Fundamentals of Plastic Welding

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EWI
We Manufacture Innovation

THE ASSEMBLY SHOW
CELEBRATING 10 YEARS

Workshop Agenda

- Who am I and who is EWI? (5 min)
- Plastic Welding Basics (30 min)
- Ultrasonic Welding (30 min)
- Laser Welding (30 min)
- Vibration Welding (30 min)
- Hot Plate Welding (30 min)
- Testing and Evaluation (20 min)
- Questions (5 min)

Introduction

- About the Speaker
- About EWI
- About EWI’s Polymer Services

About Me – Miranda Marcus

Career

- EWI (2013-Now)
  - Senior R&D engineering consultant, polymer joining
- Dukane Intelligent Assembly Solutions (2006-2013)

Education

- UAkron, PhD Polymer Engineering (2020)
  - Thesis: Theory-Driven Engineering Model to Predict Strength of Ultrasonic Plastic Welds
- OSU, MS Welding Engineering (2006)
  - Thesis: Rapid Embossing of Micro-Channels in PMMA
- OSU, BS Welding Engineering (2005)

Who is EWI

Advanced Manufacturing Engineering Services

Columbus
OHIO

- Joining
- Forming
- Materials Engineering
- Structural Integrity
- Modeling
- Inspection
- Polymers
- Testing

Buffalo
NEW YORK

- Additive Manufacturing
- Automation
- Data Science
- Metrology

Loveland
COLORADO

Sales Office

90+
Technical Experts
14 PhD, 28 MS, 37 BS

$40M+
Capital Equipment

160,000
Total Square Feet

EWI Markets

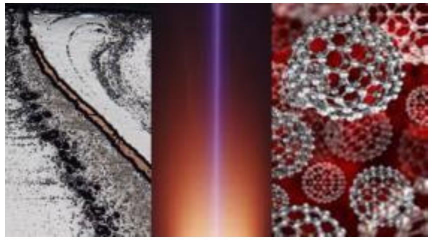

Transportation


Oil & Gas


Aviation


Advanced Energy

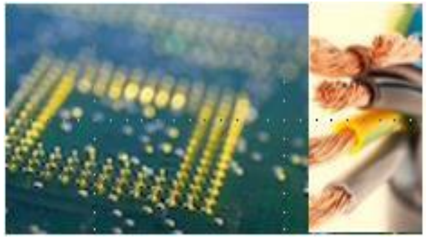

Heavy Industry


Government

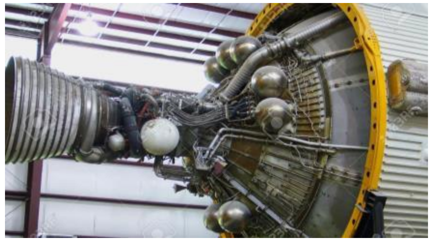

Defense


Packaging


Automotive


Consumer Products


Medical Devices


Space Exploration

Technical Services

- Materials selection
- Manufacturability
- Joining constraints

- Joint designs
- Design optimization DFx
- Analytical modeling

- Process validation
- Process monitoring and controls
- Onsite training and support

- Process feasibility
- Joining trials
- Property characterization

- Process optimization
- Rapid prototyping
- Testing and analysis

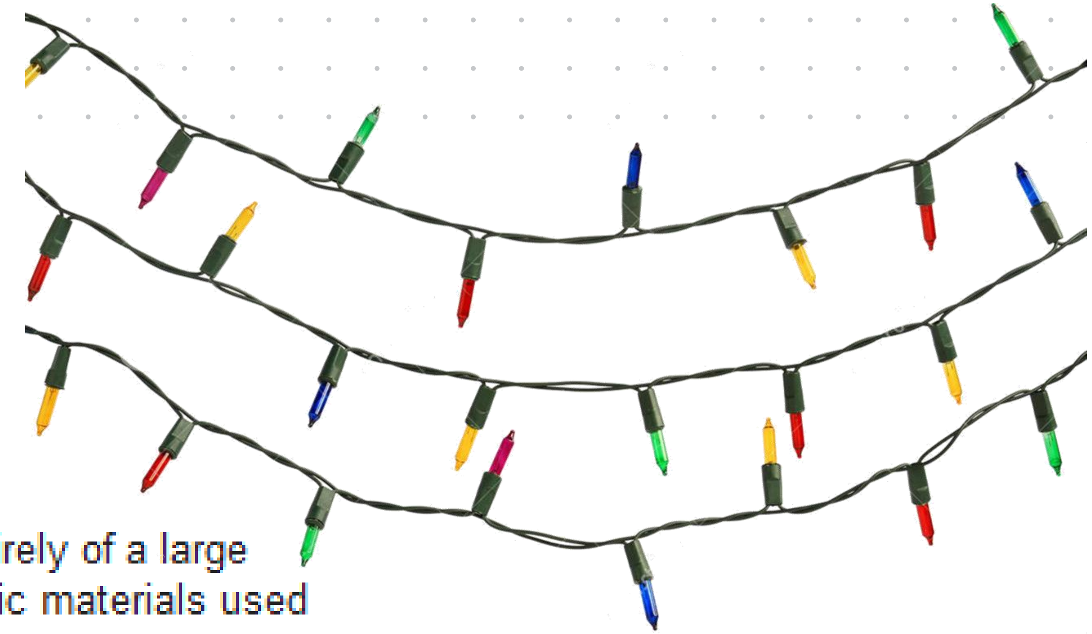
- Onsite troubleshooting
- Continuous improvement
- Failure analysis

Applied R&D bridges the gap between research and application.

Polymer Welding Basics

- Polymer basics
- Weld process and zones
- Polymer weld strength
- Material considerations
- Process selection

What is a Polymer?

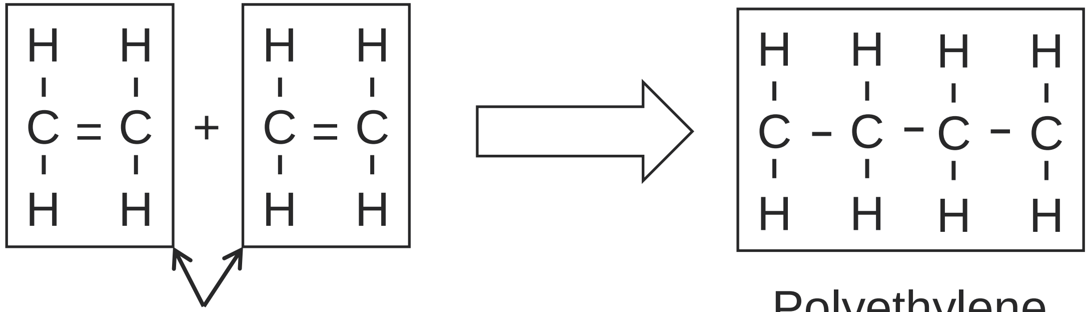


pol·y·mer

/ˈpäləmər/

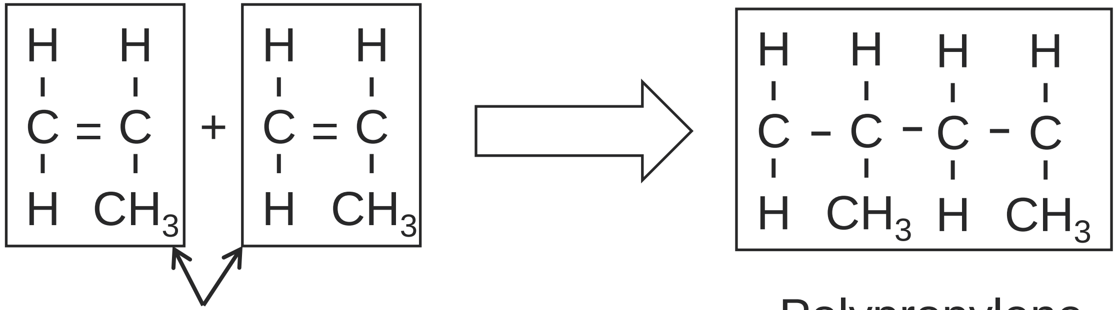
noun CHEMISTRY

a substance that has a molecular structure consisting chiefly or entirely of a large number of similar units bonded together, e.g., many synthetic organic materials used as plastics and resins.



Ethylene
“mer” groups

Polyethylene



Propylene / Propene
“mer” groups

Polypropylene

Polymer Chains

- Linear polymers - flexible
- Branched polymers - stiff
- Crosslinked polymers - unweldable

Amorphous vs. Semi-Crystalline

Can Not Weld!

POLYMER

THERMOSET | THERMOPLASTIC

AMORPHOUS

- Polymethylmethacrylate (acrylic)
- Polycarbonate (PC)
- Polystyrene (PS)

SEMI-CRYSTALLINE

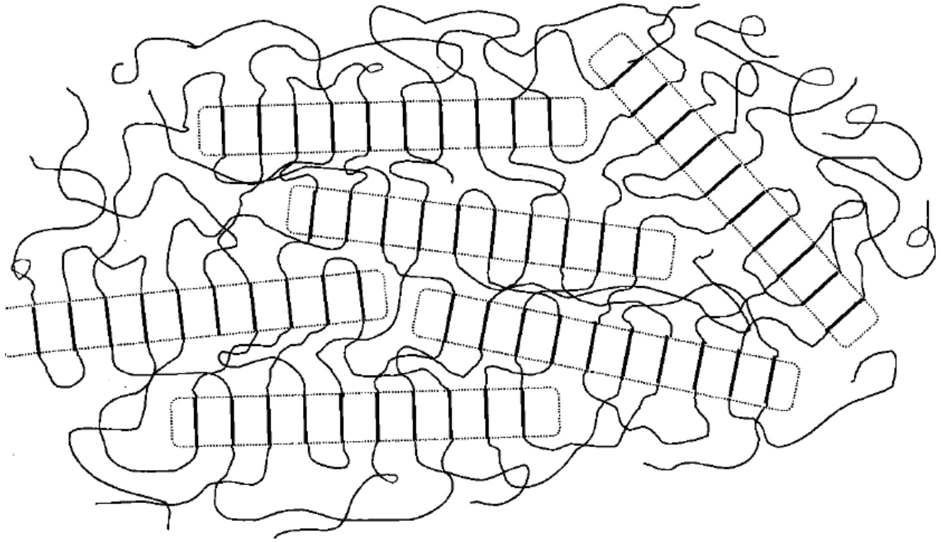
- Polyamide (nylon)
- Polypropylene (PP)
- Polybutylene Terephthalate (PBT)

Molecular Structure

- Crystalline regions are ordered areas.

- Amorphous regions are disordered.

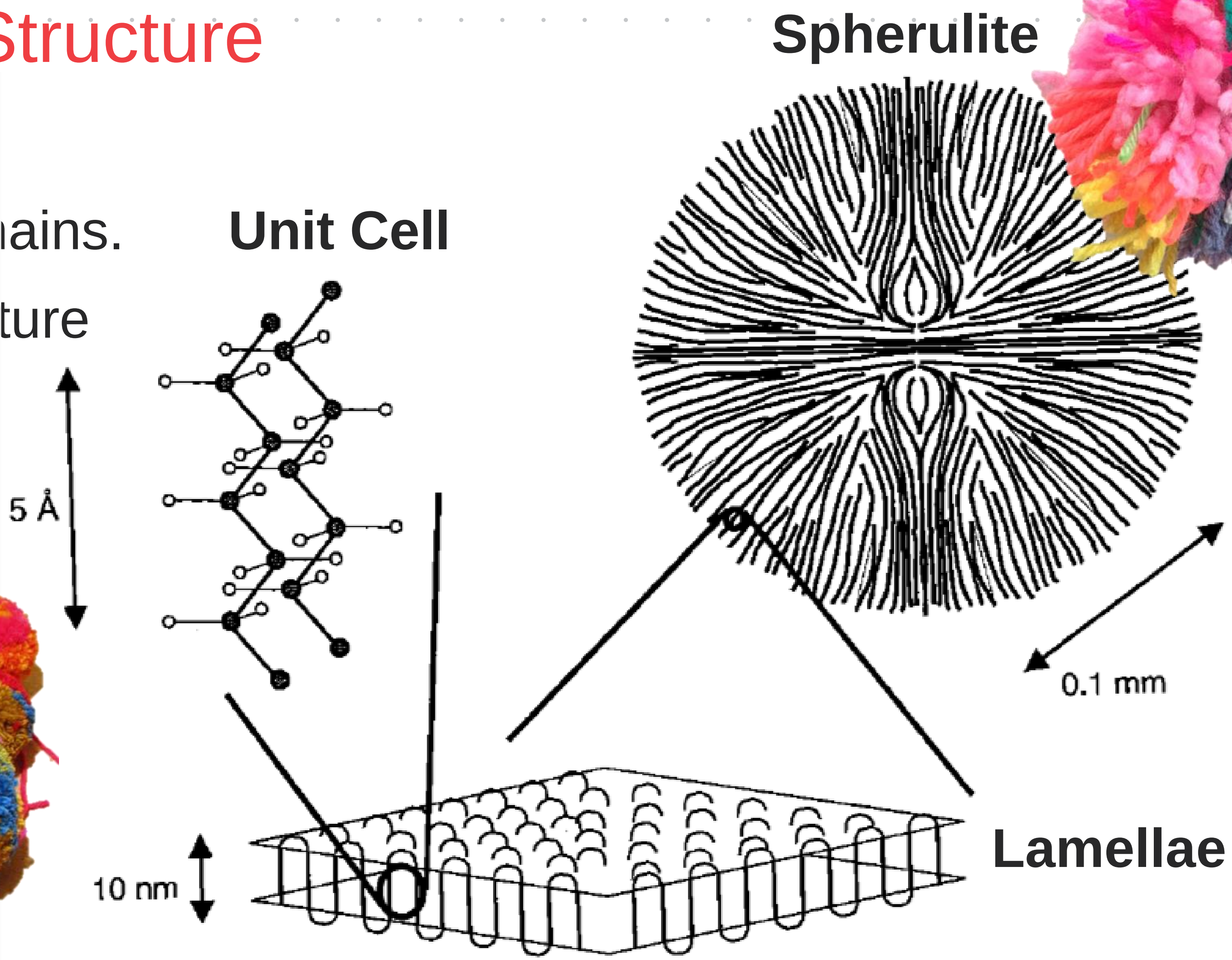
- Semi-crystalline materials have a combination of both.



Ch. 13 Crystalline Polymers, p. 511-565 Polymer Chemistry, Hiemenz & Lodge

Levels of Crystalline Structure

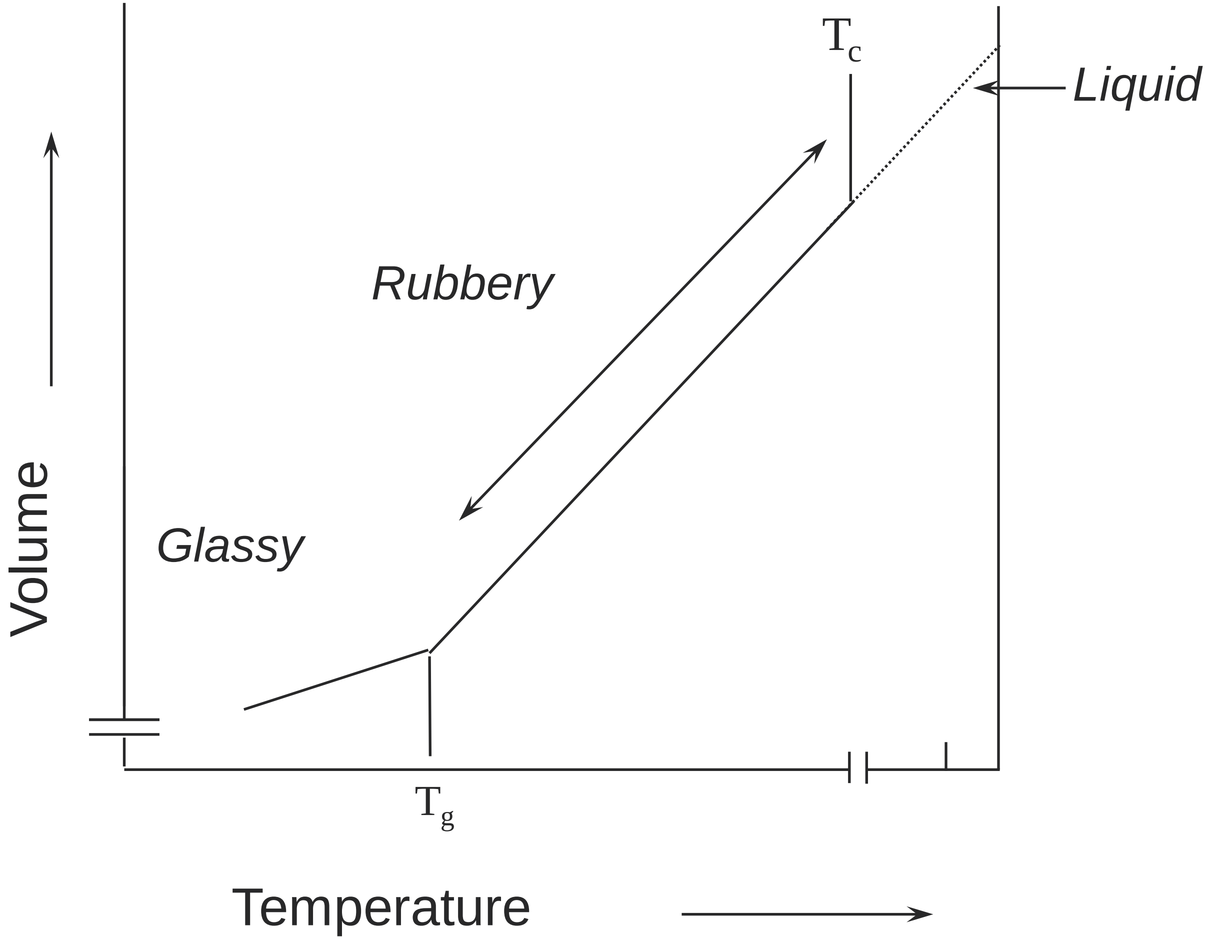
- Unit cells pack individual chains.
- Lamellae is the larger structure of unit cells.
- Spherulites are formed by lamellae.



Ch. 13 Crystalline Polymers, p. 511-565 Polymer Chemistry, Hiemenz & Lodge

Amorphous Polymers

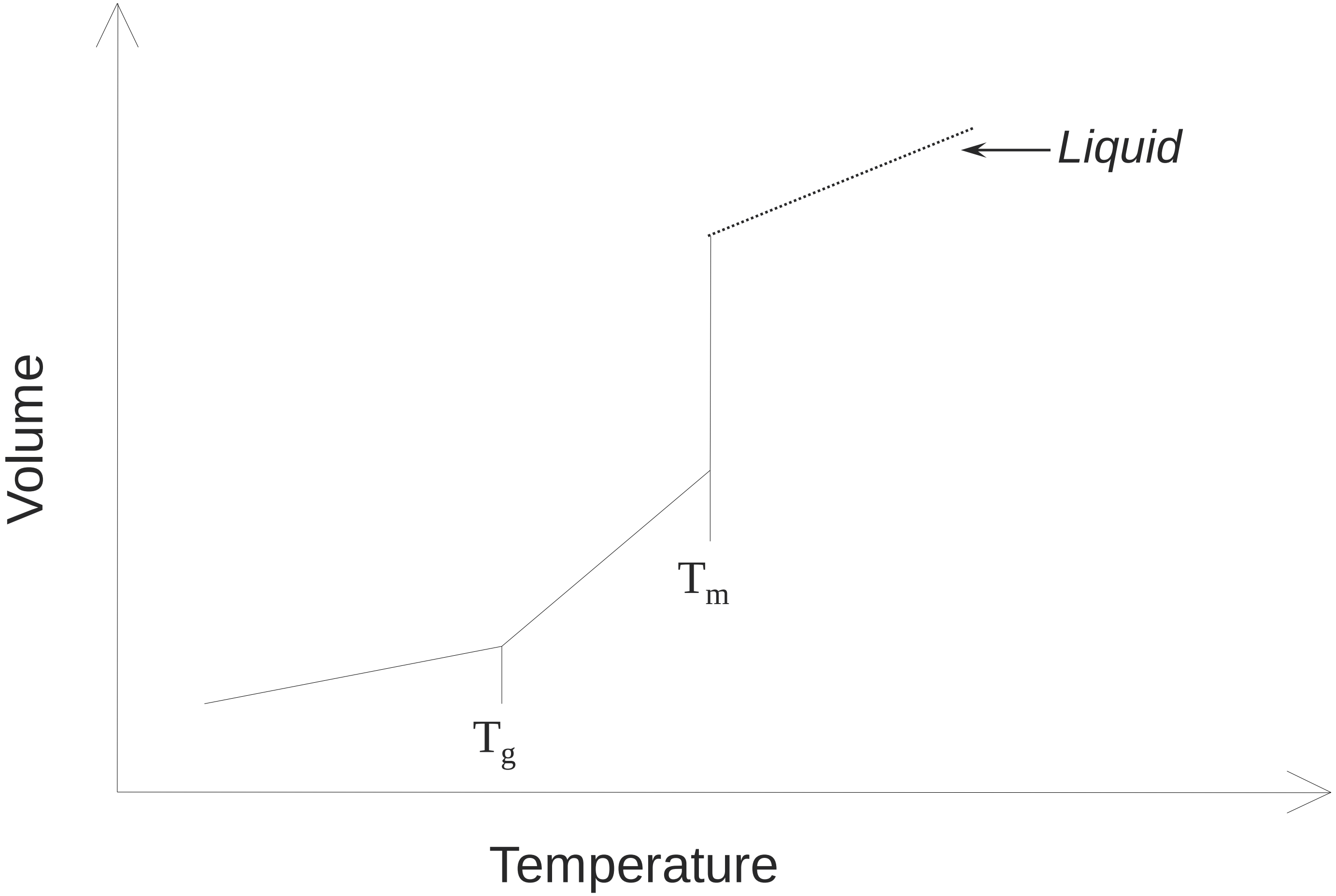
- Gradually lower viscosity as temperature rises.



T_g = Glass Transition Temperature
T_c = Critical Flow Temperature

Semi-Crystalline Polymers

- The crystalline structure must be melted, requiring heating to overcome the *heat of fusion.*



T_g = Glass Transition Temperature
T_m = Melting Temperature

Amorphous vs. Semi-Crystalline Properties

Amorphous

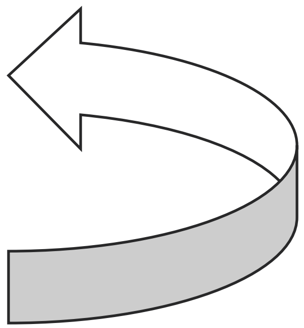
- **Easier to weld**
  - Broader processing windows.
- **T > T_g for welding**
- **Generally flexible**
- **Viscosity changes gradually above T_g**
- **More likely be transparent**

Semi-Crystalline

- **More challenging to weld**
  - Narrower processing windows.
- **T > T_m for welding**
- **Generally rigid**
- **Higher working and processing temperature**
- **Better solvent resistance**

Polymer Welding Steps

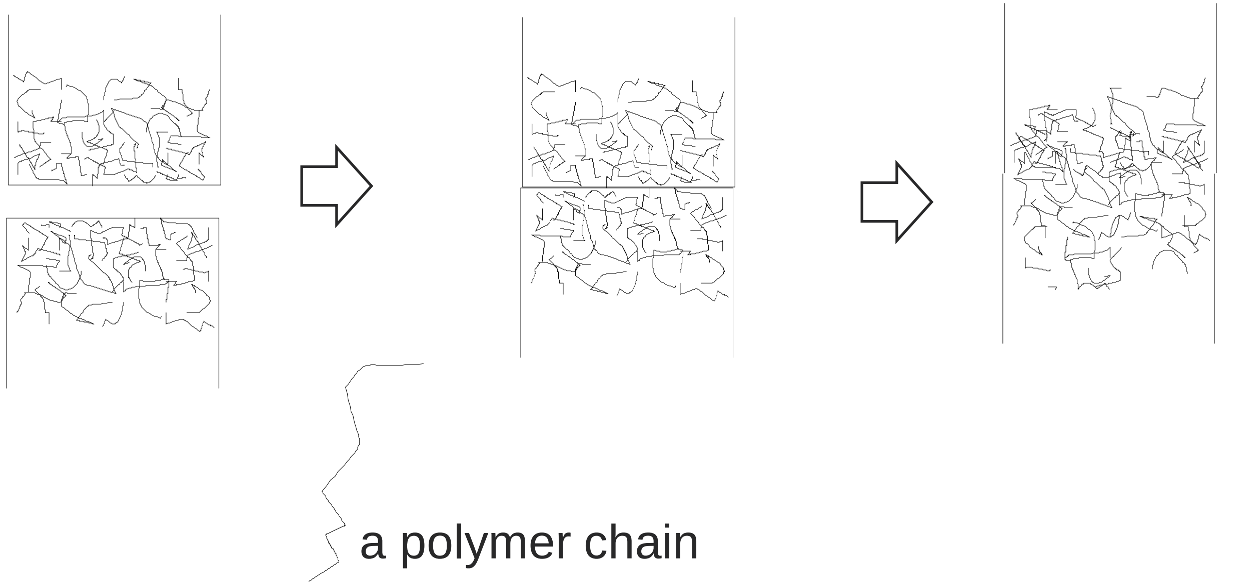
- Surface preparation
  - Joint design
  - Cleanliness
  - Texture
- Pressing
  - Constant force versus constant velocity
- Heating
  - Method of heating defines the welding process
- Cooling
  - Usually not controlled



Heating and pressing may be reversed depending on the process.

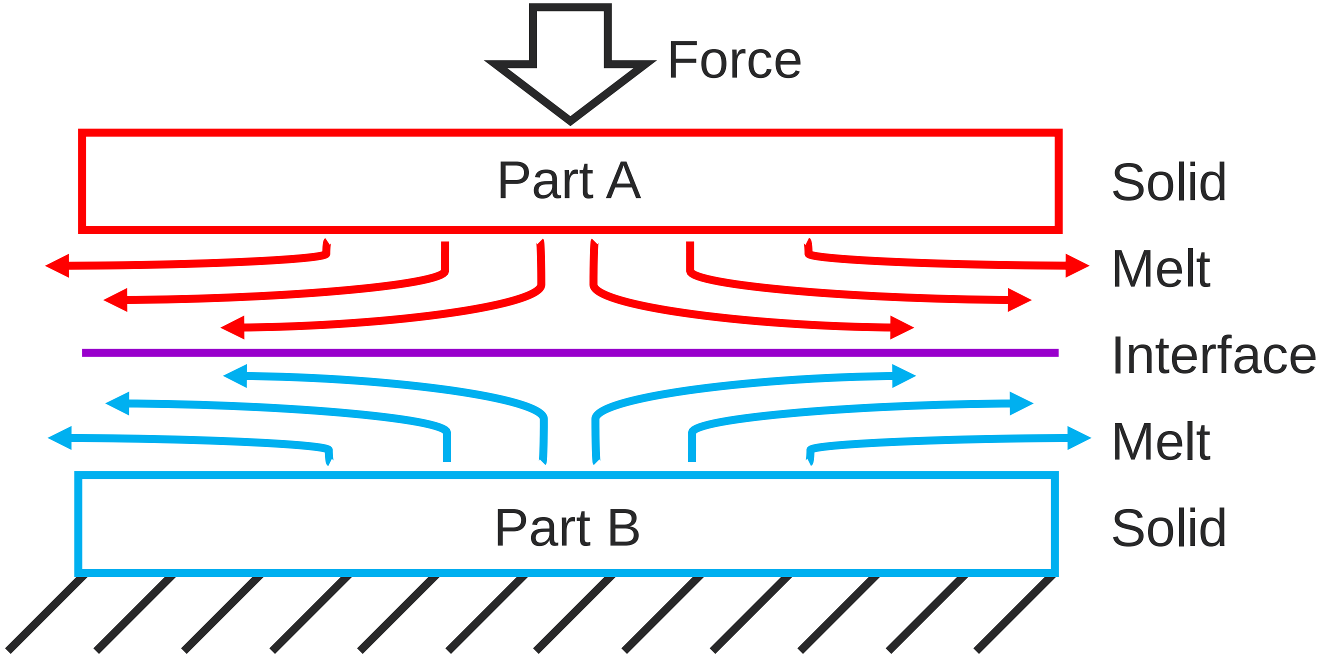
What is a weld?

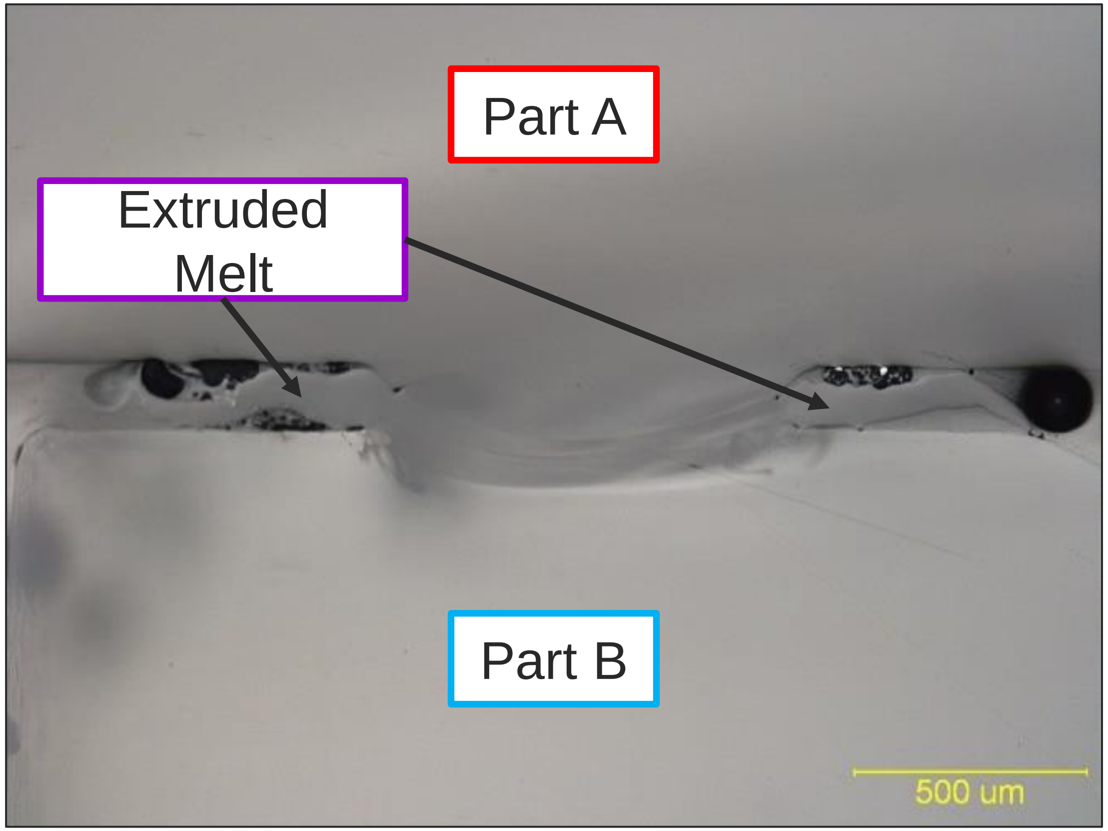
- A weld is more than just an adhesive bond (i.e., surface interactions).
  - Need intermolecular diffusion across the joint interface!
- Polymer chain entanglement across the melt layers creates a weld.



Flow of Polymer in Weld Joint

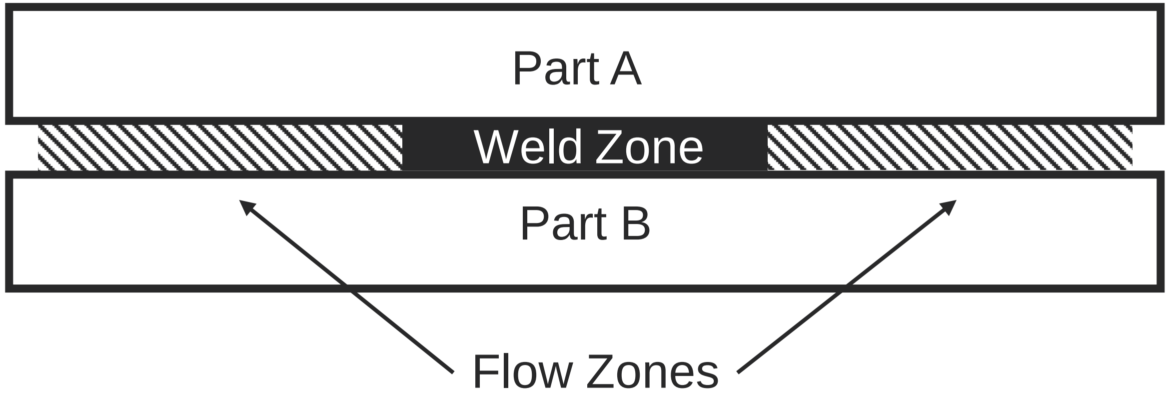
- Polymer flows transverse to collapse direction.





