

Advances in Welding and Joining Technologies

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Module 7

Welding and Joining of Non-metals

- ✓ Plastic welding
- ✓ Ultra-short pulse laser welding
- ✓ Laser transmission welding
- ✓ Glass and ceramic welding
- ✓ Biocompatible plastic to metal welding

Principle of Plastic Welding

Plastics welding is the process of joining two pieces of **thermoplastics** at heated state and under a pressure as a result of **cross-linking of their polymer molecules**

- The work pieces are fused together **with or without filler material**
- Joint forms when the parts are cooled below the Glass Transition Temperature (for amorphous polymers) or below the melting temperature (for crystalline polymers)

Welding techniques for Polymeric materials

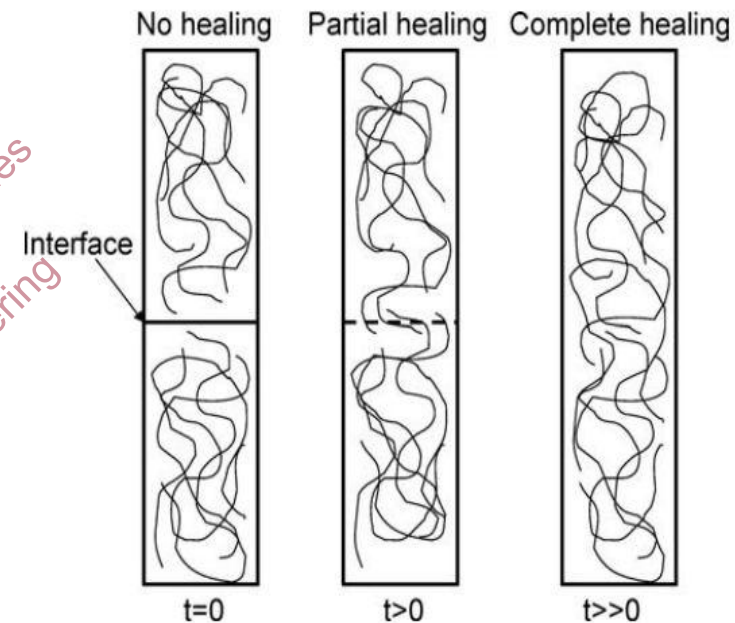
Interfaces will conform each other by intermolecular diffusion and chain entanglement and weld each other

- Healing of the interfaces is basically diffusion of polymer chains across the interface
- Pressure is required to improve melt flow across the interface
- Degree of welding (DW) – **material properties, temperature, interfacial pressure and time**

amorphous polymers – must be heated above glass transition temperature

Semi-crystalline polymers – above melting temperature

Thermosets cannot be welded without the addition of tie-layers such as thermoplastic layers



Types of Plastic welding

Different processes for welding of thermoplastics

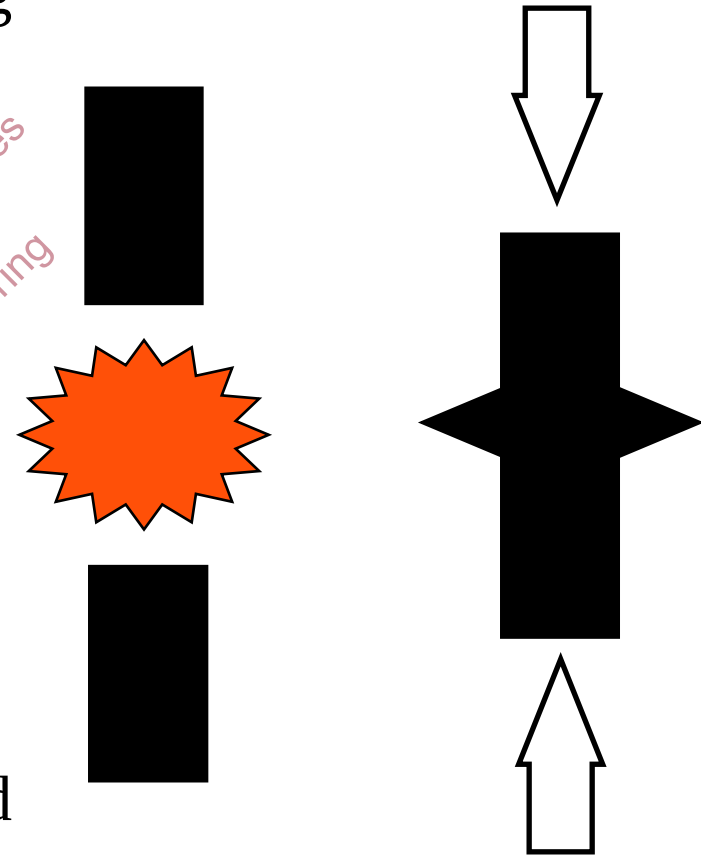
- ✓ Hot Gas Welding
- ✓ Hot Plate welding
- ✓ Ultrasonic welding
- ✓ Spin welding
- ✓ Vibration welding
- ✓ Friction stir welding
- ✓ Radio frequency welding

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Hot Gas Welding

Hot Gas Welding is a plastics welding process, utilizing heat of hot gas stream.

- ✓ Thermoplastics
 - Adhesive is heated until it softens, then hardens on cooling
- ✓ Hot gas softens filler and base material
- ✓ Filler is pulled or fed into the joint
- ✓ The polymer molecules are cross-linked when the work pieces cool down, forming a strong joint.



