Review paper:

Recent Advances in Thermoplastic Microfluidic Bonding

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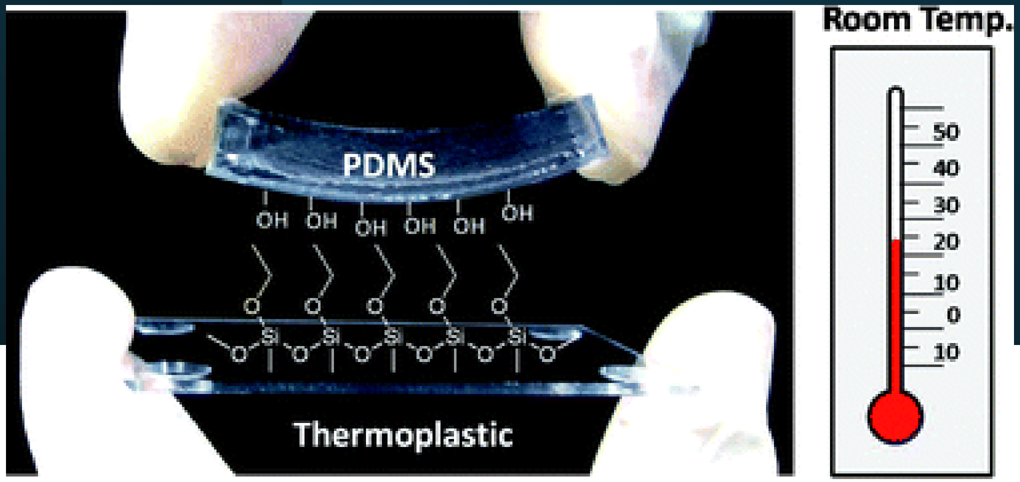
Introduction

"Recent developments and comparative analysis of bonding techniques for thermoplastic microfluidic devices"

I chose this paper because it provides a comprehensive overview of various microchannel encapsulation methods, allowing me to understand current trends and practical applications in thermoplastic microfluidic bonding.

Keywords : Thermoplastic microfluidics , Bonding techniques , Direct bonding , Indirect bonding , Laser welding , Adhesive bonding , Surface modification , Microchannel sealing , TPU compatibility , Lab-on-a-chip fabrication