Zones

- Weld zone
  - Melting of base material on both sides
  - Lower velocity flow
- Flow zones
  - Melted material flows between parts, some heating and diffusion at surfaces may occur.
  - Highly oriented
  - Weaker



Factors That Affect Strength

- Joint Area
- Temperature
  - Too little prevents diffusion, too much degrades polymer
- Diffusion
  - Affected by viscosity – dependent on temperature, velocity (stress, shear rate)
  - Limited by duration
- Microstructure
  - Crystallization (semi-crystalline polymers)
  - Chain orientation (amorphous)
- Stress Concentration Geometry
  - Melt flow extension and shape
- Shrink
  - Insufficient hold time and pressure may allow separation during cooling

Temperature

- Too little heating means no chain movement and no diffusion.
  - Need to get to **critical flow temperature**
    - Temperature at which the polymer changes from acting mostly like a solid to mostly like a fluid
    - Tg + 100°C for amorphous, Tm for semi-crystalline
- Too much heating leads to degradation which weakens the polymer and may produce hazardous fumes.
  - Welding of fluoropolymers can yield hydrogen fluoride.
  - **Polyvinylchloride (PVC)** can turn brown and give off hydrogen chloride.
  - Flame-retardant plastics can produce halogens or acid gases.

What is Intermolecular Diffusion?

- Voyutski proposed that autohesion of rubber polymers occurs via a diffusion process to create a transition zone between two formerly separate surfaces.
- Rouse and Doi-Edwards each proposed models for the mechanism of diffusion via reptation.
  - Reptation => heated polymer chains vibrate and move in a snake-like fashion
- Experimentally, there is a correlation between the contact time between two polymer melt surfaces and the weld strength.
  - Fusion times greater than $\tau_d^{1/4}$ do not increase weld strength.

Intermolecular Diffusion Formula

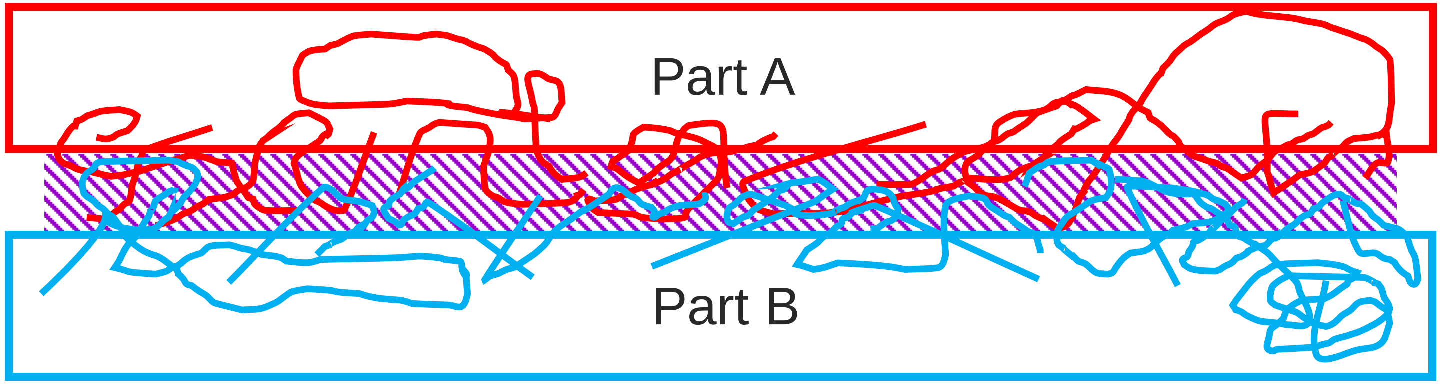
- Doi-Edwards Diffusion Model:

$$\tau_d = \frac{\zeta L^2}{\pi^2 K_B T} \qquad \zeta = \frac{36 M_0 \eta}{\rho N_A L^2}$$

  - τ_d is diffusion time
  - L is the polymer chain characteristic length
  - K_B is the Boltzmann constant
  - T is temperature
  - ζ is the monomeric friction factor[2]
  - M_0 is the monomer molecular weight
  - η is the viscosity
  - ρ is the density
  - N_A is Avogadro's number

Healing of the Weld Joint

- Yang and Pitchumani model for healing via reptation, of a weld:
- $D_h(t) = \left[\int_0^t \frac{1}{t_w(T)} dt\right]^{1/4}$
  - where $D_h(t)$ is the degree of healing as a function of time, and $t_w(T)$ is diffusion time as a function of temperature, T.
  - At full healing, $D_h(t)=1$, the weld strength equals the bulk strength.

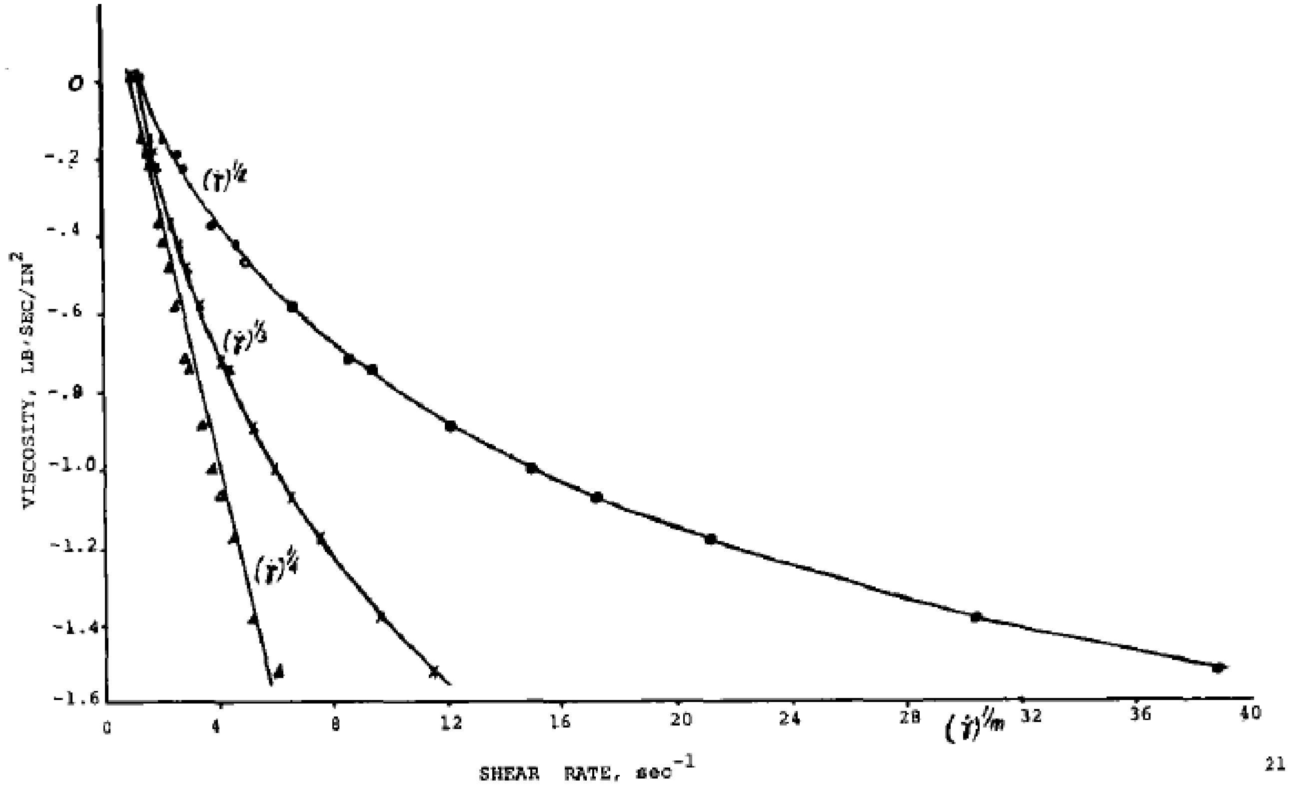


Degree of Healing Equation with Diffusion

- The Yang-Pitchumani and Doi-Edwards equations can be combined:

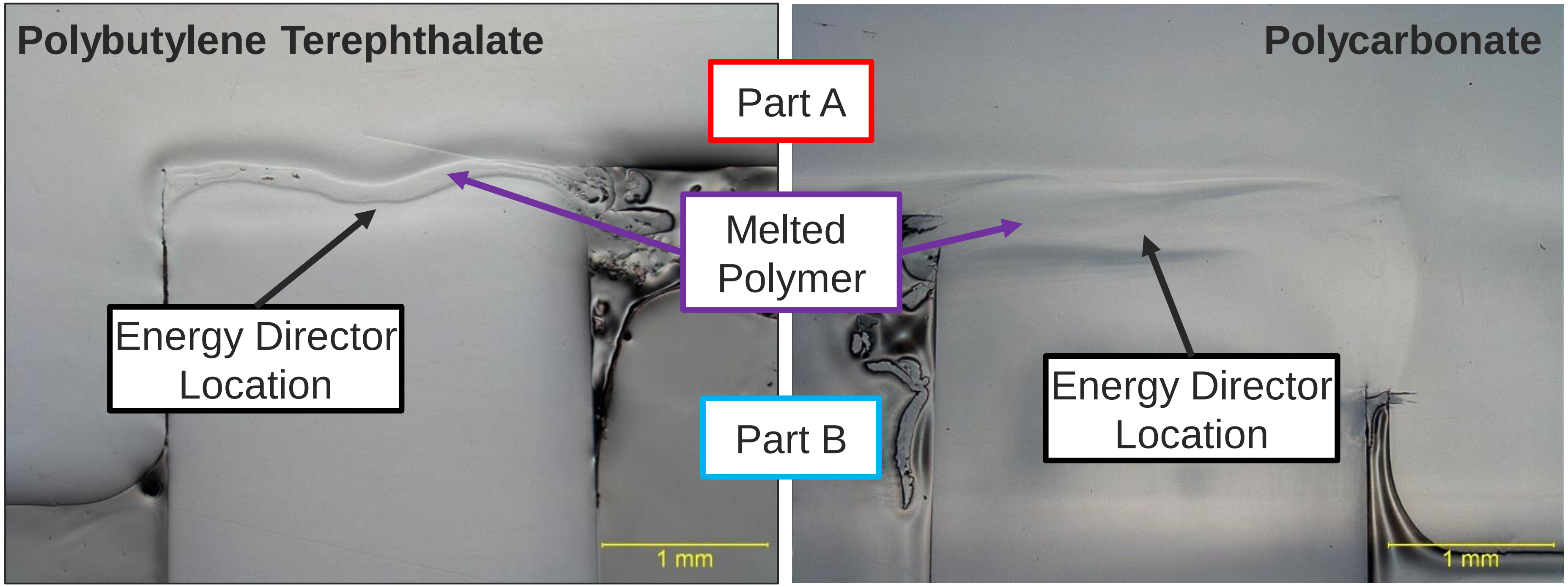
$$D_h(t) = \left[\frac{\pi^2 K_B N_A \rho}{36 M_0} \int_0^t \frac{T(t)}{\eta(t)} dt\right]^{1/4}$$

- Temperature depends on heat generation, conduction, convection.
- Viscosity depends on temperature, shear rate, material properties.
- Can be estimated via simulation



Microstructure

- Change in microstructure noted in amorphous and semi-crystalline polymers welds
  - Polymer chain orientation (amorphous)
  - Crystallinity (semi-crystalline)



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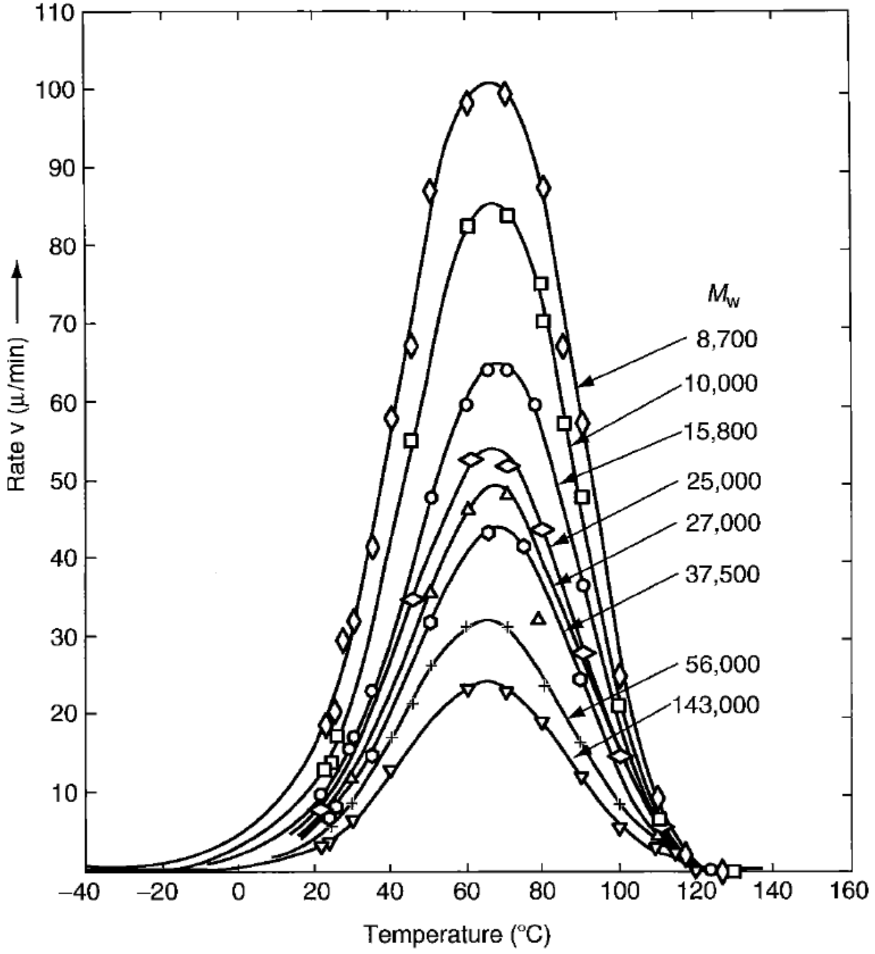
Crystallinity

- Crystallinity depends on cooling rate and stresses.
- Type of crystalline growth depends on material type.
- The Avrami equation can be used to predict the rate of crystallization:
- $\phi_C = 1 - e^{-Kt^m}$
  - where φ_C is the crystallized fraction, K is the rate constant, and m is the Avrami exponent.

Hiemenz, Lodge, 2007.

Crystal Growth Rate

- The temperature of peak growth rate is the same regardless of molecular weight.
- Crystal growth rate is always slower for polymers with higher molecular weight.
  - Greater chain entanglement to overcome



Hiemenz, Lodge, 2007.

Polymer Chain Orientation

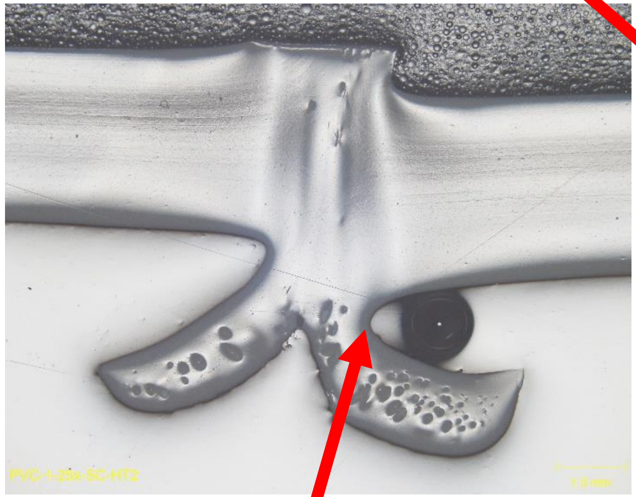
- For amorphous polymers, the highly oriented polymer chains induced by a high rate of shear flow will lead to anisotropy and a reduction in tensile strength.
  - Chain orientation can be calculated using the shear rate of the melt flow (from simulation).

$$tan\phi = r \tan\left(\frac{\dot{\gamma}t}{r + 1/r}\right)$$

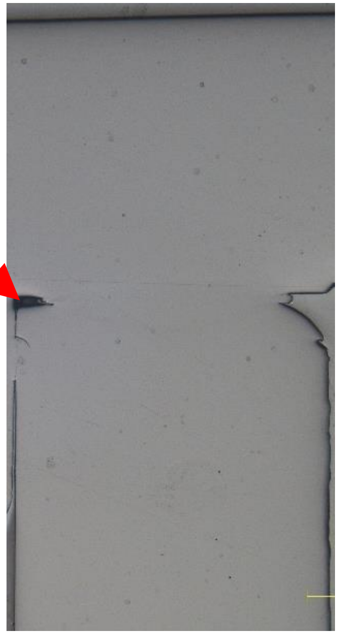
    - where Φ is the change in the orientation trajectory, r is a shape factor which is approximated as 10 for rod-like polymers, $\dot{\gamma}$ is the shear rate, and t is the time under flow.

Stress Concentration

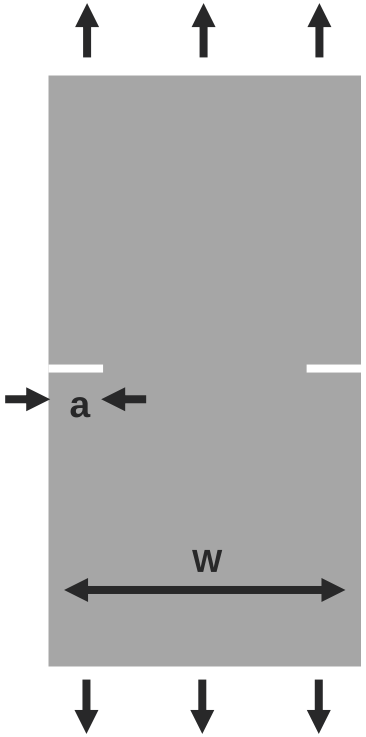
- Edge Cracks



- Sharp Corners from Melt Extrusion



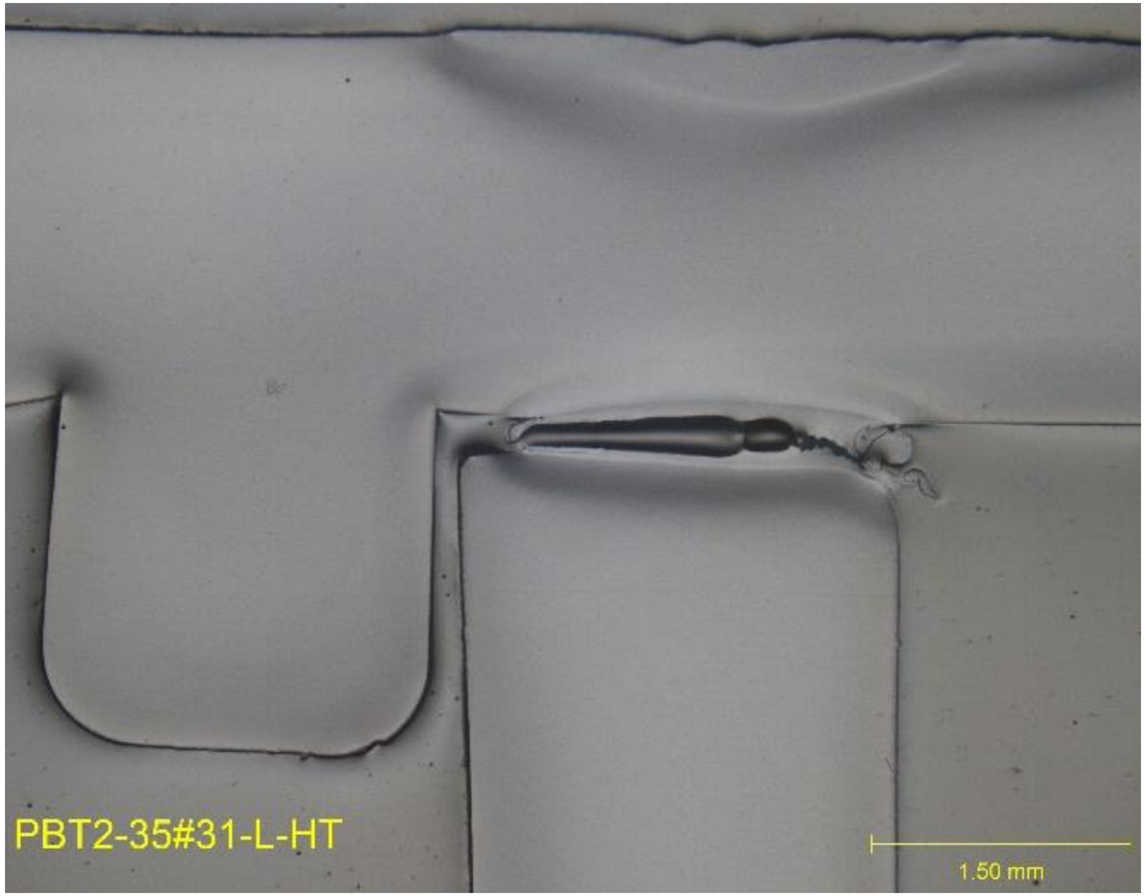
Weld geometry



Strip with two edge cracks

Shrink

- Materials with a high coefficient of thermal expansion will shrink significantly on cooling.
- Polymers with higher crystallinity will experience more shrink.
- If insufficient pressure is applied during hold, or for insufficient time, voids in the weld may occur.



Material Quality and Consistency

- Suppliers/Batches
  - Material properties may not be consistent, large changes can affect the weld.
- Regrind
  - Affects material properties, thus weldability
- Molding/Extrusion/Forming Processes
  - The process used to shape the polymer into the form to be welded affects material properties.
  - Material may be degraded or have residual stress before welding.

Effects of Common Fillers and Additives

- Flame retardant
  - May reduce processing window if reacts below polymer degradation temperature
- Mold release/Lubricants
  - Reduces intermolecular and surface friction
- Impact modifiers/Plasticizers
  - Inhibits transfer of ultrasonic vibrations through a part
- Glass and mineral filler
  - Reduces the amount of base resin available to weld
  - Often concentrates at the part surface, making initial heating more difficult
  - Increases wear on the tooling
  - Max about 33 wt.%

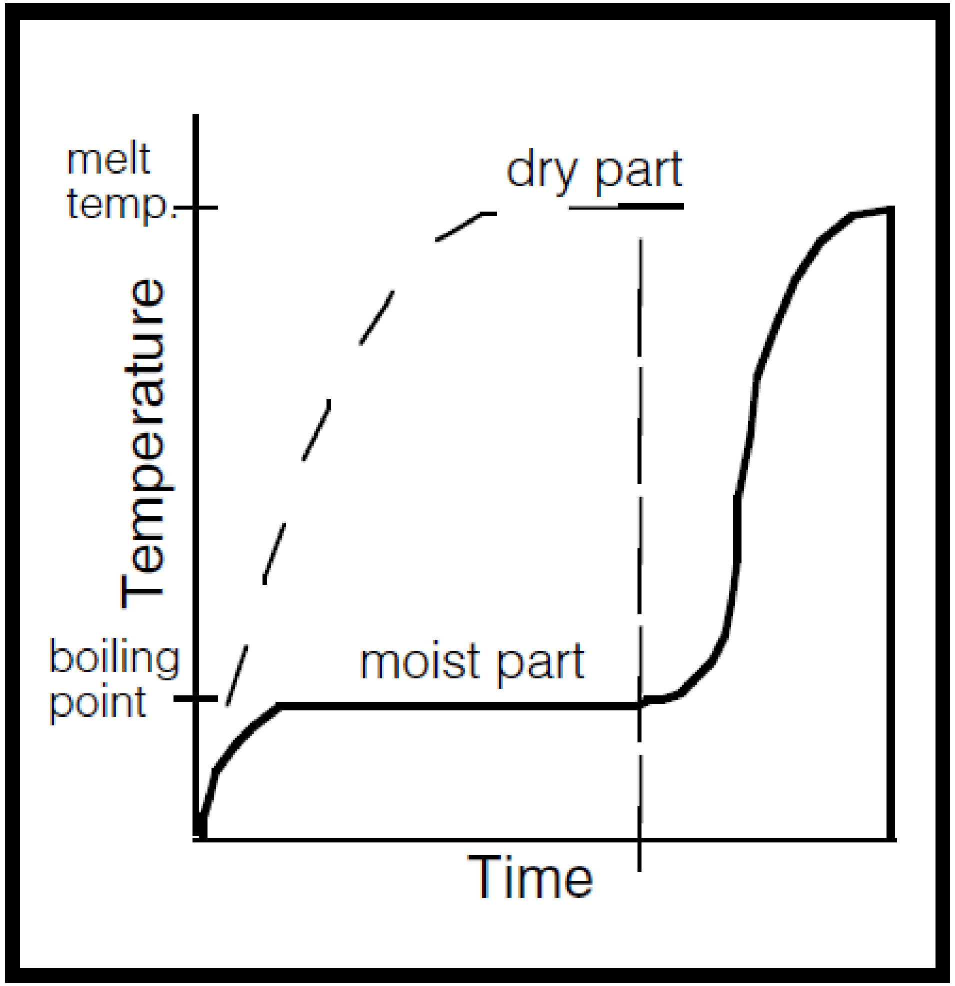
Effect of Glass and Talc Fill - Hot Plate Welded Polypropylene

Filler Type	Percent Filler	Bulk Strength	Weld Strength	Weld Strength as a Percent of Bulk Strength
Glass	0	38.4	38.9	100%
Glass	20	43	34	78%
Glass	30	48	26	55%
Talc	0	41	40	99%
Talc	20	39	27	68%
Talc	40	36	16	45%

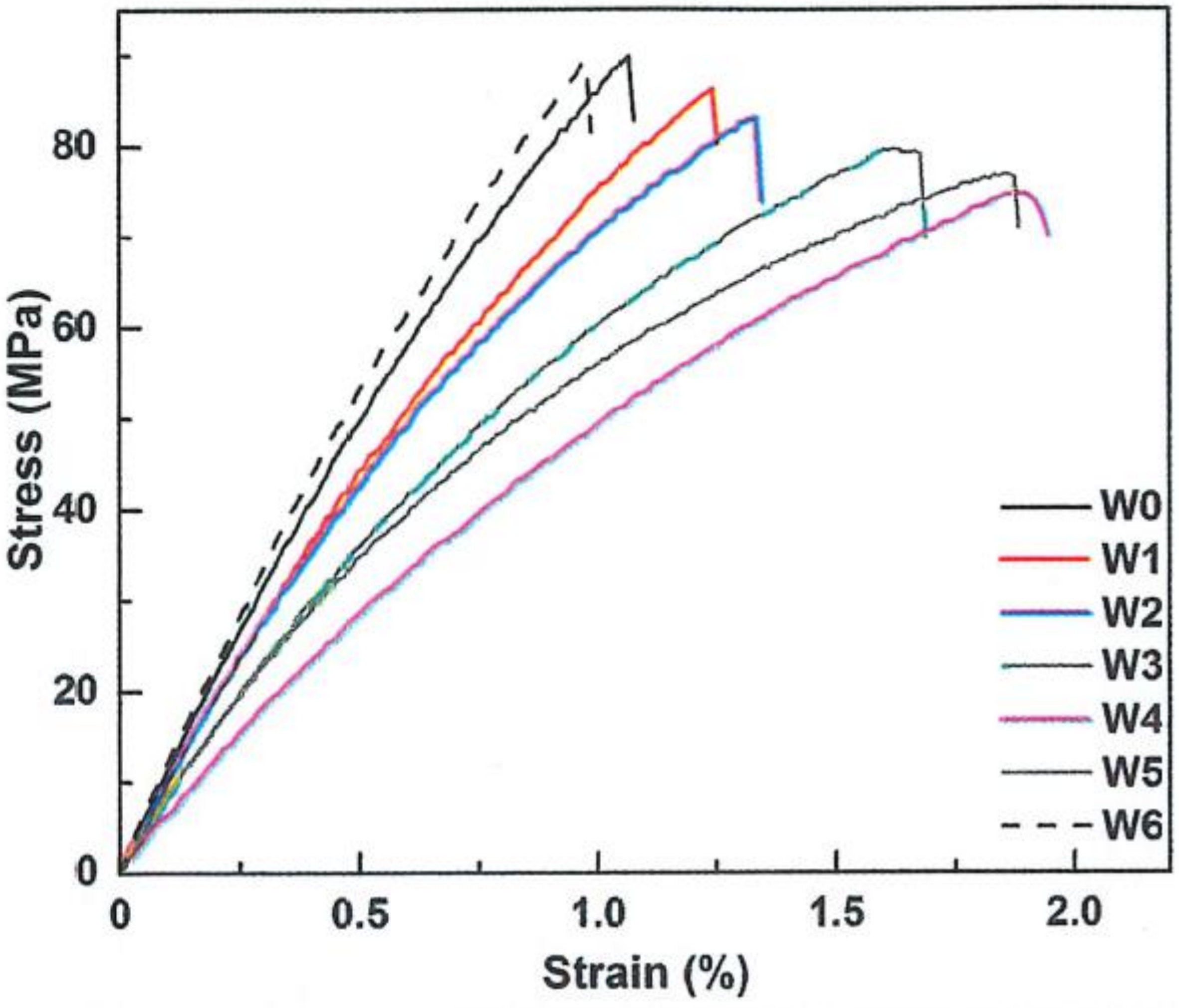
Potente and Brussel, ANTEC 98, 1062.

Hygroscopicity

ABS
PA (Nylon)
PBT
PC
PET
PU



Effect of Moisture – Increased Brittleness in Weld



Sample	Moisture (wt%)
W0	0
W1	0.4
W2	0.9
W3	1.7
W4	2.6
W5	2.4
W6	0

Zhi, Tan, Liu, "Effect of moisture on the ultrasonic welding of carbon-fiber reinforce polyamide 66 composite", Welding Journal, *Vol. 96, June 2017.*

Process Selection

- Component size and joint geometry
- Material properties
- Strength and cosmetic requirements
- Production speed

Common Processes

- Ultrasonic welding
- Vibration welding
- Spin welding
- Laser welding
- Infrared welding
- Radio frequency (RF) welding
- Resistive/induction welding
- Hot plate welding
- Extrusion welding
- Hot gas welding
- Adhesives

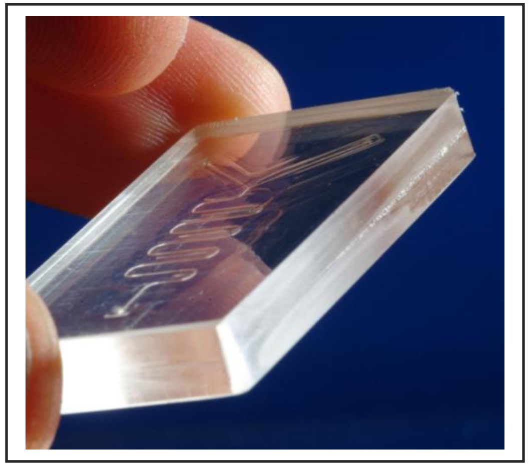
Ultrasonic Welding

- Common applications:
  - Car components, food packaging, electronics, medical devices, toys

- **Advantages:**
  - Fast (< 1 second)
  - Advanced, modern equipment with sophisticated control and monitoring features
  - Economical

- **Disadvantages:**
  - Material dependent
  - Geometry limitations
  - Requires specific joint design
  - Requires tight dimensional tolerances of molded parts

Laser Welding



- Common applications
  - Medical devices, housings, headlights, taillights

- **Advantages**
  - Very clean process
  - Little to no weld flash
  - Precise control/selective heating
  - No vibration
  - Simple joint designs (uniform contact of mating surfaces)

- **Disadvantages**
  - Relatively new welding process (still learning)
  - Optical properties of polymer are very critical.
  - Eye protection is mandatory for operators.

Vibration Welding

- Common applications
  - Headlights, taillights, instrument panels, manifolds, containers

- **Advantages**
  - Fast (2-10 s)
  - Applicable to large parts
  - Can weld internal walls
  - Well-established process, with excellent control possible

- **Disadvantages**
  - High capital cost (equipment and fixtures)
  - Noise
  - Thin walls tend to flex or rock rather than rub against the other weld surface.

