiny medical implants, lamps and lighting assemblies, jewellery, dental appliances, aerospace items, hermetic sealing, batteries, thermocouples, wires, TV tube parts, sensing devices, electronic instrumentation, moulds and tool build up and many other types of miniature work

Resistance microwelding

Joining of non-ferrous materials in the fabrication of precision components such as sensors, actuators and medical devices –wire diameter 20 to 400 μm and electrode force 1 – 700 N

Ultrasonic microjoining

Microelectronic wire bonding used for semiconductor chip-level interconnections using wire diameters typically less than 25 μm

Fusion microwelding

Arc welding - an important joining process

Regulated and controllable outputs of less than 1 amp

Mainly GTA and Plasma welding

Peak pulse controls the penetration

background pulse allows solidification without extinguishing the arc

Power Beam Welding – Laser and electron beam

Very fine control over power and positioning

Focus a high energy beam onto a very small spot size

Deep penetration with little distortion

EBW - under a vacuum

LBW - inert gas atmosphere

Lasers - beam energy down to of the order of tens of microns

laser energy - pulsed to reduce thermal input and hence distortion

Laser and Plasma in Microjoining

✓ **Laser welding**

- ✓ Intense laser light rapidly heats the material-typically calculated in milli-seconds.
- ✓ a non-contact process, very little distortion of final joint geometry, narrow heat effected zone
- ✓ Precisely controlled intense heat source

➤ **Micro plasma arc welding**

- Low amperage capability
- Stable, concentrated arc at low amperes
- Gentle arc transfer (arc start) with no high frequency noise
- High energy density reduces heat affected zone
- Short weld times possible

Solid state bonding

- ✓ No melting of material
- ✓ Joints are made - plastic flow occurs at the interface; intimate contact and form a bond
- ✓ Microjoining processes - ultrasonic vibration or friction welding
Diffusion bonding - either in the liquid or solid phase

Friction Welding

- Heat generation by friction - applied pressure or extensive stirring of materials
- Suitable for wide range of materials including non-metals and dissimilar combination
- Geometry of components is symmetric in nature
- Preferably used to join components to heat sinks in the electronics industry

Example: aluminium heat sinks to alumina substrates

Most commonly used for attaching tubes or rods to bulk or sheet components

Solid state bonding

Micro friction stir welding (μ FSW)

- Down scaling of FSW with thicknesses of 1000 μm or less
- **Applications:** thin walled structures, electrical, electronic and micro-mechanical assemblies
- Advantageous over fusion welding
- Specifically useful for joining dissimilar materials

CNC programmable micro-milling machines

Challenges: Exit hole is left at the end of the weld

Scale sensitive and careful selection of tool design and fixture

Applications: Aluminium alloys, Brass, Pure copper, Aluminium to copper, Polypropylene, Polypropylene/polyethylene

Welding traverse speeds: 50 and 500 mm/min

Rotational speed: upto 3000 rpm

Weld joints in butt, lap and spot formats

Solid state bonding

Ultrasonic Bonding

- Displacing the interfacial oxides and contaminants and using pressure to form a bond
- Normally high frequency vibration with a low pressure to cause plastic flow
- Small rise in temperature
- ✓ It is commonly used for plastics, and especially for joining dissimilar materials
- ✓ Most significant process in the electronics industry
- ✓ Choice in cases of thermally sensitive materials
- ✓ Bonding force can be much lower compared to thermo-compression bonding
- ✓ Advantageous if materials are susceptible to deformation or cracking.

Solid state bonding

Diffusion Bonding

- ✓ Principle of solid-state diffusion - the atoms of two solid, metallic surfaces intermix themselves over time
- ✓ Diffusion is aided by intermediate heat ($0.5 - 0.7 T_m$) along with high pressure for a period of time
- ✓ Asperities on the two surfaces contact and plastically deform - they interlink, forming interfaces between the two surfaces
- ✓ Cause minimal distortion to components
- ✓ Prior to welding, these surfaces must be machined to as smooth a finish as economically viable, and kept as free from chemical contaminants as possible.

Solid state bonding

Diffusion Bonding

- Currently, this method is widely used in the joining of high-strength and refractory metals
- Also used to weld of alternating layers of thin metal foil, and metal wires or filaments
- Typical materials that are welded include titanium, beryllium, and zirconium in electronics, aerospace and nuclear industries

Fick's law of diffusion:

$$J = -D \frac{dC}{dx}$$

J - diffusion flux, D - diffusion coefficient, dC/dx - concentration gradient

Time dependent diffusional flux: $J = \frac{M}{At}$

M - mass or amount of atoms being diffused, A - cross sectional area, t - time

Solid state bonding

Diffusion Bonding

Normally, mass and area are constant for a joint, therefore

$$t = -\frac{1}{D} \left(\frac{M}{A} \right) \left(\frac{dC}{dx} \right)^{-1}$$

time required is largely dependent on the concentration gradient, and the diffusion coefficient

Diffusion coefficient: $D = D_0 \exp \left(\frac{Q_d}{RT} \right)$

Q_d - activation energy for diffusion, R - universal gas constant, T is the temperature of the process, and D_0 is a temperature-independent pre-exponential that depends on the materials being joined.

Soldering / Brazing

- ❑ A lower melting point material is drawn into the gap between the components by capillary action
- ❑ No melting of the components themselves
- ❑ Difference is defined by the melting point of the filler metal
- ❑ Brazing considered to be occurring at temperatures greater than 450°C
- ❑ Joints gain strength from the wetting of the parent metals by the molten solder or braze metal
- ❑ Any contamination would cause a reduction in wetting and consequent lowering of joint strength
- ❑ Also gap between parent materials influence joint strength

Soldering/Brazing

- ❑ Both similar or dissimilar materials can be joined by selection of proper filler alloy or by using coatings
- ❑ Soldering - primary joining processes for electronics and electrical industries, and used to produce printed circuit boards
- Traditionally solders containing lead have been used in various applications
- Concerns about toxicity and health hazards drives to develop lead free solders

Adhesive Bonding

- Rely on attractive forces between the molecules at the surface of the adhesive and those of the surfaces to be joined.
- The larger the molecules the better the adhesion, which is why organic adhesives are commonly used.
- The liquid adhesive is used to wet the surfaces to be bonded.
- This is then cured, or hardened, to form a solid bond.
- This curing can be aided by applying temperatures of approximately 150°C.



Adhesive Bonding

- Like brazing or soldering, the thickness of the adhesive should be minimal to provide a strong bond.
- Recent developments: doping the adhesive with metal (typically silver) it is possible to make them electrically or thermally conductive
- The development of thermally conductive adhesives has aided heat dissipation in electronic devices
- Electrically conductive adhesives are being considered as replacements for solders

Microelectronics wire bonding

- ✓ Joining between an integrated circuit or other semiconductor device
- ✓ Wire bonding is the most cost-effective and flexible interconnect technology
- ✓ If properly designed, wire bonding can be used at high frequency (order of GHz)

Principle of the joining: ultrasonic welding

Bond head oscillates at ultrasonic frequencies, scrubbing the two metals together and forming a weld

The bonders are capable of making a bond almost every **half-second**

Process description: Brings together the two materials - to be bonded using heat – pressure - ultrasonic energy

Referred as **thermosonic bonding**

Microelectronics wire bonding

Materials Aluminium, Copper, Silver, Gold

Size: 15 μm – 100 μm

Shifting from gold to copper

Copper

- It is harder than both gold and aluminium
- The formation of oxides is inherent with this material
- Special packaging is required in order to protect copper wire
- Palladium coated copper wire is a common alternative which has shown significant resistance to corrosion

Types of bonding

- ✓ Ball bonding
- ✓ Wedge bonding

Bonding tools

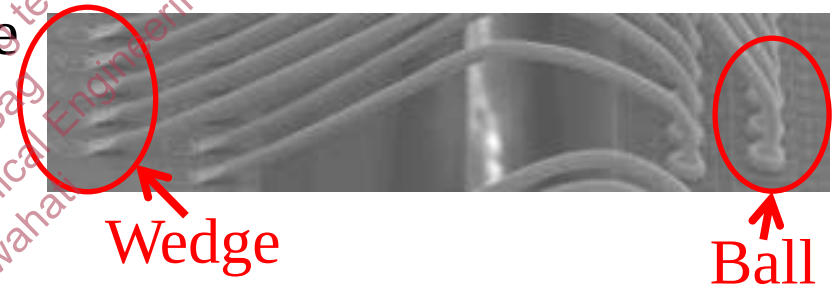
- ✓ Wedge bonding - using a wedge-shaped bonding tool
- ✓ Capillary is used for ball bonding. It can be made from ceramic

Microelectronics wire bonding

Ultrasonic wire bonding

Wedge bonding - performed using aluminium wire

- ✓ Wire is wedge bonded at one point using **ultrasonic energy**
- ✓ Drawn out in a loop then similarly wedge bonded at the other end
- ✓ Performed at ambient temperature
- ✓ Drawing - directional



Ball bonding - characterised as a thermosonic process i.e. heat ($\sim 150^{\circ}\text{C}$) is applied during the bonding process

- ✓ Ball bonding with gold wire is mostly used

Process: forming a small ball on the end of the wire

- ✓ Ball is bonded as the first joint, then the wire is drawn out in an arc before attaching this as a wedge bond
- ✓ Able to be drawn out in any direction

Microelectronics wire bonding

Preference of ball bond or wedge bond?

- ✓ Ball size is approximately 2 to 3 times the wire diameter
- ✓ A high-strength wedge bond is possible even the bond is only 2-3 mm wider than wire diameter
- Electrical characteristics of the package - affected by the method of wire bonding (temperature involvement)
- Low heat or no heat applications - use of aluminium wire instead of gold

Bonding using nano-particles

Nano-particles: 1 – 100 *nm*

- ✓ The surface energy of a substance is related to the strength of the forces between particles
- ✓ Diamond and iron with much stronger forces between their particles, have higher surface energies
- ✓ The properties of minute particles such as nanoparticles differ from larger ones because of their **high surface area to volume ratio**
- ✓ With a large surface area, surface effects like friction have a bigger impact
- ✓ A surface that appears smooth is actually quite rough at the atomic level
- ✓ Nano-sized particles come together - **the contact areas and stresses between them increase significantly**