Background

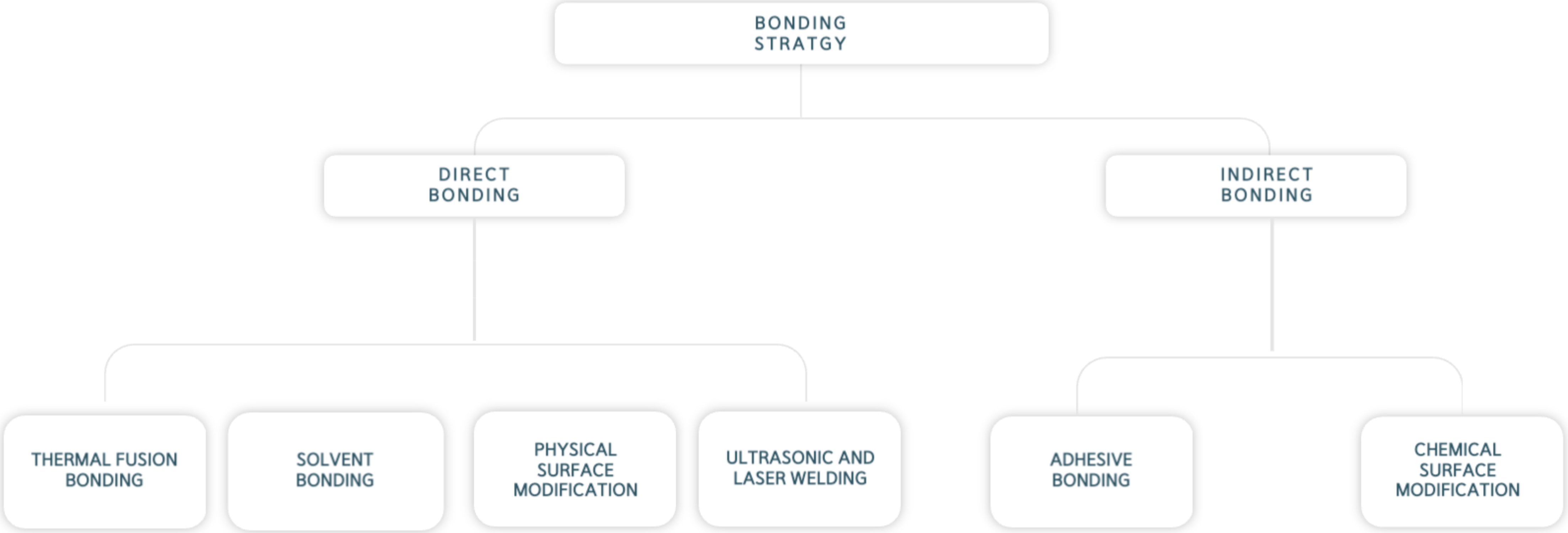


Silicone-based materials such as *polydimethylsiloxane (PDMS)* and thermoplastics are widely used in microfluidic devices. simplicity, low cost, and disposability, making it ideal for rapid prototyping.

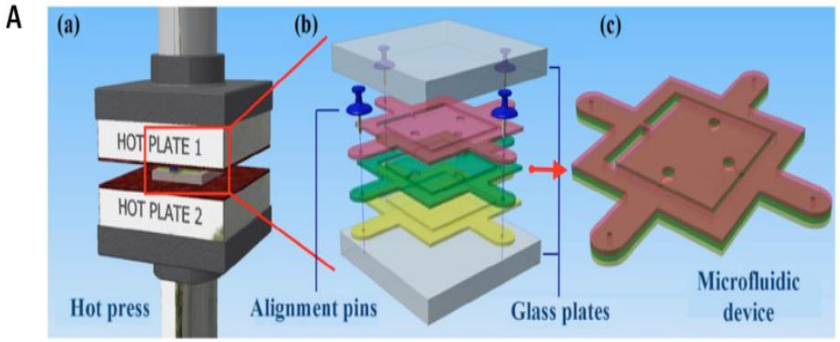
As microfluidic systems become more integrated and commercially relevant, thermoplastics are gaining attention for their durability, scalability, and compatibility with mass production.

Bonding remains a critical challenge, especially for applications involving soft materials like TPU or complex multilayer designs.

Bonding Methods for Thermoplastic Microfluidics



Direct Bonding: Thermal Fusion bonding



Thermal fusion bonding is a method of sealing thermoplastic substrates by heating them to near or above their glass transition temperature (Tg) while applying pressure simultaneously. This paper focuses on a large-area surface bonding approach, in which polymer chains inter-diffuse and fuse the substrates without the use of intermediate adhesives.

Advantages

Simple process
No adhesive required
Uniform microchannel surface

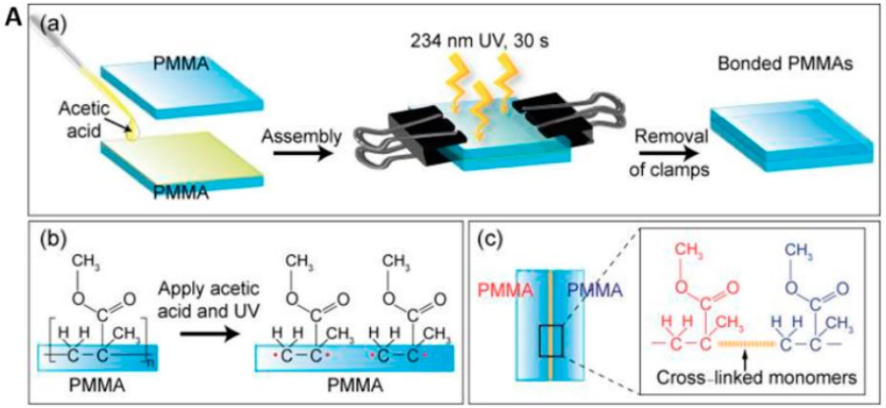
Limitations

Requires high temperature
Risk of channel deformation, clogging, collapse
Needs optimization of temperature, pressure, time

applications

TPU-Specific Considerations
Very low Tg (~ −40° C to −10° C)
Highly flexible and thermally sensitive
Prefer localized sealing over full bonding

Direct Bonding: Solvent Bonding



Solvent bonding works by applying a solvent (liquid or vapor) to the surface of thermoplastics, which softens the surface layer. When two softened surfaces are brought into contact, polymer chains inter-diffuse and entangle. As the solvent evaporates, the chains become fixed, forming a permanent bond without adhesives.