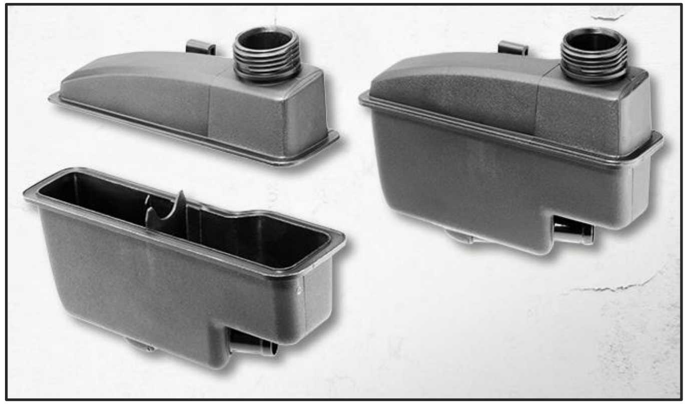
Hot Plate Welding

- Common applications
  - Pipes, fuel tanks, window frames, car components, pallets

Advantages
- Simple
- Reliable
- Suited for larger and complex part geometries
- Wide operating windows
- Relatively high tolerance to imperfections on the mating surfaces

Disadvantages
- Relatively slow
- Energy inefficient
- Produces significant flash
- Potential for sticking
- Parts have to be moved during the process.

Infrared Welding



- Common applications
  - Automotive lighting, tanks, housings

- **Advantages**
  - No vibration
  - No sticking of polymer to tooling
  - Accommodates complex geometry
  - Simple joint designs (uniform contact of mating surfaces)

- **Disadvantages**
  - Relatively new welding process (still learning)
  - Optical properties of polymer are very critical.
  - Parts have to be moved during the process.
  - Weld flash

Radio Frequency Welding

- Common applications
  - Clamshell packaging, tarps, inflatables, medical bags, seat covers, mattresses
  - 0.001-0.050 in.

- **Advantages**
  - High energy efficiency
  - Fast
  - Bonds film or thin sheets

- **Disadvantages**
  - Shielding requirement
  - Expensive equipment
  - Material dependent

Resistive/Induction Welding

- Common applications
  - Appliance components, furniture, fluid tanks, car components

Advantages
- Non-contact heating method
- Able to weld large parts
- Welding of similar, as well as dissimilar materials

Disadvantages
- High cost due to insert (ferromagnetic material)

Spin Welding

- Common applications
  - Floats, car components, pressure vessels, pipes, insulated cups/bowls

Advantages
- Rapid
- Relatively low cost of equipment
- High-quality welding for a wide range of thermoplastics

Disadvantages
- Only suitable for circular components
- Produces particulate (plastic dust)

Hot Gas Welding

- Common applications:
  - Pipes, large tanks, furniture, inflatable boats

◆ **Advantages**
- Flexible
- Easy, after some training
- Economical
- Suited to short runs
- Practical for assembly or repair of very large structures

◆ **Disadvantages**
- Slow
- Some variability between different welders
- Uneven heating for large joint areas

Extrusion Welding

- Common applications
  - Pipes, large tanks, 3D printing

Advantages

- Flexible, can be applied to most part geometries
- Can be inexpensive
- Strong welds, if parent material is cleaned and preheated

Disadvantages

- Obvious weld line
- Material restrictions
- Dependent on operator skill or expensive automation

Adhesive Bonding

- Common applications
  - Microchips to battleships

Advantages

- Works with dissimilar materials
- Works with a wide variety of joint designs
- Outstanding stress distribution
- Low capital cost

Disadvantages

- Bonding surfaces must be clean.
- Bond properties are completely independent from base materials.
- Strength development versus time
- Flow containment
- Consumable cost

Summary

Process	Part Size	Strength	Cosmetics	Cycle Time	Equipment Cost	Consumables
Ultrasonic Welding	Small	Good	Good	Fast	$	No
Spin Welding	Small	Good	Good	Fast	$	No
Vibration Welding	Small to Large	Very Good	Fair	Medium	$$$	No
Hot Plate Welding	Small to Large	Very Good	Fair	Medium	$$	No
Laser Welding	Small to Large	Very Good	Very Good	Varies	$$$	Sometimes
Infrared Welding	Medium to Large	Very Good	Fair	Medium	$$	No
Resistive / Induction Welding	Small to Medium	Good	Good	Slow	$$	Yes
Radio Frequency Welding	Small	Very Good	Very Good	Fast	$$	No
Mechanical Fasteners	Small to Large	Fair	Fair	Slow	$$	Yes
Snap Fit Joints	Small	Low	Good	Fast	$	No
Adhesive Joining	Small to Medium	Fair	Good	Slow	$$	Yes

Ultrasonic Welding

- Physics of the Process
- Equipment and Parameters
- Material Considerations
- Design Considerations
- Troubleshooting

Ultrasonic Welding

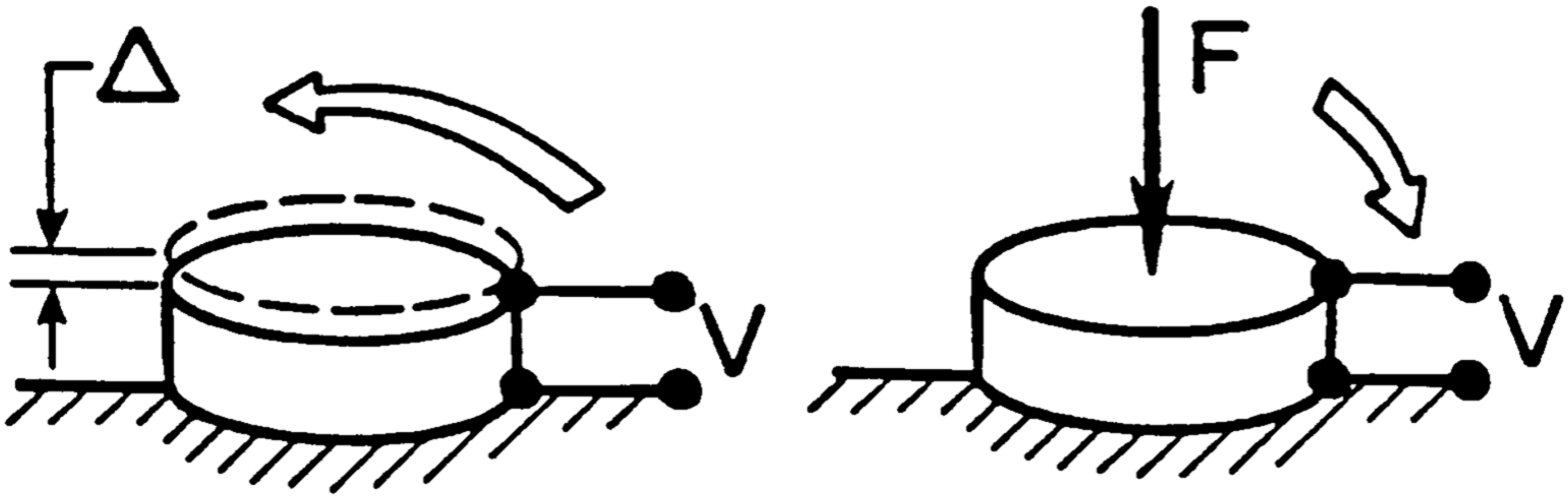
- Common applications:
  - Car components, food packaging, electronics, medical devices, toys

Advantages:
- Fast (< 1 second)
- Advanced, modern equipment with sophisticated control and monitoring features
- Economical

Disadvantages:
- Material dependent
- Geometry limitations
- Requires specific joint design
- Requires tight dimensional tolerances of molded parts

Piezoelectric Effect

- Special ceramics expand and contract when activated by a current:
  - Ultrasonic equipment uses a DC that is switched on and off rapidly.
- Conversely, when the ceramics change shape (compression, heating, etc.), they produce an electric charge.

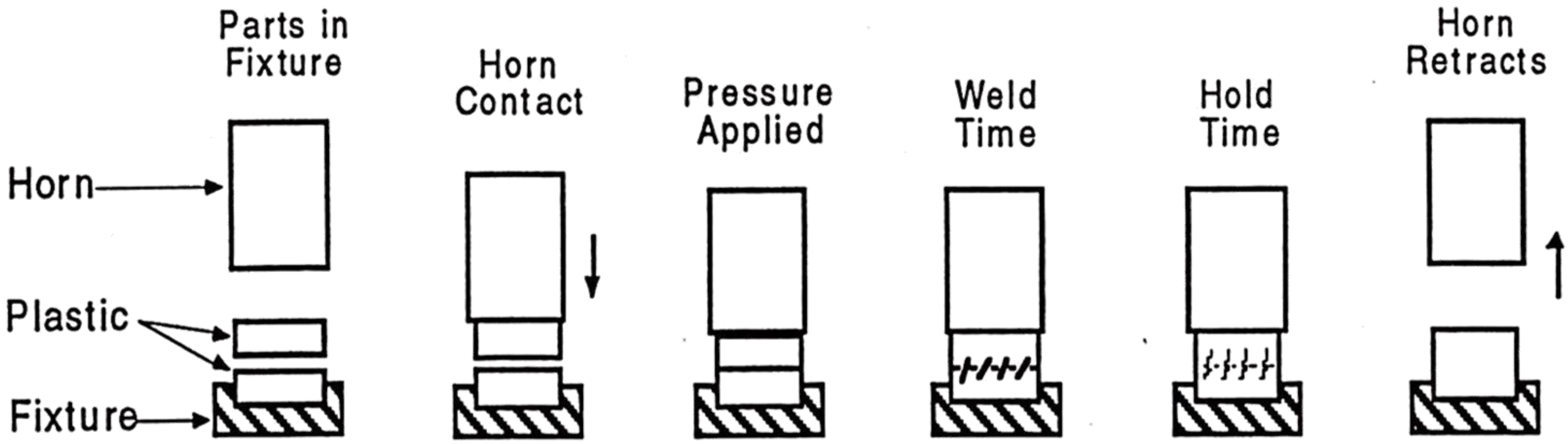


Process Physics

- Power = Force × Velocity = Energy/Time
- Viscoelastic heating:
  - $Q = (\varepsilon^2 / 2) \times (E'' \cdot \omega)$
    - *Q* is heat generation (energy / time / volume)
    - *ε* is strain amplitude
    - *E″* is loss modulus
    - *ω* is frequency of vibration

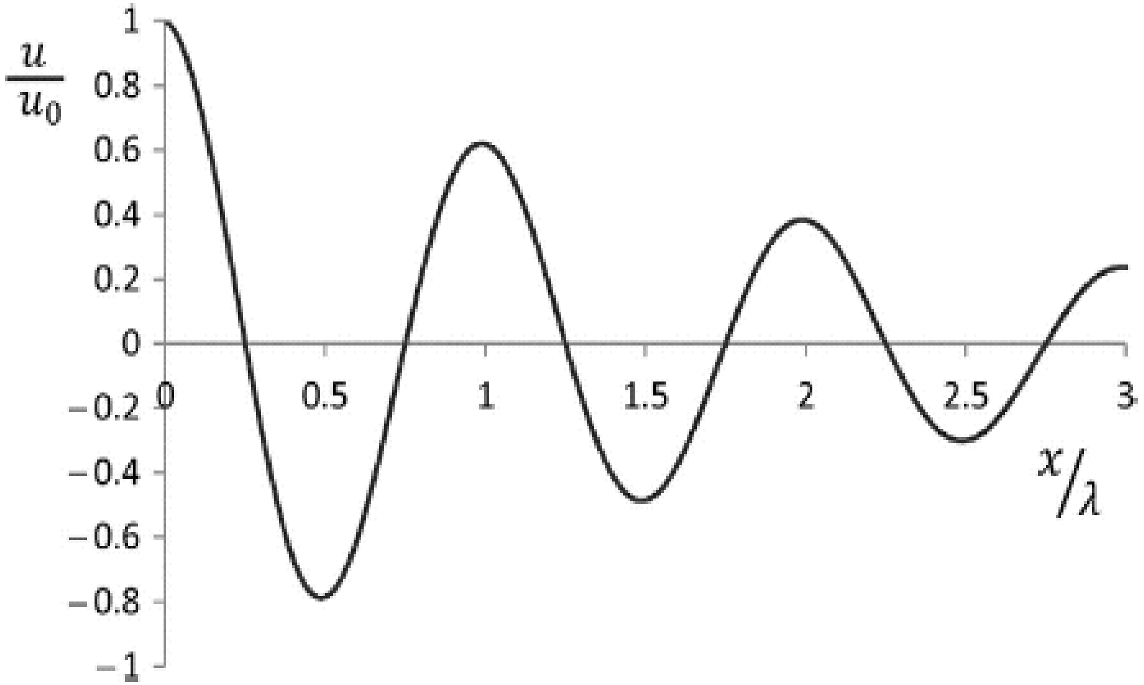
◆ **Heating rate is dependent on loss modulus, and shape (which changes as energy director melts)**

Process Steps



Attenuation and Phase Shift

- Phase depends on wave velocity in the polymer and distance to joint.
- Attenuation is loss in amplitude due to absorption of kinetic energy by viscous portion of the plastic.



Gallego-Juarez, Graff, 2015.

Attenuation and Phase Shift *(continued)*

- Benatar combined attenuation and phase:
  - Based on 1D-bar wave equation

$$u(x,t) = u_0 e^{-\alpha x} e^{-i\omega\left(\frac{x}{v}-t\right)}$$

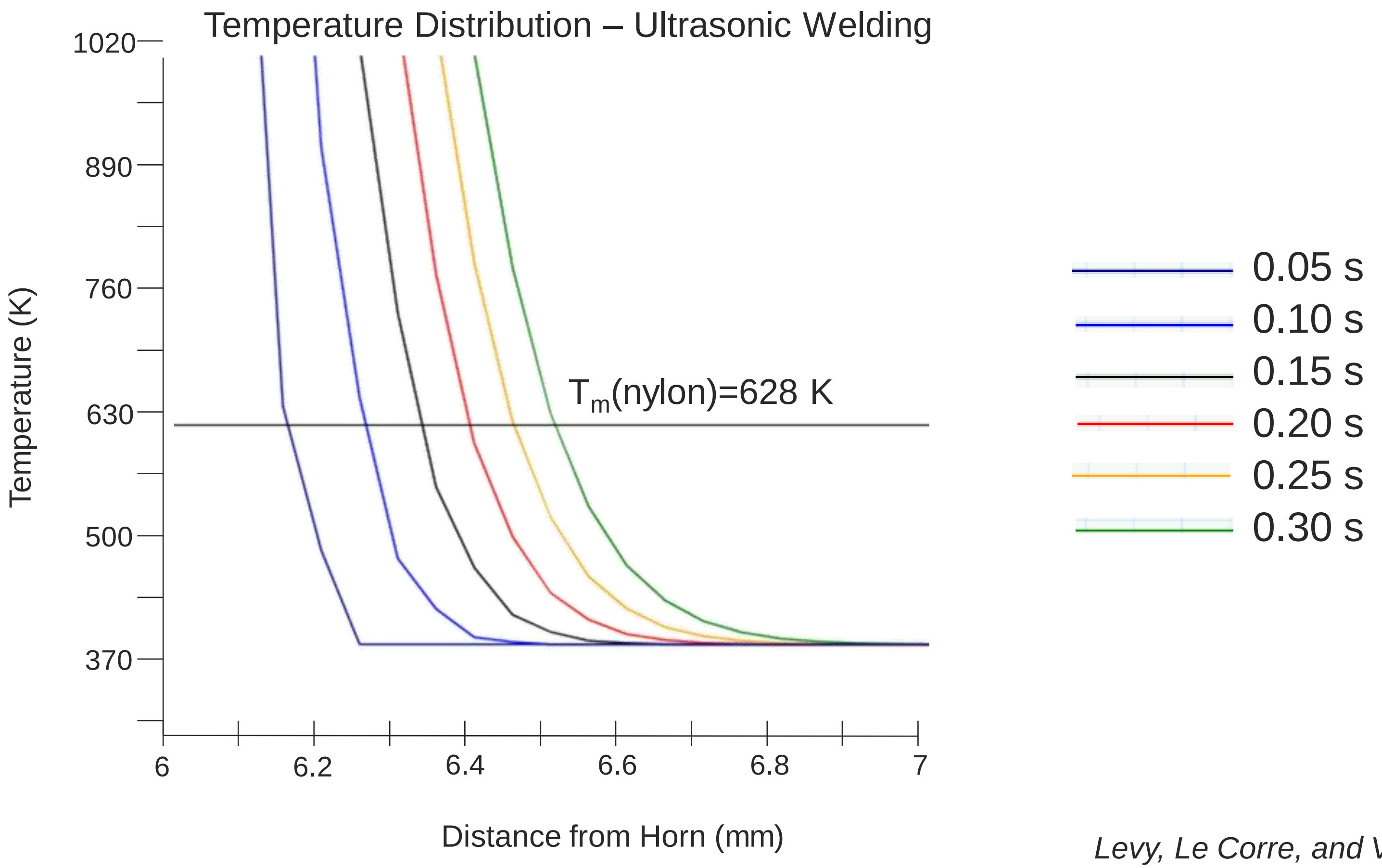
$$\alpha = \frac{\omega\sqrt{\rho}E^{IV}}{|E^*|}, v = \frac{|E^*|}{\sqrt{\rho}E^{III}}$$

  - Where:
    - *u(x,t)* is amplitude as a function of distance and time
    - u_0 is the amplitude at x=0 (at horn contact surface)
    - $E^{III} = \sqrt{|E^*|}\cos(\frac{\delta}{2})$, relates to storage component
    - $E^{IV} = \sqrt{|E^*|}\sin(\frac{\delta}{2})$, relates to loss component

Benatar, Cheng, 1989.

Internal Heat Generation

- Heat generation rate:
  $Q = \frac{1}{2}\omega E'' \varepsilon^2$



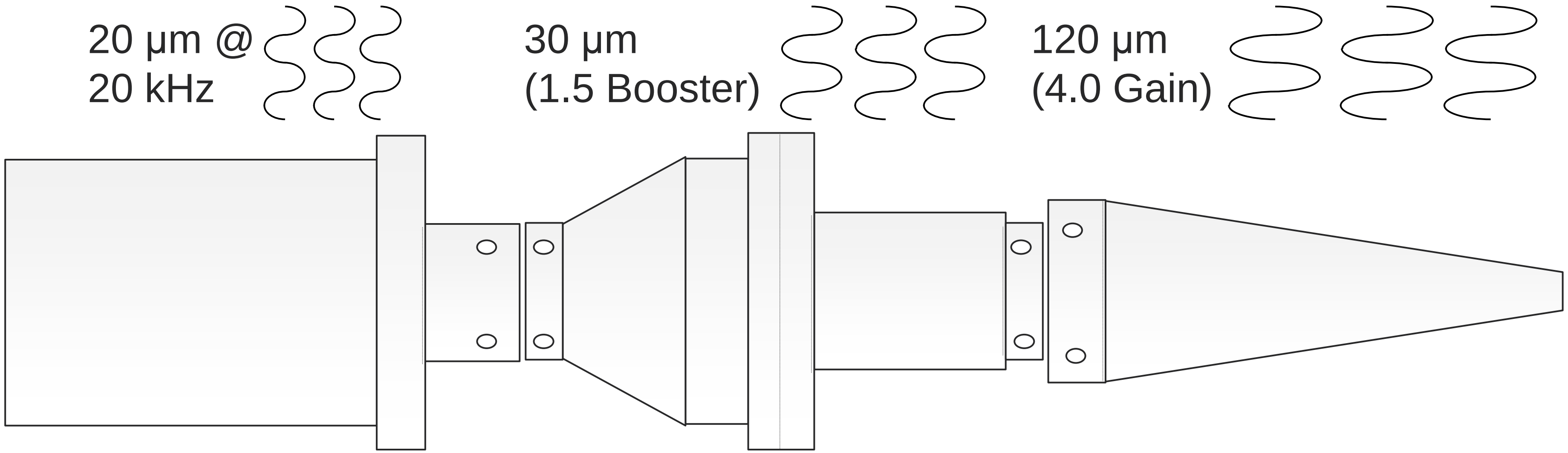
Levy, Le Corre, and Villegas, 2014.
Marcus, Anantharaman, and Aldaz, 2013.

Ultrasonic Components

Transducer transforms electrical energy into mechanical motion via piezoelectric ceramics

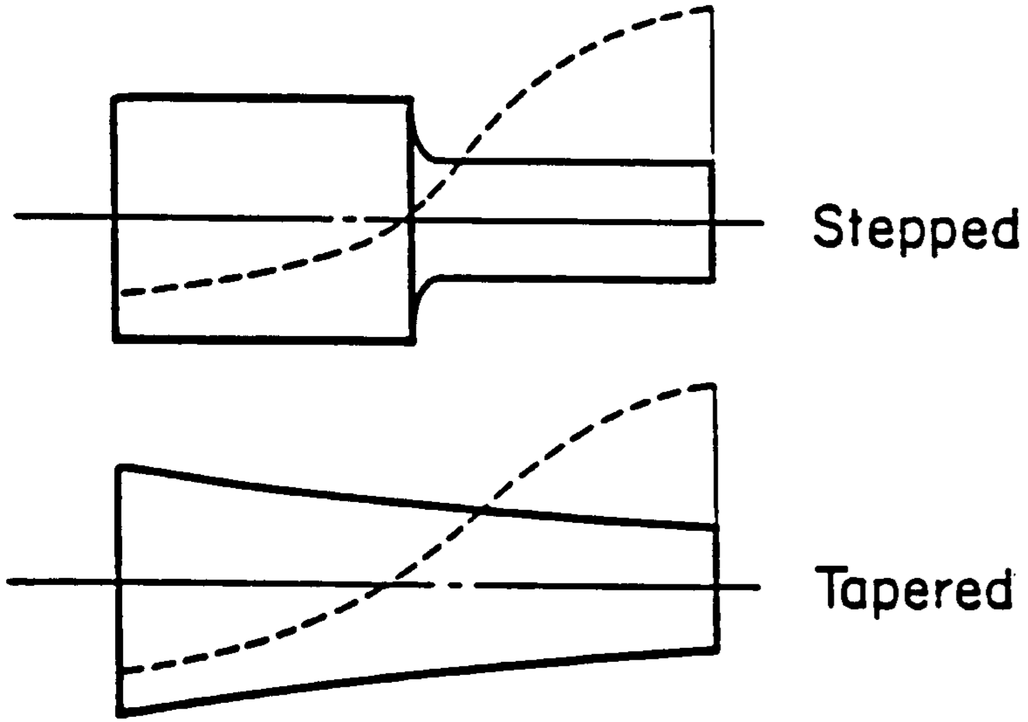
Booster used to adjust the amplitude of the ultrasonic movement

Horn is shaped to contact the part and can magnify the amplitude of the ultrasonic movement even further



Ultrasonic Horns

$$Gain = \frac{\text{Mass}_{(\text{upper})}}{\text{Mass}_{(\text{lower})}}$$



Simplification: Area (upper)/Area (lower)

- Density is uniform
- Upper and lower height are equal
- Does not account for the transition radius

Ultrasonic Welding Process Parameters

- **Primary process variables:**
  - Frequency (50-15 kHz)
  - Welding mode used
    - Time
    - Energy
    - Distance
    - Absolute distance
    - Peak power
  - Amplitude of vibration
  - Weld force/speed
  - Trigger force
- **Secondary process variables:**
  - Travel speed
  - Hold time
  - Hold pressure

Frequency and Amplitude

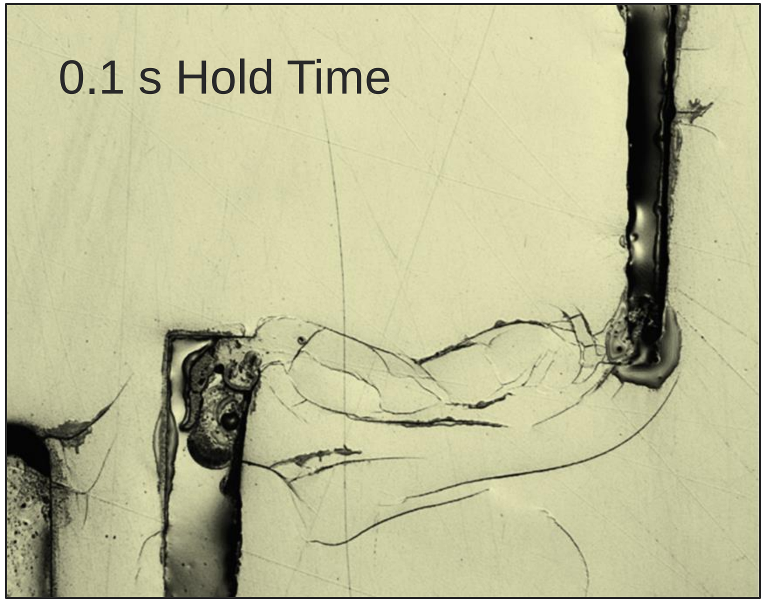
- Frequency:
  - Choice dependent on size of parts and material requirements.
  - Lower frequency = bigger parts, more amplitude.
- Amplitude:
  - Typically 50-150 microns of amplitude required, dependent on type of plastic and frequency being used.
  - Example: ~20 microns (from 20-kHz transducer) × 1.5 (booster gain) × 3.0 (horn gain) = 90 microns peak-to-peak.

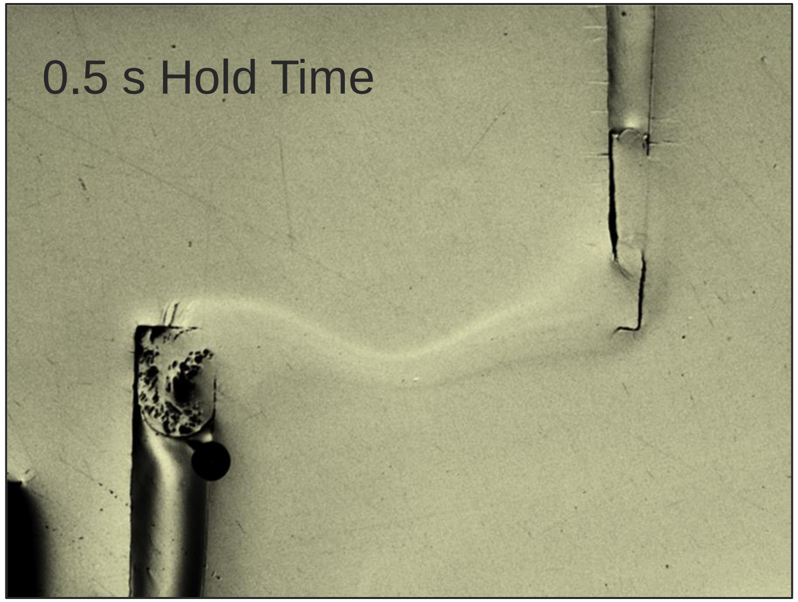
Weld Settings

- Trigger method:
  - By force recommended, unless part is weak walled.
  - Staking/swaging => pre-trigger should be used.
  - For warped parts, can use trigger delay by force.
- Weld mode and duration (time, energy, distance):
  - Welding by distance recommended for consistency
    - Set the value to match the height of the designed energy director.
  - For thin films, use energy.
  - Time can be used for initial process development or if welder only has time mode.

Weld Settings

- Hold mode and duration (time, distance):
  - A hold time of 0.5 s is generally considered minimal, unless a need for high speed is balanced by testing to confirm acceptability.

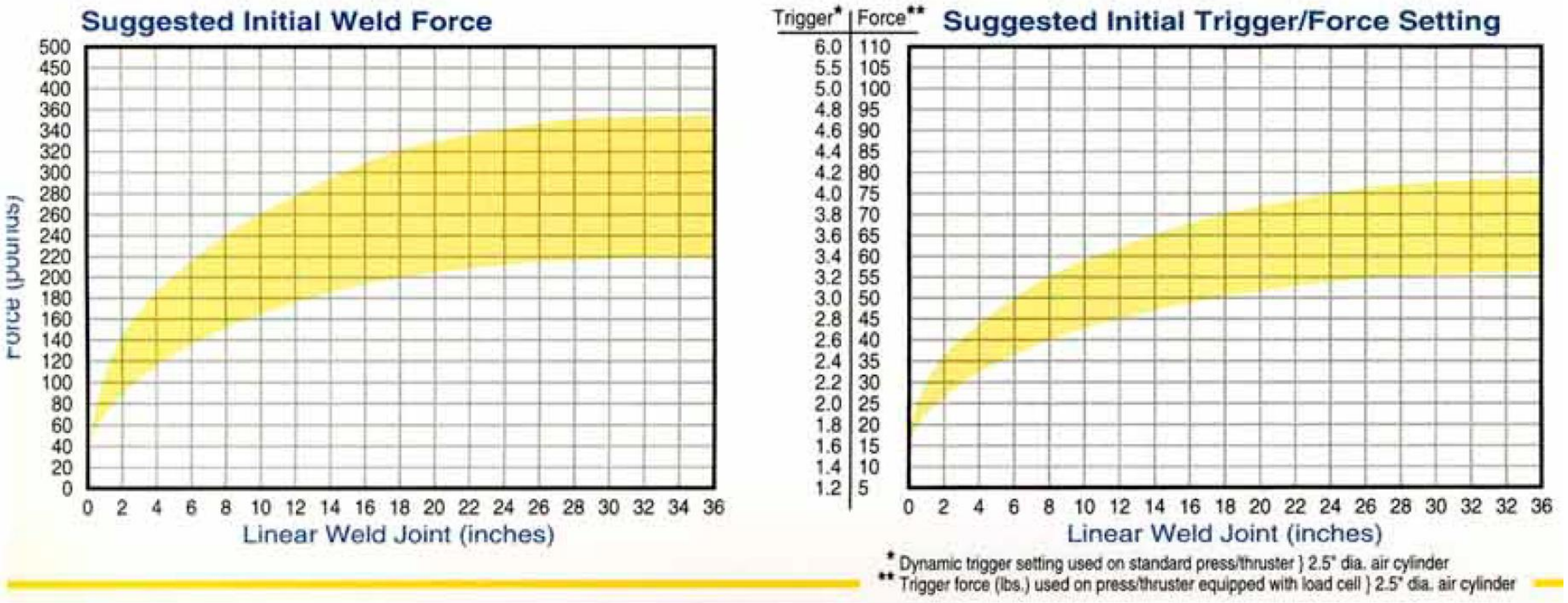




Method of Motion Control

- Pneumatic:
  - Constant force
  - Rate of displacement depends on material viscosity and load applied
  - Not well suited to consistent displacement needs.
- Servo:
  - Constant velocity
  - Force depends on material viscosity and speed
  - Displacement rate may be unsuited to viscosity, additional development may be needed.

Recommended Force



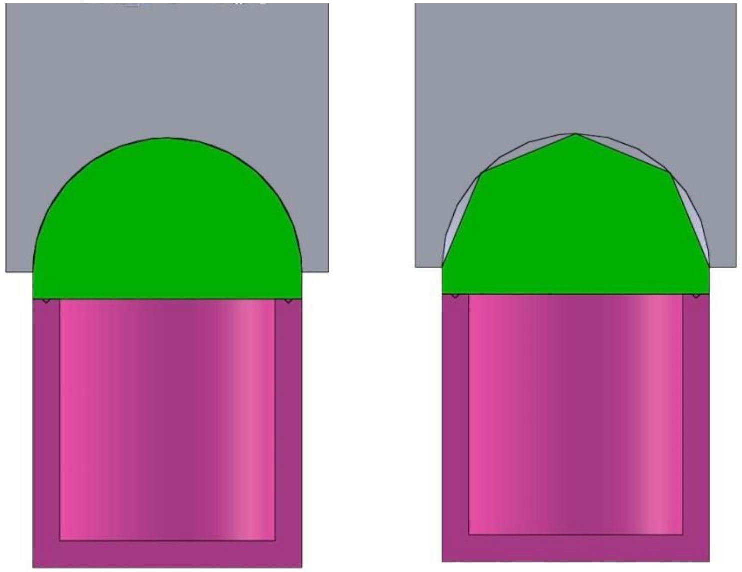
Dukane: Thermoguide.

Keep Spare Ultrasonic Horns

- The horn is the soul of the process:
  - Keep extras!
- Things that might happen to a horn:
  - Badly loaded part – horn makes contact with fixture and dents.
  - Poorly coated carbide – chips and falls off.
  - Normal wear and tear – may wear in the shape of your part.
  - Change in frequency due to wear – will not longer run.