Hot Gas Welding

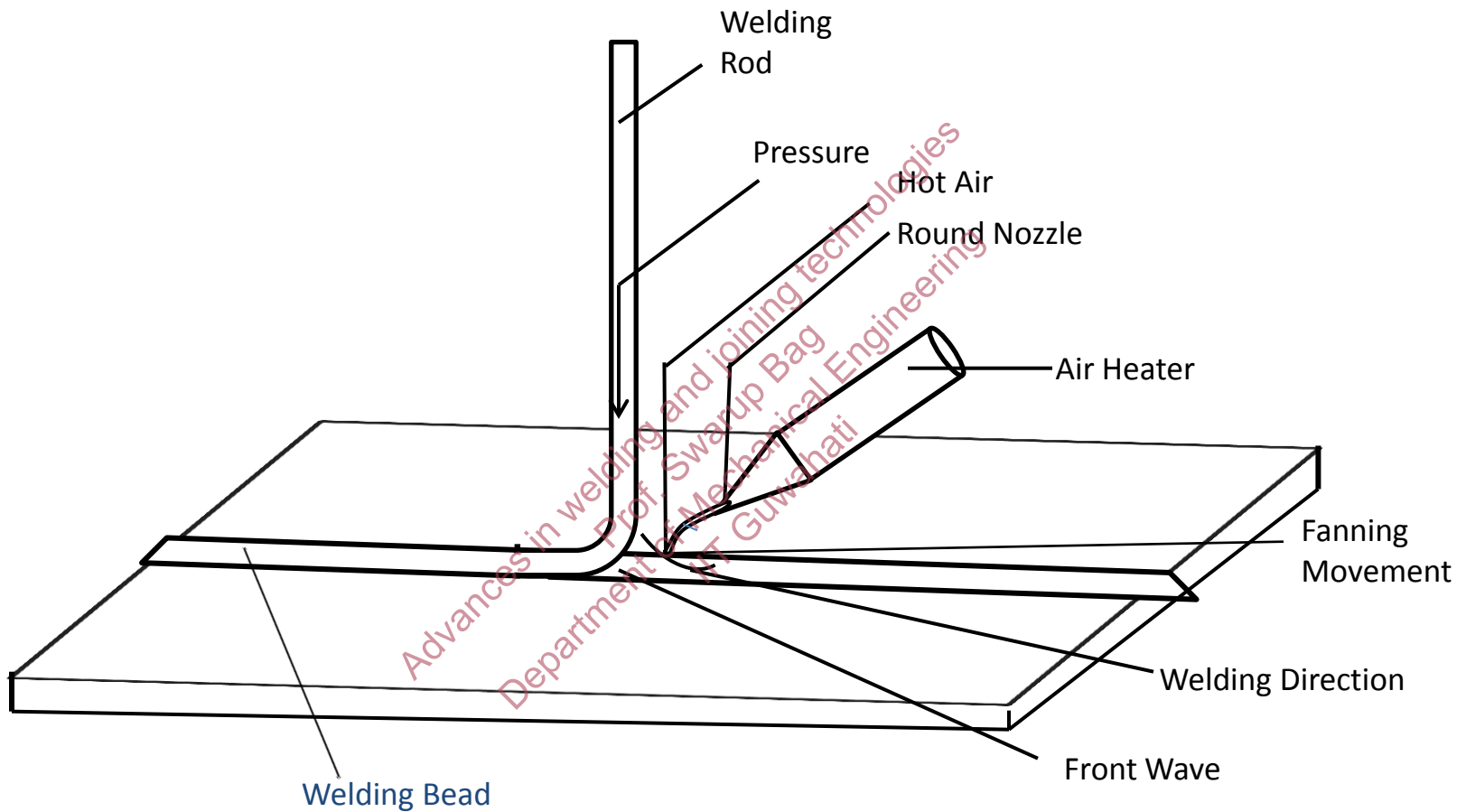
Applications:

- ✓ Containers
- ✓ Tanks for storage chemicals
- ✓ Ventilation ducting
- ✓ Tubes
- ✓ Repair works

Some polymers oxidize at increased temperature therefore they are welded by hot Nitrogen

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Hot Gas Welding



Hot Plate welding

Hot Plate Welding is a plastics welding process, utilizing heat of hot plate placed between the surfaces to be joined.

- ✓ Work pieces are pressed to the plate, heat up and soften.
- ✓ After a predetermined time the plate is removed, the parts are brought to the contact, pressed and fused together.
- ✓ Polymer molecules are cross-linked when the work pieces cool down, forming a strong joint.
- ✓ Hot plates are made mainly of Aluminum alloys, equipped with an electric heating elements and a thermocouple providing temperature control of the plate surface

Hot Plate welding

Applications:

- ✓ Components of domestic electric devices (dishwashers, washing machines, vacuum cleaners)
- ✓ Pipes
- ✓ Automotive components (lights, fuel tanks, reservoirs, batteries).

Advantages of Hot Plate Welding:

- ✓ Easily automated
- ✓ High quality tight joints
- ✓ Large parts may be welded
- ✓ Hot plate provides conforming the joined surfaces

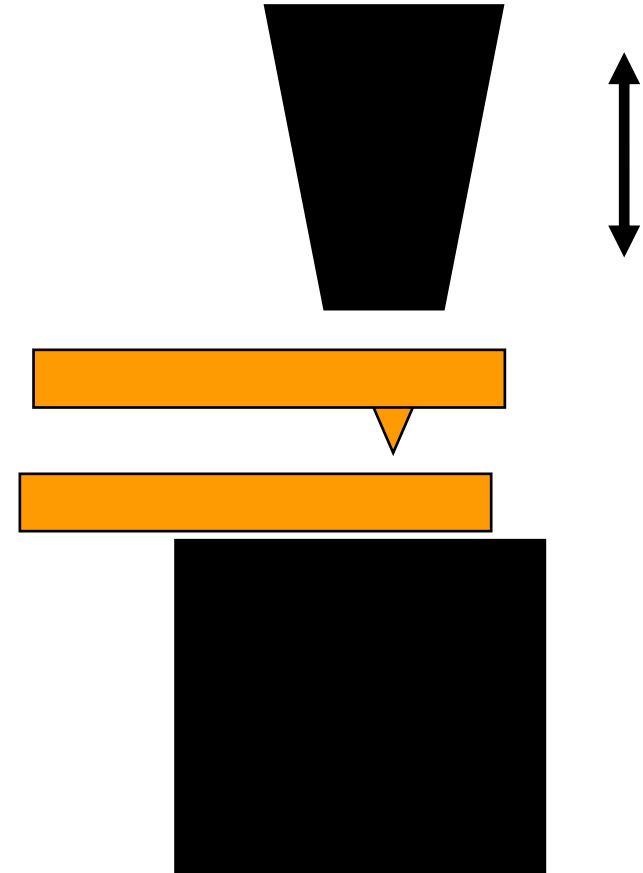
Disadvantages of Hot Plate Welding:

- ✓ Long welding cycle: up to 20 sec. for small parts and up to 30 min. for large parts
- ✓ Relatively large amount of flash (excess material) forms

Ultrasonic Welding

Ultrasonic Welding: two work pieces are bonded as a result of a pressure exerted to the welded parts combined with application of **high frequency acoustic vibration (ultrasonic)**

- ✓ Vibration causes oscillation of the material and friction between the parts, which results in **local heating of the contact area**
- ✓ The plastic melts in the contact area, the polymer molecules are cross-linked, forming a strong joint.