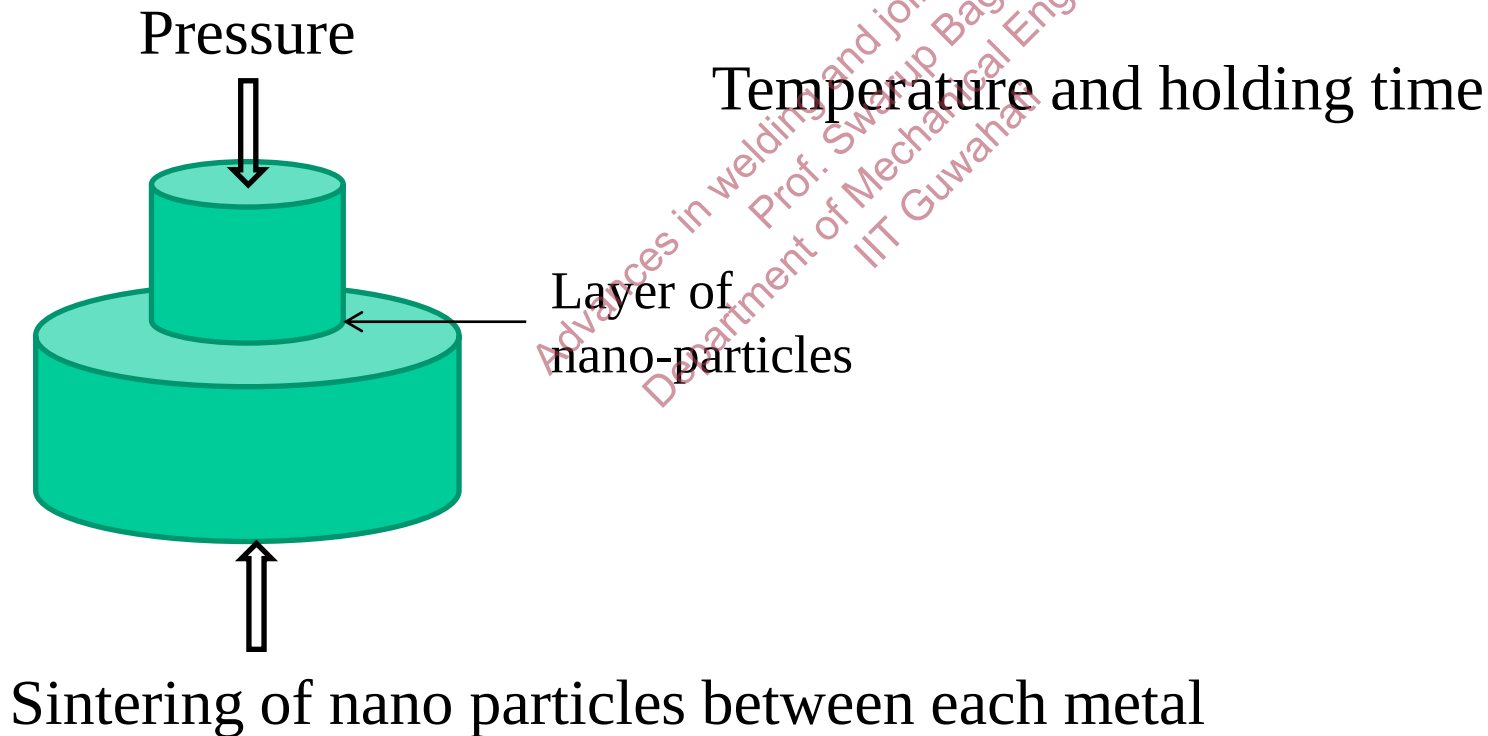
Bonding using nano-particles

- ❖ Metal nanoparticles have properties intermediate between those of metals and non-metals
- ❖ Nanoparticles have different optical properties and are **more sensitive to heat** than larger particles
- ❖ Large surface energy of the nanoparticles – affects the surface atoms of bulk metals
- ❖ A metal-to-metal bonding using nanoparticles as a filler materials
- ❖ May **achieved at significantly lower bonding temperature than fusion welding or diffusion bonding**

Bonding using nano-particles

Nanoparticles: Composite Ag consists of Ag metallo-organic nanoparticles and Ag_2CO_3 particles

Joining of various metals: Au, Ag, Cu, Ni, Ti and Al



Bonding using nano-particles

Decomposition of oxide films is needed to activate metallurgical bonding – between sintered Ag layer and each metal

Based on the shear strength of the joints, the order of bondability to each metal is as follows

$$Ag > Cu > Ni > Ti > Al$$

Identical to the order of free energy value of the oxide formation

In reduction reaction – mainly forms CO and CO₂

Joint strength of Cu, Ag and Au are relatively good

- the oxides are less stable and can be reduced by the organic shell

Joint strength of Al and Ti are extremely less

- the oxides are more stable than carbon oxides and can not be reduced easily

Thank you
for your kind attention

Advances in welding and joining technologies
Prof. Swarnop Bag
Department of Mechanical Engineering
IIT Guwahati

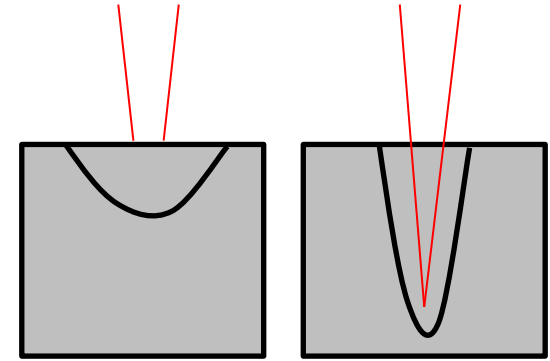
Laser microwelding

- ✓ Fusion micro joining - at least one dimension of the part being processed is **less than 100 μm** .
- ✓ **Non-contact nature and high intensity** resulting from the ability to focus it to a small diameter. This property of laser makes it a **very potent tool** for processing micro scale jobs.
- ✓ Lasers can be used very efficiently to process a variety of materials - **both metallic and non-metallic**
- ✓ The general configuration of laser micro welding is similar to the conventional process.
- ✓ **Pulse and continuous mode** of laser microwelding
- ✓ **Laser transmission welding** where a combination of a transparent material and an absorbing material is used to fuse the transparent material.

Physical Aspects of laser welding process

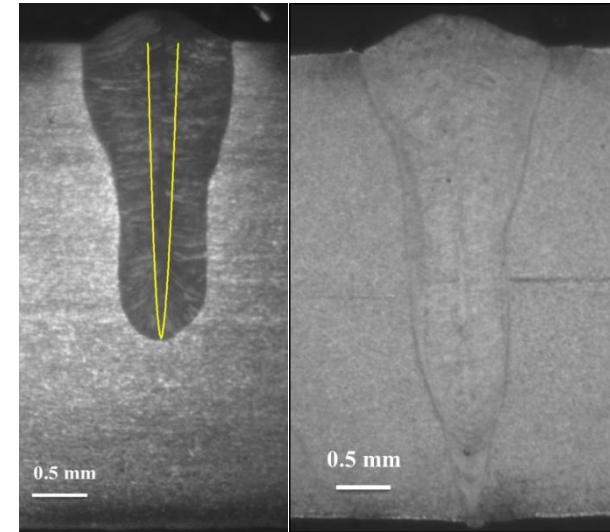
Conduction mode

- Power density less than 10^6 W/cm^2
- Laser power is transmitted usually through conduction to the surroundings.
- The penetration is controlled by the conduction only



Keyhole mode

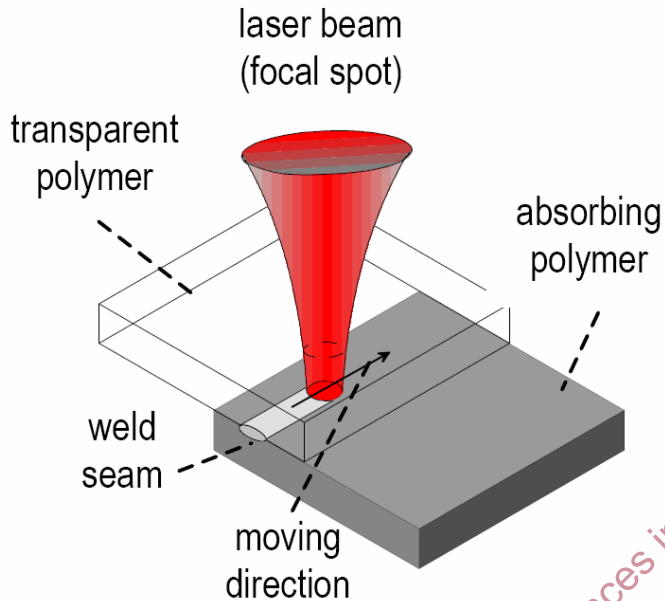
- Laser power density exceeding 10^6 W/cm^2
- Molten metal starts to vaporize
- opens up a blind hole (keyhole) in the molten metal
- Vapour pressure from the hot metal keeps the hole open during the weld
- Increase the energy efficiency of welding process due to multiple reflections of beam within cavity



Conduction mode is normally used for welding of foils and thin sheets whereas keyhole mode is used for much thicker sections

Types of laser microwelding

Laser Transmission welding



Ultra shot pulse laser welding

- pulse duration is order of femtoseconds to ten picoseconds
- the duration of laser pulse shorter than the time required for energy to be transferred to the surrounding area

Application of short pulsed laser

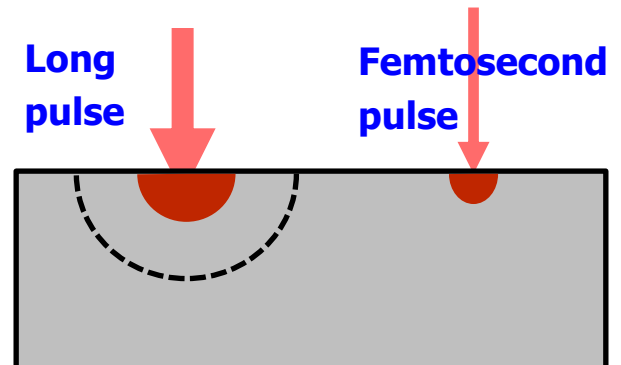
- Medical application - as replacement of mechanical drill in dentistry
- Pattern carving in wooden structure without leaving behind burn traces
- Laser micromachining and ablation
- In micro welding

Long pulse laser

- pulse duration is in nanosecond and greater than that

Application area

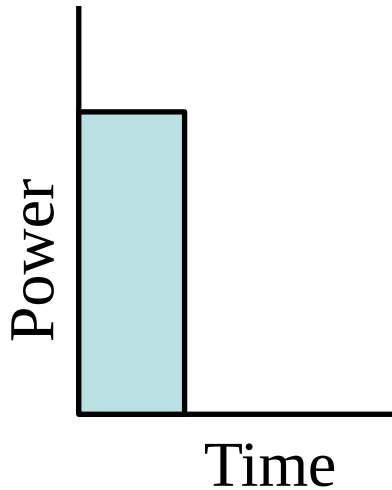
- Medical application like skin Treatment
- In macro welding
- Cutting of materials



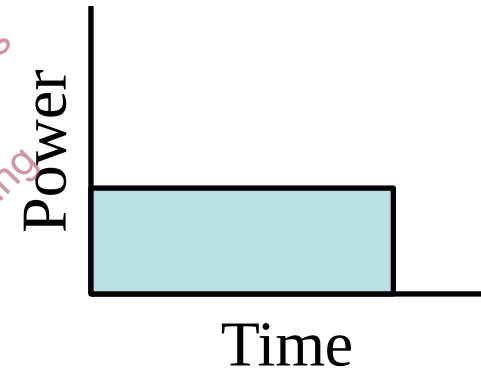
Pulse frequency – ablation to welding

Pulse shaping in laser microwelding

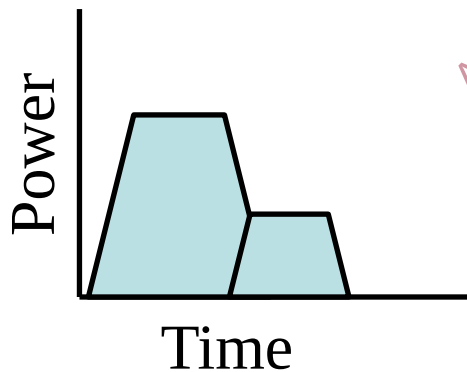
Area – pulse energy



Keyhole mode welding



Conduction mode welding



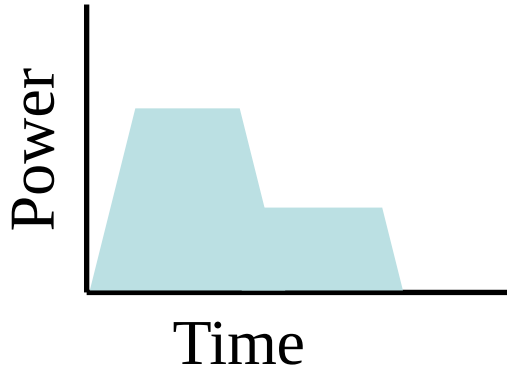
Pulse shaping

Peak power – depth of penetration
Pulse energy/time – weld volume
Frequency – overlap
Weld path – distortion

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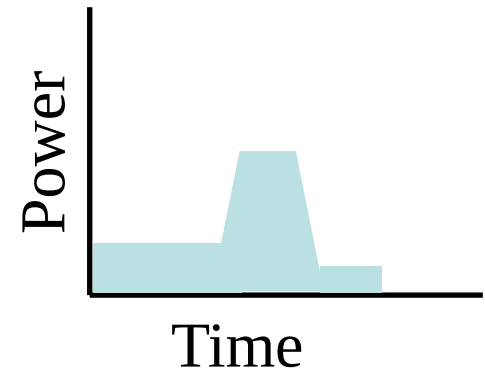
Pulse shaping in laser microwelding