Advantages

Possible to process at low temperatures

High bonding strength

Simple fabrication process

Low equipment requirements

Limitations

Risk of clogging
(solvent may flow into microchannels)

Poor bonding uniformity

Difficult to select suitable solvent for each material

Rarely applied to TPU (easily damaged or swelled by solvents)

Difficult to achieve localized bonding

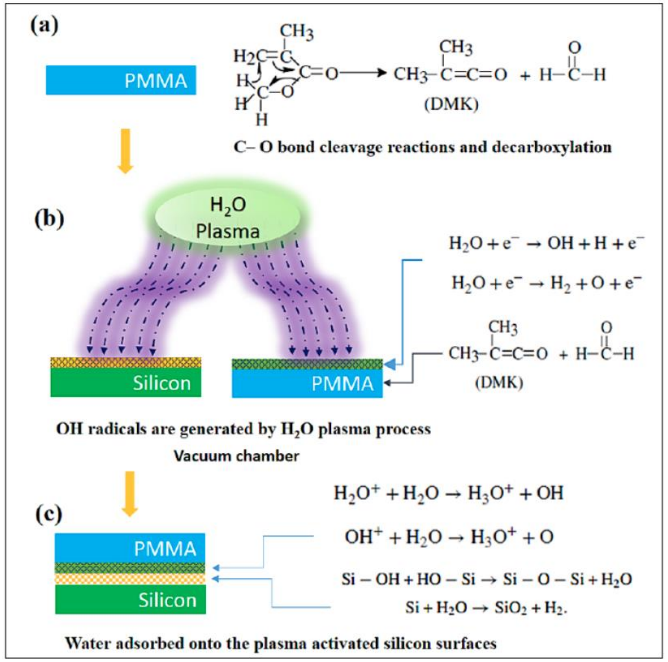
applications

Localized bonding is difficult.

Due to the properties of TPU, It is generally not suitable.

Especially,there is a high risk of microchannel damage, making it inappropriate for this application.

Direct Bonding: Physical surface modification



Physical surface modification is a direct bonding technique that utilizes physical methods such as plasma, ultraviolet (UV), or UV/ozone treatment to increase the surface energy and hydrophilicity of thermoplastic materials. This allows strong bonding between two substrates without the need for additional adhesives.

Advantages

Enables bonding without additional adhesives

Low-temperature bonding is possible due to increased surface energy and reduced Tg

Minimizes microchannel deformation by reducing thermal and mechanical stress

Limitations

Aging effect: surface activation decreases over time; bonding must occur soon after treatment