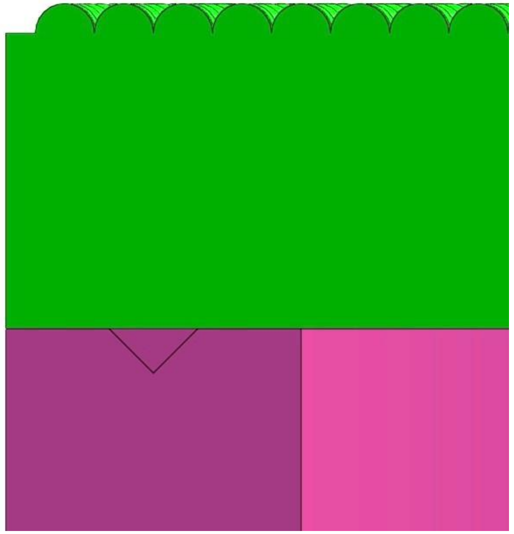
Gouging

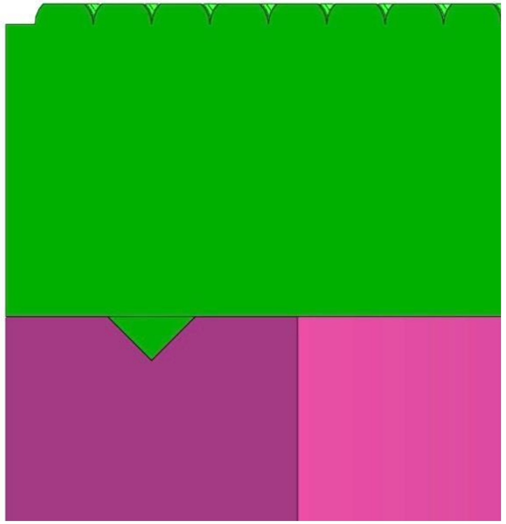
- **Sonotrode-to-part fit not correct (contour mismatch).**
- **Edges of sonotrodes can leave witness marks.**
- **DO NOT MACHINE YOUR SONOTRODE!**
  - It is an acoustic instrument.
  - Any removal of material may interfere with its function.



Texture Marring

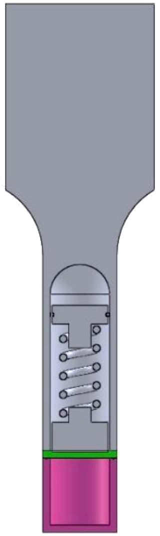
- Texture may be melted during welding.
- It can help to use a film between the sonotrode and the part as a buffer.

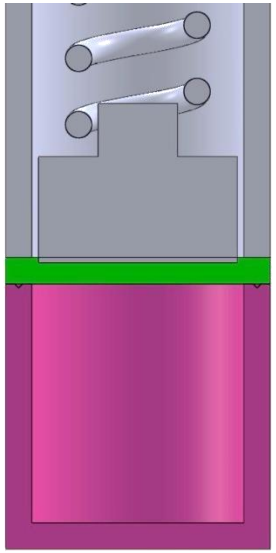




Surface Burning

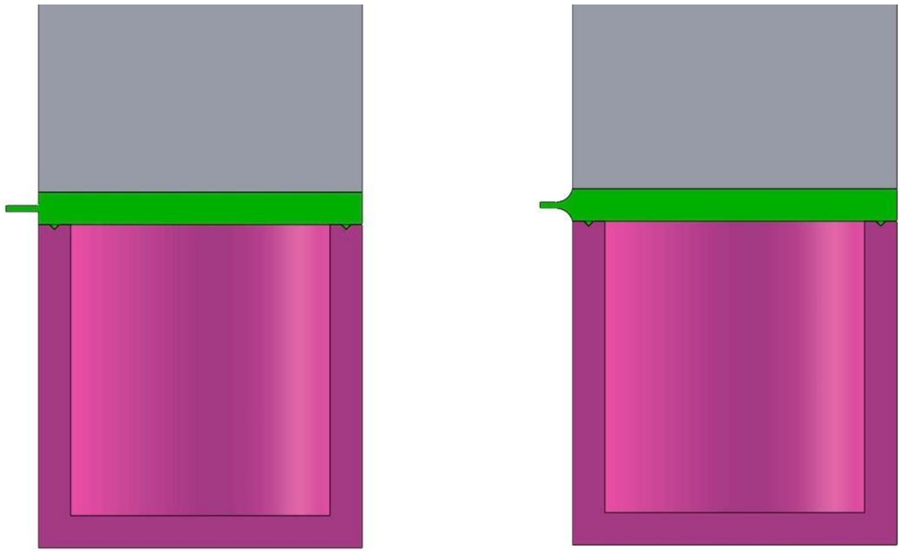
- **Diaphragmming:**
  - More likely to occur if the part being contacted is thin.
- **Cavitation of air trapped between the sonotrode and part:**
  - Heats under rapid compression and expansion.
- **Use nodal plunger.**





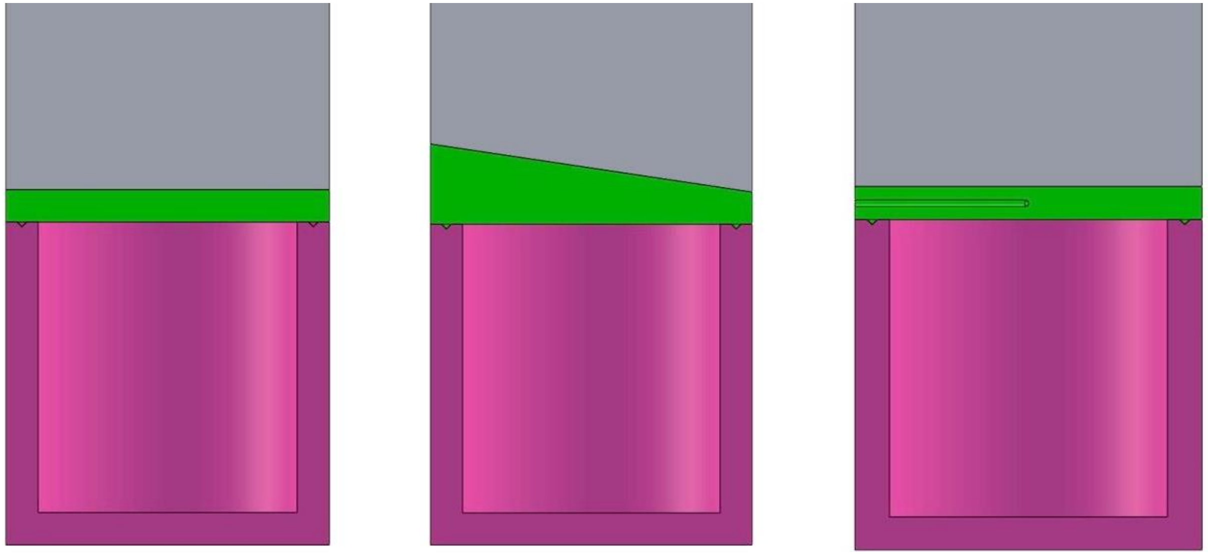
De-gating

- **Areas of stress concentration are susceptible to heating:**
  - A small feature with sharp radii may break off during welding.
- **Use radii as large as possible and avoid thin walls.**



Uneven Welding

- **Variations in the sonotrode contact surface or joint surface:**
  - Variations in joint size.
  - Hole in part above joint.



Common Compatible Materials

	ABS	ABS/PC	PBT	PC	PC/PBT	PMMA	PPO	PS	PVC
ABS	☺	☺	☹	☹	☹	☺	☹	😐	😐
ABS/PC	☺	☺	☹	☺	😐	😐	☹	☹	☹
PBT	☹	☹	☺	☹	😐	☹	☹	☹	☹
PC	☹	☺	☹	☺	😐	☺	😐	☹	☹
PC/PBT	☹	😐	😐	😐	☺	😐	☹	☹	☹
PMMA	☺	😐	☹	☺	😐	☺	☹	☹	☹
PPO	☹	☹	☹	😐	☹	☹	☺	☺	☹
PS	😐	☹	☹	☹	☹	☹	☺	☺	☹
PVC	😐	☹	☹	☹	☹	☹	☹	☹	☺

Ease of Weldability Estimates

- **Near field → horn contact to joint surface <0.25 in. (6.35 mm).**

Amorphous	Near	Far
ABS	1	2
ABS / PC	2	2
PMMA	2	3
PPO	2	2
PC	2	2
PEI	2	4
PES	2	4
PS	1	1
PSU	2	4
PVC	4	5
PC / PBT	2	4

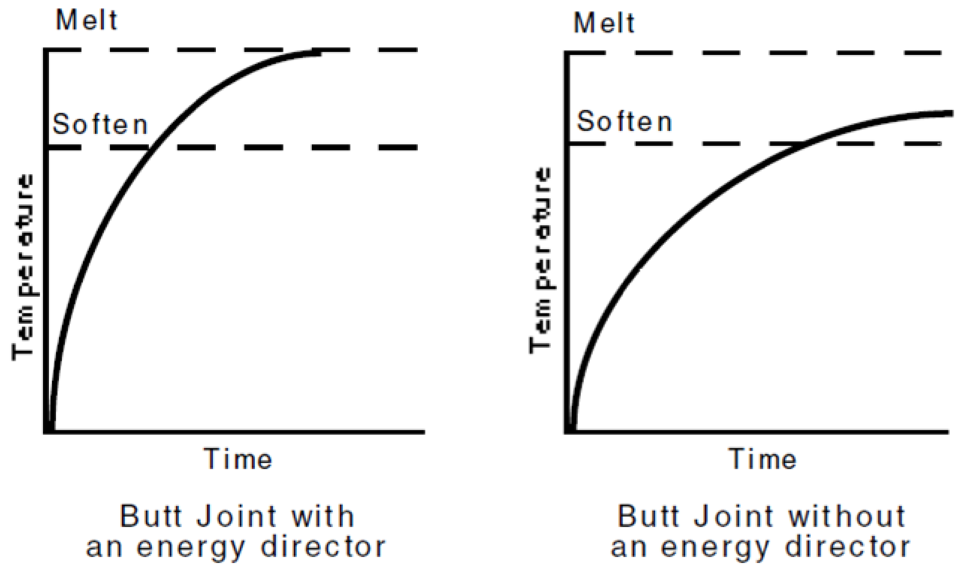
Semi-Crystalline	Near	Far
POM	2	4
PTFE	N/A	N/A
LCP	4	5
PA	2	4
PET	3	5
PBT	5	5
PEEK	4	5
PE	5	5
PMP	4	4
PPS	2	4
PP	4	5

Selecting a Joint Design

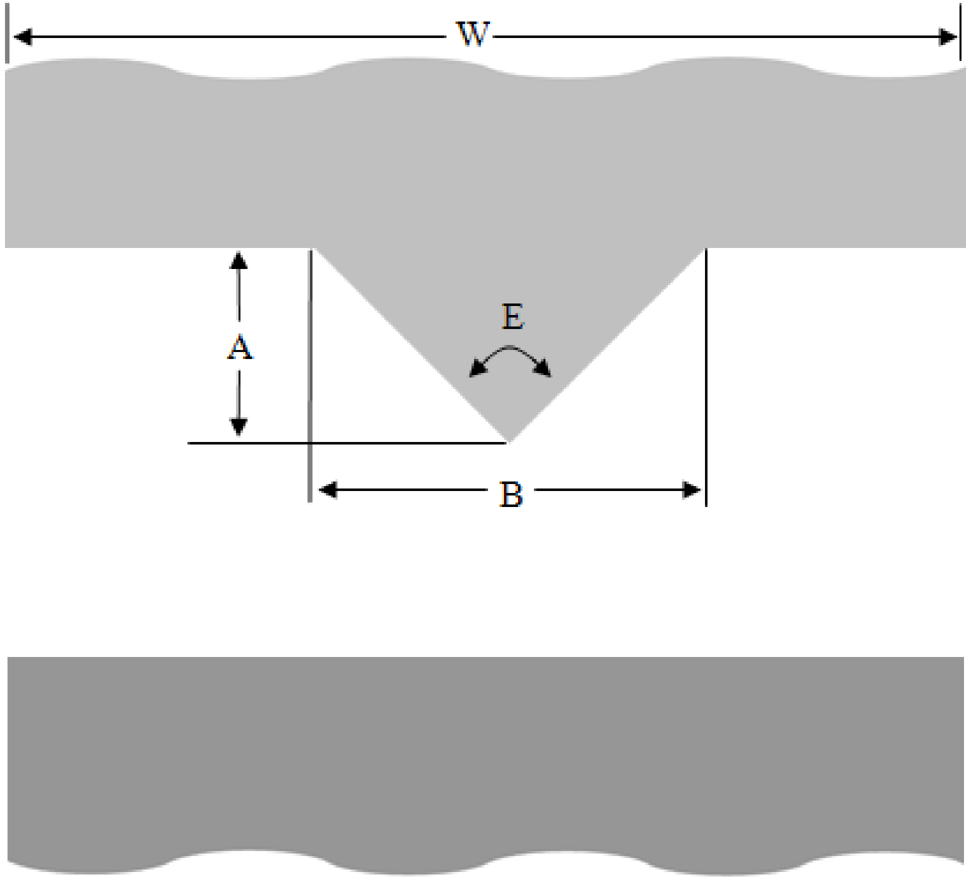
- Load to be transferred
- Geometry of the parts
- Region for load transfer
- Operating environment
- Reliability
- Material properties
- Joining process

Joint Design

- Joint should be loose fitting.
- Energy director:
  - Very small initial contact area.
- Shear joint:
  - Can provide excellent mixing of materials.
  - Support in the joint area is critical to prevent stress.

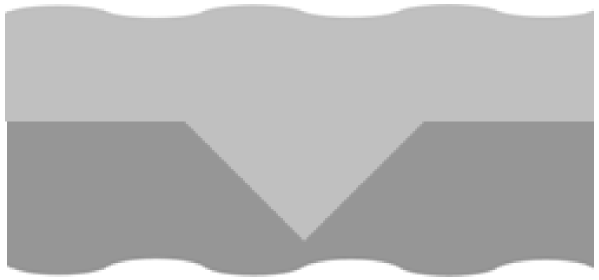


Energy Director

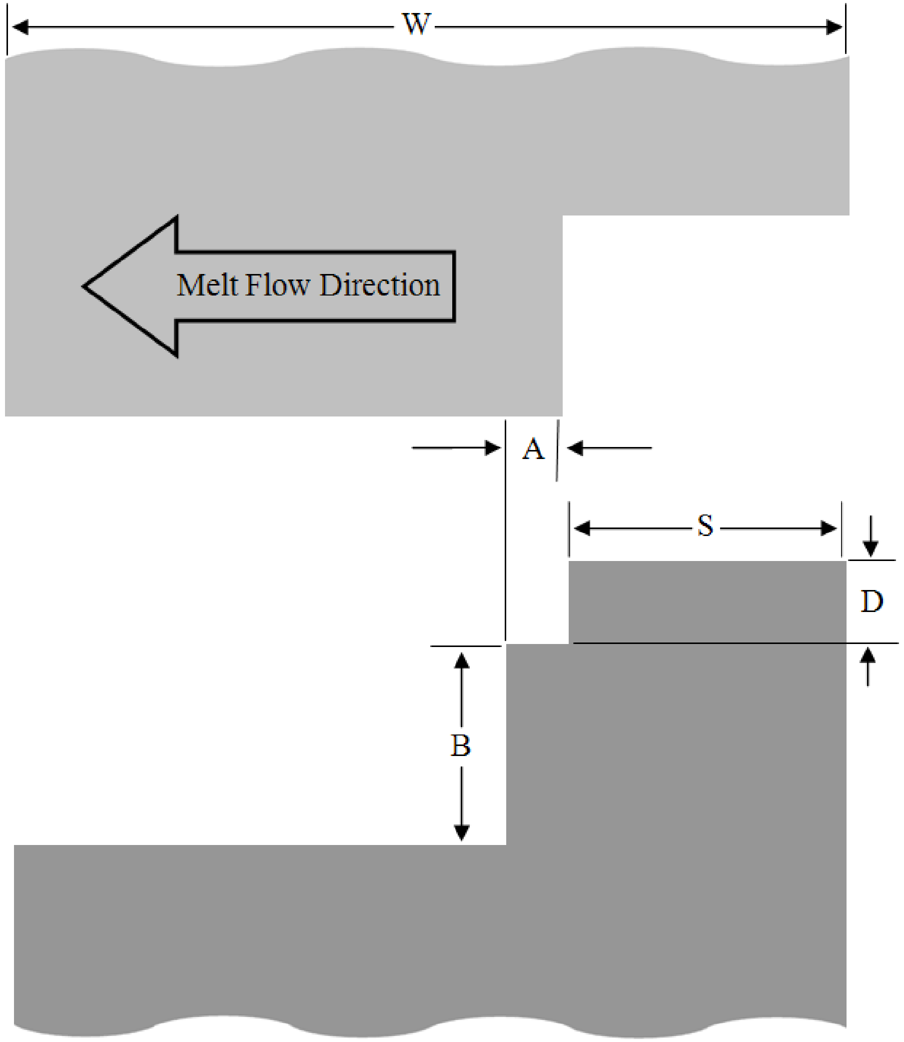


Dimension	Guidelines
W	Minimum 0.090 in.
B	W/4 to W/5
A	B/2 or 0.866B
E	60 or 90 degrees

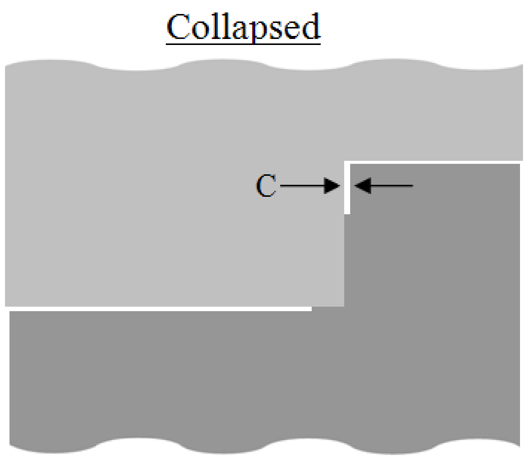
Collapsed



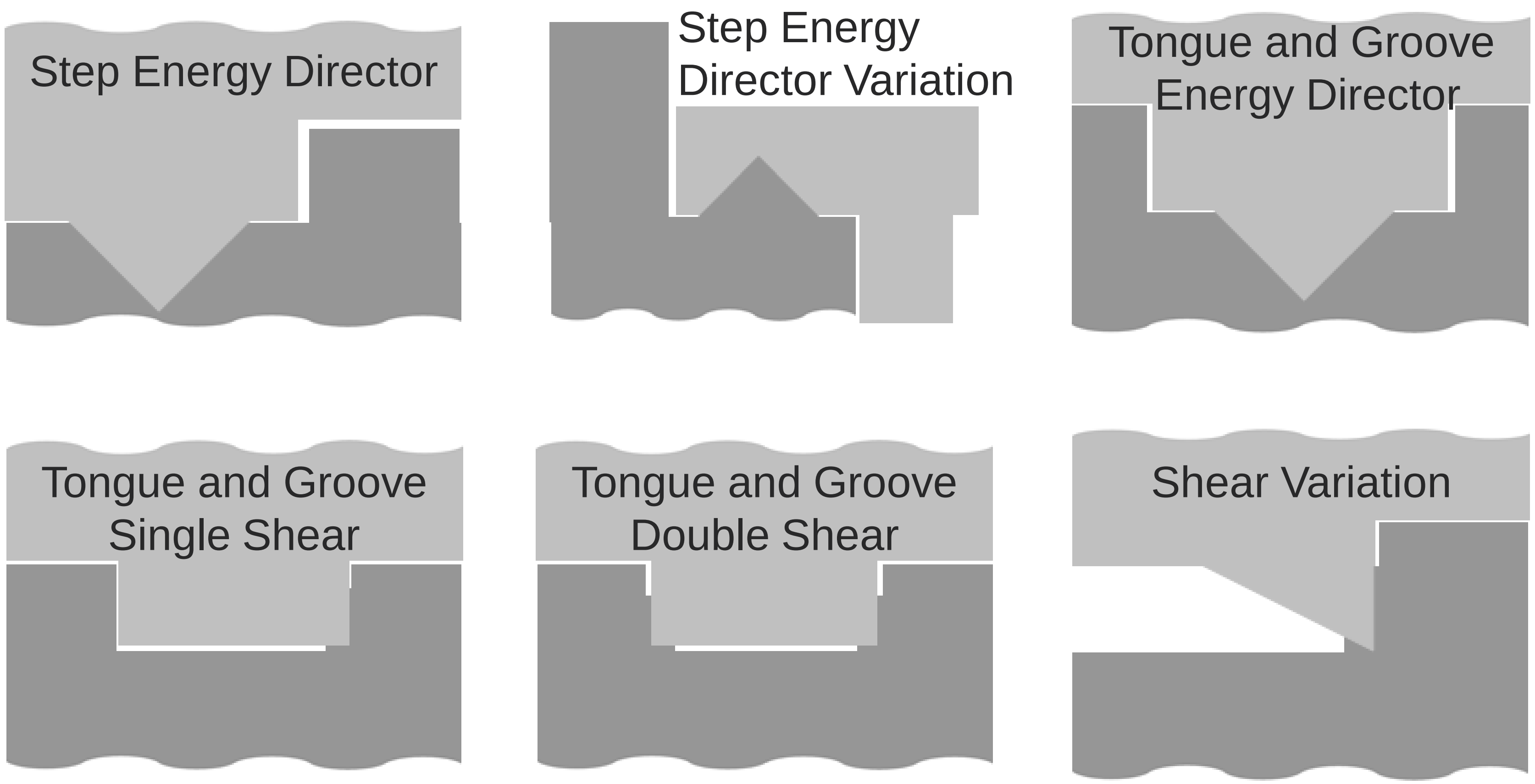
Shear Joint



Dimension	Guidelines
W	Minimum 0.060 in.
B	Approximately 0.030 in.
A	0.008-0.020 in.
D	0.020-0.050 in.
S	Minimum 0.020 in.
C	0.00300.005 in.



Other Joint Designs



Uneven Welding

Issue	Solution
Filler Content Too High or Inconsistent Distribution	Check mold design and molding conditions
	Reduce filler percentage
Improper Joint	Ensure joint design has uniform size and shape
Improper Horn Fit	Check alignment, fit, and leveling of horn to fixture using carbon paper
Lack of Intimate Contact at Joint	Ensure there are no sink marks or knock out pin locations at the joint
Mating Part Halves Fit Together Poorly	Ensure parts are not warped
	Ensure there is no interference other than the designed joint
	Increase trigger forces/trigger delay/hold pressure/ hold time
Thin Part Wall	Add ribs or thicken wall
	Modify fixture to prevent outward flexing of wall

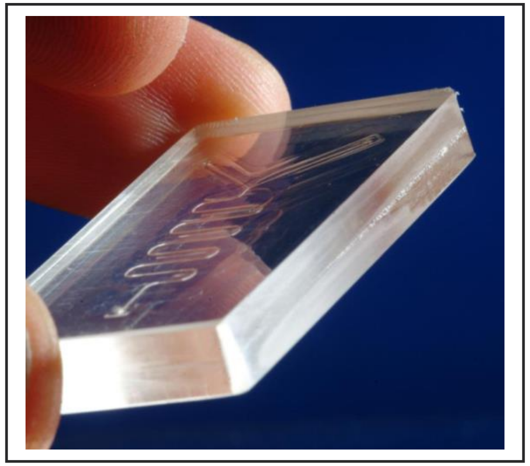
Inconsistent Welding Part to Part

Issue	Solution
Cavity to Cavity Variations	Add or move gate(s) shape/location
	Check for cavity wear
Changes in Air Line Pressure	Add surge tank with a check valve
	Raise compressor output pressure
Changes in Line Voltage	Use an in-line voltage regulator
	Use welder with line load regulation
Material Properties Inconsistent	Check molding conditions for variation over time
	Improve regrind quality and/or reduce regrind percentage
Materials Incompatible	Change to compatible materials/resin grade
Moisture in Molded Parts	Bag and seal parts after molding (use desiccant, if needed)
	Dry parts before welding

Laser Welding

- Physics of the Process
- Equipment and Parameters
- Material Considerations
- Design Considerations
- Troubleshooting

Laser Welding



- Common applications
  - Medical devices, housings, headlights, taillights

Advantages
- Very clean process
- Little to no weld flash
- Precise control/selective heating
- No vibration
- Simple joint designs (uniform contact of mating surfaces)

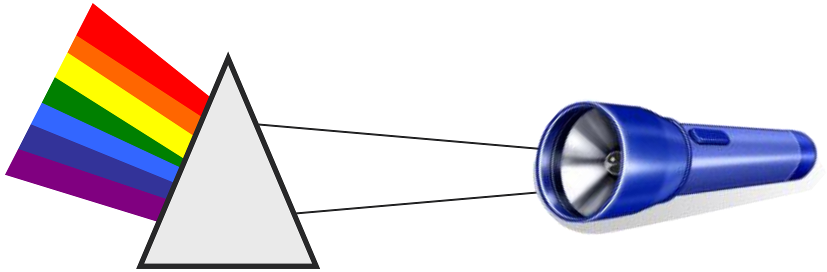
Disadvantages
- Relatively new welding process (still learning)
- Optical properties of polymer are very critical.
- Eye protection is mandatory for operators.

What is LASER?

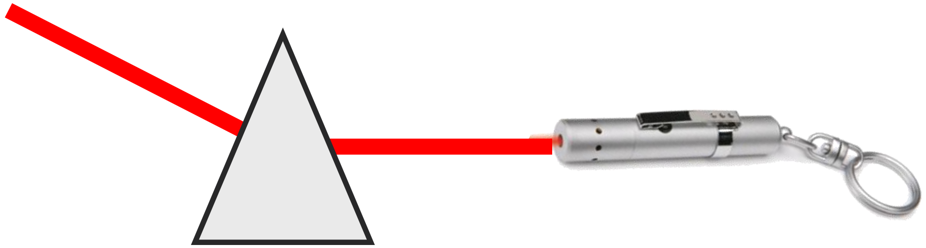
- Light Amplification by Simulated Emission of Radiation
- High-Brightness =>
  - Monochromatic
  - Coherent
  - Directional

Monochromatic

- A single wavelength
  - Or a narrow band of wavelengths



White light from a flashlight <u>is</u> **<u>not</u>** <u>monochromatic</u> because it is composed of many colors



Light from a diode laser pointer <u>is monochromatic</u> because it is composed of only one color

Coherent

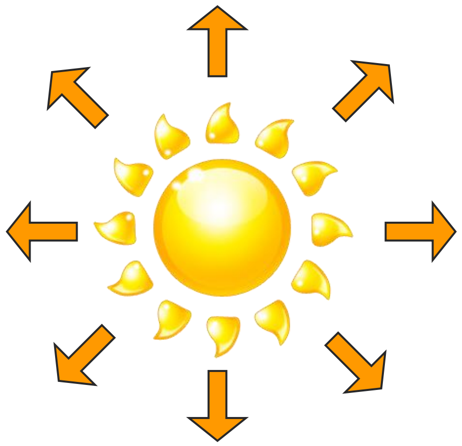
- Laser light travels “in-phase”
- All of the light waves are synchronized

“Out of Phase”
(not coherent)

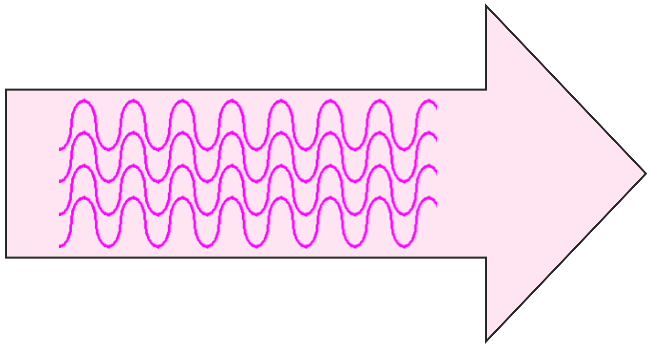
“In Phase”
(coherent)

Directional

- Laser light travels in the same direction because of the way it is generated
- This makes it easy to manipulate and focus the beam



Sunlight is **not** directional



Laser light is directional

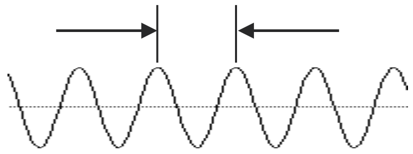
High-Brightness

- Because light is monochromatic, coherent, and directional, it can be focused many times smaller than light from the sun (100 times better)
- Laser light can produce high “power density” or high “energy density”

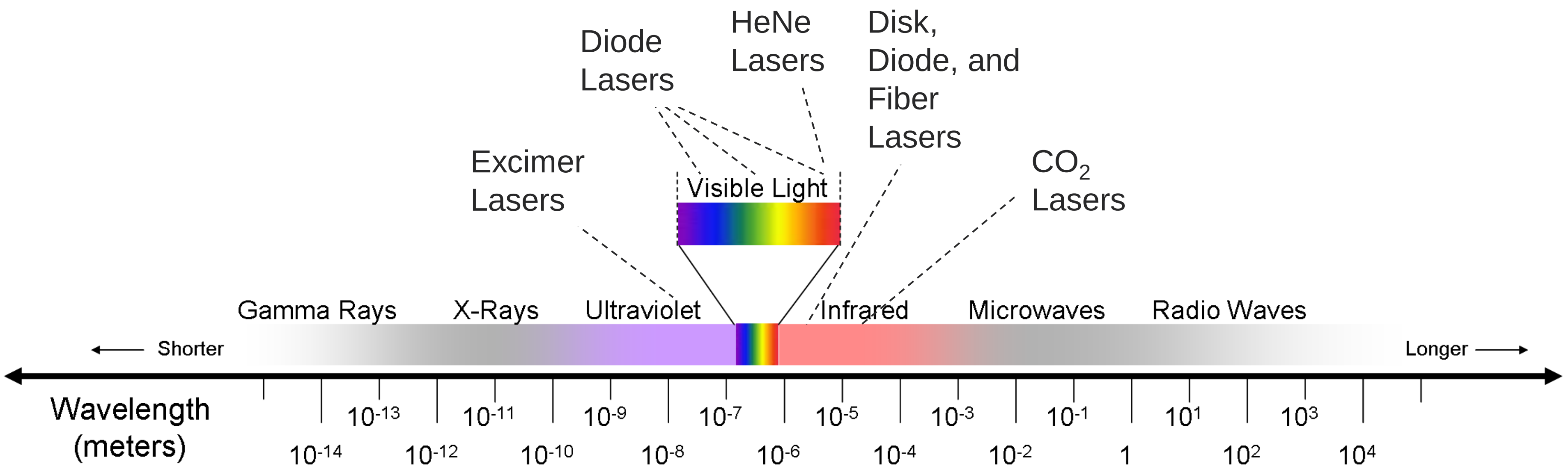
$$\textbf{Power Density} = \frac{\text{Laser Power}}{\text{Area of the laser beam or focused spot}}$$

$$\textbf{Energy Density} = \frac{\text{Laser Energy}}{\text{Area of the laser beam or focused spot}}$$

Electromagnetic Spectrum

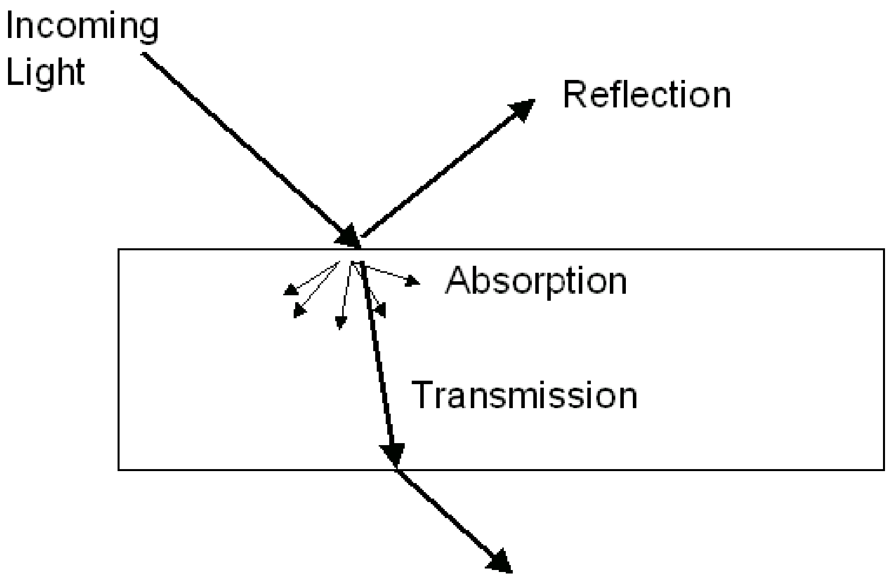


- Different lasers produce different wavelengths of light
  - Visible (ROYGBIV)
  - Ultraviolet (UV) – not visible
  - Infrared (IR) – not visible

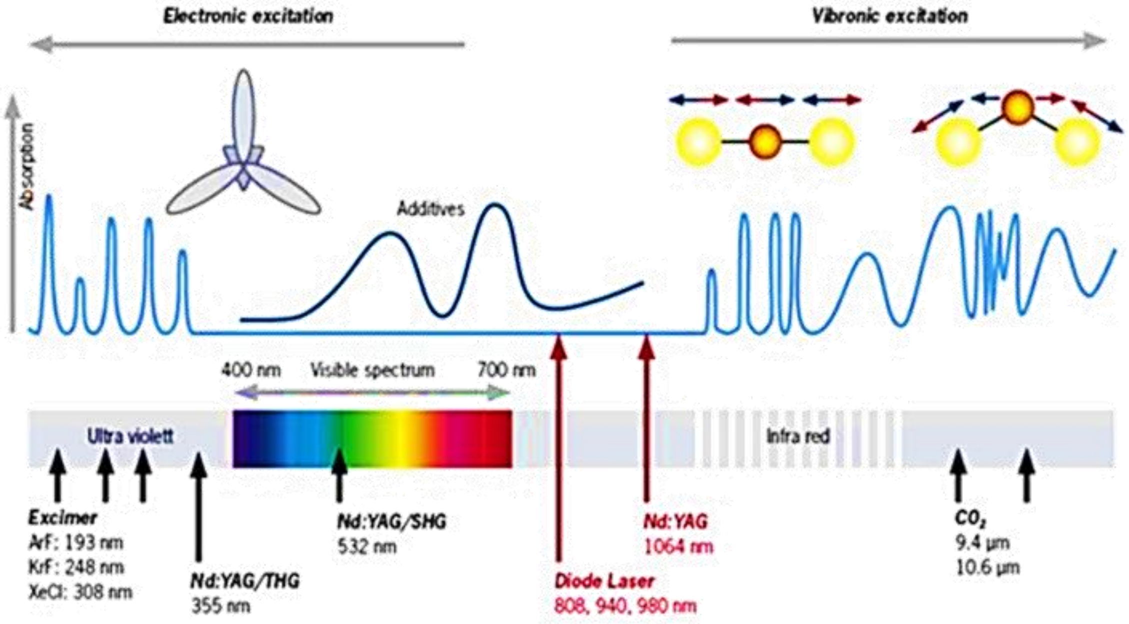


Wavelength Effects (and Affects)

- Wavelength determines how light reacts with matter
  - Absorption
  - Reflection
  - Transmission



Effect of Wavelength on Welding Plastics



Most polymers (lighter blue curve) are usually transparent or translucent in the visible and near IR range. By adding pigments (darker blue curve), suitable absorption of the laser wavelength is achieved.