Power is varied over pulse time



Crack sensitive materials

Upslope at beginning –
prevent thermal shock
Downslope at end –
controlled cooling

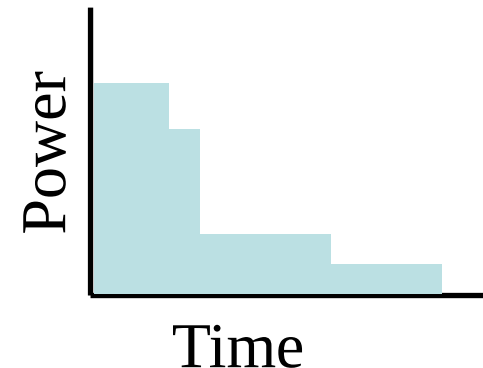


Large tolerance

Low peak power – melt first material and
then second material

Power reduced gradually – stable the melt
and cool down

High peak power – to start melting
Molten material – absorption rate increases
Reduce power – rapidly, not gradually

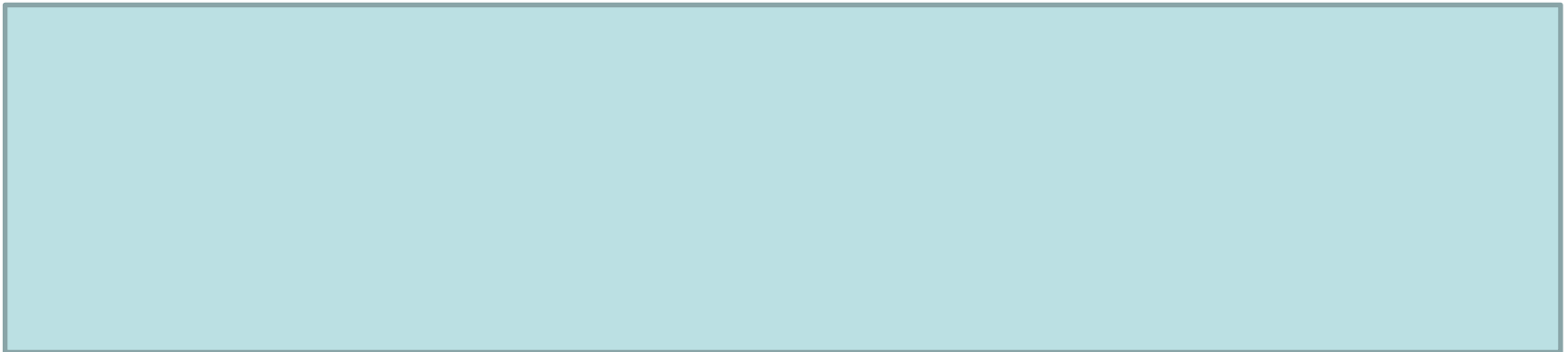


High reflective material

Process parameters in ultra-short pulse laser welding

Laser Transmission welding

- **Pulse energy:** energy delivered in a single pulse
- **Power density:** number of laser photons impinging on the material
- **Pulse duration:** the length of the time that the laser energy pulse is ON
- **Peak power:** Maximum power over pulse on time
- **Pulse frequency:** kHz - MHz
- **Focal Spot diameter:** diameter of spot which is focused on the object surface
- **Relaxation time:** time in which energy is stored in the electron, after the relaxation time it is converted into heat



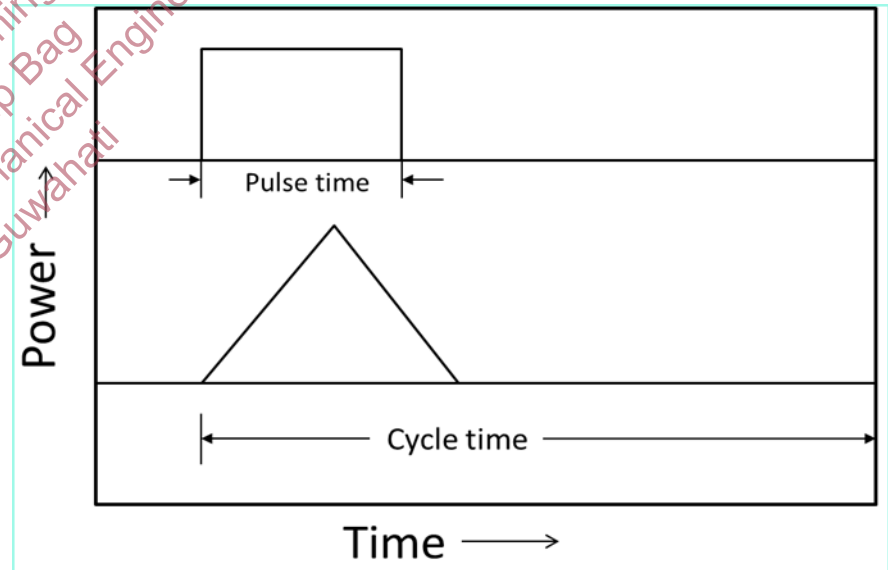
Pulse shaping in microwelding

Material: Borosilicate glass, Laser transmission welding

Laser: Yb-fiber laser, Ultra-shot laser pulses - 406 fs pulse length, 0.5 μJ pulse energy at 1 MHz pulse repetition rate

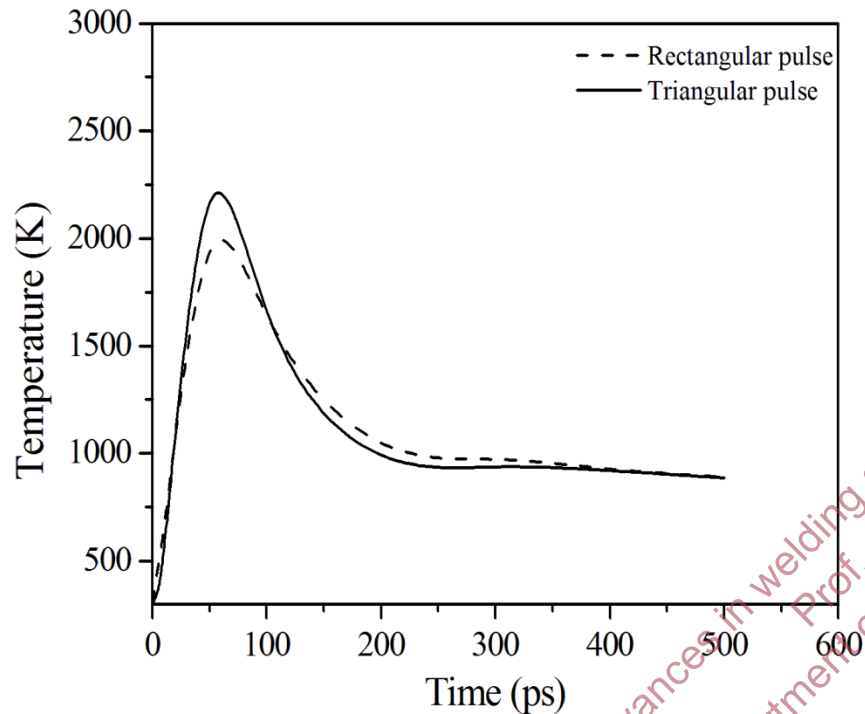
Laser scanning velocity: 1 to 10 mm/s

- ❑ The thermal wave speed of glass $\sim 0.9 \text{ m/s}$
- ❑ The relaxation time for glass is $\sim 3.7 \times 10^{-7} \text{ s}$ which is relatively more than the gold (in picosecond level).
- ❑ The laser pulse duration is comparable with thermal relaxation time
- ❑ There exists a thermal non-equilibrium state between electrons and metal lattice.



Pulse shaping

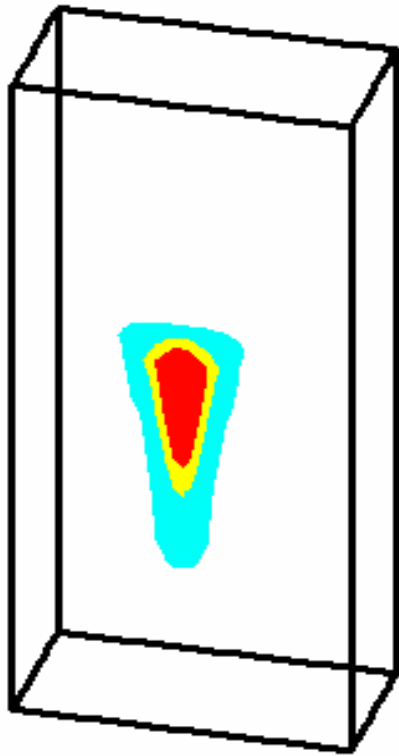
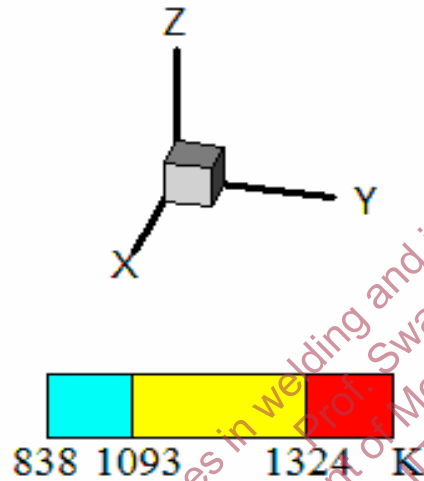
Pulse shaping in microwelding



- peak temperature is far away from the end of first pulse due to presence of thermal inertia
- there is clearly a time lag due to thermal relaxation in a hyperbolic nature of non-Fourier heat conduction
- temperature history differs for triangular and rectangular pulse shapes

time-temperature history of a 0.406 ps pulse length
ultra-short laser

Ultra- shot pulse laser welding



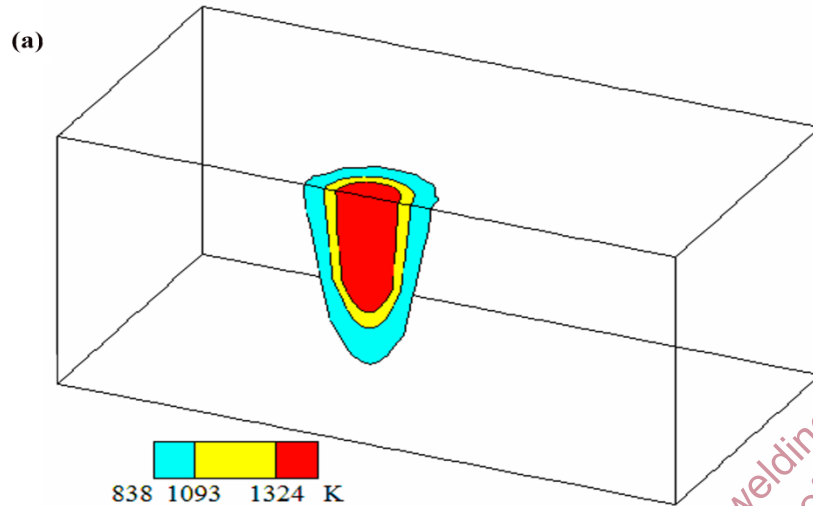
✓ heat is concentrated in a narrow zone and may result in high thermal stress over a small zone.

the thermal conductivity of glass is less as compared to metal and leads to the development of temperature over a narrow zone

rectangular pulse shape at scanning velocity of 1.0 mm/s

laser has been focused at a depth of 50 μm from the top surface

Ultra- shot pulse laser welding



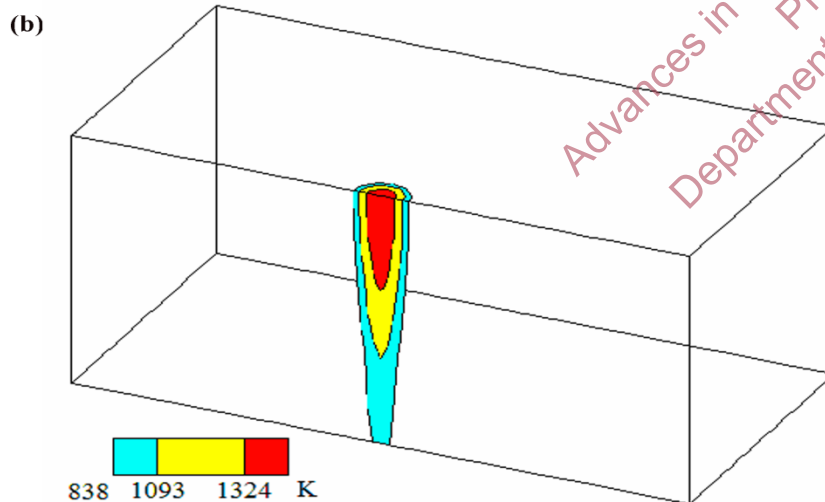
scanning speed of 1.0 mm/s
rectangular pulse shape

- ✓ triangular pulse may produce stiff temperature gradient over a small zone

When the molten zone cooled down and re-solidified, the contraction stress acted inside the molten zone and tensile stress act at the bottom section of narrower part.