Requires equipment such as a plasma cleaner or UV/ozone generator

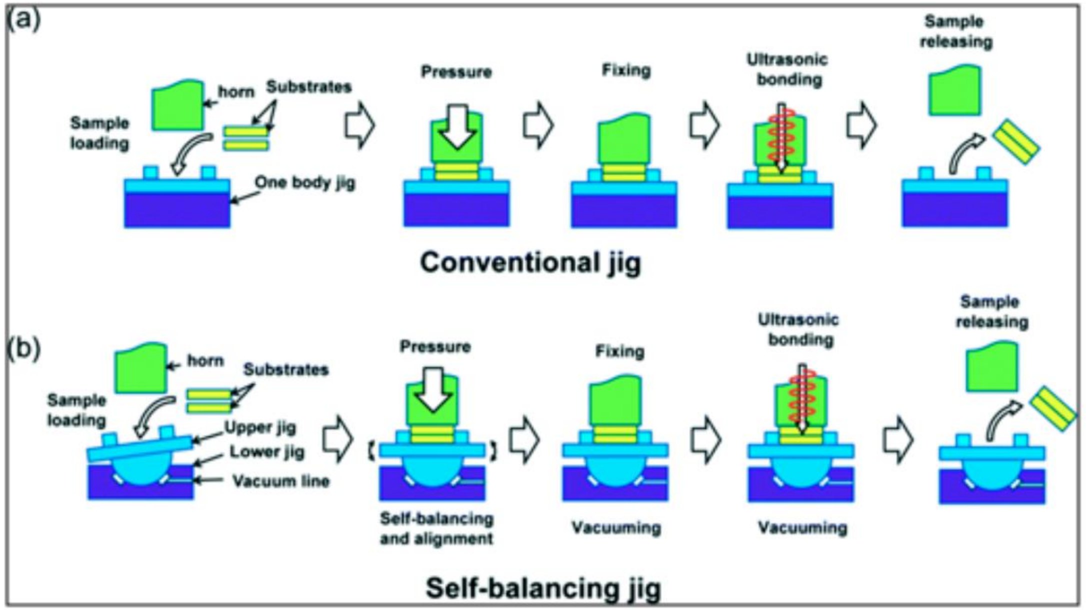
Sometimes requires post-treatment (e.g., thermal annealing) to enhance bonding strength

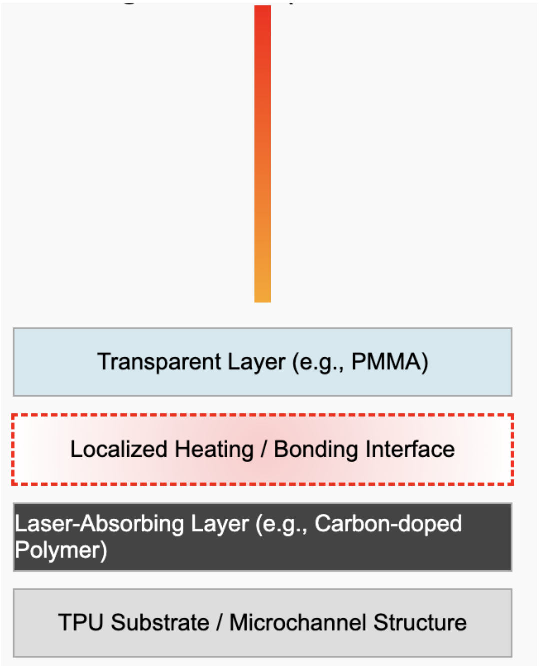
applications

Directly applying this method to TPU may be challenging due to its low Tg and thermal sensitivity

However, if you're bonding another thermoplastic (e.g., PMMA, COC) to TPU or using it as a top layer,
surface modification of the upper layer (e.g., via plasma or UV treatment) can be beneficial for achieving localized and low-temperature bonding without damaging the TPU or blocking microchannels.

Direct Bonding: Ultrasonic and laser welding





Ultrasonic welding is a technique that delivers high-frequency vibrations (20–40 kHz) to the surface of thermoplastic materials, generating frictional heat that melts the material and forms a bond. Typically, a localized protruding structure called an Energy Director (ED) is designed to concentrate heat at specific regions.
By applying both mechanical pressure and ultrasonic vibrations, rapid thermal fusion bonding can be achieved within a few seconds.

Laser welding utilizes the principle that the upper layer is transparent to the laser while the lower layer absorbs it. Localized heating at the interface causes melting and bonding without adhesives. Commonly used lasers include Nd:YAG and fiber lasers (e.g., 1064 nm). By selecting proper materials or applying an absorbing layer, highly precise, non-contact bonding can be achieved while preserving the microchannel structure

Advantages

Rapid bonding: bonding is completed within a few seconds

Strong bonding strength without the use of adhesives or solvents

Localized heating minimizes thermal damage to the entire device

Suitable for large-scale production due to its speed and automation potential

Limitations

Design-dependent: requires the inclusion of Energy Directors (EDs) for effective bonding

Not suitable for soft or heat-sensitive materials like TPU, as the vibration and heat can deform or damage them

Risk of microchannel deformation or collapse, especially in fine microfluidic structures

Requires precise alignment and pressure control

applications

TPU deformation risk is high
ultrasonic vibration and heat may rupture or deform TPU