No absorption of pure polymer material between 800 and 1100 nm

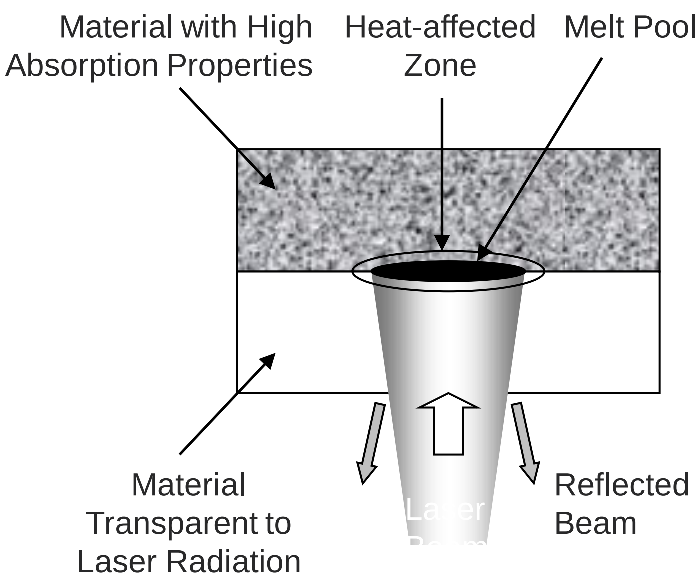
Laser absorption only by additives !

Nielsen, S.E., Kristensen, J.K., Strange, M., "Laser welding of plastics – Weld compatibility investigations" 2013

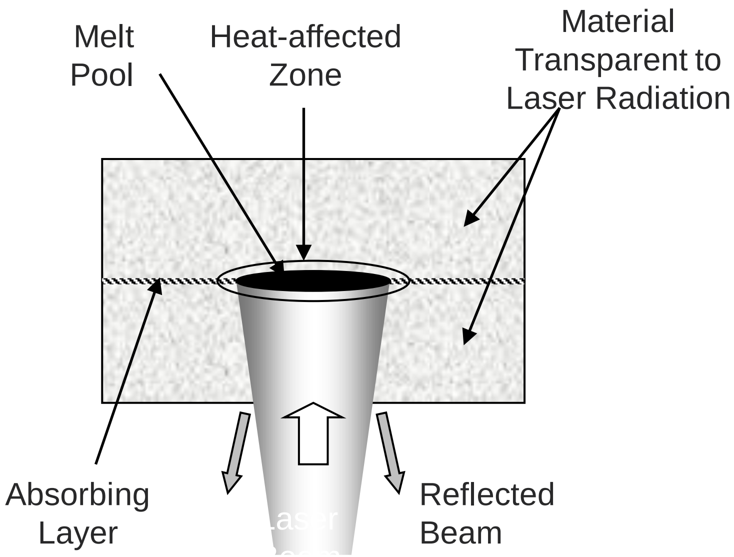
Through-Transmission Laser Welding

- Through-transmission laser welding (TTLW):
  - Lasers: 808 to 1064 nm

Traditional Through-Transmission Laser Welding



Through-Transmission Laser Welding with Absorbing Interlayer



Courtesy of OSU Plastics and Composites Joining Lab

Determining Optical Properties

- Know percent light transmitted/absorbed at the laser wavelength planned:
  - May find this information from material or equipment supplier.
  - Send samples of the material to a lab that can test transmittance at multiple wavelengths (example below).

KENTEK
"Laser People Helping Laser People"®

Filter Number: **ACRX-IR3**

Filter Color: Green

VLT (%): 24

NOTE: OD values below are average minimum values of representative lots of filter material according to manufacturers specifications. They are not guaranteed minimums for every lens. Minimum protection values will be specified on each product.

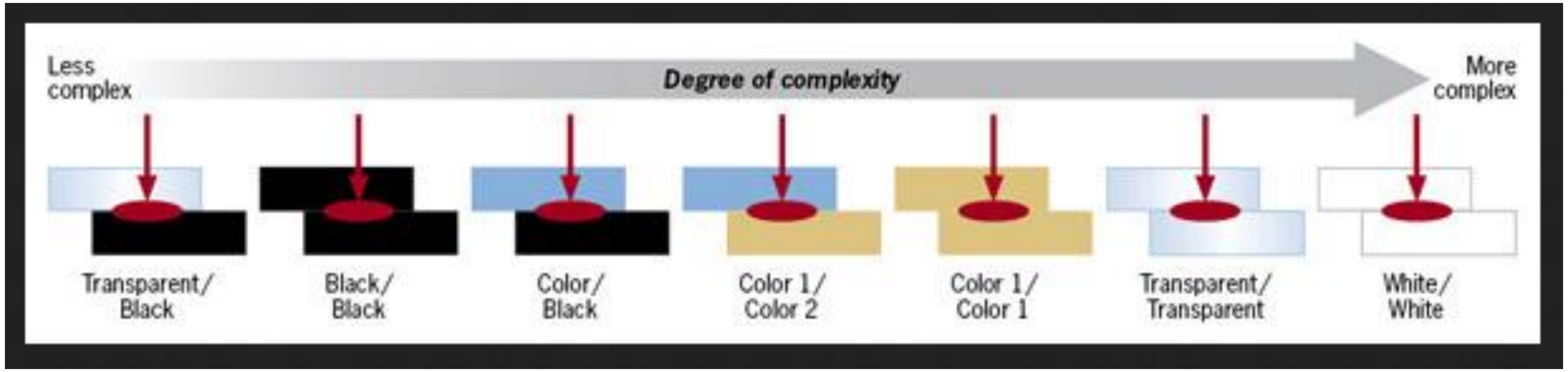
Laser Filter OD Values:

Product Markings: OD>3 @ 808nm, OD>4 @ 830 -1700nm, OD>6 @ 1064nm, OD>6 @ 1090nm

nm	OD	nm	OD	nm	OD	nm	OD	nm	OD	nm	OD	nm	OD	nm	OD	nm	OD	nm	OD	nm	OD
200	7+	255	7+	310	7+	365	7+	420	6.84	475	3.11	530	0.39	585	0.59	640	0.91	695	1.31	750	2.08
201	7+	256	7+	311	7+	366	7+	421	6.81	476	3.02	531	0.39	586	0.59	641	0.91	696	1.32	751	2.10
202	7+	257	7+	312	7+	367	7+	422	6.78	477	2.93	532	0.39	587	0.60	642	0.92	697	1.33	752	2.12
203	7+	258	7+	313	7+	368	7+	423	6.76	478	2.84	533	0.39	588	0.60	643	0.93	698	1.34	753	2.14
204	7+	259	7+	314	7+	369	7+	424	6.74	479	2.75	534	0.39	589	0.61	644	0.93	699	1.35	754	2.16
205	7+	260	7+	315	7+	370	7+	425	6.71	480	2.65	535	0.39	590	0.61	645	0.94	700	1.36	755	2.18
206	7+	261	7+	316	7+	371	7+	426	6.68	481	2.55	536	0.39	591	0.62	646	0.95	701	1.37	756	2.20
207	7+	262	7+	317	7+	372	7+	427	6.65	482	2.45	537	0.40	592	0.62	647	0.95	702	1.38	757	2.22
208	7+	263	7+	318	7+	373	7+	428	6.61	483	2.35	538	0.40	593	0.63	648	0.96	703	1.39	758	2.24
209	7+	264	7+	319	7+	374	7+	429	6.58	484	2.25	539	0.40	594	0.63	649	0.96	704	1.40	759	2.26
210	7+	265	7+	320	7+	375	7+	430	6.54	485	2.15	540	0.40	595	0.64	650	0.97	705	1.41	760	2.28

Color Compatibility

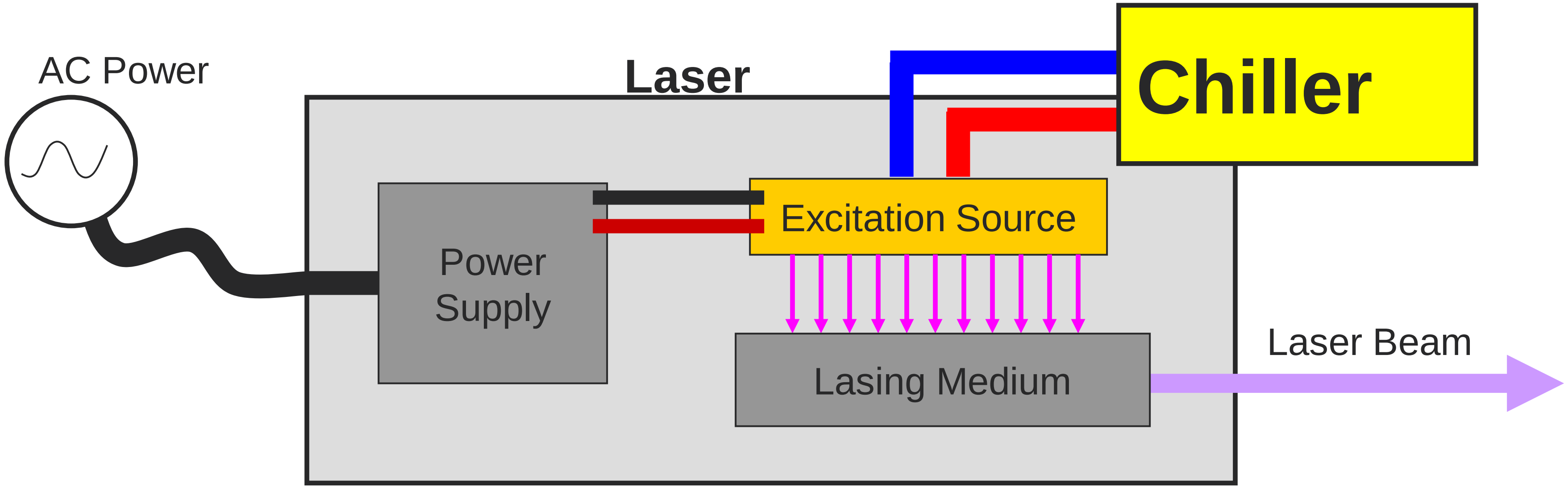
- **Laser welding of natural to black is easiest combination.**
- **White to white is most difficult:**
  - Titanium oxide filler inhibits laser transmission to joint and absorption in bottom layer.



http://www.treffert.org/specifications/laserwelding-and-lasermarking-of-polymers/

Basic Laser Components

- Power Supply
- Excitation Source (ex. Flash Lamp, Diode Laser)
- Lasing Medium (determines laser wavelength)
- Cooling System



Common Industrial Lasers

- Diode / Ytterbium Fiber Laser
  - Wavelength = 800-1070 nm
  - For through-transmission laser welding of polymers
- Thulium Fiber and CO Lasers
  - Thulium: 2000nm wavelength
  - CO: 5000nm wavelength
  - For ‘keyhole’ or butt laser welding of unfilled polymers
- CO_2 Laser
  - Wavelength = 10600 nm (10.6µ)
  - Excellent for cutting, ablation, marking polymers

Beam Delivery

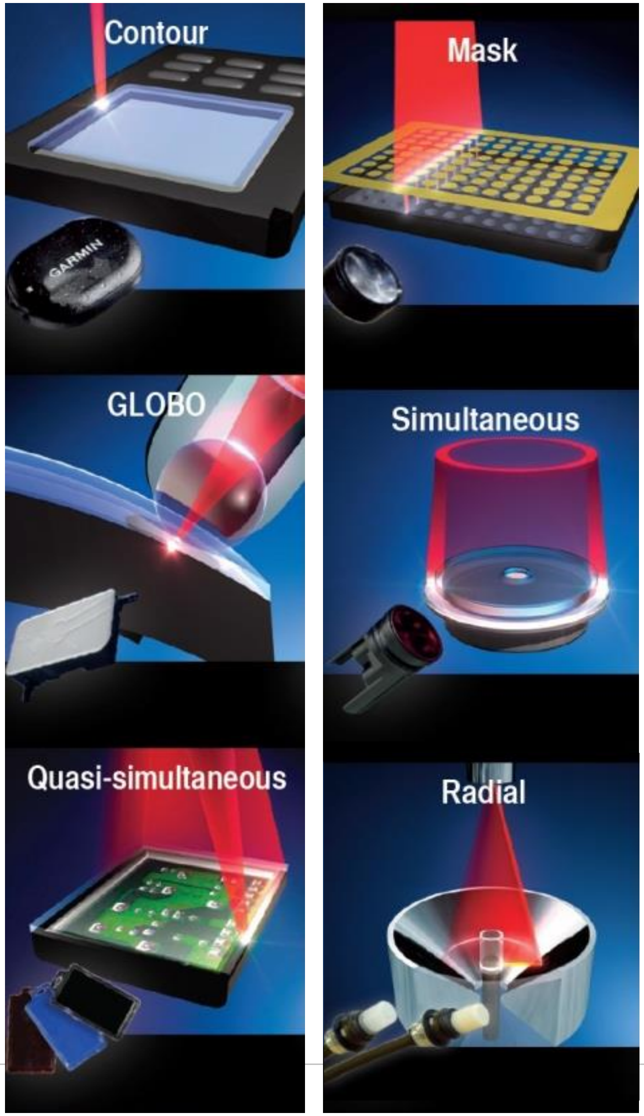
- CO and CO_2 lasers cannot transmit through most glass
  - Mirror delivery
  - May need gas shielding
- Diode and Fiber lasers can transmit through most glass
  - Fiber optic delivery

Laser Delivery Methods

Contour

Globo / Roller

Quasi-Simultaneous



Mask

Simultaneous (DOE)

Radial

Images courtesy of Leister

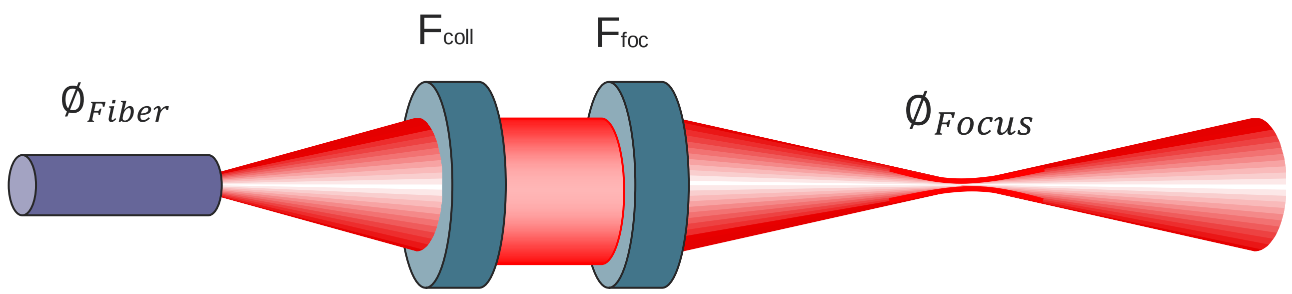
Comparison of Laser Delivery Methods

	Contour welding	Simultaneous welding	Quasi-simultaneous welding	Mask welding
Flexibility	very high	low	high	low
Welding time	long	short	moderate	moderate-long
Complexity of weld profile	very high	moderate	high	moderate
Tolerance compensation	none	possible	possible	none
Plant cost	moderate	very high	high	moderate-high
Usable laser type	Nd:YAG; diode	diode	Nd:YAG	diode

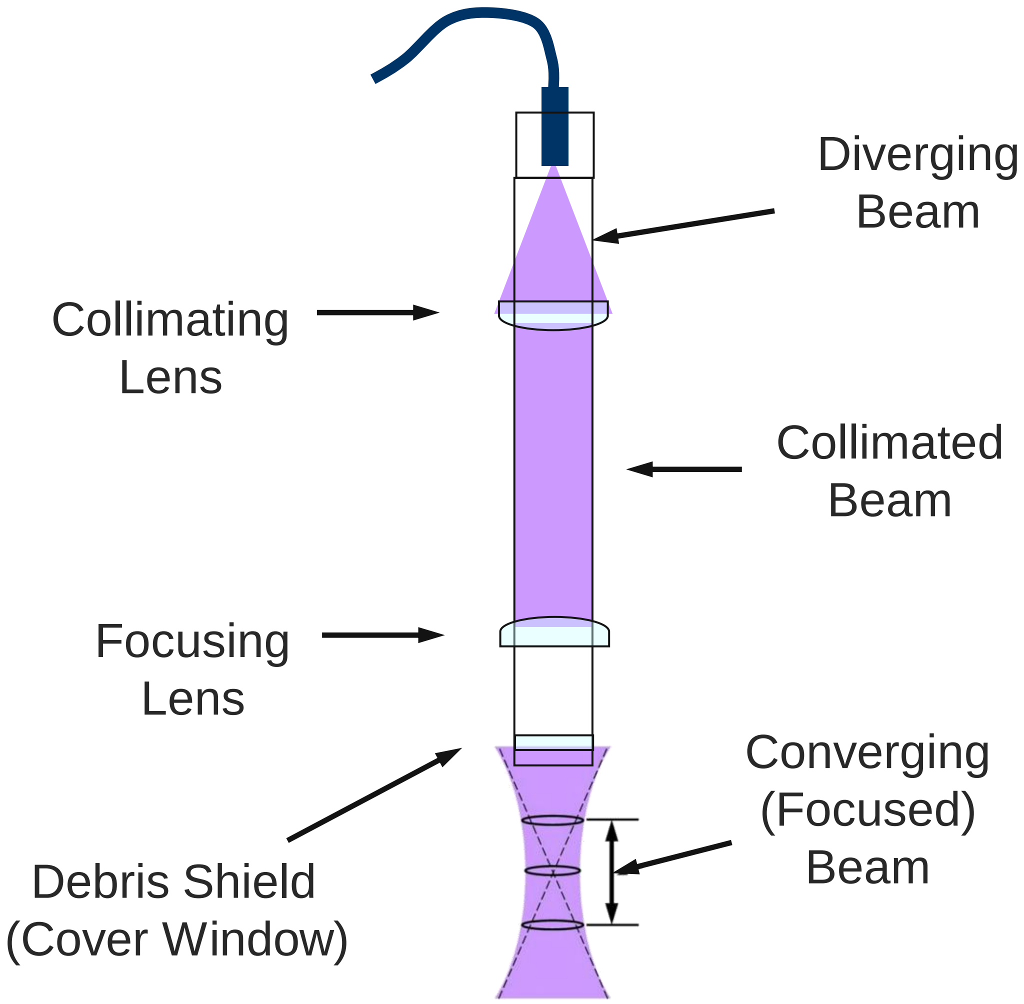
From "Laser Welding of Engineering Plastics" by BASF

Focusing Optics

- Focusing optics focus and concentrate the laser beam to a small spot or "waist"



$$\emptyset_{Focus} = \emptyset_{Fiber} * \frac{F_{Foc}}{F_{Coll}}$$



Obtaining Desired Spot Size by Choosing Delivery Fiber and Focus Optics

FOCUS HEAD LENS COMBINATION		FIBER DIAMETER (MICRONS)						
Collimating Focal Length (mm)	Output Focal Length (mm)	100	200	300	400	600	800	1000
70	50	0.003	0.006	0.008	0.011	0.017	0.022	0.028
70	70	0.004	0.008	0.012	0.016	0.024	0.031	0.039
70	75	0.004	0.008	0.013	0.017	0.025	0.034	0.042
70	100	0.006	0.011	0.017	0.022	0.034	0.045	0.056
70	120	0.007	0.013	0.020	0.027	0.040	0.054	0.067
100	50	0.002	0.004	0.006	0.008	0.012	0.016	0.020
100	70	0.003	0.006	0.008	0.011	0.017	0.022	0.028
100	75	0.003	0.006	0.009	0.012	0.018	0.024	0.030
100	100	0.004	0.008	0.012	0.016	0.024	0.031	0.039
100	120	0.005	0.009	0.014	0.019	0.028	0.038	0.047
120	50	0.002	0.003	0.005	0.007	0.010	0.013	0.016
120	70	0.002	0.005	0.007	0.009	0.014	0.018	0.023
120	75	0.002	0.005	0.007	0.010	0.015	0.020	0.025

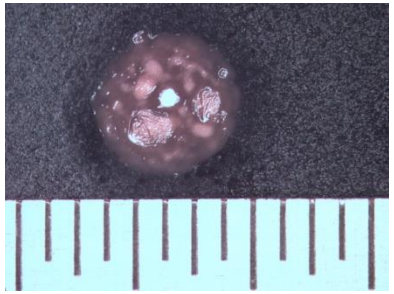
NOTE: *Spot diameter in inches*

- Must not exceed the capacity of a fiber or you will melt it
- Same laser can produce spot sizes from 0.002 to 0.067-inch

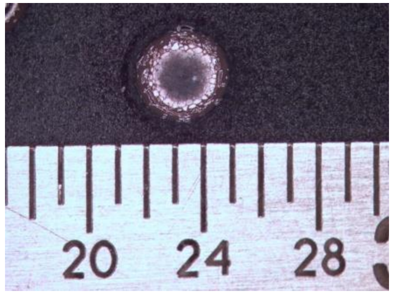
From Unitek Miyachi Manual

Finding Focus Length

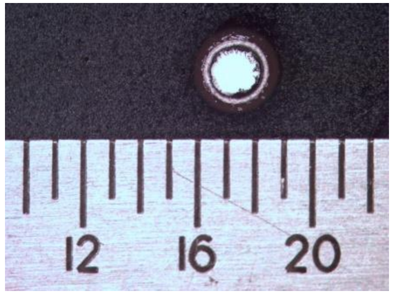
7.2 cm
from lens



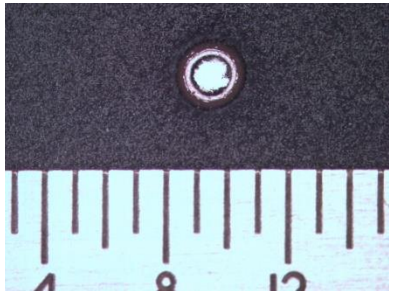
8.0 cm
from lens



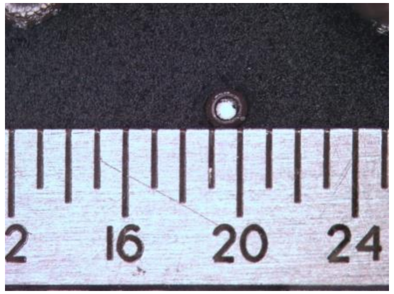
8.2 cm
from lens



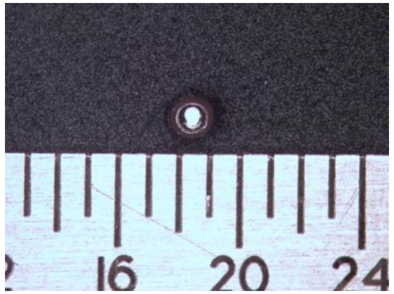
8.4 cm
from lens



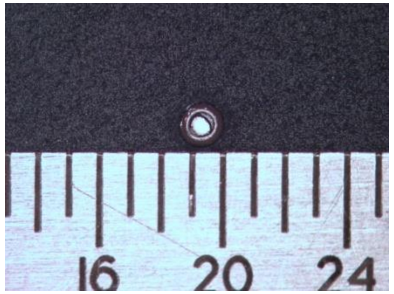
8.5 cm
from lens



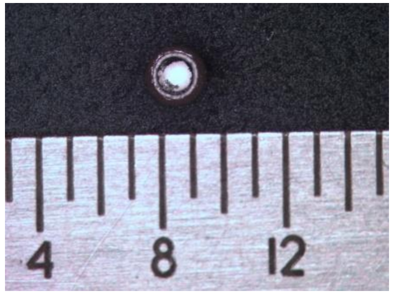
8.6 cm
from lens



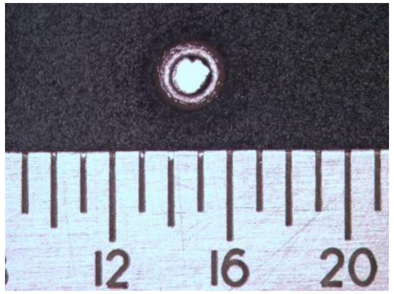
8.7 cm
from lens



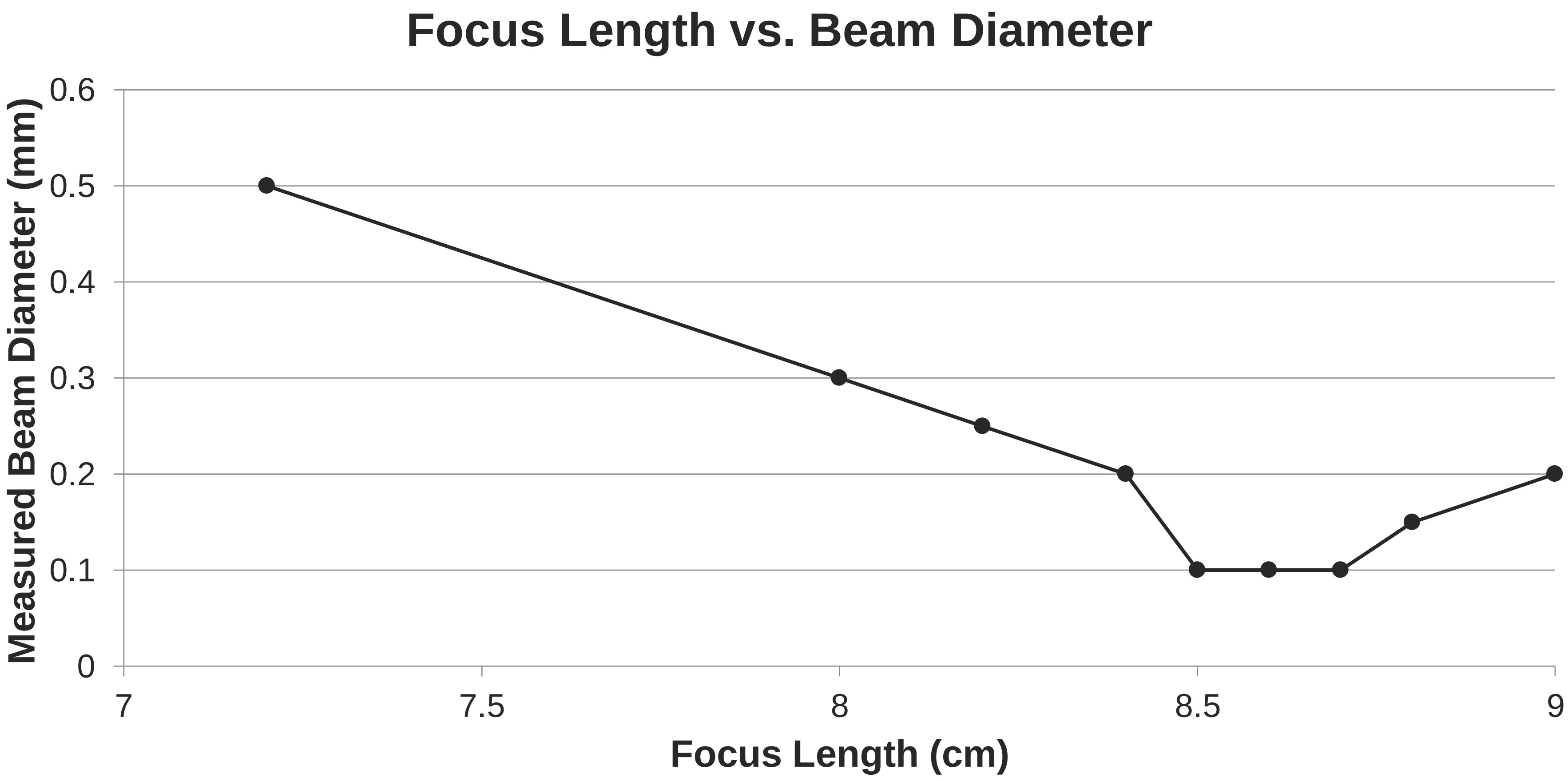
8.8 cm
from lens



9.0 cm
from lens

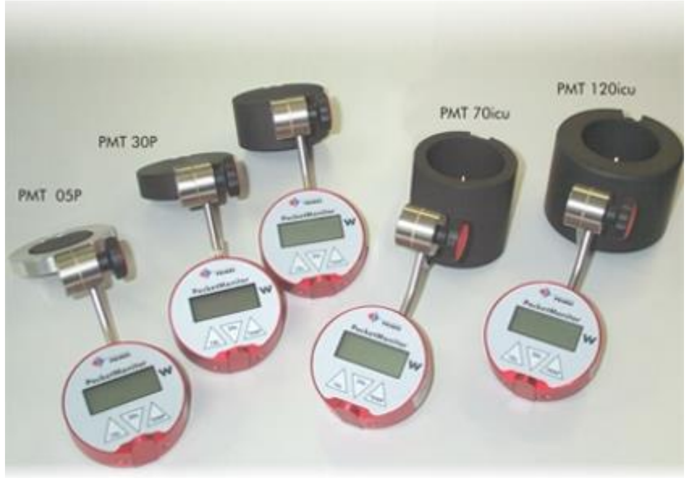


Finding Focus Length

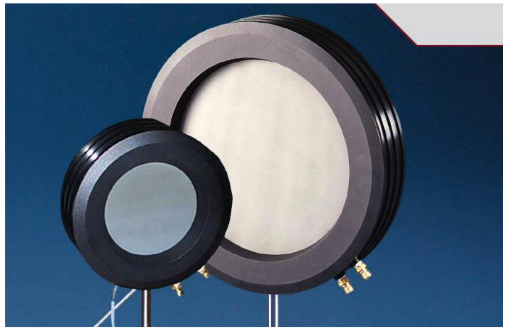


Power Measurement

- Power should be measured from the laser focus head to ensure consistent heat input.
- Example of power measuring devices.



PRIMES

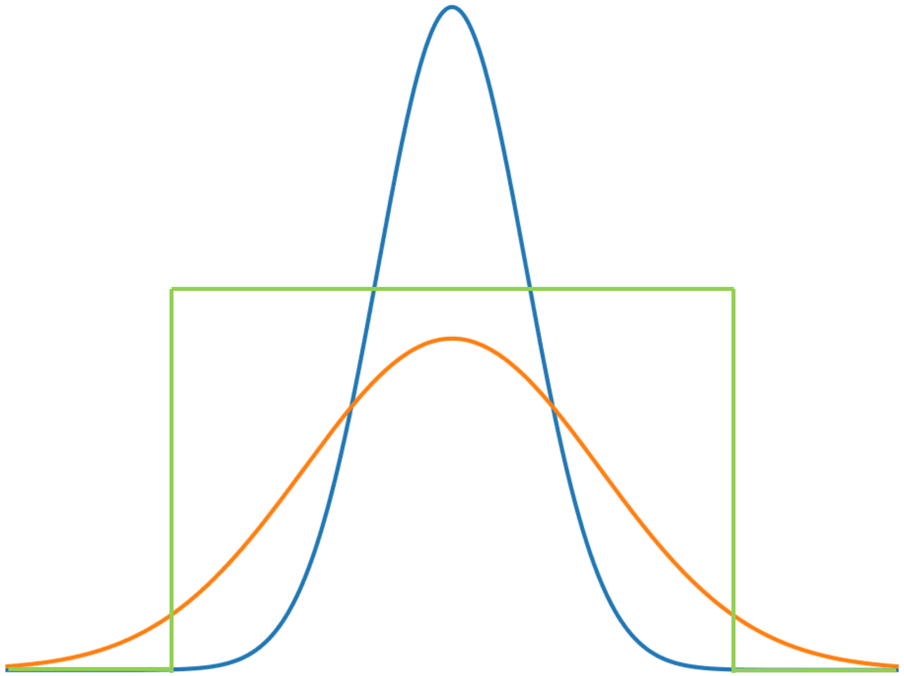


COHERENT.