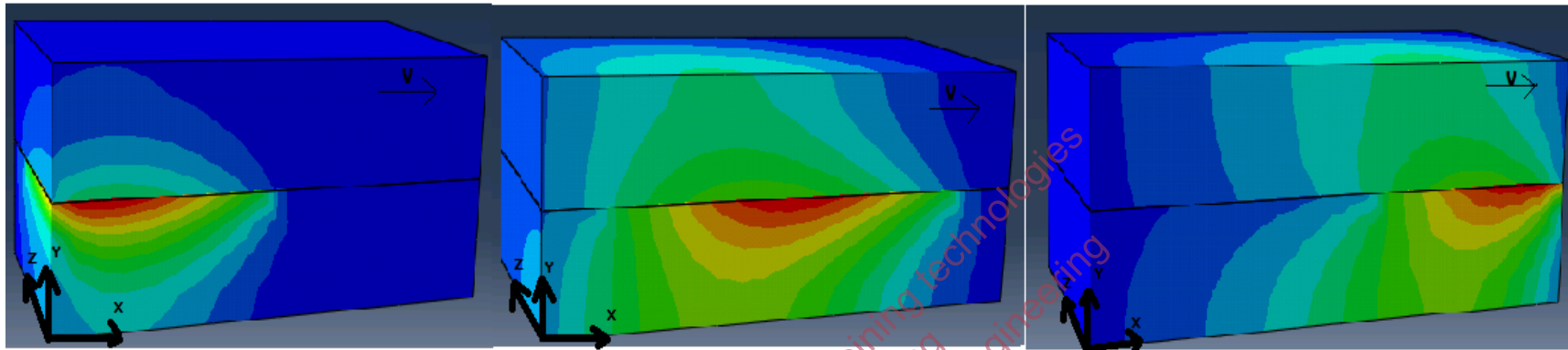
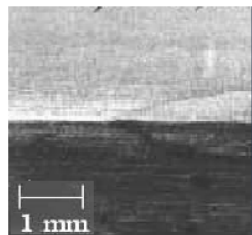
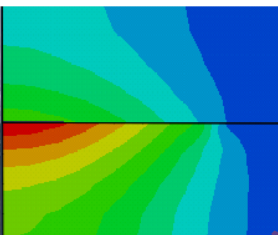
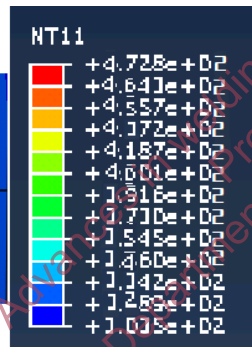
This stress concentration would lead to crack generation in the bottom side of the molten zone.

- ✓ The use of rectangular pulse may reduce the formation of crack.



scanning speed of 10 mm/s
triangular pulse shape

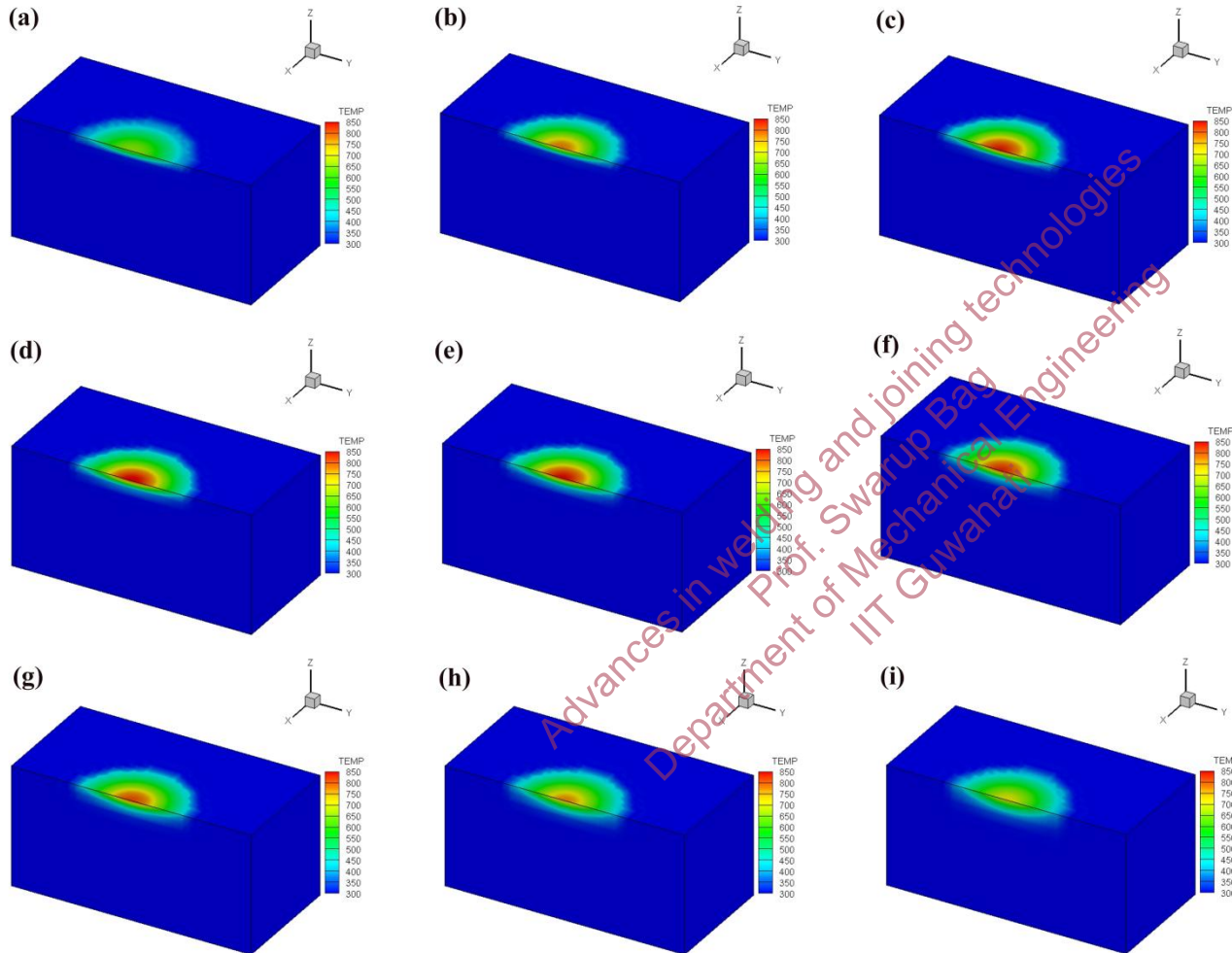
Laser Transmission welding



3D computed temperature distribution:
velocity of 2 mm/s and power density of
2.8 W/mm²

Material	Density (kg/m ³)	Thermal conductivity (W/m-K)	Specific Heat (J/kg-K)	Melting Point (K)
Polypropylene	920	0.16	80	438

Ultra-short pulse laser heating – Dual phase lag



100 nm – thick gold plate

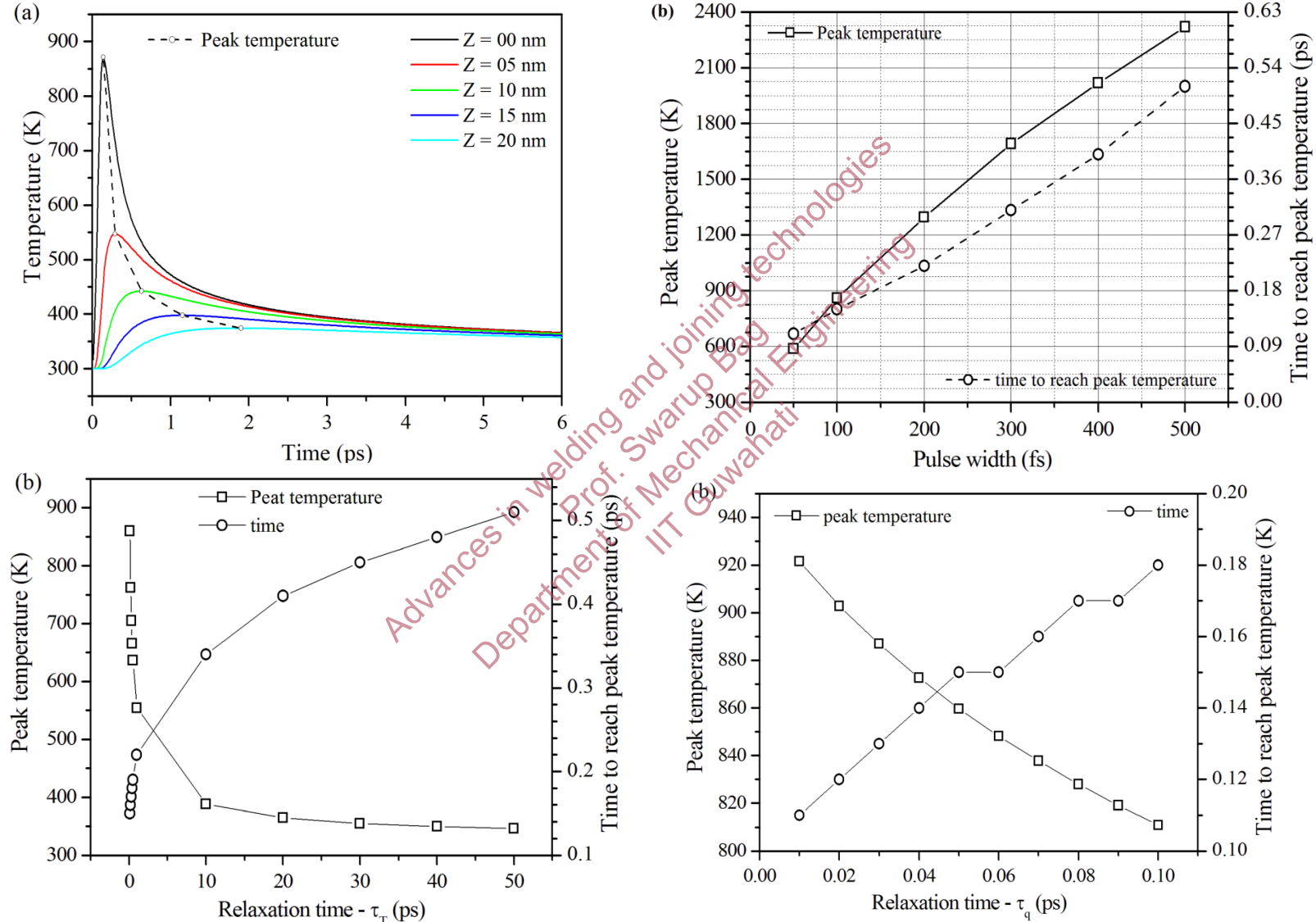
100 fs - pulse width

2.66 kW - peak power

76 - MHz pulse repetition rate

Ref. S. Kumar, S. Bag and M. Baruah: Finite element model for femtosecond laser pulse heating using dual phase lag effect, Journal of Laser Applications, 28(3), 032008:1 - 14, 2016.