Ultrasonic Welding

Process Parameters:

- ✓ Ultrasonic Welding cycle takes about 1 second
- ✓ The frequency of acoustic vibrations is in the range 20 to 70 kHz
- ✓ The amplitude of the acoustic vibrations is about 0.05 mm
- ✓ Thickness of the welded parts is limited by the power of the ultrasonic generator
- ✓ Ultrasonic Welding is used mainly for processing amorphous polymers- Polystyrene (PS), Acrylonitrile-Butadiene-Styrene (ABS)

Ultrasonic Welding

Applications:

- ✓ Medical equipment (filters, face mask, valves, cardiometry reservoir)
- ✓ Automotive components (glove boxes doors, filters, valves, airflow sensors)
- ✓ Appliance (vacuum cleaner, steam iron, dishwasher components)
- ✓ Electrical equipment (switches, terminal blocks, connectors)
- ✓ Electronic and computer components
- ✓ Toys

Ultrasonic Welding

❑ Advantages:

- ✓ Short welding cycle
- ✓ Easily automated and controllable
- ✓ Small amount of flash forms
- ✓ Low energy consumption

❑ Disadvantages:

- ✓ Only small and thin parts may be welded
- ✓ Proper tool design is required

Spin Welding

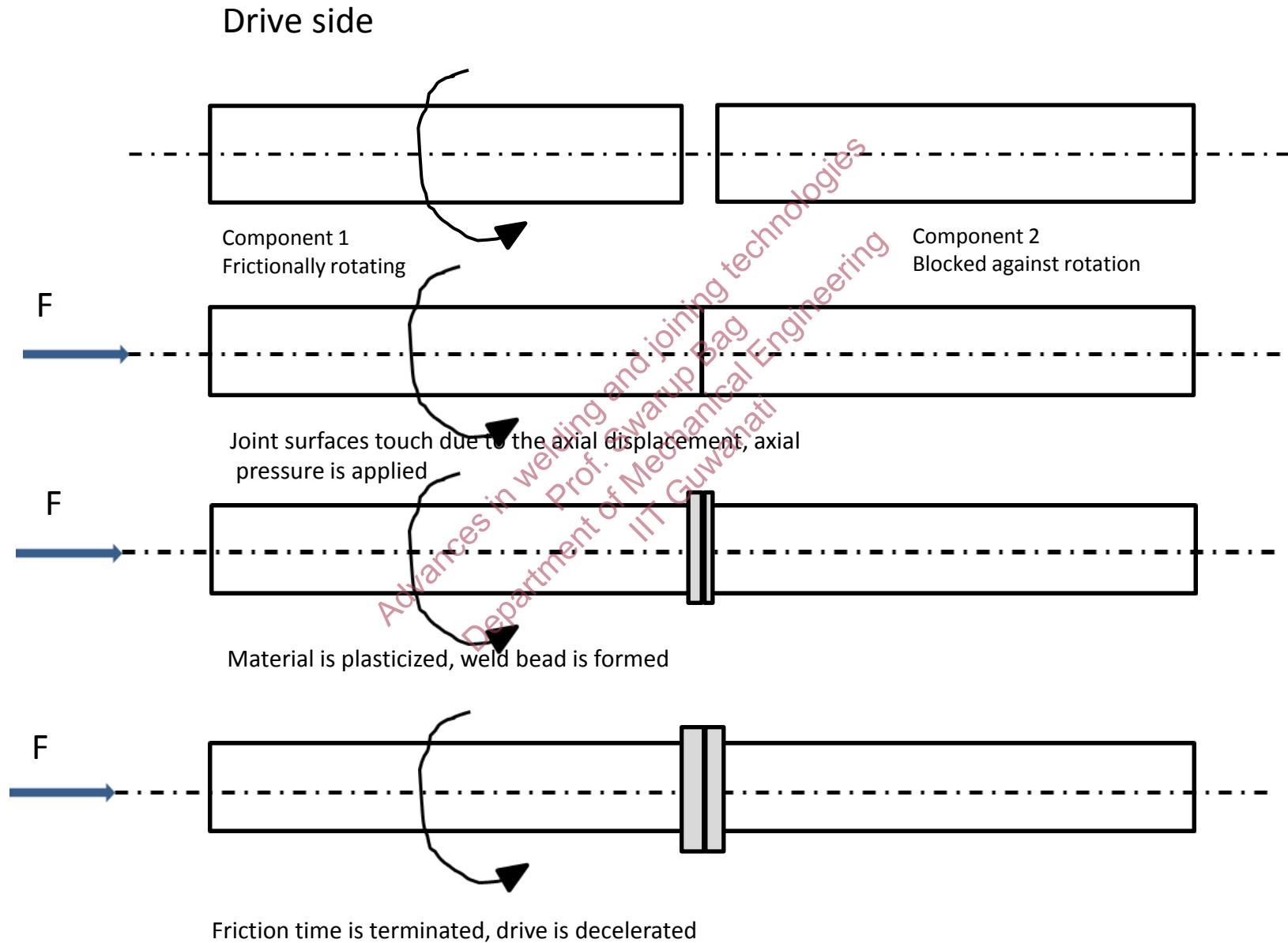
Spin Welding is a plastics welding process (similar to Friction Welding), in which two cylindrical parts are brought in contact by a friction pressure when one of them rotates.

- ✓ Friction between the parts results in heating their ends.
- ✓ After a predetermined time the rotation stops and the molten regions of the work pieces are fused together under an axial pressure applied until the joint is cooled down.

Applications:

- ✓ Spin Welding is used for manufacturing aerosol bottles, floats and other **circular parts**.

Spin Welding



Spin Welding

Advantages:

- ✓ Reproducibility
- ✓ Large parts may be welded
- ✓ High quality weld
- ✓ Oxidizing polymers may be welded

Disadvantages:

- ✓ At least one of the parts to be welded should have a circular symmetry
- ✓ Minimum rigidity required

Vibration Welding

Vibration Welding is plastics welding process, in which two work pieces are **vibrated at certain frequency and amplitude**

Parts rub against each other under a pressure causing a friction between their surfaces, which generates heat.

- ✓ Heat results in melting polymer in the joint region
- ✓ The work pieces are fused together and after a predetermined time the vibration stops
- ✓ The polymer molecules are cross-linked when the work pieces cool down, forming a strong joint.