Microchannel preservation is difficult
possible collapse or blockage during welding

Localized bonding requirement is theoretically possible, but challenging in practice due to vibration spread

Ultrasonic welding is not ideal for soft, multilayer structures like yours involving TPU and delicate microchannels

Advantages

Allows localized bonding at specific regions

Non-contact process minimizes damage to delicate structures

Well-suited for preserving microchannel integrity

No adhesives or solvents required

Enables precise bonding location control

Limitations

Requires material compatibility (transparent top, absorbing bottom)

Needs high-cost, precise equipment (e.g., Nd:YAG or fiber laser)

TPU is sensitive to direct laser exposure

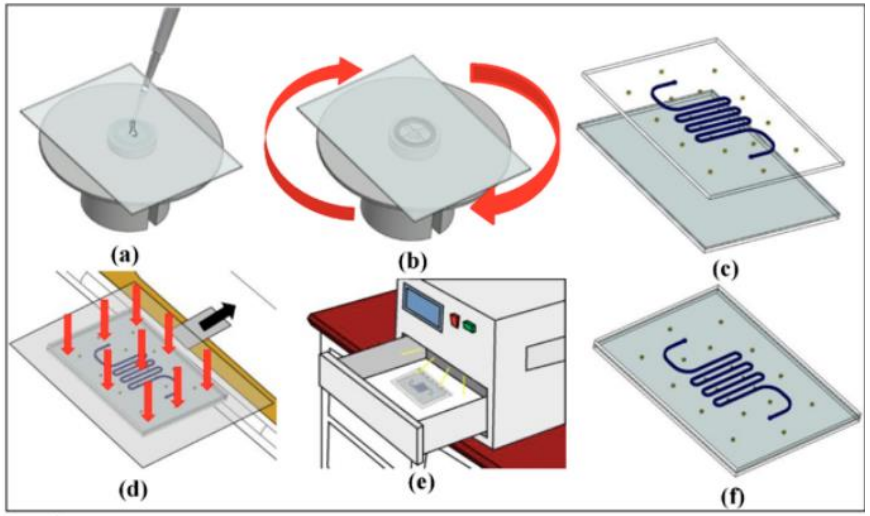
May require additional absorbing layer coating

applications

By bonding only the upper layer, TPU and microchannel structures can be preserved

Localized sealing allows safe silicone oil injection without leakage or rupture

Indirect Bonding: Adhesive Bonding



Adhesive bonding involves applying an external adhesive layer (in liquid, film, or tape form) between thermoplastic substrates. The adhesive is then cured via heat, UV light, or chemical reaction, creating a permanent bond. It is especially useful for low-temperature bonding, which is ideal for thermally sensitive materials like TPU or PLA. However, there are risks such as microchannel clogging, increased device thickness, and reduced optical or gas permeability.

Advantages

Low-temperature bonding : Suitable for materials sensitive to heat (e.g., TPU)

Simple and fast process: Just apply and press (UV-curing or mild heating is sufficient)

Minimal equipment required:
Can be performed with basic lab tools like UV lamps or hotplates

Good material compatibility:
Can bond dissimilar materials that cannot be thermally fused

Limitations

Risk of channel clogging: Liquid adhesives may leak into microchannels

Increased thickness: Films or tapes may affect alignment and microfluidic precision