Ultra-short pulse laser heating – Dual phase lag



Ref. S. Kumar, S. Bag and M. Baruah: Finite element model for femtosecond laser pulse heating using dual phase lag effect, Journal of Laser Applications, 28(3), 032008:1 - 14, 2016.

Applications of laser microjoining

Metals

Laser conditions								Object material			
Type	Mean power (W)	Pulse energy (J)	Pulse length (ms)	Pulse frequency (Hz)	Spot size (μm)	Power density (W/cm ²)	Speed (mm/s)	Type of joint	Material	Thickness (μm)	Weld dimensions (μm)
Pulsed Nd:YAG	125	~ 17	0.1-20	1000	60	-	8.3 – 38.3	Bead-on-plate	SS304	500 - 2000	-
CW fiber	100	-	-	-	30	100x10 ⁶	30 - 800		SS304	50 - 500	
	200					833 - 3333	SS304		150 - 500		
						500 - 2667	Aluminium		150 - 300		
						167 - 833	Copper		110 - 150		
Pulsed Nd:YAG	-	1 – 2.25	4	39	200	8.75	lap	AISI 316L	100x100	480-750 (W) 100-240 (D)	
Pulsed Nd:YAG	102	-	-	20	80	~ 2x10 ⁶	1.6	Bead-on-plate	AlMg3	200	150-350 (W) 230-460 (D)
Direct diode	50	-	-	-	300 X 1800	~ 9.2x10 ³	100-125	butt	SUS304H	50	-
	100					~ 19x10 ³	250-300			50	
	100					~ 57x10 ³	50-100			100	
	300					~ 57x10 ³	225-350			100	
Pulsed fiber	40 - 100	-	2 - 4	200	25	-	4	Bead-on-plate	SS304	260	65- 430 (D) 60-250 (W)
	80	-	4	200	-	-	4	lap	Titanium	260x260	300 (W) 350 (D)

Applications of laser microjoining

Non-Metals

Laser condition				Object material	
Pulse duration (fs)	Wavelength (nm)	Spot diameter (μm)	Speed (mm/s)	Materials	Thickness (μm)
350	1045	4	0.5 – 2.0	Borosilicate glass (D263)	200 X 1000
947	1558	-	0.1/0.2	Non-alkali glass	200 X 200
			0.2	Non-alkali glass and silicon	
4 – 6	355	-	-	Pyrex glass and silicon	500 X 500
-	1064	3000	-	PE film and black PE sheets	50 X 6000

Laser Transmission welding
Nanosecond Nd:YAG laser
Femtosecond fiber laser

PE: Polyethylene

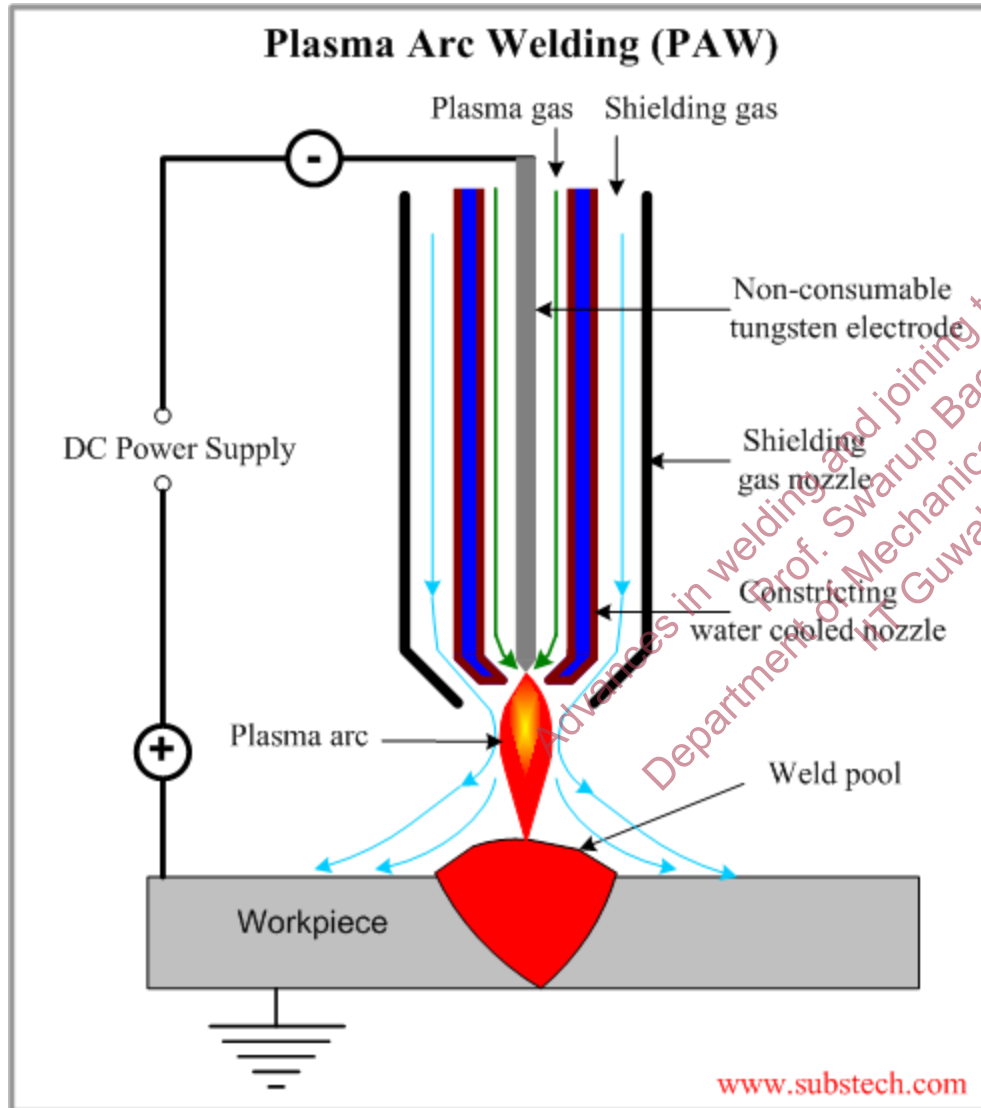
Applications of laser microjoining **Dissimilar materials**

Laser condition				Object material	
Type	Average output Power (W)	Spot diameter (μm)	Speed (mm/s)	Materials	Weld dimensions (μm)
CW diode	2.2	800	~ 1.67	PI/Ti	200 – 300 (W)
	3.8		~ 21.67		
CW fiber	1.0	300	~ 1.67	PI/BSG coated with 0.2 mm thick Ti	-
CW fiber	1.0	200	~ 1.67	PI/Ti	-
				PI/BSG coated with 0.2 mm thick Ti	~ 330 (W)
CW fiber	2.2	300	2 ~ 16	PI/Ti	-
	3.8		10 ~ 33		-

PI: Polyamide

BSG: Borosilicate glass

Mechanism of plasma microwelding



Principle of Operation

Non-transferred arc process

Transferred arc process

PAW is used in three modes

- Micro-plasma (< 15 Amperes)
- Melt-in mode (15–400 Amperes)
- Keyhole mode (>100 Amperes)

Types of Metals Welded

practically all commercially available metals

Invented by Robert M. Gage in 1953 and patented in 1957.

Equipment for MPAW

Power Supply: DC power source – open circuit voltage of 70 volts or above

Plasma Torch: Either transferred arc or non transferred arc type Torch is water cooled to increase the life of the nozzle and the electrode.

High frequency generator and current limiting resistors are used for arc ignition.

Arc starting system may be separate or built in the system.

Electrode

Tungsten–2% thoriated carbon and the plasma nozzle is copper

Shielding gases

Two inert gases or gas mixtures are employed

Process parameters of MPAW

Gases At least two separate (and possibly three) flows of gas are used in PAW:

- Plasma gas – flows through the orifice and becomes ionized.
- Shielding gas – flows through the outer nozzle and shields the molten weld from the atmosphere

Gas flow rate: 4 – 6 lpm

Current Type and Polarity: DCEN is standard

AC square-wave is common on aluminum and magnesium

Welding current: Current can be constant or pulsed at frequencies up to 20 kHz

Welding speed: Increase in welding speed decreases the width of weld and depth of penetration.

Nozzle diameter: A focused beam leads to better penetration.

Electrode diameter: 1 mm

Pulsed Current plasma arc welding

Pulse Shaping : The use of pulse shaping can enhance welding. Most welding cases use a square welding pulse.

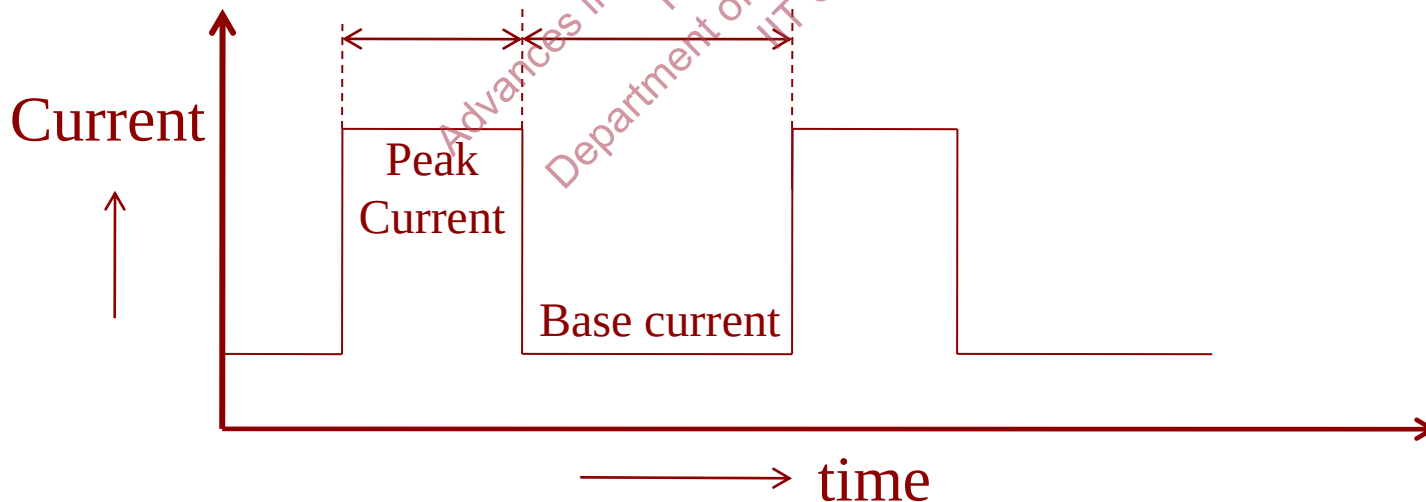
Peak power : This is a direct parameter that can be selected on the laser. It controls the maximum power of each pulse.

Pulse width : The pulse width is the duration of the laser pulse. The units are milli-seconds.

Pulse energy : The pulse energy is the energy contained within a pulse and is product of peak power and pulse width.

Average power : It represents the power averaged over the period of the pulse.