Vibration Welding

Process Parameters:

- ✓ Vibration Welding cycle is very short (**milliseconds**)
- ✓ Frequency of vibrations is in the range **100 to 500 Hz**
- ✓ Amplitude of the vibrations is about **0.5 - 5 mm**
- ✓ Most polymers (amorphous, semi-crystalline and crystalline) produced various fabrication methods (Thermoforming, Extrusion, Injection molding, Blow molding, Compression molding, Transfer molding) may be welded by Vibration Welding

Vibration Welding

Applications:

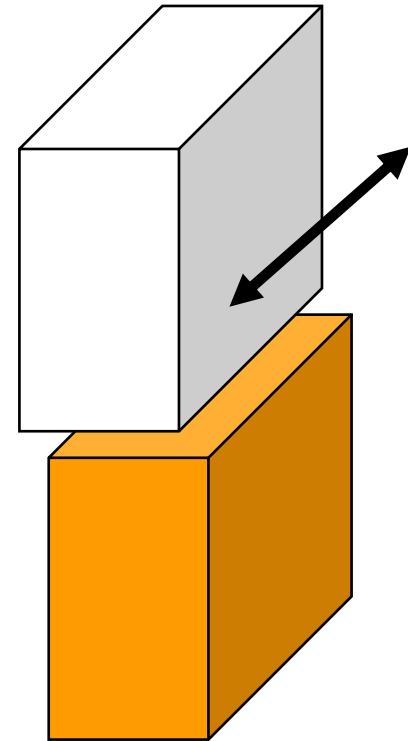
- ✓ Vibration Welding is used in automotive and domestic appliance industries

Advantages:

- ✓ Oxidizing polymers may be welded
- ✓ Easily automated
- ✓ High productivity
- ✓ Large and complex parts may be welded

Disadvantages:

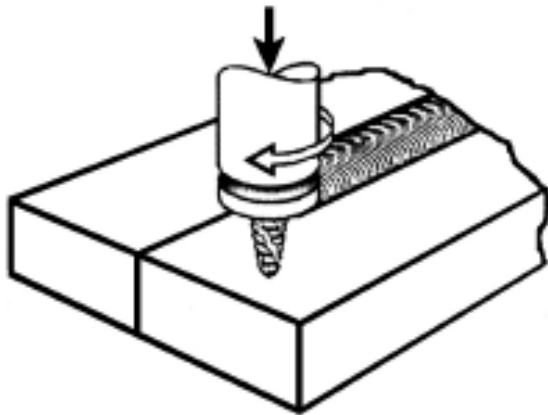
- ✓ Relatively expensive equipment
- ✓ Minimum rigidity required



Friction stir welding

Friction welding: **Relative motion between two parts, results in frictional heating**

- ❑ Linear and orbital welding: - a wide range of geometries
- ❑ Spin and angular welding:- circular weld geometries



applicability of FSW to polymeric materials – polypropylene sheets.

- 15 mm thick plate
- traditional milling tool with 8 mm diameter, 6 grooves, 30° groove slope
- 400 mm/min translation speed and 630 1/min rotation speed

**tensile strength - 11.5 MPa ~
50 % of base material**

- ❑ **crystallinity is reduced in the seam i.e. the amorphous content is higher in the seam than in the matrix**
- ❑ **cohesive strength at the interface between the matrix and the seam**
- ❑ **matrix fracture surface a significant embrittlement**
- ❑ **optimization of parameters and the tool geometry**

Radio frequency welding

Referred as – dielectric welding

- ❑ Internal heat generation by dielectric hysteresis losses in thermoplastics
- ❑ Rapidly changing electrical field results in intermolecular friction and heat generation
- ❑ Typical cycle time 1 – 5 s – relatively fast process
- ❑ Used for thin sheets (0.03 mm to 1.27 mm)
- ❑ Material must have high dielectric loss (PVC – most common material)
- ❑ Applications: packaging – welds are relatively appealing cosmetically

Advancement:

- ❑ Using additives and consumables the non-polar material materials can be sealed with RF welding
- ❑ Other improvements include machine design with automatic tuning of power supply and quick change-over of tooling

Ultra Short Pulse Laser Welding

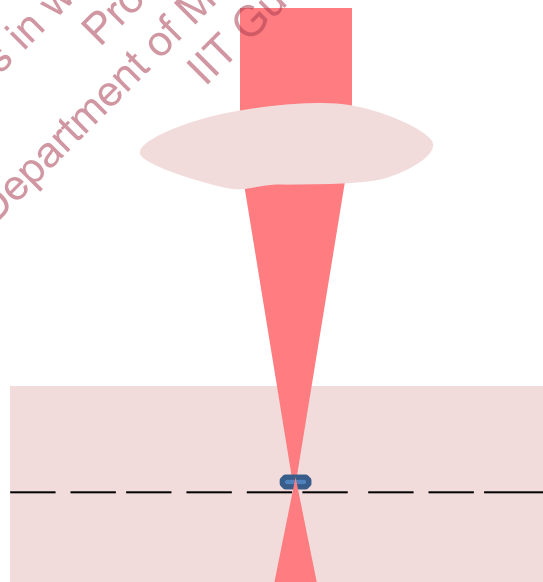
- ✓ An **ultra short pulse (USP) laser or ultrafast lasers** is a laser that emits ultra short pulses of light, generally of the order of femtoseconds to ten picoseconds
- ✓ Extremely high powers in ultrashort pulses can be achieved with Yb:YAG (Holmium-doped YAG crystals).
- ✓ Ho-YAG is usually operated in a pulsed mode.
- ✓ Time of heat transfer is extremely small and the heat affected area is also very small

USP Laser Welding-Process Parameters

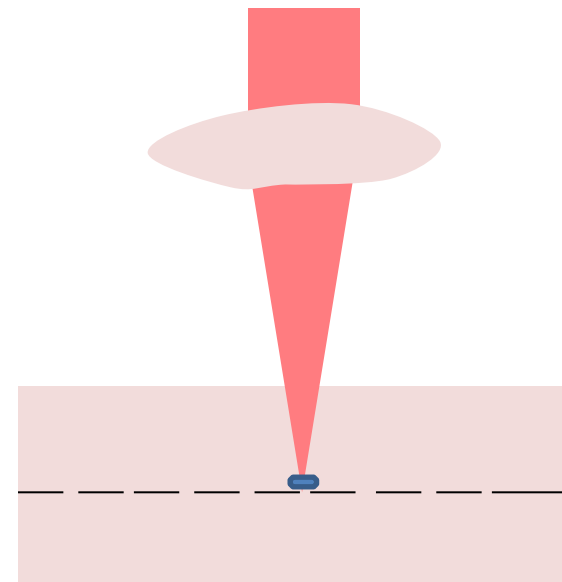
- ✓ USP lasers emit laser pulses with extremely short pulse duration, typically in the range 10 fs (10^{-15} s) to 10 ps (10^{-12} s).
- ✓ Very high peak power density is obtained up to some TW/cm^2
- ✓ The main process parameters of ultrafast pulsed lasers are:
 - Ultra fast: < 10 fs to some ps
 - Energy per pulse: from some nJ to some mJ
 - Pulse repetition frequency: from some kHz to 100 MHz
 - Average power: from 1W to 100W

USP Laser Welding- Process Principle

- ✓ Laser energy of femtosecond pulses absorbed by the nonlinear process is utilized as a heat source for fusion welding of glass.
- ✓ Extremely short pulse duration allows nonlinear absorption processes which differs from conventional absorption processes leading to non-equilibrium states in the processed region.
- ✓ While linear absorption requires an opaque material, nonlinear absorption occurs even in transparent materials at high energy densities.