OPHIR
Laser Measurement Group
Spiricon
Laser Beam Diagnostics
Member of the Ophir Group

Power Distribution

- Some power meters can show the power distribution (i.e. Gaussian vs. Top Hat)



Laser Parameters

- Welding parameters:
  - Pulsed or continuous
  - Wavelength
  - Average laser power in watts
  - Beam delivery (direct beam or fiber delivery)
  - Focused spot size
  - Focal distance and distance to work
  - Travel speed

Factors Affecting Laser Penetration

- wavelength
- energy density
- welding technique
- welding speed

Polymer
- spectral absorption
- molecular structure
- crystallinity/size of crystallites
- fillers (glass fibers, carbon black)
- colorant
- additives (e.g. flame retardant)
- moisture content
- thermal conductivity/ heat capacity
- heat of fusion/melting temp.
- heat of vaporisation
- surface structure

- shape
- wallthickness
- workhold fixture
- molding
- joint gap-width

From "Laser Welding of Engineering Plastics" by BASF

Material Compatibility

LPKF Laser Welding Material Compatibility Chart

transmissive/ absorbing	ABS	ABS/ PA	ASA	COC	MABS	PA 12	PA 612	PA 6	PA 6-3-T	PA PACM 12	PA 66	PBT	PBT/ASA	PC	PE-HD	PE-LD	PEEK	PES	PMMA	POM	PP	PPS	PPSU	PS	PSU	PTFE	SAN	TPE
ABS	++		++	×	++			×			×	++	+	++	×	×		+	++	+	×			×	+		++	++
ABS/PA	++		++		×			++			++	+	+					+		×	×				+		++	
ASA	++		++		×			×			×	++	++							×	×						++	
COC	×			+										×					+					×			×	
MABS	++		×		++			×			×	×	×					×		×	×				×		×	
PA 12						++	++	−	++	++	×	−			×	×		−	×	×	×							
PA 612						++	++	+	++	++	×	×							×									
PA 6						−	−	++	++	−	++	×			−	−		×	×	×	−			+				
PA 6-3-T						+	++		++	−	++	−		×				−	×	×	×							
PA PACM 12						+	++	×	++	++	−	−						×	×	×	×							
PA 66						×	−	++	++	×	++	×		−	−	×		×	×	×	−	×		+				+
PBT	++		++		×	×	+	−	×	×	×	++		++	×	×		+	×	×	×			×	+		++	
PBT/ASA	+				×			×			×							+		×	×				+		×	
PC	++			×					−		−	++		++	×	×			++		×	−		−			++	+
PE-HD	×					×		−			−	×		×	++	++			−	−	×			×			×	
PE-LD	×					×		−			−	×		×	++	++			−	−	++			×			×	
PEEK																	++											
PES	+		×		×		×	×			×	+	+					++		−	×			×	++		×	
PMMA	++			+		×	×	×	×	×	×	−		×	−	−		×	++	+	−			+			++	
POM	−		×		×	×	×	×	−	×	×	×	×		−	−		−	+	++	×			×	×		×	
PP	×		×		×	×	×	−	×	×	−	×	×			++		×	−	−	++	×			×		×	++
PPS						×	×	−		−	−			++				−	×	−	×	++					−	
PPSU																							++					
PS	×		×	×	×			+			+	×	×	−				−	+	×	×			++	×		−	
PSU	+		×		×			×			×	+	+					++		×	×				++		×	
PTFE																										++		
SAN	++		++	×	×			×			×	−		+	×	×			++	×	×			−			++	
TPE											+			+							++			×				++

++ Excellent weld   + Good weld   − Poor weld   × No weld   (blank) No research available

Data in this table can vary according to the wavelength of the laser.

http://www.laserplasticwelding.com/laser_plastic_welding_material_chart.pdf

We Manufacture Innovation

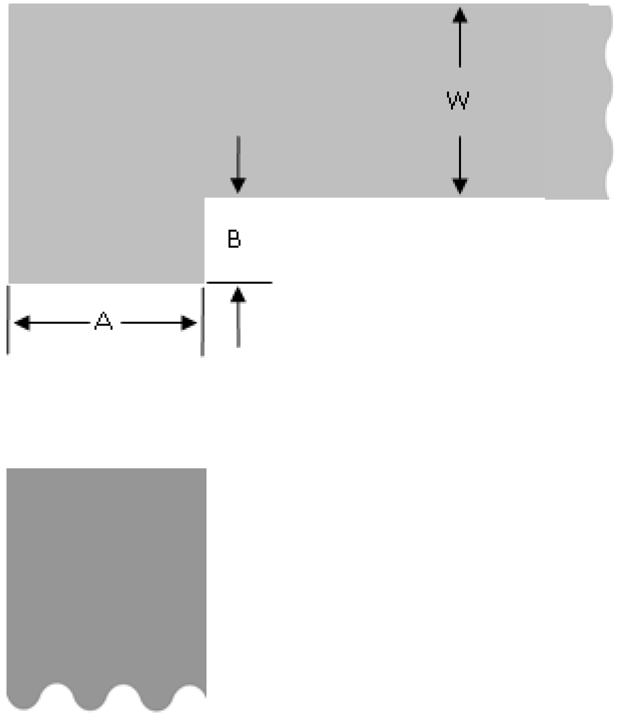
Design Constraints

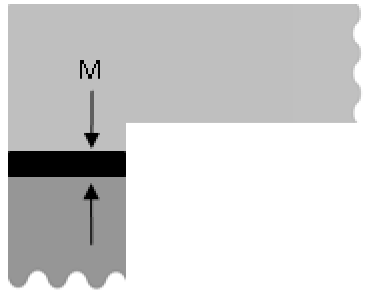
- The parts must be in intimate contact during welding:
  - Application of significant force may be needed.
- The distance from the top surface to the joint must be consistent to prevent uneven heating at the joint:
  - – Moving up or down changes the spot size and therefore, the heating.

Joint Design – Butt

- All that is needed is a flat-to-flat surface.
- If a quasi-simultaneous or simultaneous welding method is to be used, a rib must be included to allow for collapse, similar to joints used for vibration welding.

Location	Dimension	General Guidelines
A	Butt joint width	1.2 W
B	Butt joint height	0.050 - 0.080 in.(1.25 - 2.0 mm)
M	Melt down	0.040 - 0.060 in. (1.0 - 1.5 mm)
W	Wall thickness	Minimum 0.120 in. (3 mm)

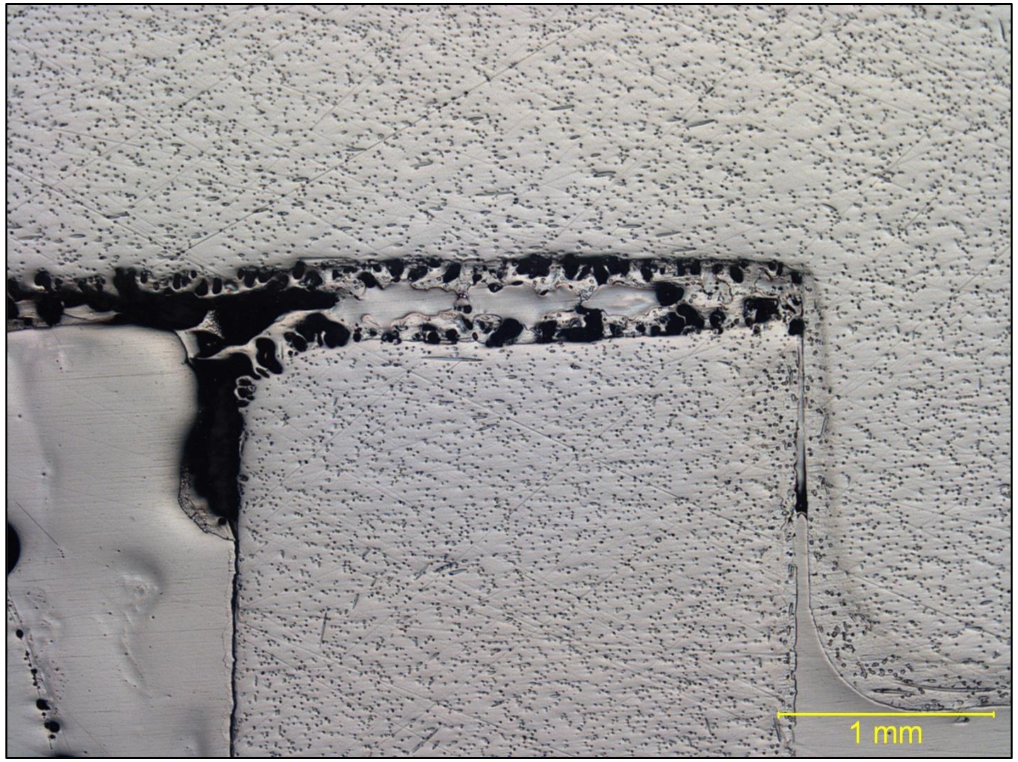




Laser Welding Troubleshooting

Issue	Solution
Porosity in Weld	Increase force
	Dry parts/pack with desiccant
Overweld	Reduce weld duration /power
Weak Weld	Ensure lower part is sufficiently laser absorbing
	Ensure upper part is sufficiently laser transparent
	Increase weld duration/power
Uneven Weld	Ensure tooling contacts part uniformly and provides support in all areas of the joint
Burns	Ensure parts are clean

Insufficient Pressure



Vibration Welding

- Physics of the Process
- Equipment and Parameters
- Material Considerations
- Design Considerations
- Troubleshooting

Vibration Welding

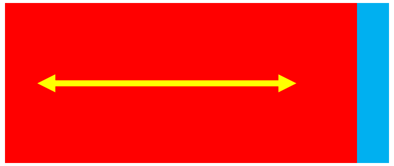
- Common applications
  - Headlights, taillights, instrument panels, manifolds, containers

- **Advantages**
  - Fast (2-10 s)
  - Applicable to large parts
  - Can weld internal walls
  - Well-established process, with excellent control possible

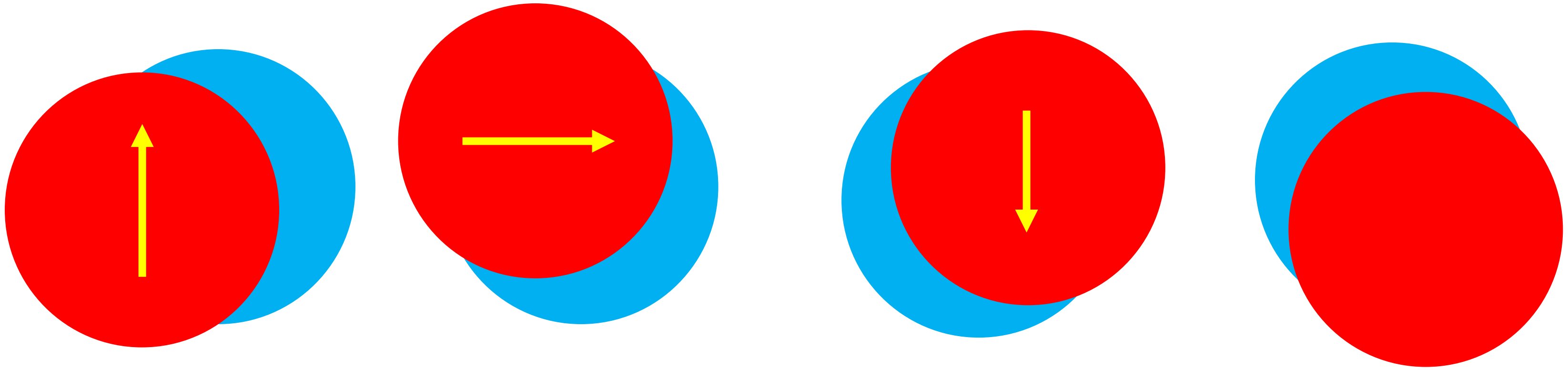
- **Disadvantages**
  - High capital cost (equipment and fixtures)
  - Noise
  - Thin walls tend to flex or rock rather than rub against the other weld surface.

Vibration Welding Types

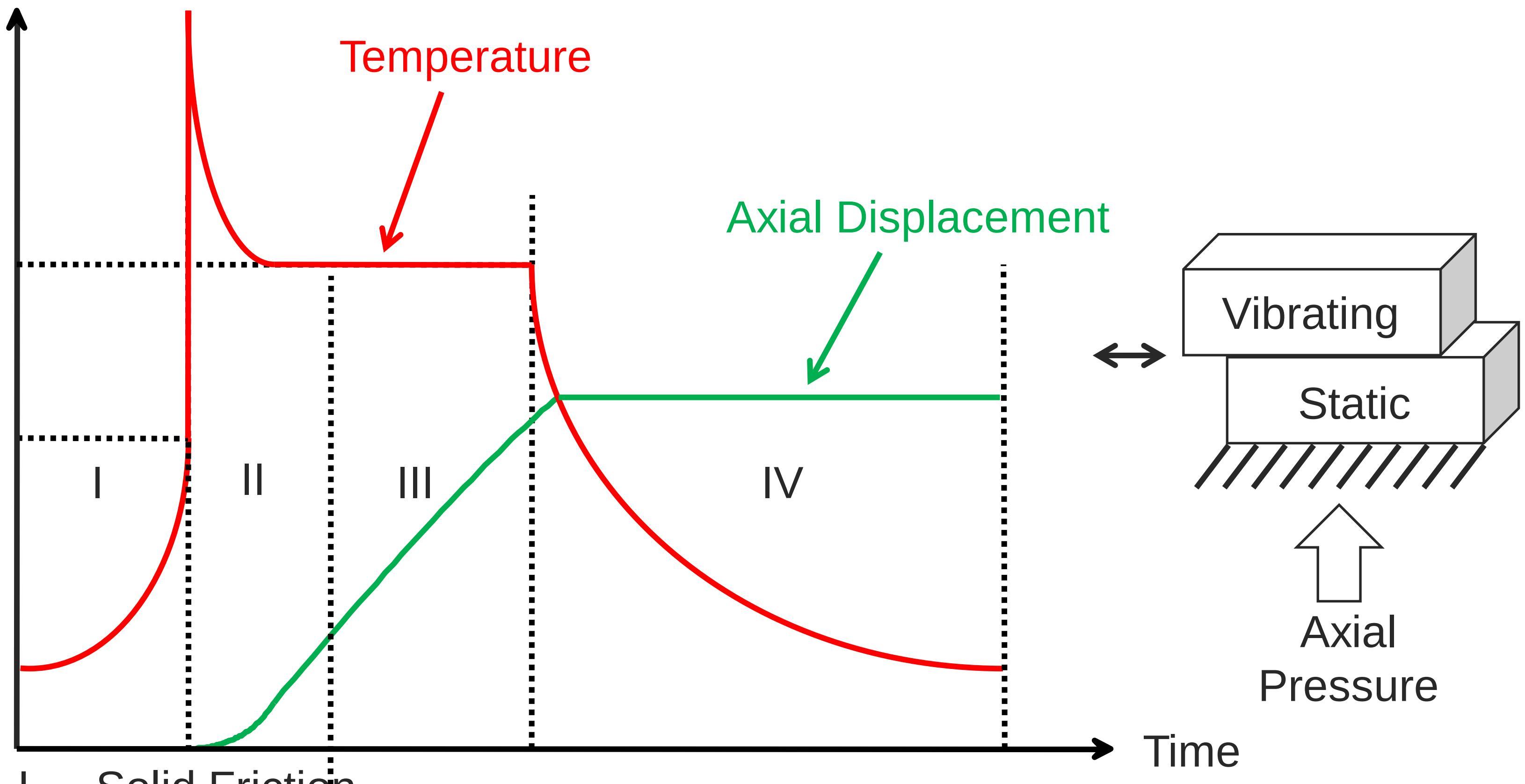
- Linear Vibration Welding
  - Low vs. High Frequency
  - Motion in a single direction



- Orbital Vibration Welding (uncommon)
  - Lower amplitude vibrations in multiple directions



Process Steps

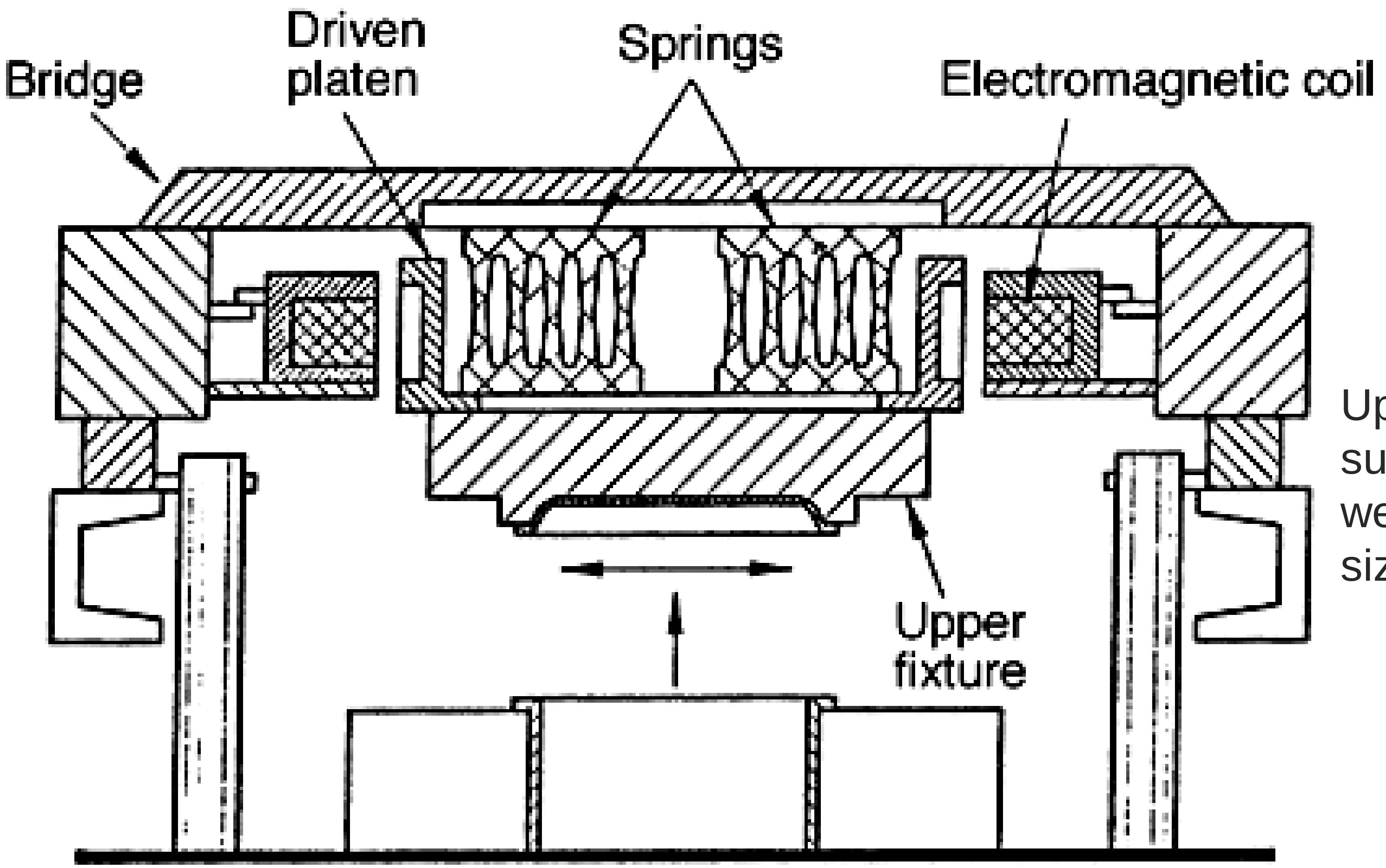


I. Solid Friction
II. Unsteady State Friction
III. Steady Friction
IV. Cooling

Process Physics (Linear)

- Power = Force x Velocity = Energy / Time
- Solid State Heating
  - $Q = (F_n \cdot \mu) \times ([2 \cdot A \cdot \omega] / \pi)$
    - F_n is Normal Force
    - μ is the Coefficient of Friction
    - A is the amplitude of vibration
    - ω is the frequency of vibration
- Viscous Heating
  - $Q = (\eta / 2 \cdot h) \times ([A^2 \cdot \omega^2] / 2)$
    - η is Melt Viscosity
    - 2h is Melt Thickness

Vibration Welding Equipment



Upper fixture is subject to weight and size limitations

(*Source: The Process of Vibration Welding by Jordan Rotheiser, Plastic Decorating July/August 2005*)

Method of Motion Control

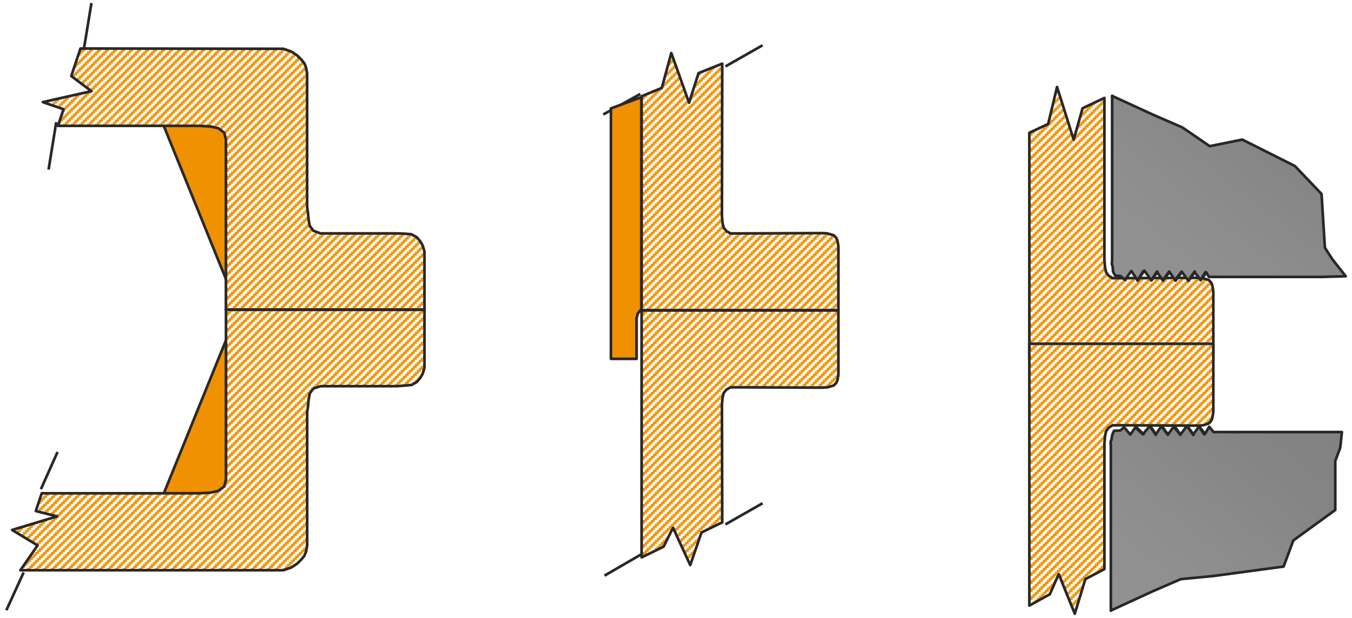
- Pneumatic
  - Constant force
  - Rate of displacement depends on material viscosity and load applied.
  - Not well suited to consistent displacement needs
- Servo
  - Constant velocity
  - Force depends on material viscosity and speed
  - Displacement rate may be unsuited to viscosity, additional development may be needed.

Vibration Welding Part Design

- Flange
  - Allows gripping of the plastic components during the vibration welding process
- Support
  - Prevents buckling of the joint walls with ribs, if this is not sufficient or possible, fixtures should provide braces against buckling.
- Plane of joint
  - Maximum incline of 10 degrees in the direction of vibration, over short distances

Part Design and Flexure

Design: Wall Flexure



Internal Gussets   Internal Tabs   Knurled Fixtures

Courtesy: Branson Ultrasonics

Important Material Properties

- High coefficient of friction
- Low thermal conductivity
- High stiffness
- High toughness
- Moderate filler content (for flexible polymers)

Material Weldability

Material	Weldability	Ave. Coefficient of Friction (μ)
Polytetrafluoroethylene (PTFE)	F	0.06
High Density Polyethylene (HDPE)	A	0.14
Polybutylene Terephthalate (PBT)	A	0.19
Polyoxymethylene (POM)	B	0.2
Polypropylene (PP)	A+	0.25
Polyetheretherketone (PEEK)	C	0.28
Nylon 66	A	0.37
Polycarbonate (PC)	A+	0.53
Polymethylmethacrylate(PMMA)	A	0.58
Polyvinylchloride (PVC)	A	0.6
Polyurethane (TPU)	D	2.96

High Tg!

Soft!

Recommended Ranges of Welding Pressure

Material	MVR (cm^3/10 min)	Welding Pressure (N/mm^2)
ABS	2-50 (220/10)	1.0-2.0
PA6	18-110 (275/5)	0.5-3.0
PA66	10-180 (275/5)	0.5-3.0
PC	3-12 (200/1.2)	1.0-2.0
HDPE	0.1-80 (190/5)	0.5-8.0
PMMA	1-25 (230/3.8)	1.0-2.0
POM	1-40 (190/2.16)	1.0-4.0
PP-H	1-100 (230/2.16)	0.5-4.0
PPE + SB	8-270 (250/21.6)	2.0-6.0
PS	3-25 (200/5)	1.0-4.0
SAN	8-25 (220/10)	1.0-2.0

Note: MVR = melt viscosity range

Material Compatibility

	PA6	PA66	PA46	PBT	PET	TPE-E	PC	PC+ABS	ABS	HDPE	LDPE	PMMA	POM	PP	PPS	PS	PVC	SAN
PA6	+	+	+						+									
PA66	+	+	+						+									
PA46	+	+	+															
PBT				+	+	+	+	+	+									+
PET				+	+	+	+	+										
TPE-E				+	+	+	+	+										
PC				+	+	+	+	+	+			+			+			+
PC+ABS				+	+	+	+	+	+			+			+			+
ABS	+	+		+			+	+	+			+				+	+	+
HDPE										+								
LDPE											+							
PMMA							+	+	+			+						
POM													+					
PP														+				
PPS							+	+							+			
PS									+							+		
PVC									+								+	
SAN				+			+	+	+									+

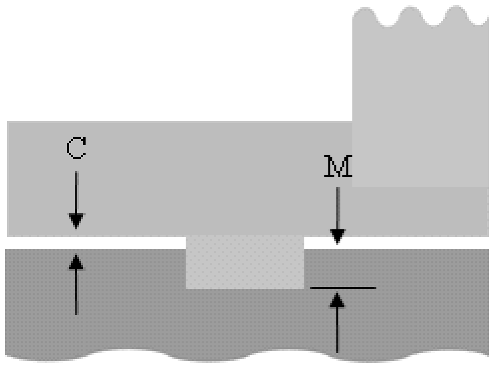
(Source: DSM Vibration Welding Guide)

Joint Design Considerations

- Must be loose fitting
- Self alignment
- Flash
  - Molten polymer will escape from the joint interface.
  - Excessive flash can be hidden by adjusting weld pressure, weld time, or weld amplitude.
  - Flash traps can be designed into the joint to hide the flash altogether.
- Sufficient rigidity to prevent buckling under high welding pressure
- Joint thickness must be at least 75% of amplitude.