Lower gas permeability: Adhesive layers may interfere with gas exchange

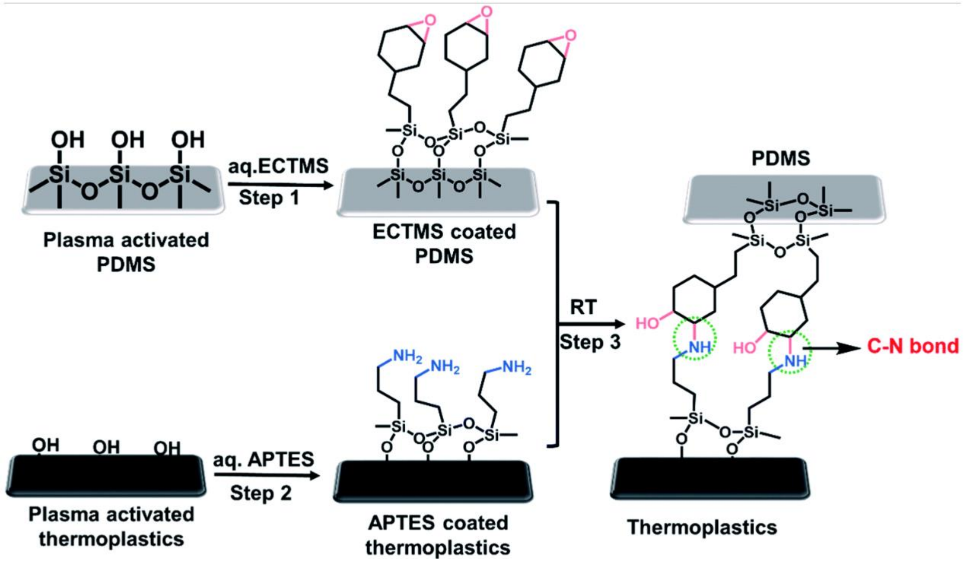
Chemical instability: Some adhesives may degrade or react with fluids

Reduced optical clarity: Unsuitable for optical detection if adhesive is not transparent

applications

When using film adhesives or UV-curable glue, protect the microchannel area with masking film or laser-cut stickers, apply the adhesive only to the sealing regions, and cure it quickly with UV light to prevent spreading and preserve the structure.

Indirect Bonding: Chemical Surface Modification



Chemical surface modification involves treating the surface of thermoplastic materials using chemical reagents (such as silane coupling agents or strong oxidizers) to introduce reactive functional groups. These functional groups (e.g., –OH, –COOH, $-NH_2$) promote bonding either directly between surfaces or via further reactions with adhesives or other layers.

Advantages

Improves bonding strength by creating reactive groups on the surface

Enables bonding between dissimilar materials

Enhances surface wettability → better adhesive spreading or fluid contact

Can be combined with other bonding methods (e.g., plasma, adhesive) to increase effectiveness

Limitations

Requires handling of hazardous chemicals (e.g., piranha solution, chromic acid)

May require long processing time (e.g., soaking, rinsing, drying)

Not suitable for heat- or solvent-sensitive materials like TPU

Risk of surface over-etching or degradation if not well controlled

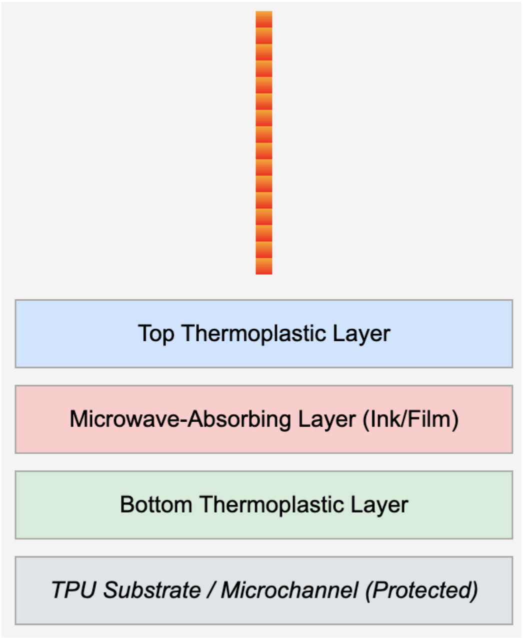
applications

Chemical surface modification is not directly suitable for TPU, as it is highly sensitive to strong acids, solvents, or surface etching.

However, you can apply this method to the upper thermoplastic layer only (e.g., PMMA), to enhance bonding performance without affecting the TPU.

It may be combined with plasma treatment or UV-curable adhesive bonding for stronger interface bonding, but must be used selectively and carefully.

Indirect Bonding: Microwave Bonding



Microwave bonding uses microwave radiation (typically 2.45 GHz) to heat and bond thermoplastic materials. Microwaves cause polar molecules or additives in the polymer or adhesive layer to vibrate and generate heat internally, leading to localized melting and bonding of the substrate materials.