No absorption



Non-linear absorption

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USP Laser Welding- Process Principle

- ✓ Due to **non-linear absorption** processes, the laser pulse energy is deposited solely in the focal region, which leads to local melting of the sample.
- ✓ Laser focus is placed at their interface, the combined action of **nonlinear absorption processes and heat accumulation** leads to welding of the samples
- ✓ If the time between successive pulses is shorter than the time required for heat diffusion out of the focal volume heat accumulation occurs leading to a **stepwise increase of the temperature**. Thus, the glass (optical transparent materials) can be locally molten and then re-solidify.
- ✓ As the **cooling rate is much faster**, the solidified **glass exhibits a higher fictive temperature** (defines the structure of a glass) than the non-laser modified glass.

USP Laser Welding- Joint Formation

- ✓ By moving the laser focus, continuous welding seams can be induced
- ✓ If the laser focus is located at the interface of two samples, the re-solidification of the molten material forms strong bonds between the samples
- ✓ Breaking strength may be enhanced by using high repetition rate laser system
- ✓ This process is ideally suited to locally weld glass samples

USP Laser Welding-Advantages

The application of ultrashort laser pulses at high repetition rates as local heat source offers several advantages:

- ✓ As **no annealing step** is required to strengthen the bonds, materials with widely different thermal expansion coefficients can easily be joined.
- ✓ No **thermal or shock-wave** damage as compared to longer pulse duration and high peak power laser
- ✓ **Limited HAZ** (few μm) as compared to long pulse laser.
- ✓ Since the HAZ is very small, the **induced thermal stress** in the material is minimized
- ✓ The workpiece follows high rate of heating and cooling over a narrow zone as compared to long pulse laser.

USP Laser Welding- Materials and Limitations

○ **Materials used for welding**

Different glasses:

- ✓ Fused silica
- ✓ borosilicate glass
- ✓ ULE (ultra low expansion) glass

○ **Limitations**

- ✓ Development of a suitable delivery system
- ✓ Cost of generating ultrashort laser pulses

USP Laser Welding- Applications

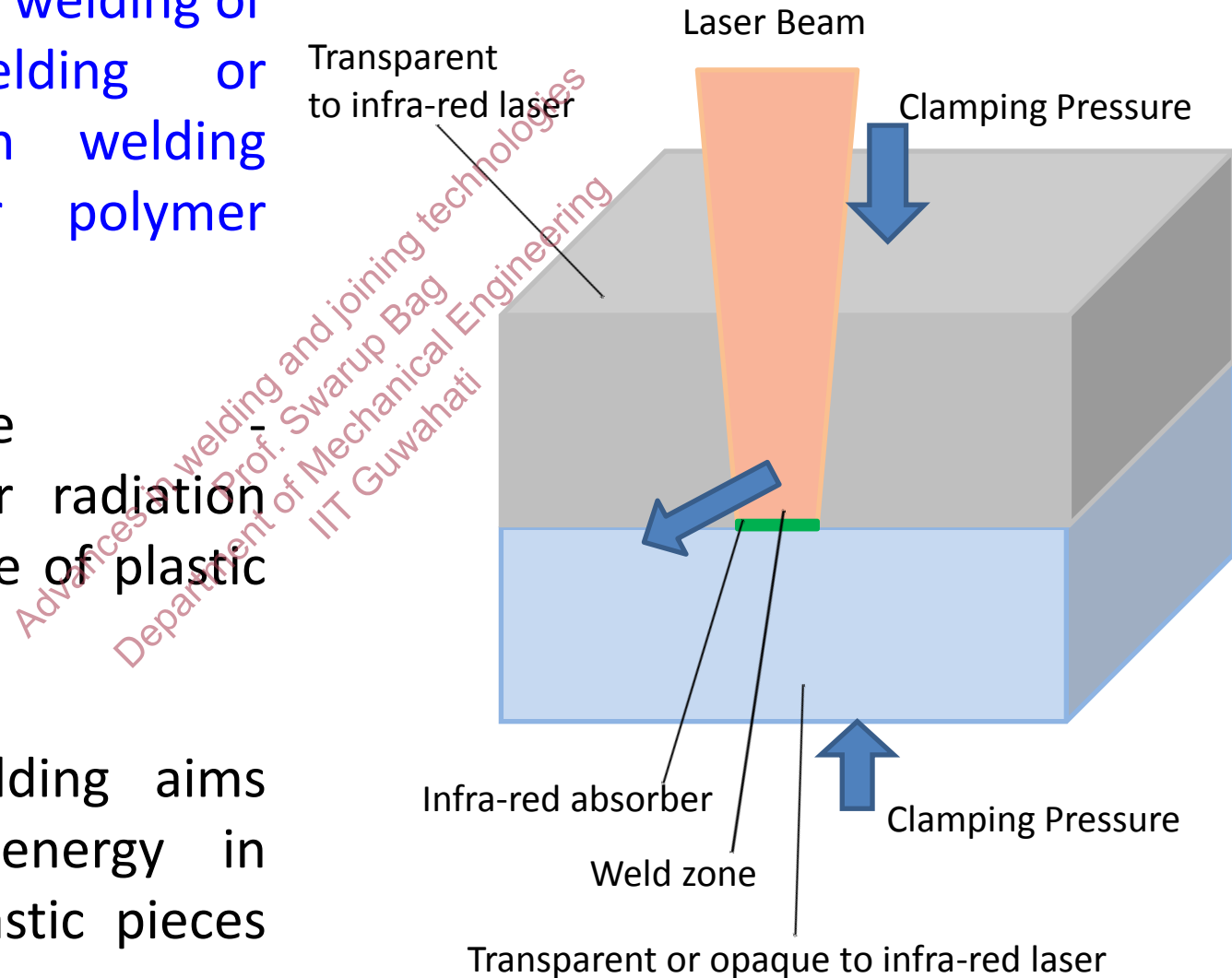
○ Areas of Applications

- ✓ Bio-medicals: Passed through optical fiber surgical devices to resurface joints, remove rot from teeth, vaporize cancers, and pulverize kidney and gall stones.
- ✓ Optical coherence tomography (OCT)- allows 3D imaging.
- ✓ Rapid-prototyping
- ✓ Micro-fabrication