Butt Joint

	Dimension	General Guidelines
A	Butt Joint Width	1.2 W
B	Butt Joint Height	0.050 - 0.080 in. (1.25 - 2.0 mm)
C	Cosmetic Gap Height	0.020 - 0.040 in. (0.5 - 1.0 mm)
M	Melt Down	0.040 - 0.060 in. (1.0 - 1.5 mm)
W	Wall Thickness	Minimum 0.120 in. (3 mm)



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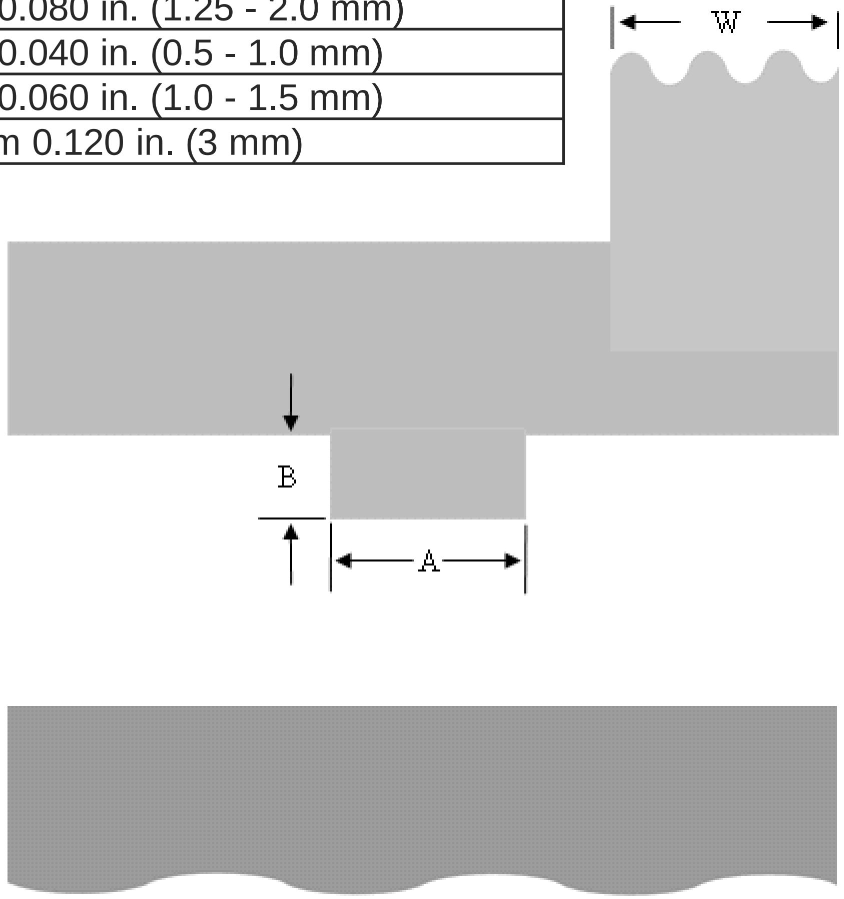
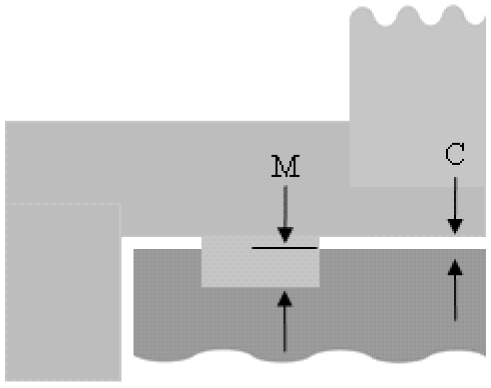


Butt Joint with External Flash Trap

	Dimension	General Guidelines
A	Butt Joint Width	1.2 W
B	Butt Joint Height	0.050 - 0.080 in. (1.25 - 2.0 mm)
C	Cosmetic Gap Height	0.020 - 0.040 in. (0.5 - 1.0 mm)
D	Vibration Clearance	0.040 in. (1.0 mm) Minimum
M	Melt Down	0.040 - 0.060 in. (1.0 - 1.5 mm)
W	Wall Thickness	Minimum 0.120 in. (3 mm)



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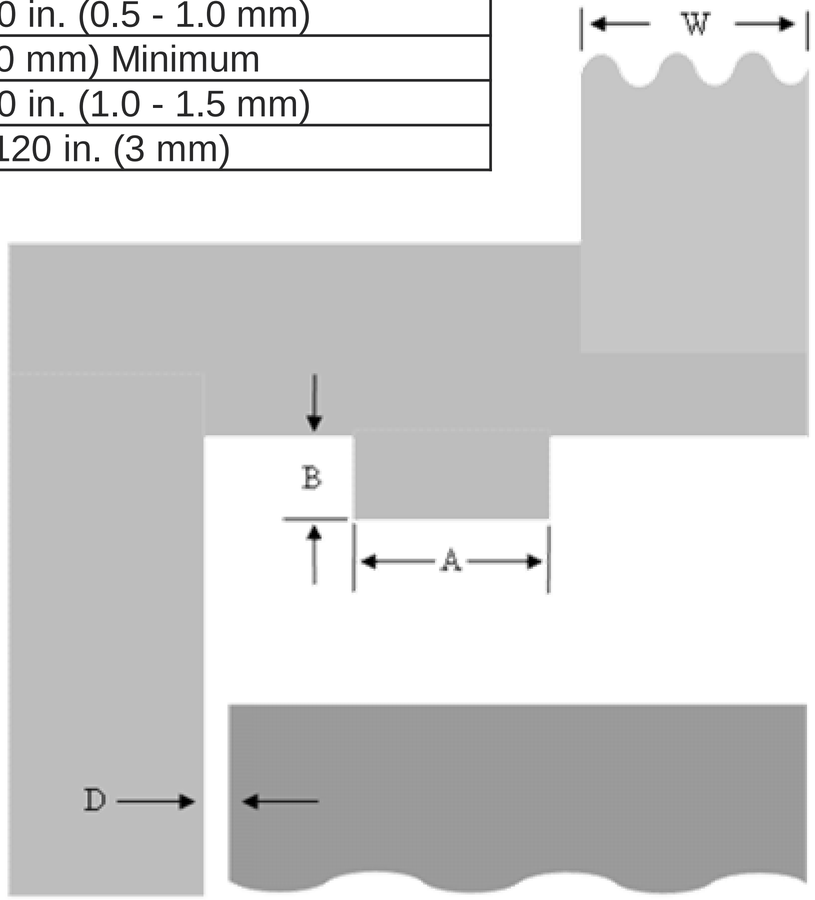
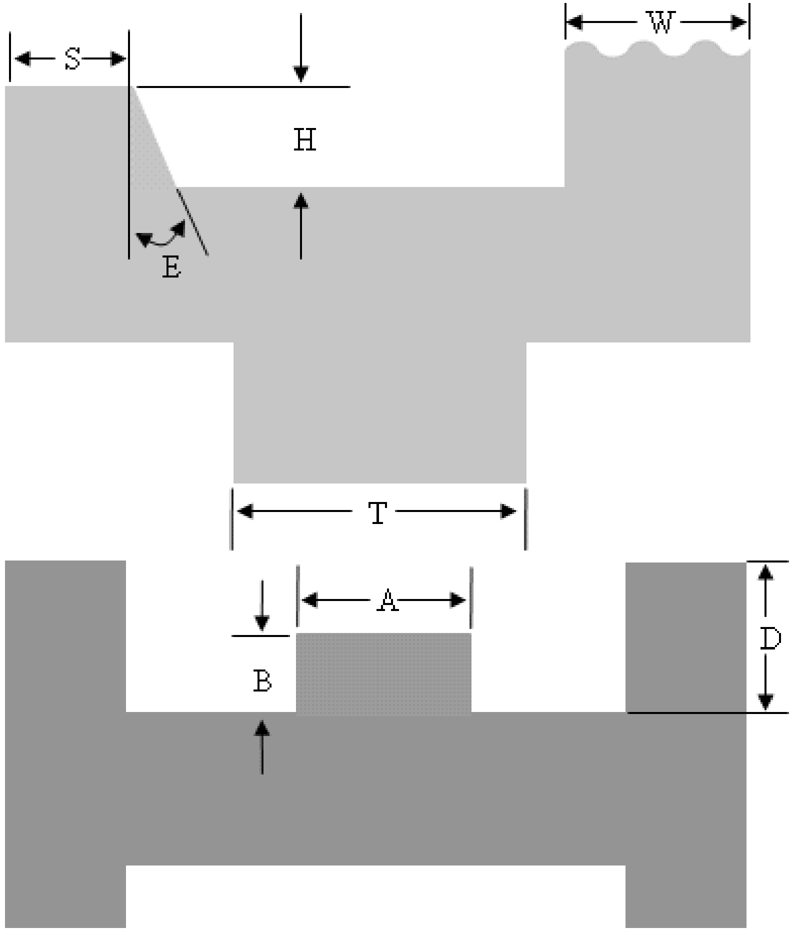
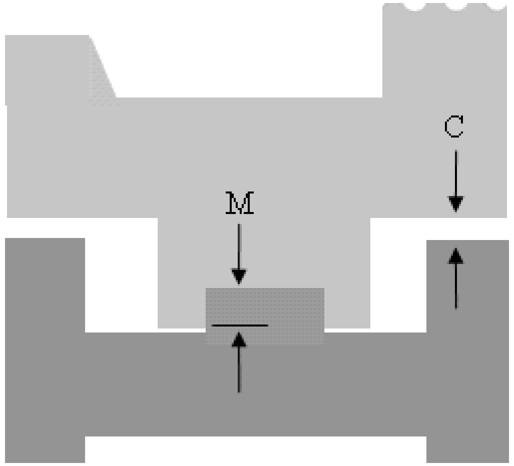


Butt Joint with Internal Flash Trap

	Dimension	General Guidelines
A	Butt Joint Width	~ 0.160 in. (4 mm)
B	Butt Joint Height	~ 0.060 in. (1.5 mm)
C	Cosmetic Gap Height	~ 0.040 in. (1.0 mm)
D	Groove Depth	2B
E	Side Wall Taper	15 degree
H	Side Wall Height	0.080 in. (2 mm)
M	Melt Down	0.060 in. (1.5 mm)
S	Side Wall Width	0.060 in. (1.5 mm)
T	Tongue Width	A + 0.080 in. (2 mm)
W	Wall Thickness	0.120 in. (3 mm)





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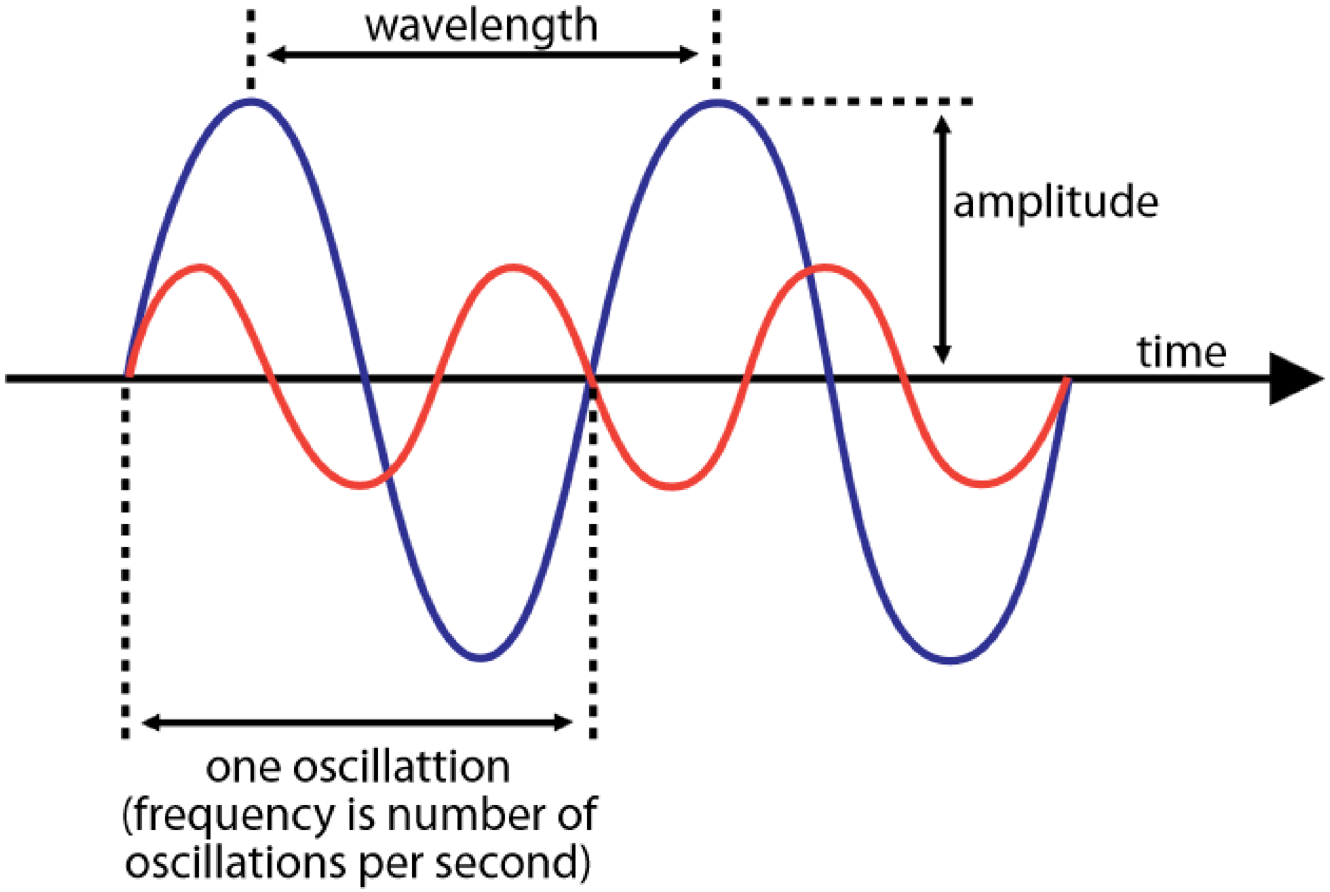
Vibration Welding Process Parameters

Frequency	100-120 Hz	240Hz
Amplitude	1.5-4.0 mm	0.4-1.5 mm
Pressure	1500 – 4000 kPa If pressure is too low, flash appears powdery or hair-like.	
Weld Mode & Duration	0.5-10 sec (for inconsistent parts) 1-3 mm	
Hold Time	1-20 sec	

Frequency / Amplitude

- Frequency
  - Choice dependent on size of parts and material requirements
  - Lower frequency = bigger parts, more amplitude
- Amplitude
  - Typically 1-3 mm of amplitude required, dependent on type of plastic and frequency being used

High vs. Low Frequency



(Source: DSM Vibration Welding Guide)

Weld Settings

- Trigger method
  - By force recommended
  - For warped parts, can use trigger delay by force
- Weld mode and duration (time, energy, distance)
  - Welding by distance recommended for consistency
    - Set the value to match the height of the designed joint.
  - Time can be used for initial process development or if welder only has time mode.

Vibration Welding Troubleshooting

Issue	Solution
Excess Vibration or Autotune Error	Ensure tool and part are within maximum weight allowance
	Tighten all bolts
Overweld	Reduce weld duration/distance
Weak Weld	Ensure parts are not warped
	Ensure there is no interference other than the designed joint
	Add ribs or thicken wall
Uneven Weld	Ensure tooling contacts part uniformly and provides support in all areas of the joint
Porosity in Weld	Bag and seal parts after molding (use desiccant if needed)
	Dry parts before welding
Weak weld	Increase weld duration/distance
	Change to material with greater surface friction

Hot Plate Welding

- Physics of the Process
- Equipment and Parameters
- Material Considerations
- Design Considerations
- Troubleshooting

Hot Plate Welding

- Common applications
  - Pipes, fuel tanks, window frames, car components, pallets

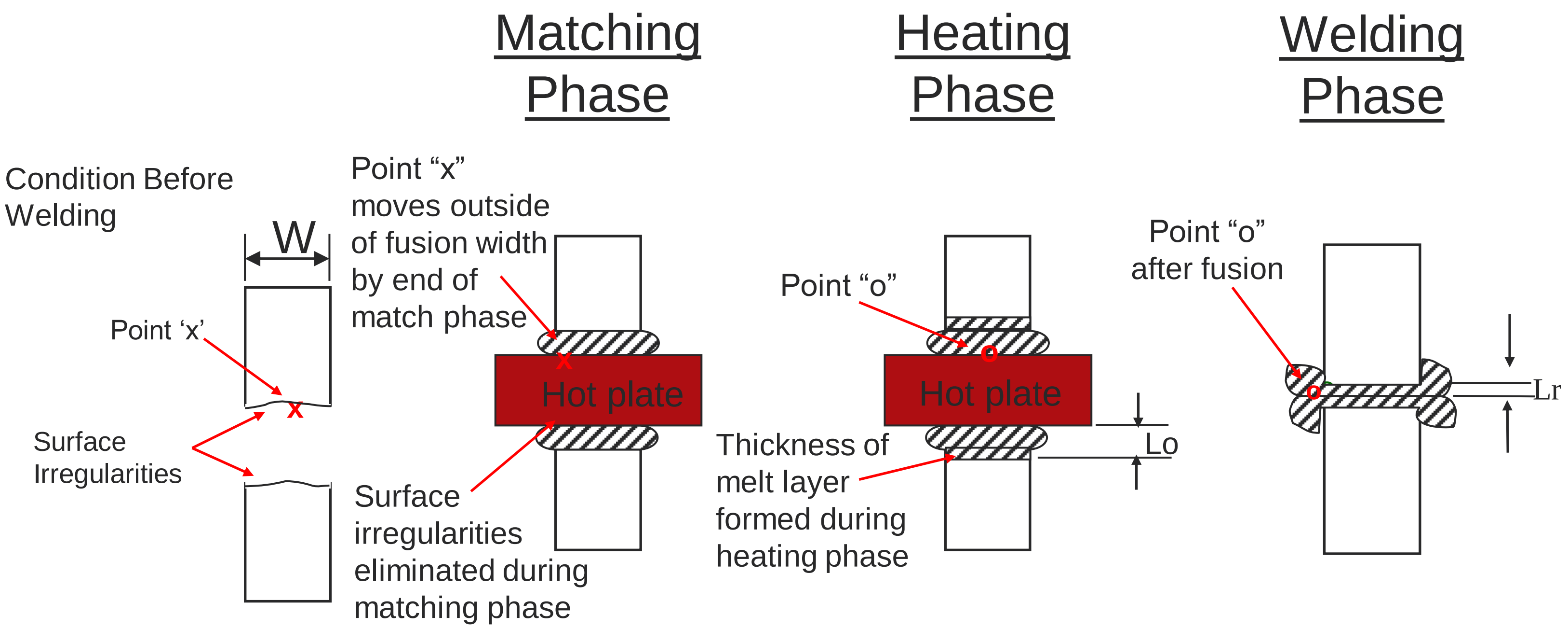
Advantages
- Simple
- Reliable
- Suited for larger and complex part geometries
- Wide operating windows
- Relatively high tolerance to imperfections on the mating surfaces

Disadvantages
- Relatively slow
- Energy inefficient
- Produces significant flash
- Potential for sticking
- Parts have to be moved during the process.

Hot Plate Welding Phases

- Matching phase:
  - Improve contact between part and hot plate to maximize heat transfer and push out any surface impurities.
- Heating phase:
  - Build melt layer thickness.
- Change-over:
  - Retract parts and hot plate.
  - Keep as short as possible.
- Welding phase:
  - Squeeze out entrapped gases, damaged material.
  - Create conditions for joint formation.
- Cooling phase:
  - Re-solidification under pressure.

Hot Plate Welding Phases



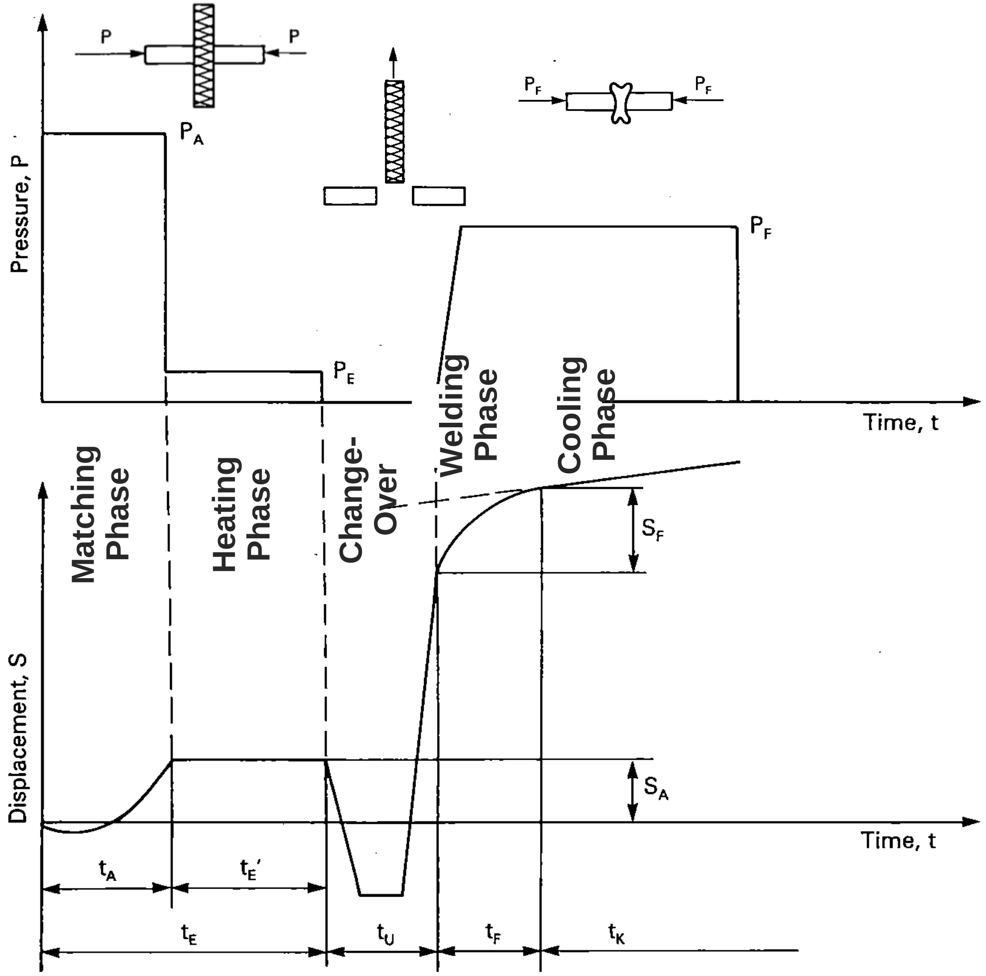
Nomenclature

L_0 = Melt layer after heating (0.34w)

L_r = Melt remaining at end of weld (0.25 L_0)

W = Cross sectional thickness of joint

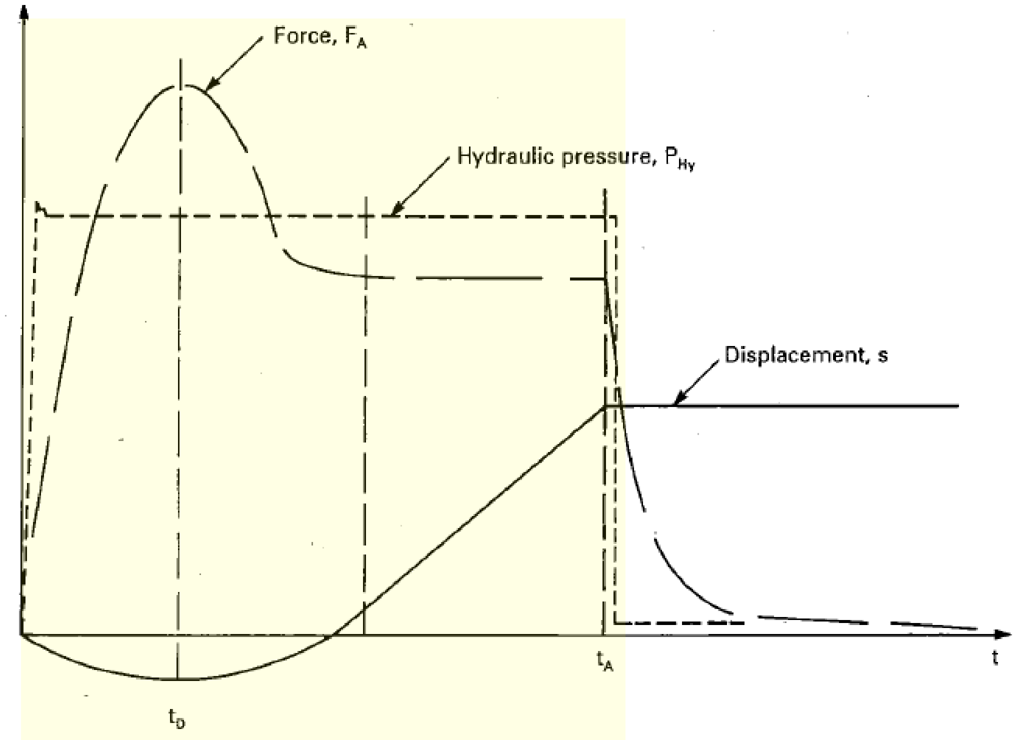
Hot Plate Process



Potente, Michel, Tappe, "The principles of hot plate welding of semi-crystalline thermoplastics", Joining Plastics in Production, *1988.*

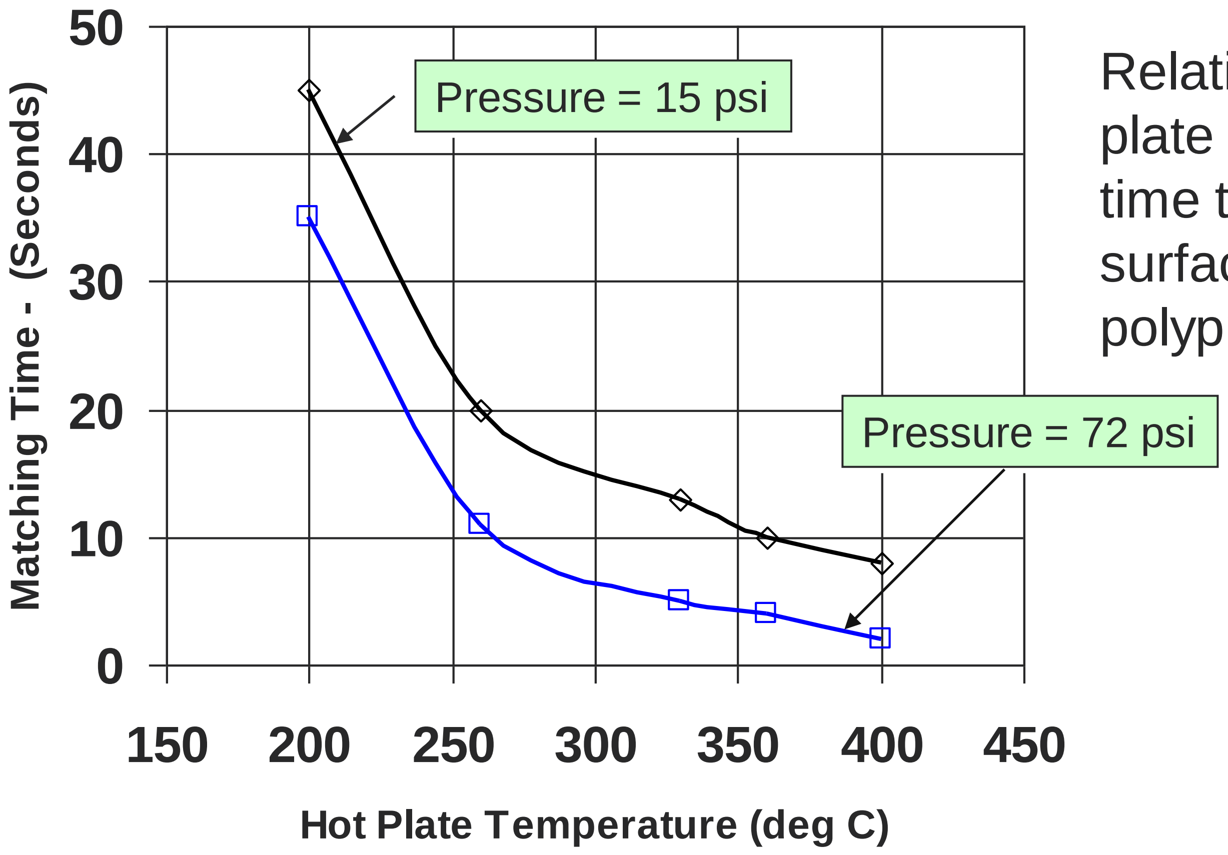
Matching Phase

- Displacement and force during Matching Phase
- Note slight increase in force during initial expansion of polymer on heating.



Potente, Michel, Tappe, "The principles of hot plate welding of semi-crystalline thermoplastics," Joining Plastics in Production, *1988.*

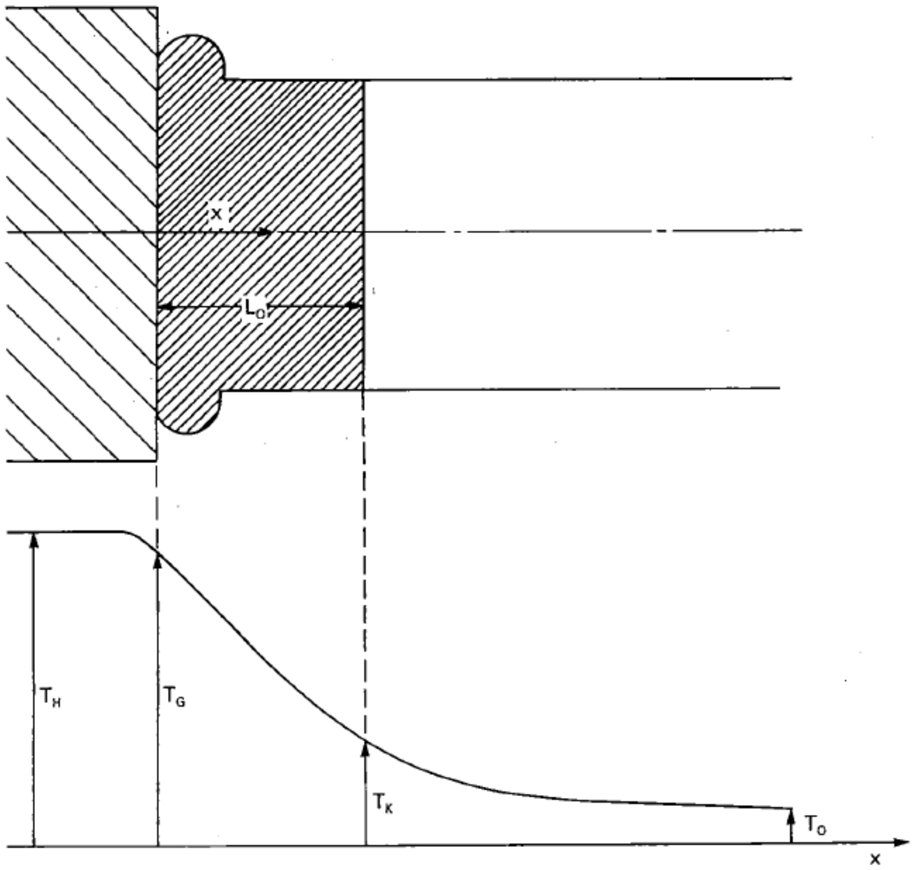
Matching Time vs. Pressure



Relationship between hot plate temperature and time to match 1 mm of surface irregularity on polypropylene.

Heating Phase

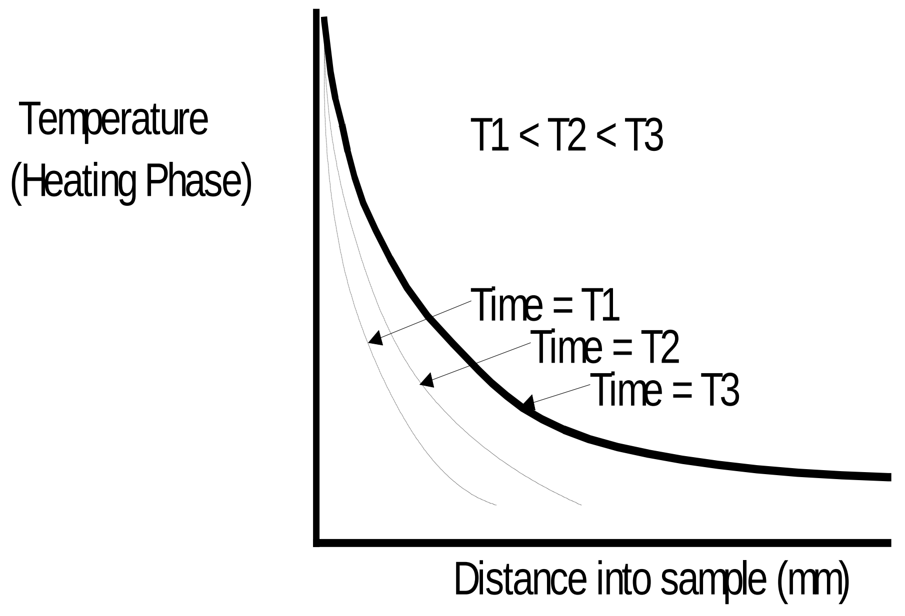
- Low pressure heating to develop melt layer
- Empirical data shows ideal melt layer thickness, L_0, is 30%-40% of the joint thickness.



Potente, Michel, Tappe, "The principles of hot plate welding of semi-crystalline thermoplastics", Joining Plastics in Production, *1988.*

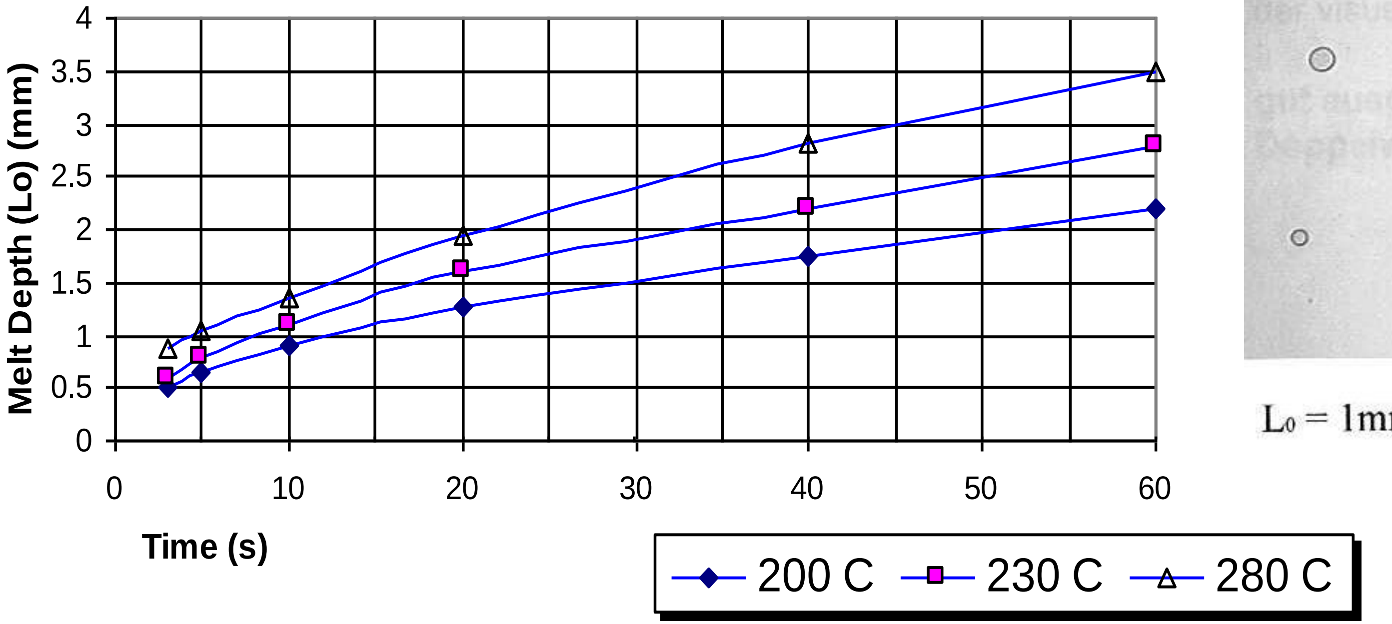
Heating Phase

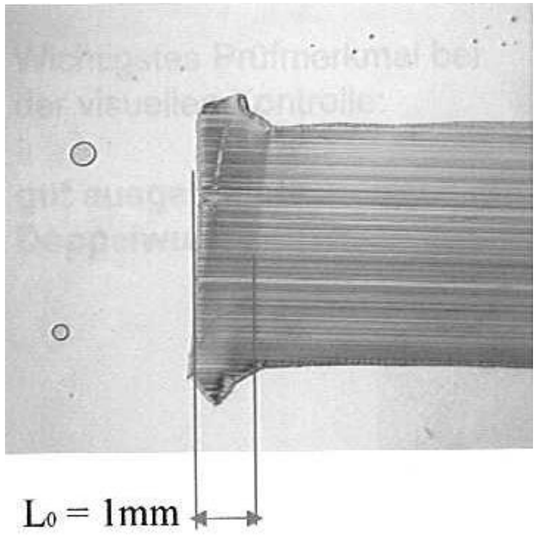
- Platen temperatures and heating time:
  - Thermoplastics are good insulators so heating is localized.
  - Longer heating times give less steep gradients.
- While deeper layers of melt have traditionally been desirable, good welds can be obtained with short times and high temperatures if changeover time is low.