Advantages

Fast and selective heating: only the absorbing regions heat up

No direct contact required → clean and localized bonding

Can reduce thermal damage to non-target areas

Works at relatively low global temperatures

Suitable for complex shapes and curved surfaces

Limitations

Requires absorbing materials (e.g., ink, thin film with additives)

Not all thermoplastics absorb microwaves well

TPU and delicate structures may still be affected by indirect heating

Difficult to control heating distribution precisely

Specialized microwave equipment needed

applications

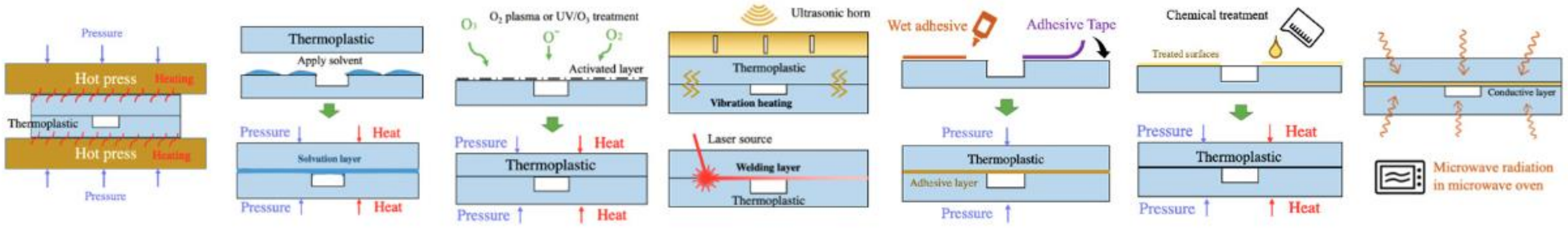
TPU itself does not absorb microwaves well, but by adjusting the surrounding materials or introducing an intermediate absorbing layer, indirect heating can make partial bonding possible.

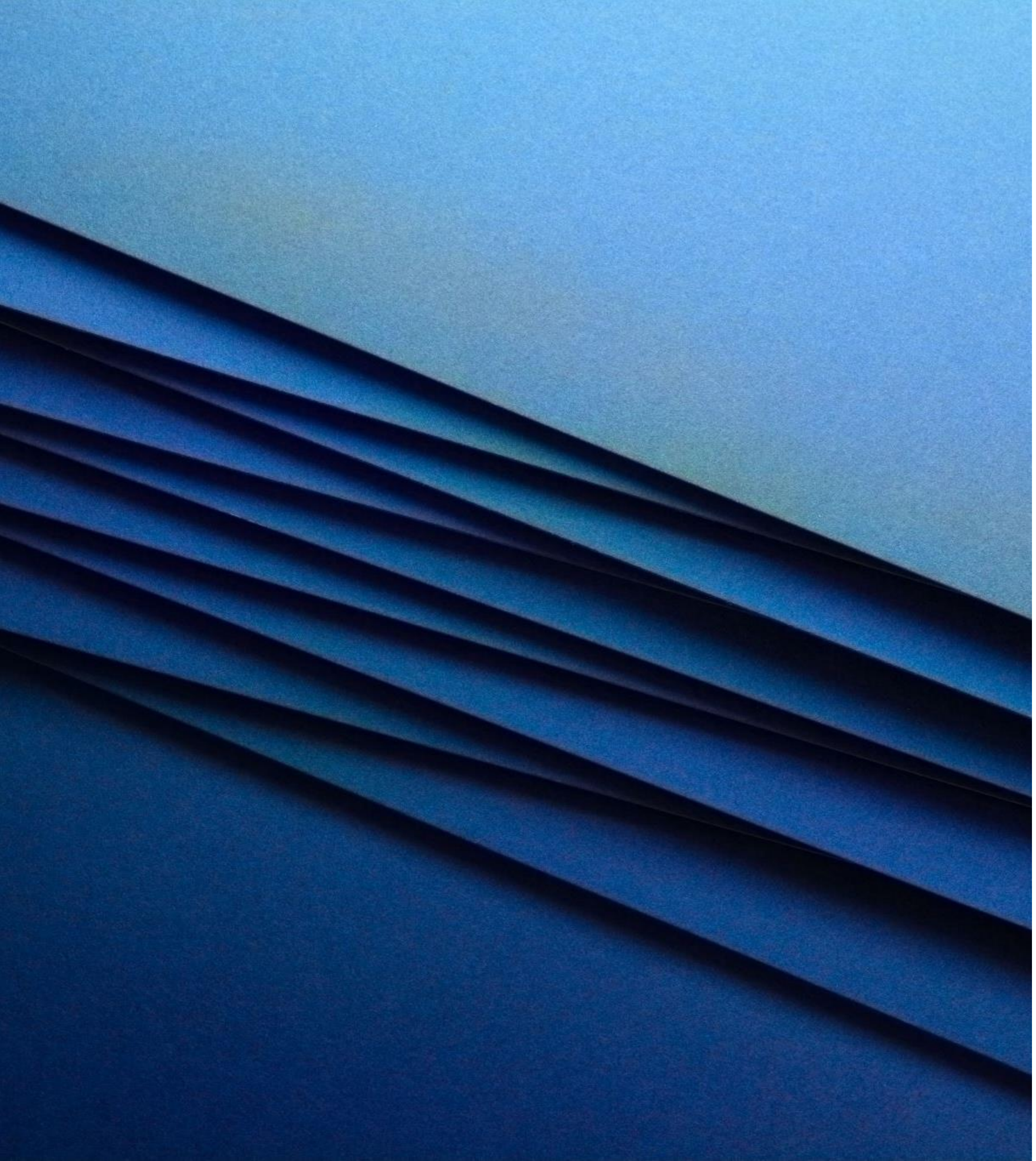
If microwave-absorbing ink or film is selectively placed near the microchannel area, bonding can be localized to specific regions.