Laser Transmission Welding

Transmission welding also known as laser transmission welding or laser plastic welding or through-transmission welding (TTLW) and laser polymer welding

- ✓ Basic principle - transmitting laser radiation through one piece of plastic to create a weld
- ✓ Transmission welding aims to apply the energy in between two plastic pieces at their interface



Process Requirement

Transmissive Upper Part: The upper layer needs to be transparent to laser wavelengths (808 nm or 980 nm) in the infrared and near-infrared spectrum

Absorbing Lower Layer: The lower needs to have the ability to absorb the light energy to create heat
The most common, and best, absorbing additive is carbon black doped at a rate of about 0.5%.

Clamping and Contact: The thermal energy must be transferred to the upper layer to allow for it to soften and melt

For consistent contact clamping force is used

Process Requirement

Material Compatibility: Plastics to be joined require **similar chemical compatibility**

Two plastics have similar melting/softening ranges - both plastics will be melting at or near the same time

Materials:

- ✓ Nylon - PA 6 and variations
- ✓ Polypropylene - **PP**
- ✓ Polycarbonate - **PC**
- ✓ Acrylonitrile-Butadiene-Styrene - **ABS**
- ✓ Polystyrene - **PS**
- ✓ Polytetrafluoroethylene - **PTFE**
- ✓ Polymethyl methacrylate - **PMMA**

Laser Transmission Welding

Advantages:

- ✓ Minimal mechanical stress
- ✓ Precise energy control
- ✓ Strong/durable welds
- ✓ Minimal flash and particulate development
- ✓ Clean consistent welds down to the micrometer range
- ✓ Fast cycle times

Laser Transmission Welding - Applications

□ Automotive

- ✓ Sensor housings
- ✓ Lighting
- ✓ Instrument clusters
- ✓ Interior panels
- ✓ Fluid control devices

□ Medical Device

- ✓ Catheters
- ✓ Microfluidics
- ✓ Fluid control

Glass Welding - Process Principle

- ✓ Glasses have a melting range, called the **glass transition**. When heating the solid material into this range, it will generally become **softer and more flexible**
- ✓ When it crosses through the glass transition, it will become a very **thick, sluggish, viscous liquid** (very little surface tension), becoming sticky (honey-like), so welding can usually take place by simply pressing two melted surfaces together
- ✓ The two liquids will generally **mix and join** at first contact
- ✓ Upon cooling through the glass transition, the welded piece will solidify as one solid piece of amorphous material

Glass Welding - Heat Sources

- ✓ Heating is usually done with a gas or oxy-gas torch, or a furnace, because the temperatures for melting glass are often quite high
- ✓ This temperature may vary, depending on the type of glass.
 - Lead glass (crystal) becomes a weldable liquid at around 870 °C
 - Quartz glass (fused silica) must be heated to over 1,650 °C
- ✓ Sometimes a tube may be attached to the glass, allowing it to be blown into various shapes, such as bulbs, bottles, or tubes
- ✓ When two pieces of liquid glass are pressed together, they will usually weld very readily

Glass Welding - Limitations

- ✓ As glass is **very brittle** in its solid state, it is often prone to **cracking** upon heating and cooling. This is because the brittleness of glass does not allow **uneven thermal expansion**
- ✓ Quartz has very **low α** , while soda-lime glass has very **high α**
it is usually important to closely match their **coefficients of thermal expansion**, to ensure that cracking does not occur
- ✓ Welded glass need to be **cooled very slowly** and evenly through the glass transition, in a process called **annealing**, to relieve any internal stresses created by a temperature gradient