Pulse repetition rate : The pulse repetition rate equates to the number of flash lamp pulses per second and may be expressed in Hz



Characteristics of pulsed current MPAW

Electron beam microwelding

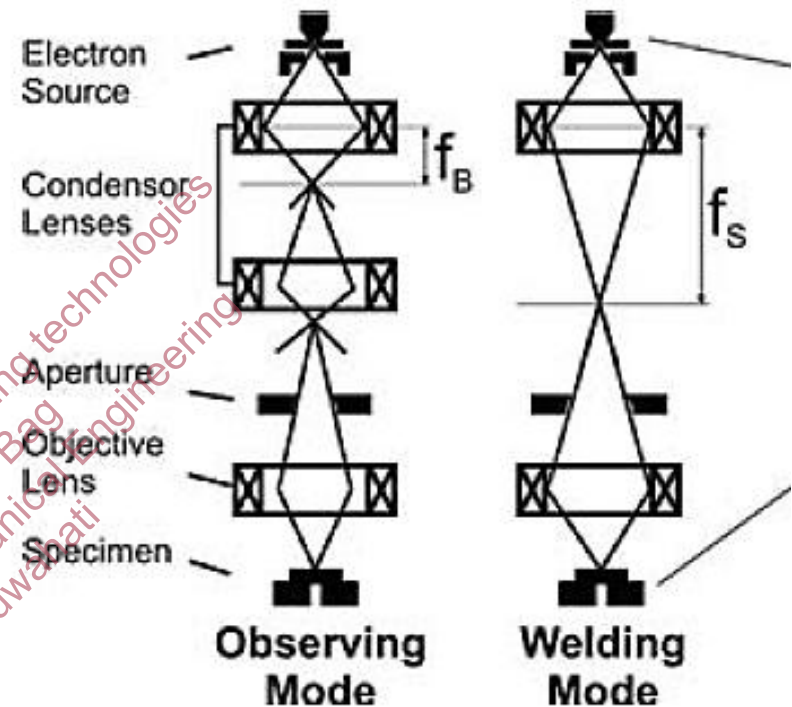
- ✓ Is almost always conducted under a vacuum, hence it provides probably the highest quality joints as compared to laser
- ✓ Beam power (100 W to 5 kW) is not suitable for welding of microscale components
- ✓ Simple modification of Scanning Electron Microscope (SEM) optics is suitable for microwelding
- ✓ Developed by Zeiss company having maximum power of 6 W

Electron beam microwelding

SEM principle

Analysis of substrate – **lowest possible energy input and high resolution**

- ✓ Multiple apertures for the screening of off-axis electrons
- ✓ Two condenser lens – for the reduction of excess electrons
- ✓ Creates low power beam with extremely small focused spot on the sample surface



Ref: G. Smolka et al.: Micro electron beam welding and laser machining – potentials of beam welding methods in the micro-system technology, *Microsystem Technologies* 10 (2004) 187–192

Microwelding mode

Removal of the apertures and one condenser lens

Apertures – reduce the effective beam-power

Modification is reversible – may be used as both an observation tool and as a welding tool

- ✓ Joining of thermoelements made of NiCr/Ni wire combinations with a wire diameter of 70 μm each allows almost globular beads for temperature measurement in the micro range.
- ✓ By means of materials with favourable heat-conductive properties, such as copper or aluminium, micro soldering with the electron beam as the heat source is examined using Cu-Sn soldering.
- ✓ Welding of LIGA (nearly pure nickel) gear to tool steel gage pin

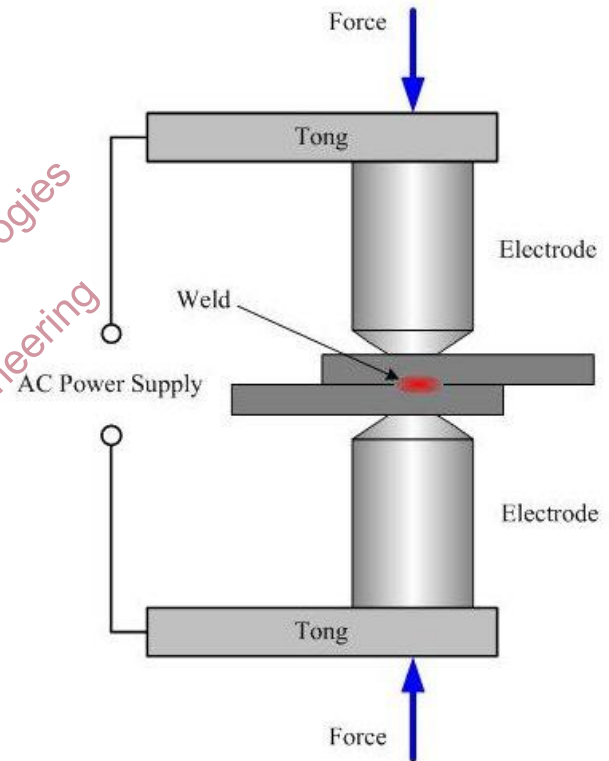
Resistance microwelding

Heat generated by the electrical resistance of substrates to the passage of electric current

Mainly used in fabrication of electronic components

Heat generation
 $H = I^2 R t$

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Resistance R includes all electrodes and sheets and contact surfaces

Resistance microwelding

Difference from large scale welding

The electrode pressure is much lower in microwelding

Much lower electrode pressure result in higher contact resistance

- reduces welding current
- promotes electrode sticking

The maximum nugget diameter is about 33 % of electrode diameter

Chances of electrode sticking is more in microwelding mode since electrodes are not water cooled

Mostly used for non-ferrous metals and alloys such as copper, nickel, platinum, aluminum

For regular welding – mostly steels

Sheets for microwelding – often coated with Au, Ag, Ni, Sn etc

For regular – usually uncoated or coated with Zn

Microwelding of plastics

Practical importance in medical and electronic devices

Where complexity in structure exists

Manufacture of polymer component – few microns in size is possible

Joint of $\sim 100 \mu\text{m}$ wide is often required

Hermetic seal is often required - use either adhesive bonding or welding

Adhesive – no heating is required but curing time may be significant

Welding – small HAZ to reduce distortion and affecting coating or surrounding equipment

Microwelding of plastics

Heat generation

From mechanical motion

- spin welding - vibration welding - ultrasonic welding - friction stir welding

From external heat source

- hot plate welding - hot bar welding - impulse welding - hot gas welding - extrusion welding

Electromagnetism

- resistive implant welding - induction welding - dielectric welding - microwave welding - infra-red welding - laser welding

Thank you
for your kind attention

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Microjoining of medical components and devices

Medical devices made from a wide range of materials:

- ensure that they are safe to be implanted
- biocompatibility and extreme reliability for human body
- outer case hermetically sealed enclosure and long-term corrosion resistance

Medical metals: titanium, shape memory alloys, platinum (Pt) alloys, stainless steel (316L), and plastics

Welding techniques: Resistance welding, Ultrasonic welding, transmission laser welding and radio frequency (RF)/dielectric welding (spot and seam welding).

- ✓ metal-ceramic joining techniques for orthopaedic applications and tissue adhesives and sealants for surgical applications.

Challenges and issues in selecting materials

- electrical and biocompatibility performance
- corrosion resistance
- surface quality
- microscale weldability
- weldability of dissimilar combination of materials

Materials and joining methods

Platinum/Tantalum/Titanium – Resistance, laser, ultrasonic

Kovar alloy/Stainless steel – Resistance, laser, brazing

Lead free solders – Brazing, soldering, ultrasonic

Polyurethane – laser, adhesive

Silicone - adhesives

Microjoining of medical components and devices

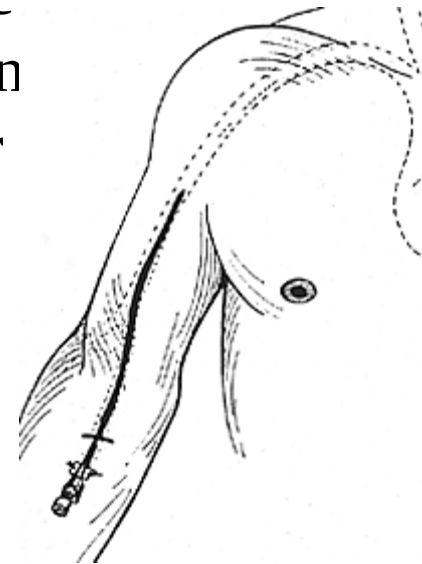
Vascular devices: Catheters and guidewires to balloon angioplasty and stents

Different shape, size and functionalities

Catheter is a thin tube made from medical grade materials that can be inserted in the body – generally single-use device

Guidewire for catheter application: some part of the wire

- Joining small diameter wire in butt weld configuration
- mostly joining of 316L SS wire to nitinol end effector (some part)
- SS316L provides good torque transmission and low cost
- Alignment of the diameters and control in weld zone is difficult



Balloon catheters – joining of polymer balloon to polymer tube on guideways

- direct laser welding or adhesive bonding

Microjoining of medical components and devices

Stent (permanent implants) – typically laser cut from tube and welded on small wire

- is collapsed and delivered in precise location
- challenges of excellent surface and edge finish, control of HAZ and extreme control on orientation and laser cutting path

Pumps and sensors – Several types of internal and external pumps are used

Example: Insulin pump and left ventricular assist devices

Challenges: Welding and joining of plastic foils

Bonding fragile semiconductor layers to each other

Microscopic circuit assembly

Wire or tube attachment for interconnects

Microjoining of medical components and devices

Pacemaker manufacturing

- Mainly a pulse generator and leads

Pulse generators consists of

- Battery – to generate electricity
- Circuitry – to generate, control and deliver the pulses

Battery - is hermetically laser sealed to prevent leakage of chemicals

Battery and circuitry – are inside a titanium case that is hermetically laser sealed

Internal circuits – connected through brazed joint

Connector block - encapsulated in a biocompatible polymer such as polyurethane – interconnected by Ti wires using laser and resistance microwelds

Microjoining of medical components and devices

Radioactive seed implants

- internal radiation therapy has been developed as an alternative to external beam irradiation for cancer treatments
 - Use a radioactive substances sealed in seed that are implanted near the cancer
 - The cancer cell is destroyed by the energy given off as radioactive material decays

Radioactive substances – sealed inside Ti tube by laser microwelding

Laser microwelding – developed and suitable for precision manufacturing

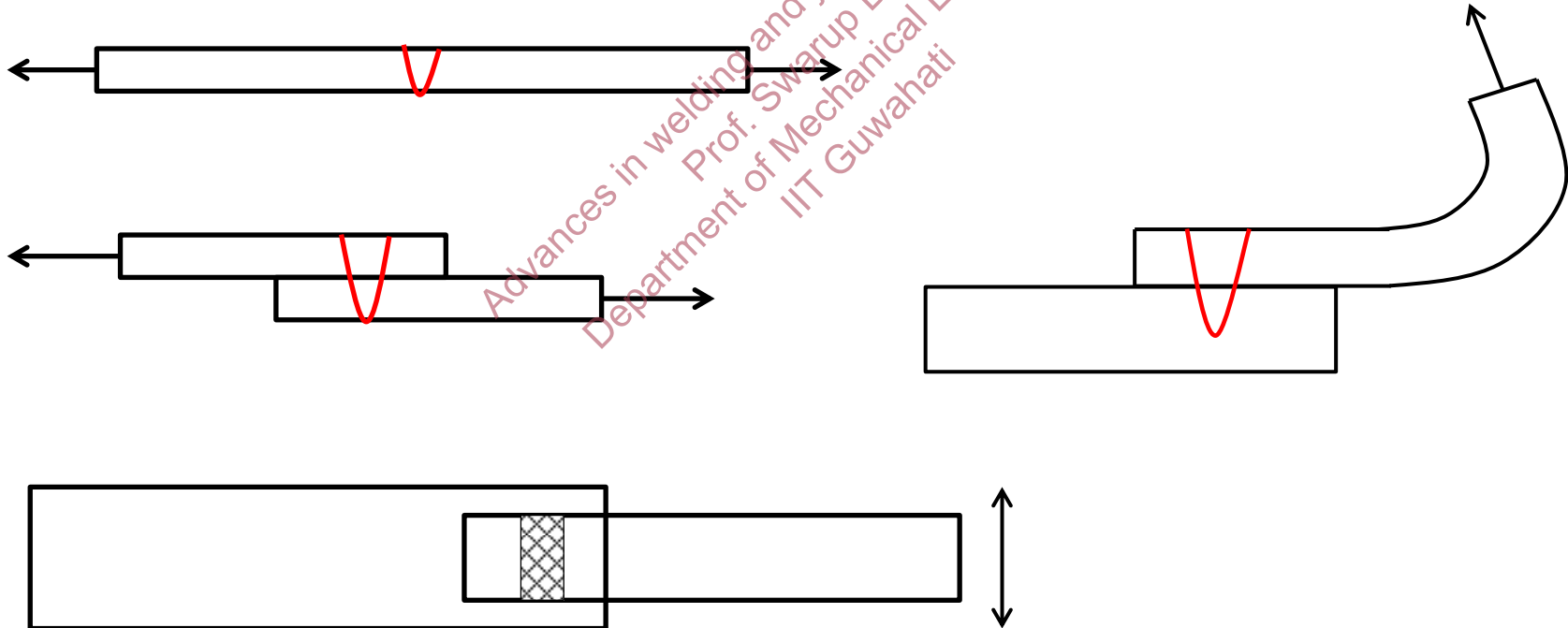
Microjoining of medical components and devices