However, controlling the heat distribution is challenging, and TPU may still be sensitive to indirect heating

Conclusions

Thermoplastic bonding for microfluidics	**Direct bonding** Bonding without additional material				**Indirect bonding** Bonding involves using additional material		
Category	**Thermal bonding**	**Solvent bonding**	**Physical surface modification**	**Ultrasonic welding Laser welding**	**Adhesive bonding** (Wet) (Dry)	**Chemical surface modification**	**Microwave bonding**
Process							
Facilities	Hydraulic hot press, bonder, hot plate, or custom-made heater	Beakers, sprayer; hot plate, hot press bonder, …	O_2 plasma, UV/O_3 chamber, or UV light; hot press bonder	Ultrasonic horn; Laser source	Dry adhesive tape, or wet adhesives; Bonding machine	Wet bench; hot press bonder	Microwave oven; conductive layer coater
Key process parameters	Bonding temperature, pressure and time	Solvent time; Bonding temperature, pressure and time	Treatment time; Bonding temperature, pressure and time	Ultrasonic frequency; laser intensity	Adhesive selection, bonding temperature, pressure and time	Chemical selection, bonding temperature, pressure and time	Conductive layer selection, microwave power and time
Bond Strength	Low ~ Moderate	Moderate ~ High	Moderate	Low ~ Moderate	Low ~ Moderate	Moderate ~ High	Low ~ Moderate
Optical transmissivity	Will not affect	Will not affect	May degrades depending on treatment conditions	Will not affect (ultrasonic) Opaque or degrades depending on interface layer (laser)	May degrades depending on tape selection	May degrades depending on chemical selection	May degrades depending on conductive layer
Fabrication Throughput	Low	Moderate	Moderate ~ High	Moderate ~ High	High	Moderate ~ High	High





Summary and Future Perspectives

This paper summarizes various thermoplastic microfluidic bonding techniques and classifies them into direct and indirect bonding, explaining the mechanisms and required equipment for each method.

In applications where optical clarity is important, direct bonding methods that do not involve adhesives or surface modification are more advantageous.
However, when material compatibility is a key concern, indirect bonding methods offer greater flexibility.

Based on this review, the most promising sealing method for the current experiment is the application of Laser Welding.

The reasons are: 1. It allows localized bonding, making it possible to seal the device without damaging the microchannel region. 2. As a non-contact process, it can be applied without causing mechanical damage to soft and heat-sensitive materials such as TPU.

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