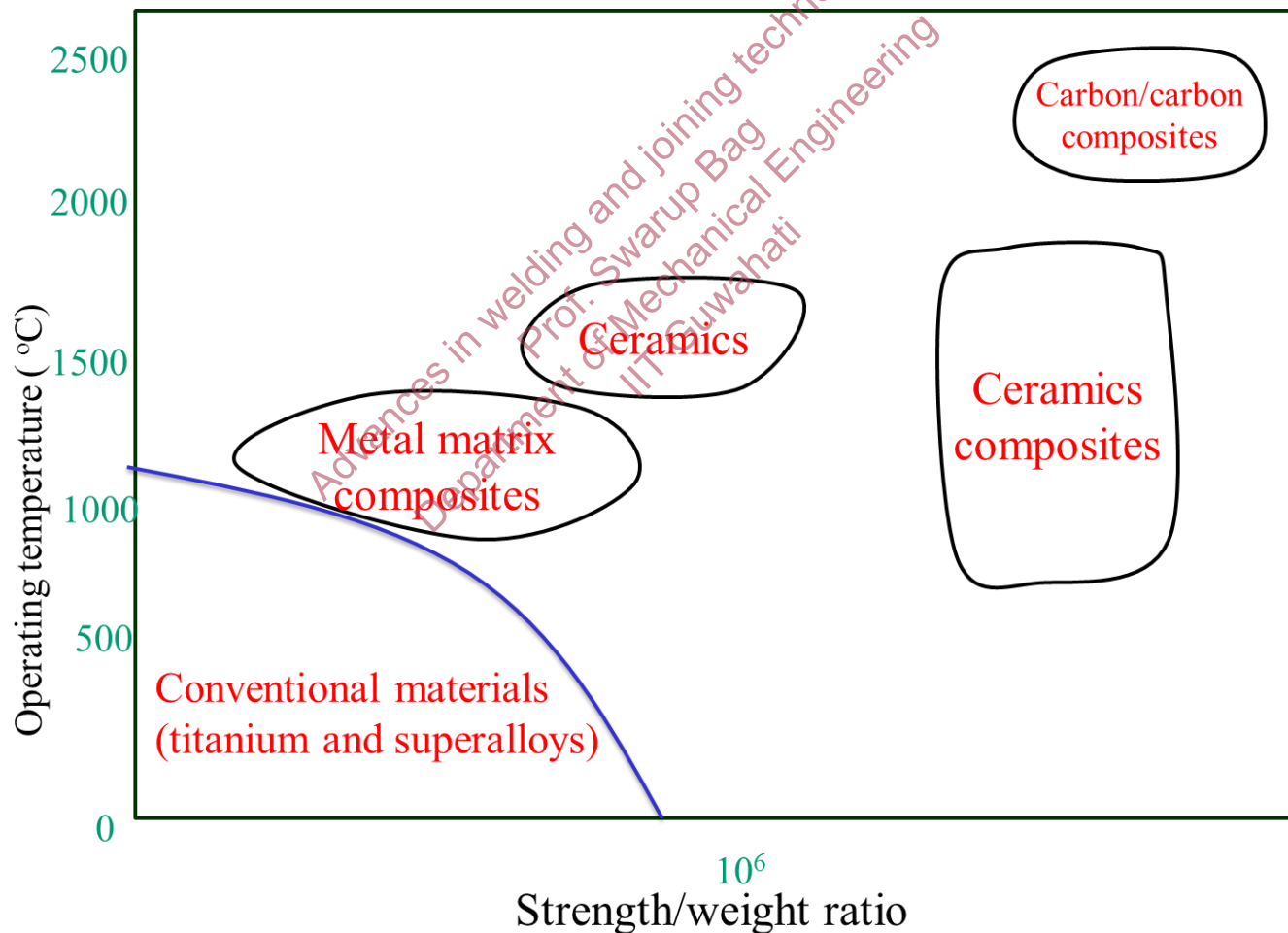
Glass Welding - Applications

Glass welding is a common practice during

- ✓ Glassblowing
- ✓ Construction of lighting, flashtubes
- ✓ Scientific equipment
- ✓ Manufacturing of dishes and other glassware
- ✓ Glass casting for joining the halves of glass molds, making items such as bottles and jars

Ceramic Welding

Ceramics have the highest potential because of their increased toughness, high heat resistance capability and the non-catastrophic fracture behavior



Processes to Weld Ceramics

- ✓ **Electron beam welding, laser beam welding, friction welding and diffusion welding** can be used to join ceramic parts.
- ✓ High beam energy is restricted to small ceramic parts, i.e., can be used only for ceramics with defined melting points (e.g. Al_2O_3), and not for SiC and Si_3N_4
- ✓ **High stresses** caused by severe temperature gradients - can easily damage ceramic joints
- ✓ Ceramics can be joined to themselves or to metals by **diffusion welding** - It is complicated to apply the necessary pressure for larger components.
- ✓ High equipment costs and long joining times lead to high production costs.
- ✓ **Brazing** is the most economical joining process for ceramics – both metallic and ceramic brazes are used

Properties and Applications of Ceramics

○ Properties:

- ✓ high temperature resistance
- ✓ extremely high hardness
- ✓ low electrical conductivity and
- ✓ high thermal insulating properties
- ✓ high chemical resistance and also lower density, compared with metals

○ Applications:

- ✓ These excellent properties are the reason for applying technical ceramics in wide fields of electronics, automotive and chemical industries.

Applications of Ceramics

- ✓ In **aerospace technology**, metals are unsuitable for the hot structure of due to their poor behavior at high temperatures, their high density and problems caused by their high coefficient of thermal expansion.
- ✓ Inherent high temperature limits of metals are also handicapping other major technologies
- ✓ Ceramic welding is applied during **furnace operation** by conveying a dry mixture of refractory aggregate and oxidizable particles together through specially designed water cooled lances.
- ✓ Ceramic welding helps in no or minimal loss of production and extending furnace or vessel life.

Limitations of Ceramic Welding

○ Material

- ✓ Monolithic ceramics, either oxides or non-oxides, are commonly used in engineering designs. The oxides are mainly based on Al_2O_3 and ZrO_2 while the non-oxides are SiC and Si_3N_4 .

○ Limitation in Process

- ✓ Require either a high expenditure of preparation of joining part (diffusion welding)
- ✓ High expenditure of equipment (EBW)
- ✓ Joining techniques using additives like brazing are not advisable because the ceramics lose their specific superior properties

Limitations for Welding of Ceramics

- ✓ Difficult to process and **small resistance to thermal shock**.
- ✓ Since ceramic material is **porous**, porosity tend to be produced in the weld bead.
 - A lot of round small porosities which are not connected each other were found along fusion boundary
- ✓ Because of the relatively small thermal conductivity compared with the high thermal expansion, stresses in the material can occur leading to its destruction

Biocompatible Plastic to Metal Welding

Need for joining of plastic to metal:

- ✓ Demand on dissimilar material joints have been increasing from the viewpoint of design requirements, energy consumption, environmental concerns, high performance and cost saving
- ✓ Metals usually have been selected since they have superior properties such as high ductility, high thermal conductivity, and high machinability
- ✓ Meanwhile for plastics, they offer excellent corrosion resistance, insulation, and lightweight
- ✓ Dissimilar materials joint between polymer and metal can be obtained from both the two different properties at the same time.

Difficulties in welding Plastic to Metal

- ✓ Technical difficulties arise - due to dissimilarities in mechanical, thermal and chemical behavior
- ✓ For example, large variation can be noticed in properties of PET (polyethylene terephthalate) and stainless steel

Material properties	PET	Stainless steel
Melting point (°C)	243 - 260	1399 - 1454
Thermal conductivity (W/m K)	0.24	138
Coefficient of thermal expansion ($10^{-5} / ^\circ\text{C}$)	6.0	1.72

Processes to Join Plastic to Metal

- ✓ Polymer–metal hybrid joints are formed using various joining techniques such as adhesive bonds (glues) or mechanical tools, such as bolts and rivets
- ✓ Use of adhesive bonding for joining aluminium and polytetrafluoroethylene (PTFE) is successfully achieved only after treating a PTFE surface with Sodium
- ✓ Bolted joints of carbon-fibre reinforced epoxy (CRFP) and titanium results in an increase in joint strength, but some drawbacks such as long processing time, high production costs and limitations of shape and size were identified

Processes to Join Plastic to Metal

- ✓ Adhesive bonds (glues) for joining have problems in terms of **environmental restrictions** on the emission of volatile organic compounds and the difficulties of mass production
- ✓ To improve the quality, production time and reliability of the dissimilar materials joint, **Laser beam welding** and **Resistance welding** are used to join plastic to metal

Resistance Welding of Biocompatible Plastic to Metal

- ✓ To join Thermoplastic matrix composites (TPCs), traditional technologies such as mechanical fastening and adhesive bonding are either too intrusive (stress concentrations resulting from hole drilling) or require extensive surface preparation incompatible with mass production requirements
- ✓ Alternatively, fusion bonding methods and particularly resistance welding, when applied to TPCs, proved to produce close-to-parent strength joints in short processing times. Additional advantages include re-processability, recycling, on-line monitoring, automation ready, cost efficiency