Mechanical Testing of Welded Joints

Small scale tensile testing equipment

Butt joint – tensile load

Lap weld – shear load/peel test/torque



Advances in laser microwelding

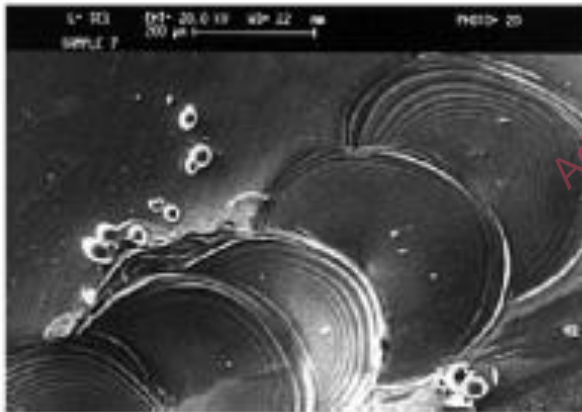
SHADOW – **S**tepless **H**igh-Speed **A**ccurate and **D**iscrete **O**ne-Pulse **W**elding

Transforms macro laser spot welder to micro laser seam welder

Maximum pulse length – diode pumped laser typically used

SHADOW

- **welding of watch components**
- **normally used for metals and alloys**



Pulse Mode

$P_H = 300 \text{ W}$, $Q_{\text{tot}} = 27 \text{ J}$

$\tau_H = 5 \text{ ms}$, $f_p = 25 \text{ Hz}$

$v_f = 300 \text{ mm/min}$



SHADOW

$Q = 9 \text{ J}$, Pulse Shaped

$\tau_H = 20 \text{ ms}$

$v_f = 30 \text{ m/min}$

Ref: A M Olowinsky, K Klages, J Gedick: SHADOW a new welding technique: basics and applications, Proc. SPIE, 5662, 191-299, 2004.

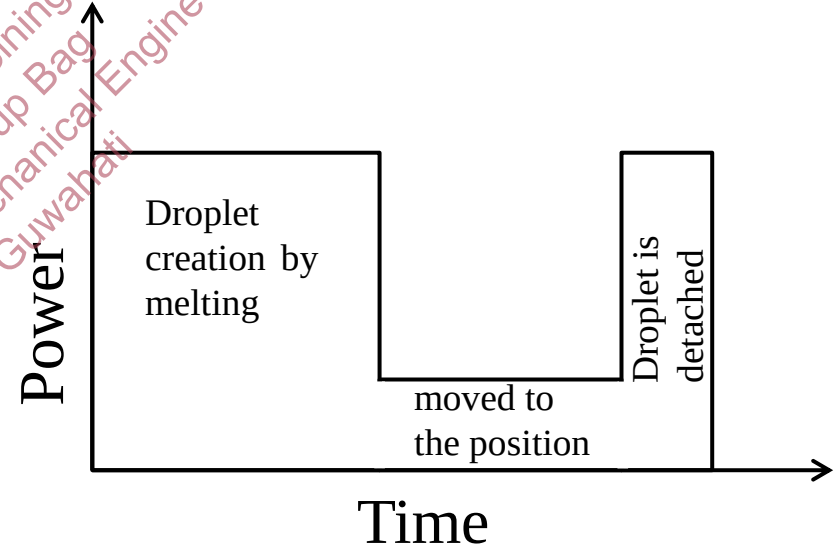
Advances in laser microwelding

Laser droplet welding

- Overcome gap bridging, highly reflective materials and heat sensitive materials
- Liquid metal droplet is created at the end of a wire by pulsed laser
- Pulse laser with triple optical beam splitting (normally Nd:YAG laser)
- A wire feed system
- A target positioning system
- Shielding gas supply
- Mechanical positioning system

Five phases

- droplet creation
- droplet detachment
- Droplet flight
- Droplet landing
- Droplet solidification



Ref: B Jahrsdoerfer, G Esser, M Geiger, E Govekar: Laser droplet weld – an innovative joining technology opens new application possibilities, SPIE, 4977, 518 – 529, 2003.

Application: Stainless steel, Titanium and stainless steel of 200 μm thick and 200 μm gap

Advances in laser microwelding

Laser spike welding

- Gaps in microwelding is problematic
- Able to join even there is gap

Principle: Recoil-pressure driven material flow to bridge gaps in lap joint by spot welding

Process:

- Melting using low power in the upper layer (conduction mode)
- Allow sufficiently large or completely penetrated weld
- Increase the laser power to generate sufficient recoil pressure
- The diaphragm-like liquid pool contact with lower layer
- Adherence via either superficial surface melting or a braze like adhesion

Lower surface clean – braze like adhesion

Lower layer is too conductive – difficult to join

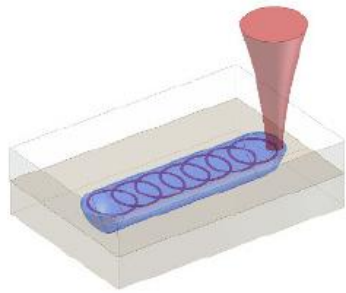
Application: Stainless steel of 250 μm thick

Ref: D K Dijken, W Hoving, J T M De Hossen: Laser penetration spike welding: A microlaser welding technique enabling novel product designs and constructions, Journal of Laser Applications, 15, 11-18, 2003.

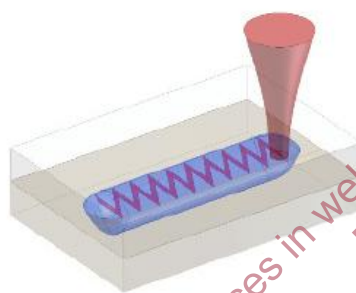
Advances in laser microwelding

TWIST – **T**ransmission **W**elding by an **I**ncremental **S**canning **T**echnique

- ✓ High beam quality laser like fiber laser – easy degradation of thermoplastic materials
- ✓ Fast rotating and slow linear motion of focused high-quality laser beam



a)



b)

- Local and temporal laser beam modulation strategy

- Dynamic periodic beam deflection is applied to control fusion and solidification

- The voids and porosity can be reduced and formation of sharp weld seam are avoided

Ref: A Boglea, A Olowinsky and A Gillner: Extending the limits of laser polymer welding using advanced irradiation strategies, JLMN-Journal of Laser Micro/Nanoengineering, 5 (2), 138-144, 2010.

TWIST

– welding of transparent polymers without any absorbing additives

Development of nanojoining technologies

**Electron beam welding, Diffusion bonding,
Ultrasonic welding , Cold welding**

Liquid-phase reflow soldering, Resistance
soldering, Active brazing, Laser brazing

Laser beam welding, Resistance welding

Adhesive bonding

Solid state nanobonding

Diffusion nanobonding using metallic nanoparticles

- ✓ Nanoparticles are sintered to form networks and these networks are joined to substrates – by diffusion with driving force to reduce surface areas
- ✓ With reduction in size of nanoparticles diffusion is enhanced because of lower activation energy and increase of specific surface energy – **results in decreasing of sintering and bonding temperature**
- ✓ This is significant in development of low temperature joining processes for polymeric based microelectronics applications

Ref: Y. Zhou and A. Hu, From Microjoining to Nanojoining, The Open Surface Science Journal, 2011, 3, 32-41.

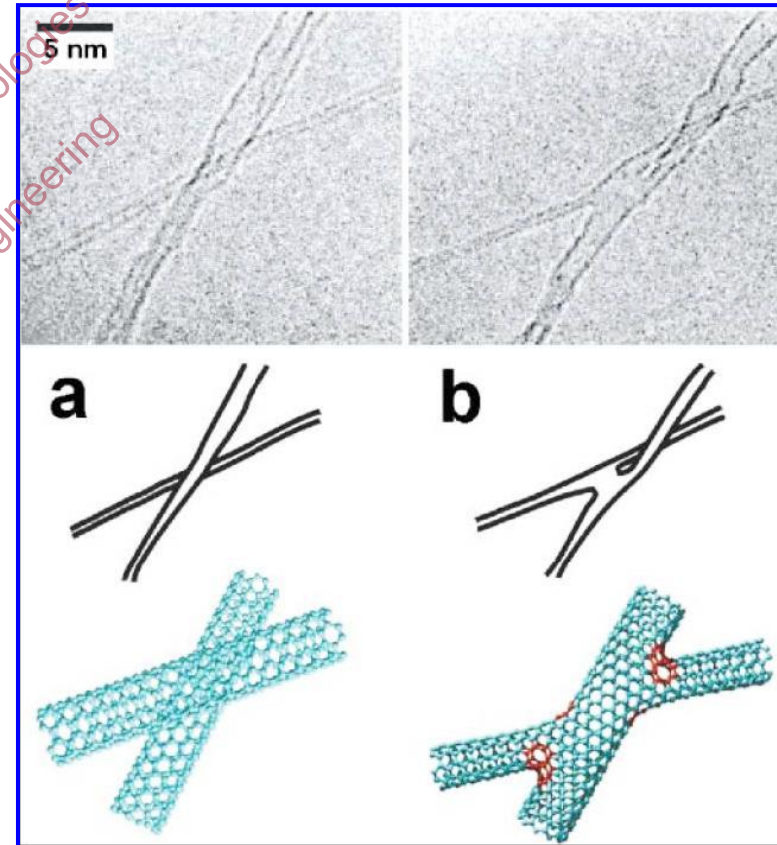
Solid state nanobonding

Direct joining of carbon nanotubes (CNTs) using a focused electron beam

- A.** A single wall CNT of ~ 2 nm in diameter crossing with another single wall CNT of ~ 0.9 nm in diameter
- B.** 60 sec of electron irradiation promotes a molecular connections between two tubes forming an junction

The electron beam is directed to induce structural defect “vacancies” or “interstitials” at the crossing point of CNT

Self arrangement of carbon atoms occurs at high specimen temperature



Ref: Y. Zhou and A. Hu, From Microjoining to Nanojoining, The Open Surface Science Journal, 2011, 3, 32-41.