LASER Welding of Biocompatible Plastic to Metal

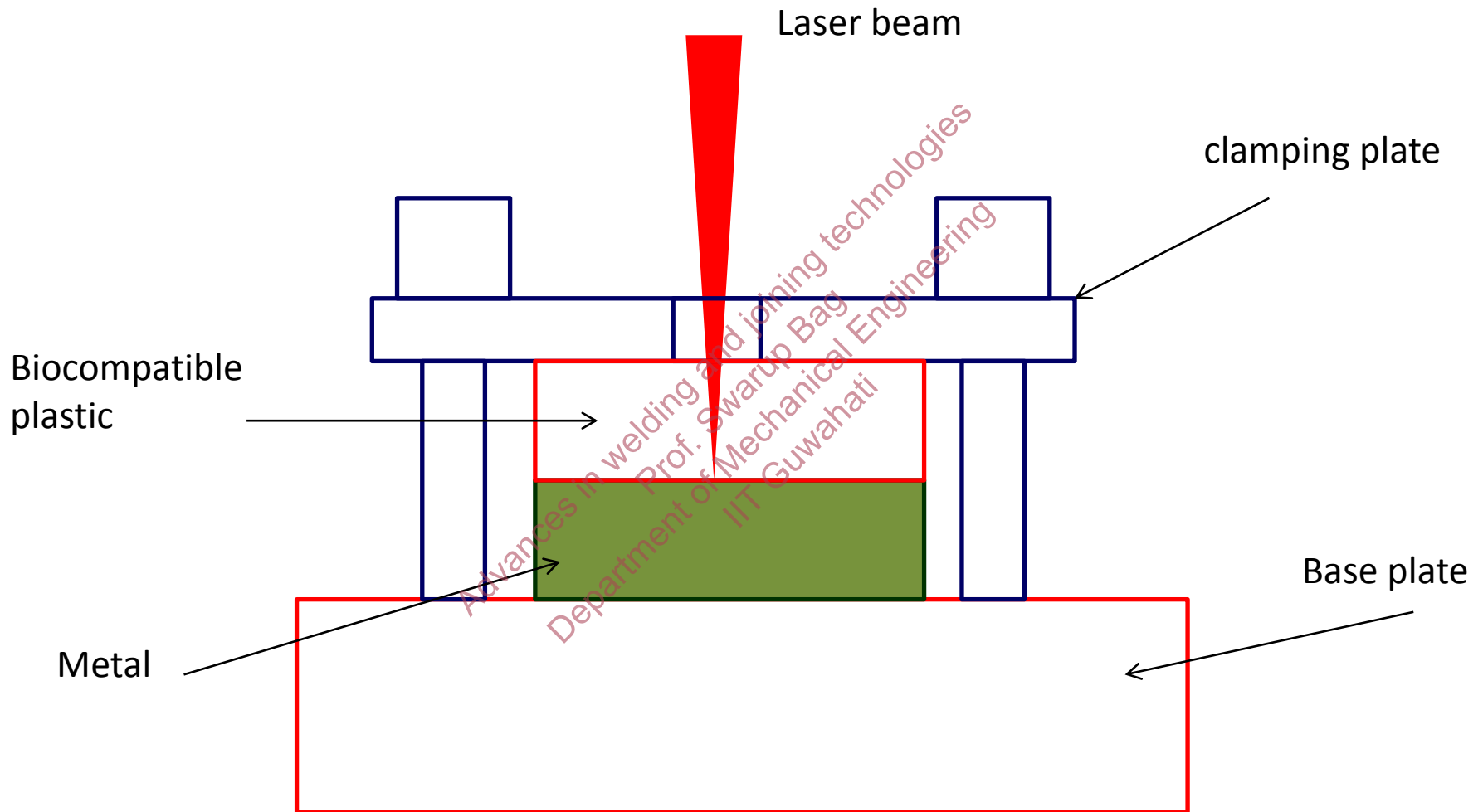
○ Advantages of LASER welding

- ✓ High precision manufacturing or material processing of small parts and geometries.
- ✓ Focused into very small size, which is useful for joining complex shape and micro parts.
- ✓ Different parts can be joined as a non-contact process.

Effect of beam offset in Laser Welding

- ✓ Laser joining can be applied by laser irradiation from the polymer side (**LTJ - Laser transmission joining**) or from the metal side (**CJ - Conduction joining**), giving more flexibility for joining options under different settings.
- ✓ The joint strength and bead width increase as a function of increasing thermal input in LTJ. Further increase in the thermal input value causes polymer degradation, extrusion, bubble formation and explosion.
- ✓ For CJ case, the joint strength and the bead width increase as a function of increasing thermal input, but further increase in the thermal input causes a decrease in the strength.

Laser Welding of Polymer to Metal



Schematic diagram of the laser welding experiment

Biocompatible Plastic to Metal Welding

Dissimilar materials welded:

- ✓ Biocompatible PET (polyethylene terephthalate) film to stainless steel
- ✓ Polymethylmethacrylate (PMMA) and stainless steel 304
- ✓ Polyethylene terephthalate (PET) and aluminium alloy (A5052)
- ✓ Polyethylene terephthalate (PET) joined to aluminum alloy (A5052), stainless steel (SS 304) and copper (Cu)
- ✓ Carbon fiber (CF) reinforced Polyetherimide (PEI) and aluminium substrates (7075)
- ✓ Thermoplastic matrix composites (TPCs) and stainless steel

Biocompatible Plastic to Metal Welding

Applications:

- ✓ In electronics, aerospace, medical, automotive industry components are frequently designed and fabricated with hybrid materials.
- ✓ Specially in medical industry recent trend is gradually moving towards miniaturization and function/design flexibility.

Summary

- Welding of thermoplastics are mainly developed by
Hot gas welding, hot plate welding, ultrasonic welding, spin welding, vibration welding, friction stir welding, radio frequency welding
- Ultrasonic welding of plastics – more precise and less time
- Ultra-short pulse laser welding is suitable for highly transparent material
- Laser transmission welding is mainly applicable for plastic materials – narrow difference in thermal properties
- Glass welding is done using oxy-gas torch or furnace
- One of the economical method for joining ceramics is brazing
- Dissimilar welding between plastic to metal – laser transmission welding is one of the best option

**Thank you
for your kind attention**

End of Module 7

Welding and Joining of Non-metals