Nanosoldering and nanobrazing

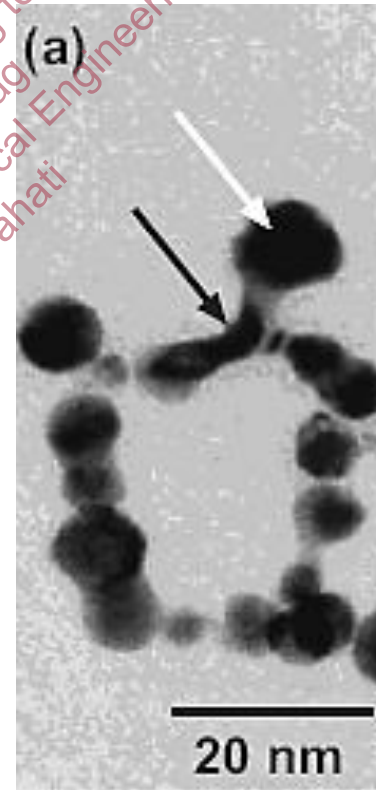
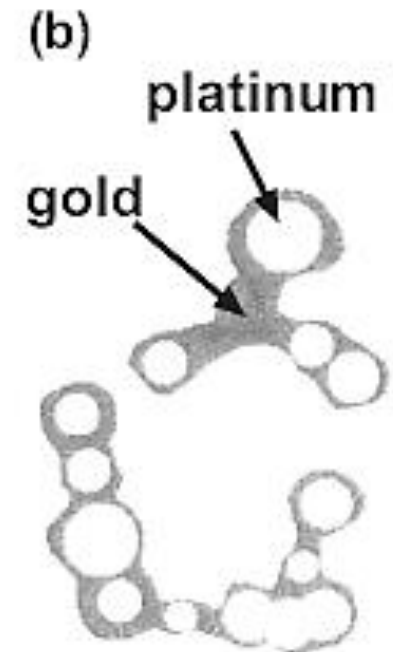
For a successful nanosoldering and nanobrazing a tiny amount of solder has to be precisely delivered to the bonding area

Is significant in the assembly and integration of nanoelectronics

Nanosecond pulse laser to melt Au nanoparticles to braze Pt nanoparticles

A. Electron micrograph of Pt and Au networks formed by laser brazing

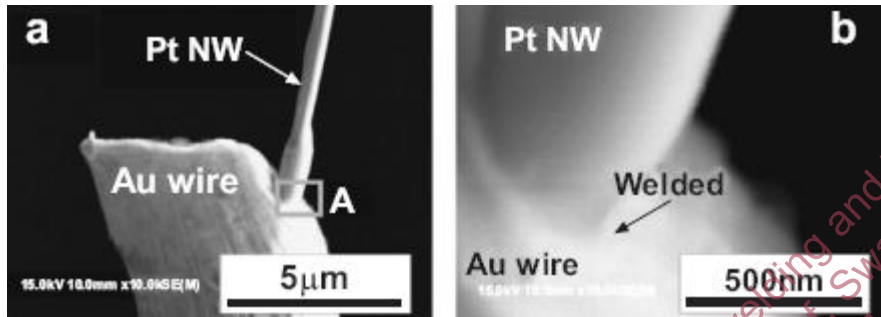
B. Schematic on how Pt nanoparticles were held together by molten Au



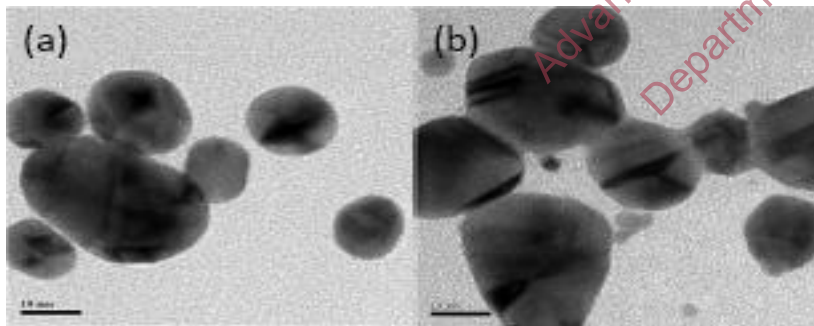
Fusion nanowelding

Heat sources – laser beam, Joule heating similar to resistance welding

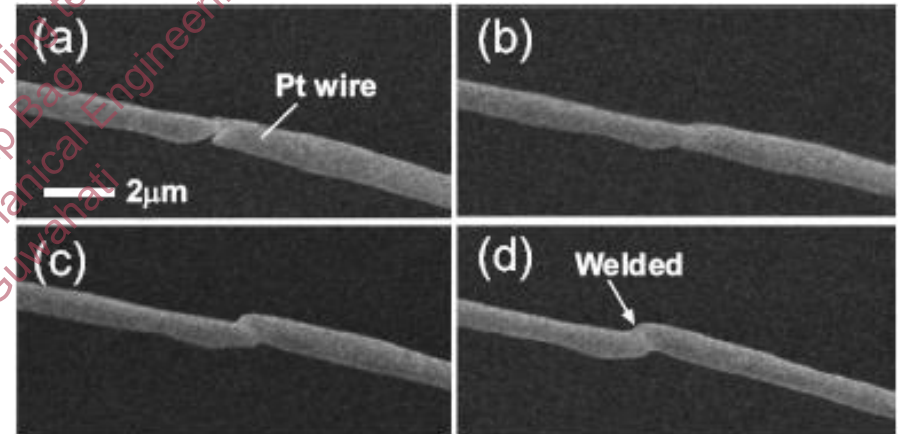
Welding of Pt nanowires - two nanowires are touched end-to-end by piezoelectric manipulation followed by a welding current



Resistance nanowelding: Pt nanowire to thin Au wire



Femtosecond laser nanowelding: Au particles with 100 fs laser pulses



SEM micrographs of welding of Pt nanowires: (a) before current supply, (b – d) the snapshots at 1 , 6, and 21 s after starting the current

Ref: Y. Zhou and A. Hu, From Microjoining to Nanojoining, The Open Surface Science Journal, 2011, 3, 32-41.

Current development in microjoining and nanojoining

- ✓ Very small possible focused beam as a form of spot or line welds of metals or non-metals are possible by laser microwelding
- ✓ High quality defect free joints are possible for highly conductive materials such as gold silver and copper in jewelry industry
- ✓ Microjoining technology is continually developing in some of the new fields like electronics, biomedical, instrumentation or sensor and packaging industry by taking the advantage of other scientific developments like robotics and automated systems.

Current development in microjoining and nanojoining

- ✓ The successful join dimension is of the order of $10\text{ }\mu\text{m}$ with a superior joint quality is achieved. Titanium, polyimide and glass and difficult to weld material such as aluminum alloys are successfully joined by laser microwelding process
- ✓ Various soldering processes and alloys widely used in microelectronics interconnections and packaging have been modified and further developed for the purpose of nanojoining
- ✓ Focused electron beam widely used in micro- and nano-joining are used in joining CNTs
- ✓ Focused ion beam which is relatively new energy source has been utilized of making nanojunctions between GaN nanowires

Future development and challenges

- ❖ exist future challenges in the current scenario of microjoining and nanojoining both for simulation tool as well as experimental characterization.
- ❖ improve understanding on underlying heat transfer mechanism in extremely short pulsed laser heat source
- ❖ there is a need for more modeling and experimental studies for proper identification of process parameters to avoid insufficient joint strength or damage of material
- ❖ real challenge lie in the metal to polymer joining in biomedical devices is due to wide difference of material properties and the nature of contact surface
- ❖ The geometric precision and cost of equipment is future challenge for mass production by microjoining and nanojoining processes

Examples: Microjoining and nanojoining

Q 5.1 In a pulse laser microwelding process, the following parameters are noted.

Laser scanning speed = 4 mm/s

Pulse energy = 6 J

Pulse width (on-time) = 5 ms

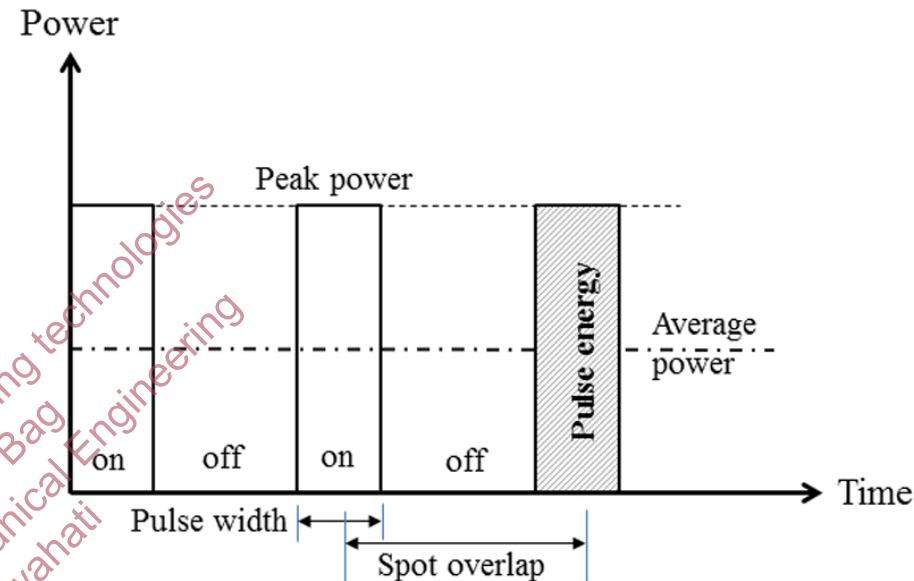
Pulse frequency = 20 Hz

Assume the shape of the pulse is square.

(a) What is peak power and average power?

(b) What is heat input per unit length?

(c) What is pulse off-time?



Examples: Microjoining and nanojoining

Q 5.2 In a diffusion bonding process, the mass concentration (kg/m^3) of carbon in parent material is 0.2 %. Over the time, t and a fixed pressure, the mass concentration of carbon increases to 1.0 % and measured at 0.2 mm depth of the sample. Assume that the process is carried out at 800°C . The activation energy for diffusion is 157 kJ/mol and D_0 for carbon in iron $0.7 \times 10^{-4} \text{ m}^2/\text{s}$.

(a) Estimate the time requirement (t) to reach such diffusion of carbon at a volume normal the depth direction. (b) What is the value of diffusion coefficient?

$$\begin{aligned} D &= D_0 e^{-Q/RT} \\ &= 0.7 \times 10^{-4} e^{-157 \times 10^3 / (8.314 \times 1073)} \\ &= 1.6 \times 10^{-12} \text{ m}^2/\text{s} \end{aligned}$$

A = cross-sectional area
 d = depth

$$\frac{dC}{dx} = \frac{(0.2 - 1)\rho \text{ kg/m}^3}{(0.2 - 0) \times 10^{-3} \text{ m}} = -4 \times 10^3 \times \rho \text{ kg/m}^4$$

Examples: Microjoining and nanojoining

Volume of diffusion bonding = $A \times d$

Mass $M = A \times d \times \rho$

$$M/A = d \times \rho$$

$$t = -\frac{1}{D} \left(\frac{M}{A} \right) \left(\frac{dC}{dx} \right)^{-1}$$

$$t = -\frac{1}{1.6 \times 10^{-12} \text{ m}^2/\text{s}} (0.2 \times 10^{-3} \text{ m} \times \rho \text{ kg}/\text{m}^3) \frac{1}{(-4 \times 10^3 \times \rho) \text{ kg}/\text{m}^4}$$

$$= 31.25 \times 10^3 \text{ s}$$

Examples: Microjoining and nanojoining

Q 5.3 In a laser welding process, the average laser power is used as 100 W and it is focused on an circular area of diameter 200 μm .

What is the power density of focused laser?

$$d = 200 \mu\text{m} = 2 \times 10^{-4} \text{ m}$$

$$P = 100 \text{ W}$$

$$A = \frac{\pi}{4} d^2$$

$$\text{Power density } \frac{P}{A} = \frac{100}{\frac{\pi}{4}(2 \times 10^{-4})^2} = 31.83 \times 10^8 \frac{\text{W}}{\text{m}^2}$$

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Examples: Microjoining and nanojoining

Q 5.4 In a resistance microwelding process, the applied voltage is 2 V and overall contact resistance between butt joined sheets is $2 \times 10^{-4} \text{ ohm} - \text{cm}^2$.

What is the amount of generated heat per unit area during the process?

$$H = I^2 R t$$

$$V = IR$$

$$H = (V^2 / R) t$$

$$H / t = (V^2 / R)$$

$$H / t = (2^2 / 2 \times 10^{-4}) = 2 \times 10^4 \text{ W/cm}^2$$

**Thank you
for your kind attention**

End of Module 5

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