Heating Phase

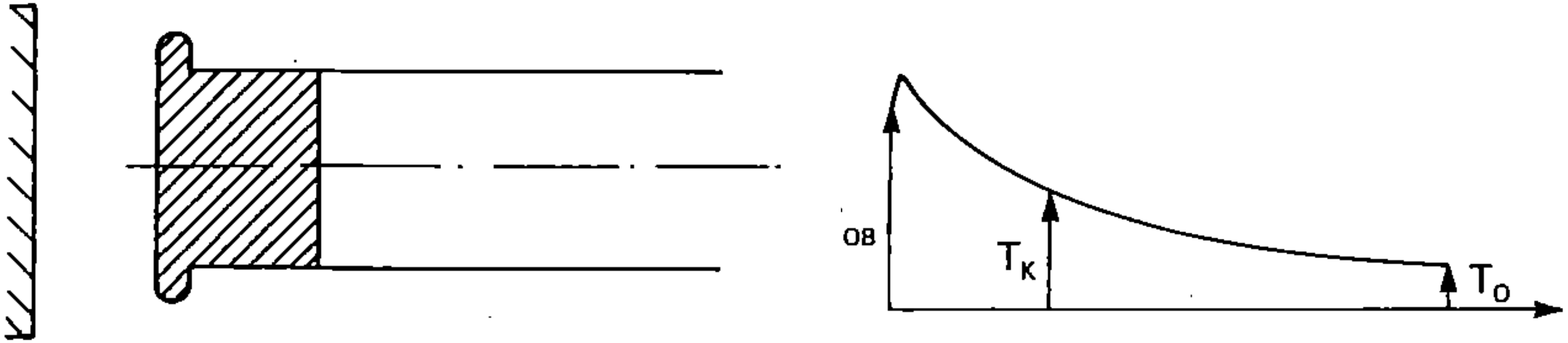
Melt Depth (L_o) vs. Time





Change-Over Time

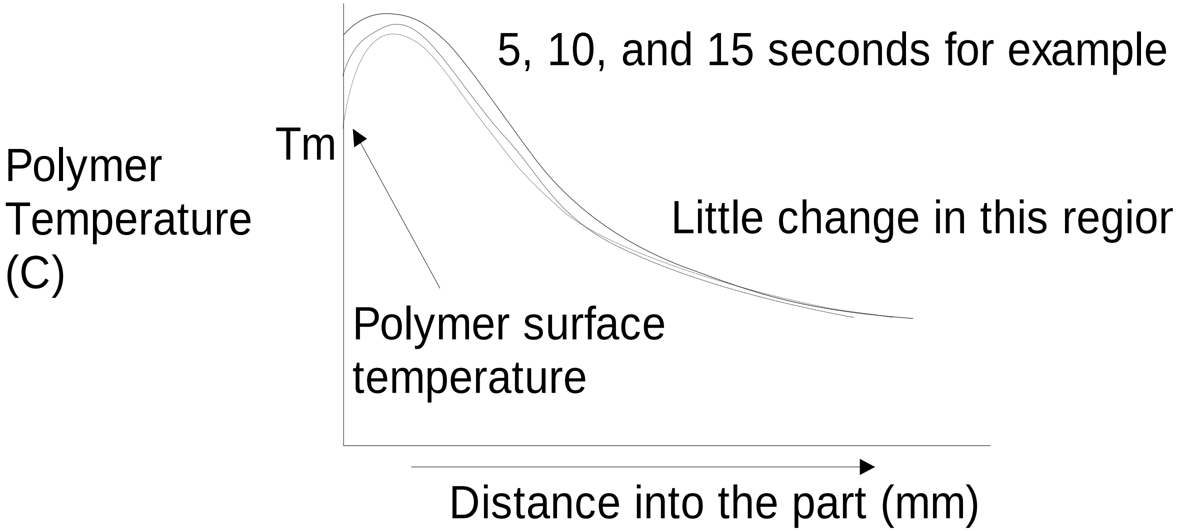
- Change-over time is the time required to remove the hot plate from the joining surfaces after the heating cycle is completed and to bring joining surfaces of the parts into a contact.
- Change-over time should be as short as possible to avoid cooling at the surface of the melted material, <3 s.



Potente, Michel, Tappe, "The principles of hot plate welding of semi-crystalline thermoplastics", Joining Plastics in Production, *1988.*

Change-Over Time

- Data shows temperatures at different times after retraction from platen.
- If too long, the surface will form a so-called “frozen” skin.
  - May create a "cold weld."
  - Weak, but failure is often not immediate.



Fusion (Welding) Phase

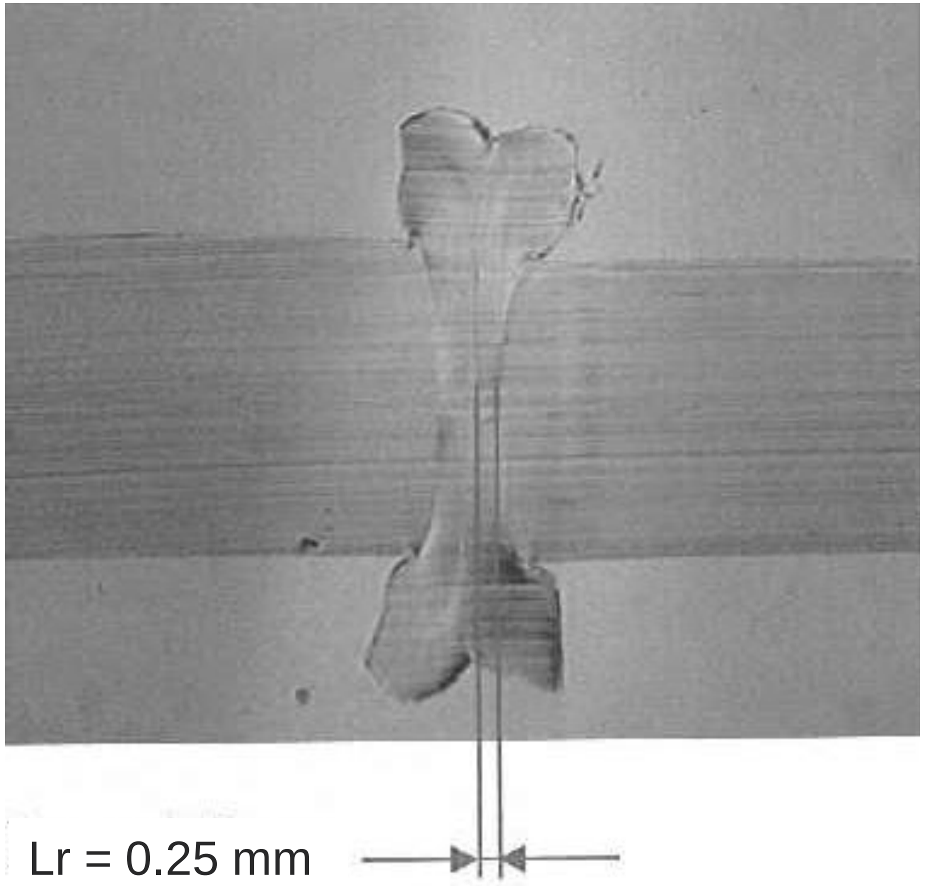
- Purpose:
  - Create a flow of material in the joining area.
  - Displace the outer portion of the melt layer into the flash.
  - Bring in contact layers of molten material with optimum properties for joint formation.

Fusion (Welding) Phase

$$0.6 < \frac{L_W}{L_0} < 0.8$$

$$\frac{L_r}{L_0} = 0.2\text{-}0.4$$

$$\frac{L_0}{d} = 0.3\text{-}0.4$$

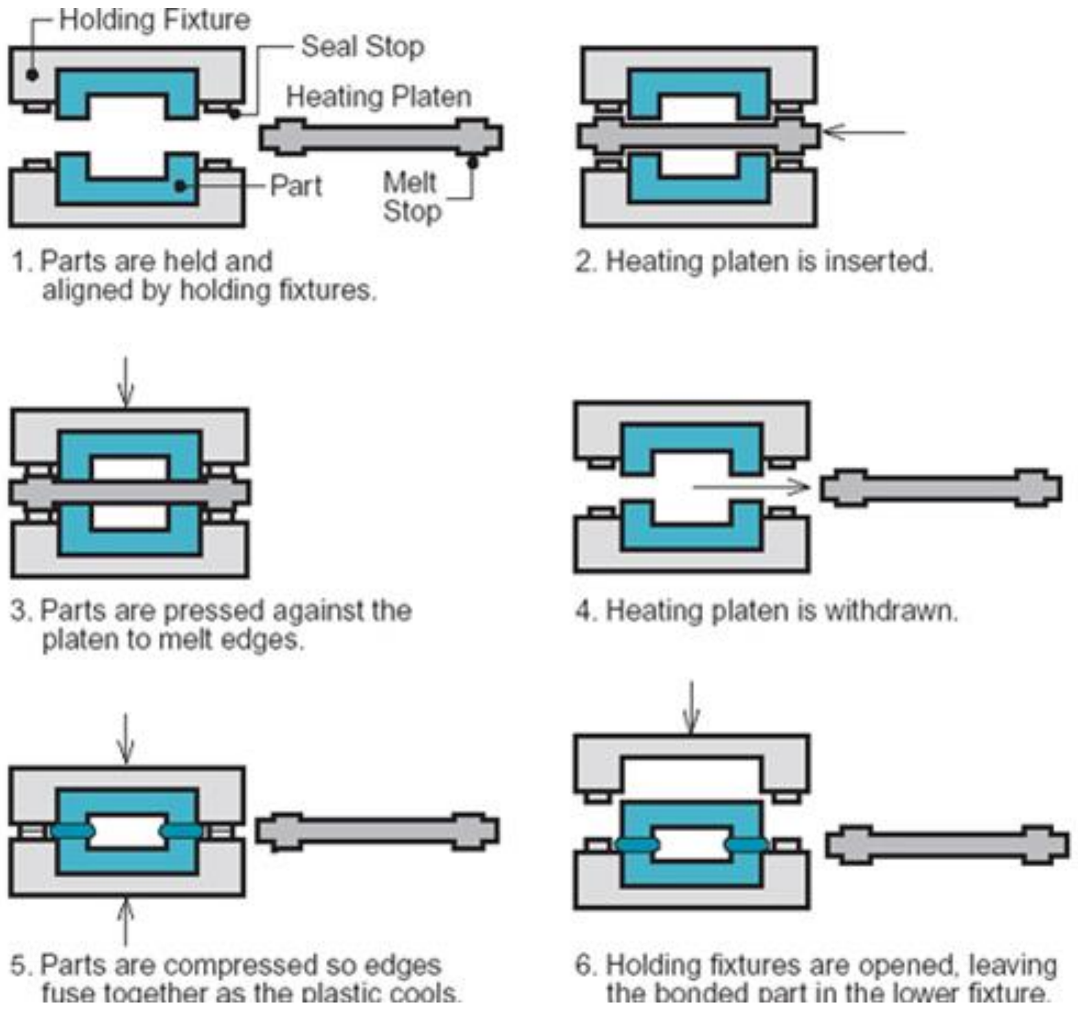


- Leave 25% of remaining melt (L_r) on both sides of the joint.
- Too much weld distance (L_W) results in a cold weld as the melt layer (L_0) is all pushed out.
- Too little weld distance results in insufficient mixing and a weak weld.

Cooling Phase

- Pressure (at same setting as during welding phase) should be applied to the joint during the cooling phase.
- At a minimum, cooling time could end once melt is below the crystallization temperature.
- Allow as long a cooling time as possible where maximum strength is required.
- Slower cooling allows more time for crystallization of the polymer.

Mechanically Defined Distances



http://www.jcwelder.com/plastic-welding-technology/

Material Weldability

- Hot plate is the most forgiving welding process for material properties.
- Nearly any thermoplastic polymer can be welded with hot plate.
- Generally, the more viscous, the less chance of sticking to the tool.
- The more thermally conductive, the lower the cycle time needed.

Material Properties

Polymer	Solid Density* ρ (g/cm^3)	Glass Transition T_g	Melting Point T_m	Usual Melt Processing Range	Melt Density* ρ (kg/m^3)	Thermal Conductivity k (W/m °C) (Btu/h ft °F)	Heat Capacity Cp (J/kg °C) (Btu/lb_m °F)	Heat of Fusion ΔH (J/kg) (Btu/lb)
HDPE	0.941-0.967	-130°C -202°F	130-137°C 266-278°F	160-240°C 320-464°F	780	0.25 0.145	2200-2400 0.52-0.57	210,000-300,000 90-130
LDPE	0.915-0.935	-130°C -202°F	106-112°C 223-234°F	160-240°C 320-464°F	760	0.20 0.115	2200-2400 0.52-0.57	190,000-240,000 80-100
LLDPE	0.910-0.925	-130°C -202°F	125°C 257°F	160-240°C 320-464°F	760	0.20 0.115	2200-2400 0.52-0.57	190,000-240,000 80-100
PP	0.890-0.910	-20°C -4°F	165°C 329°F	180-240°C 356-464°F	730	0.18 0.10	2000-2200 0.48-0.52	210,000-260,000 90-110
PVC (Rigid)	1.30-1.58	80°C 176°F	175°C 347°F	165-205°C 329-401°F	1250	0.17 0.10	1000-1700 0.24-0.41	170,000-190,000 70-80
PS	1.04-1.10	100°C 212°F	amorphous**	180-240°C 356-464°F	1000	0.15 0.09	1300-2000 0.31-0.48	amorphous**
PMMA	1.17-1.20	105°C 221°F	amorphous**	180-230°C 356-446°F	1050	0.19 0.11	1400-2400 0.33-0.57	amorphous**
PET	1.34-1.39	80°C 176°F	265°C 509°F	275-290°C 527-554°F	1160	0.18 0.10	1800-2000 0.43-0.48	120,000-140,000 50-60
ABS	1.01-1.04	105-115°C 221-239°F	amorphous**	200-290°C 392-554°F	990	0.25 0.145	1300-1700 0.31-0.41	amorphous**
Nylon-66	1.13-1.15	90°C 194°F	265°C 509°F	275-290°C 527-554°F	980	0.20 0.115	2400-2600 0.57-0.62	190,000-205,000 80-88
PC	1.2	140°C 284°F	amorphous**	250-305°C 482-581°F	1050	0.22 0.13	1300-2200 0.31-0.52	amorphous**

**Melt densities estimated for roughly mid-temperature of processing range.*

***Amorphous polymers have no* Tm *or* ΔH.

Vlachopoulos, Strutt. "Basic heat transfer and some applications in polymer processing," Plastics Technician's Toolbox, *Vol. 2, pp. 21-33, SPE 2002.*

Effect of Glass and Talc Fill (Polypropylene)

Filler Type	Percent Filler	Bulk Strength	Weld Strength	Weld Strength as a Percent of Bulk Strength
Glass	0	38.4	38.9	100%
Glass	20	43	34	78%
Glass	30	48	26	55%
Talc	0	41	40	99%
Talc	20	39	27	68%
Talc	40	36	16	45%

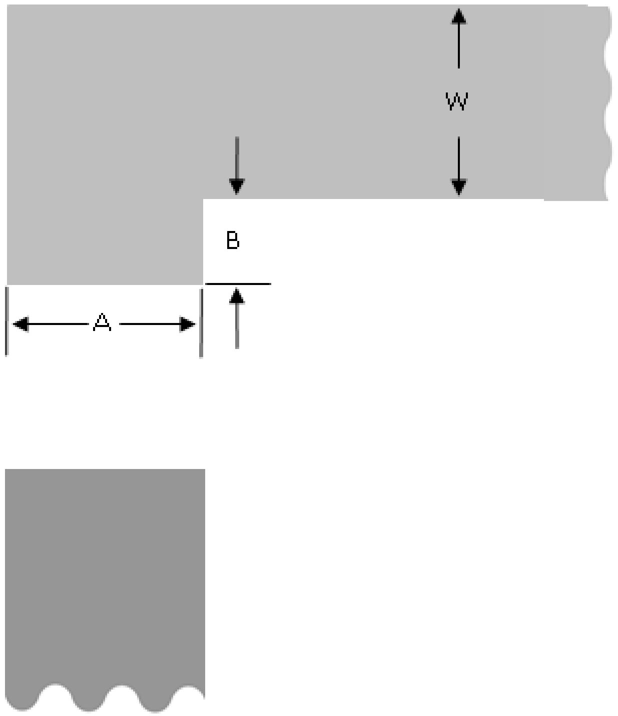
Potente and Brussel, ANTEC 98, 1062.

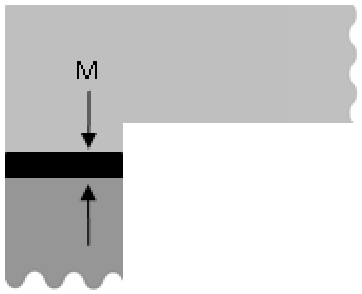
Design Constraints

- Hot plate must be able to provide even heating:
  - Contoured surfaces may require multiple, independently controlled, heating elements.
  - Internal components that extend past the joint make plate design complicated.
- Joint width should be consistent to ensure even heating.
- Thin walls may deform under pressure – use support ribs.
- Flash will be produced, if weld is in cosmetic location, design joint to hide it.

Joint Design – Butt

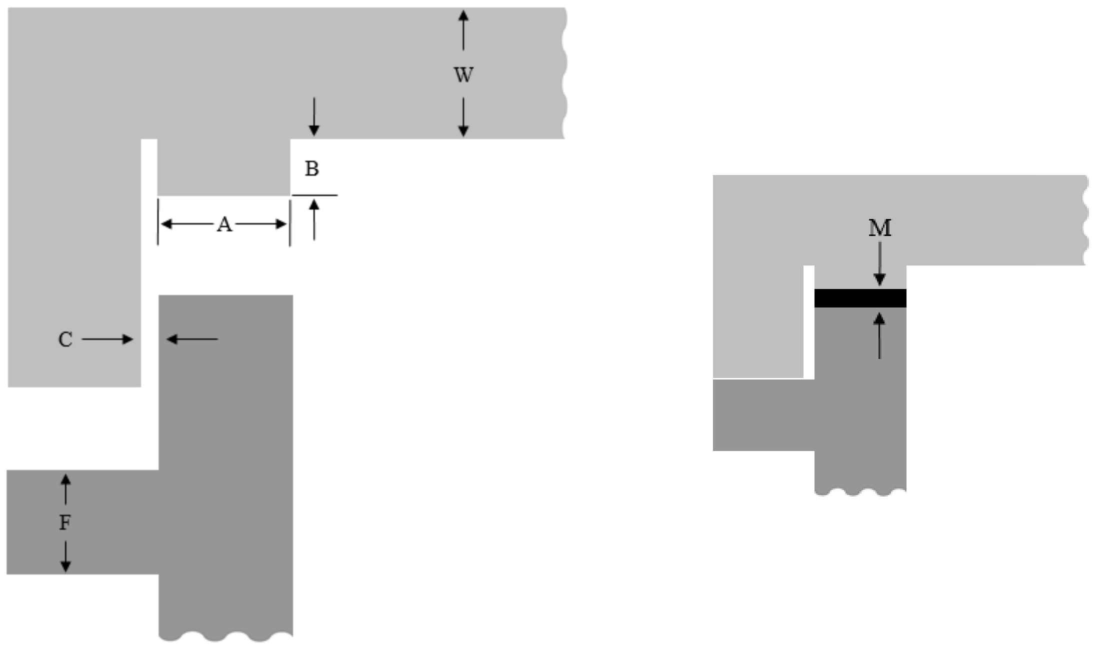
Location	Dimension	General Guidelines
A	Butt joint width	1.2W
B	Butt joint height	0.050 - 0.080 in.(1.25 - 2.0 mm)
M	Melt down	0.040 - 0.060 in. (1.0 - 1.5 mm)
W	Wall thickness	Minimum 0.120 in. (3 mm)





Joint Design – Butt with External Flash Trap and Flange

Location	Dimension	General Guidelines
A	Butt joint width	1.2 W
B	Butt joint height	0.050 - 0.080 in. (1.25 - 2.0 mm)
C	Clearance	0.040 in. (1.0 mm) minimum
F	Flange height	Minimum W
M	Melt down	0.040 - 0.060 in. (1.0 - 1.5 mm)
W	Wall thickness	Minimum 0.120 in. (3 mm)



Joint Design – Butt with External Flash Trap

Location	Dimension	General Guidelines
A	Butt joint width	1.2 W
B	Butt joint height	0.050 - 0.080 in. (1.25 - 2.0 mm)
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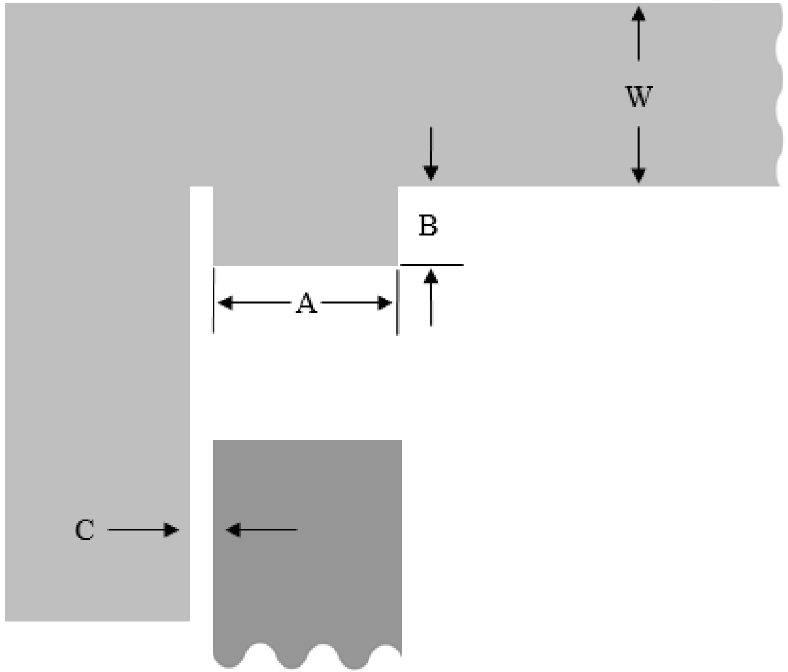
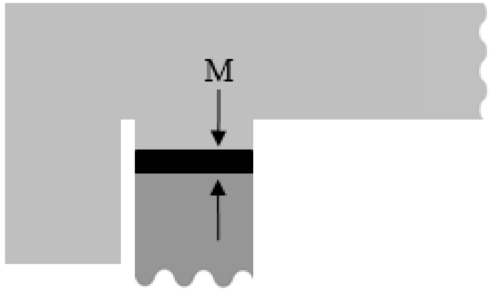
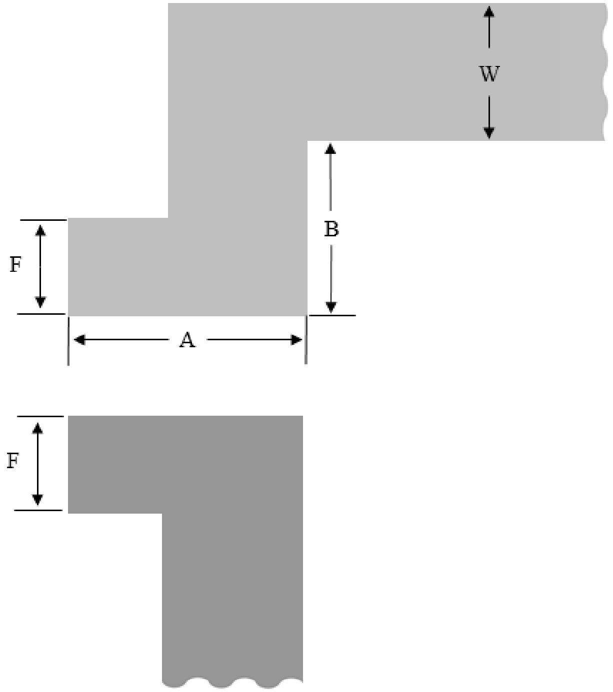
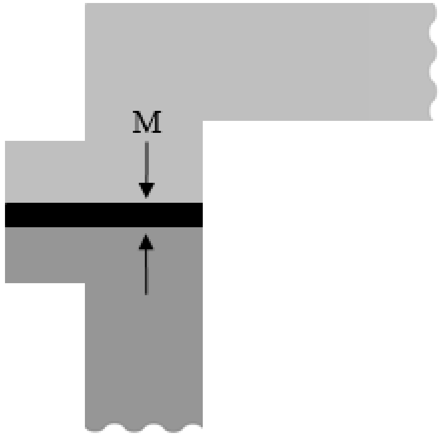




Joint Design – Butt with Flange

Location	Dimension	General Guidelines
A	Butt joint width	1.2 W
B	Butt joint height	0.050 - 0.080 in. (1.25 - 2.0 mm)
F	Flange height	Minimum W
M	Melt down	0.040 - 0.060 in. (1.0 - 1.5 mm)
W	Wall thickness	Minimum 0.120 in. (3 mm)





Welding Parameters

- Hot plate temperature:
  - Semi-crystalline = Tm + minimum 10°C (typically 30°C to 100°C above)
  - Amorphous = Tg + minimum 100°C
  - Thermocouples regulate temperature to within about 10°C
- Matching:
  - Time = 5-10 s
  - Pressure = typically 0.2-0.5 MPa
  - Alignment critical
- Heating:
  - Time depends on wall thickness (20s-30m)
  - Pressure should be minimal
- Change-over time:
  - < 3 s ideal
- Welding:
  - Pressure (increase with joint thickness)
  - Distance
- Cooling:
  - Under pressure long enough to prevent fracture during handling
  - Longer and slower cooling = stronger weld

Hot Plate Temperature

- Hot plate temperature:
  - Semi-crystalline polymers: ~60°C > T_m
  - Amorphous polymers: ~160°C > T_g

Polymer	Structure	Transition Temperature, T_g or T_m (°C)	Hot Plate Temperature (°C)
Polyethylene	Semi-crystalline	130-140°C	190-200
Polypropylene	Semi-crystalline	160-175°C	220-235
Polyamide 6/6	Semi-crystalline	280°C	320
Polystyrene	Amorphous	100-110°C	260-270
Polycarbonate	Amorphous	150°C	310

High Temp Welding

- Hot plate temperature: 300-400°C
- Matching and heating times = 2-5 s
- Viscosity of melt is lower, less sticking
- Residual material on plate evaporates:
  - Use fume extraction!
- Thermal degradation of the surfaces occurs:
  - Should be pushed out during welding phase
  - Reduced strength can occur.
- Implemented successfully for PP, ABS to PMMA
- Do not use with reinforced or filled plastics.

Troughton, "Handbook of plastics joining", 2008.

Non-contact Hot Plate

- Hot plate temperature: 400-550°C.
- Parts held 0.5-1 mm from surface, heated via convection.
- Poorly suited for larger parts due to inability to maintain parallelism:
  - For parts < 100×100 mm.

Effect of Aging and Boiling Water on ABS Hot Plate Welds

Table 37.2. The Effect of Thermal Air Aging and Boiling Water on the Properties of Hot Plate Welds of ABS

ABS Sample	Exposure Type	Aging temp.	Aging Time	Ultimate Tensile Strength		Elongation at Break	
		°C(°F)	days	MPa (psi)	% Retained	mm (inches)	% Retained
Hot plate weld	thermal air aging	120 (248)	3	19.7 (2860)	61	0.9 (0.035)	42
Parent	thermal air aging	120 (248)	3	46.1 (6690)	107	2.8 (0.110)	78
Hot plate weld	thermal air aging	120 (248)	7	20.5 (2970)	63	0.9 (0.035)	41
Parent	thermal air aging	120 (248)	7	47.2 (6850)	109	3.1 (0.122)	85
Hot plate weld	thermal air aging	120 (248)	14	12.8 (1860)	40	0.7 (0.028)	33
Parent	thermal air aging	120 (248)	14	39.1 (5670)	91	2.5 (0.098)	67
Hot plate weld	boiling water	100 (212)	3	9.3 (1350)	29	0.6 (0.024)	29
Parent	boiling water	100 (212)	3	41.4 (6000)	96	6.5 (0.256)	181
Hot plate weld	boiling water	100 (212)	7	12.6 (1830)	38	0.7 (0.028)	31
Parent	boiling water	100 (212)	7	40.5 (5870)	94	5.4 (0.213)	150

Troughton, "Handbook of plastics joining", 2008.

EWI
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THE ASSEMBLY SHOW CELEBRATING 10 YEARS

Testing and Evaluation

Options for Weld Analysis

Quantitative Methods

- Leak testing
- Tensile/shear/push testing
- Peel testing
- Bend testing
- Torsional testing
- Creep testing
- Fatigue testing
- Dimensional analysis

Qualitative Methods

- Cross-sectional analysis
- Microtome slicing
- Visual inspection
- Computerized tomography (CT) scanning
- X-ray
- Ultrasonic testing
- Fractography

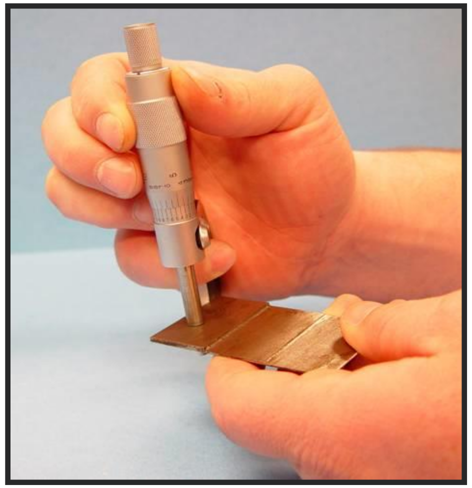
Mechanical Testing

- Test the use condition
- It's not a weld test if the weld doesn't fail!
- Test entire joint
  - Testing section often isn't representative.
- Don't compress the joint during leak testing

Mechanical testing equipment for large (left) and small (right) parts

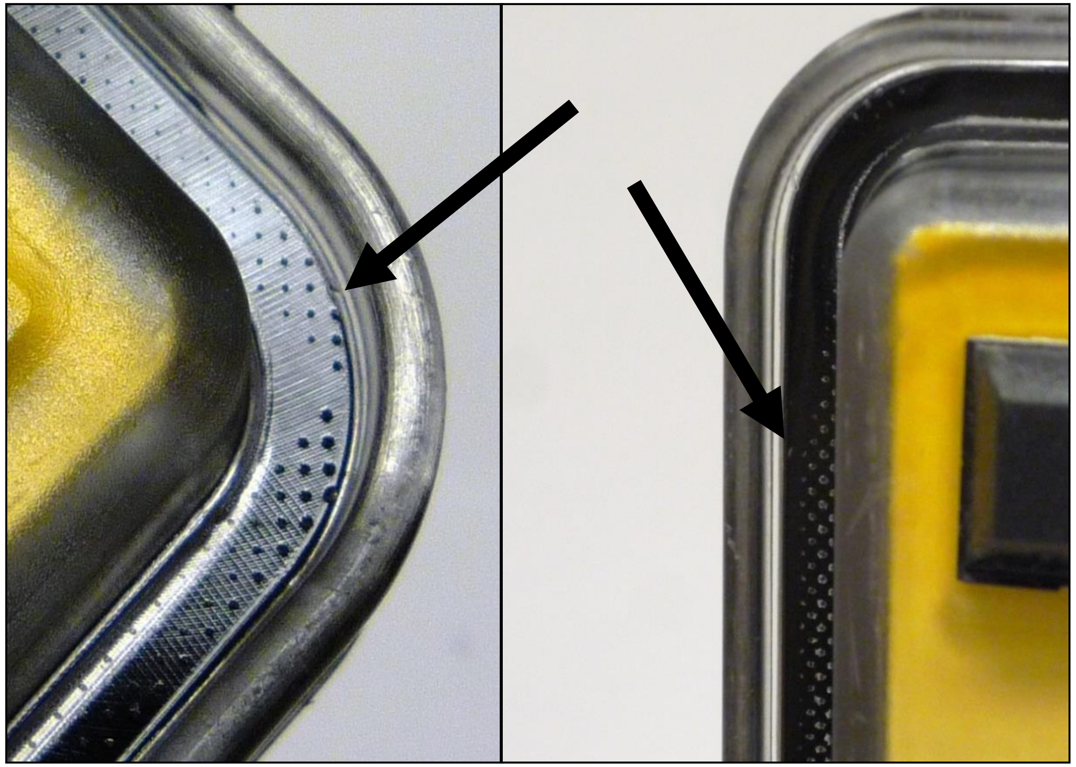
Visual Examination

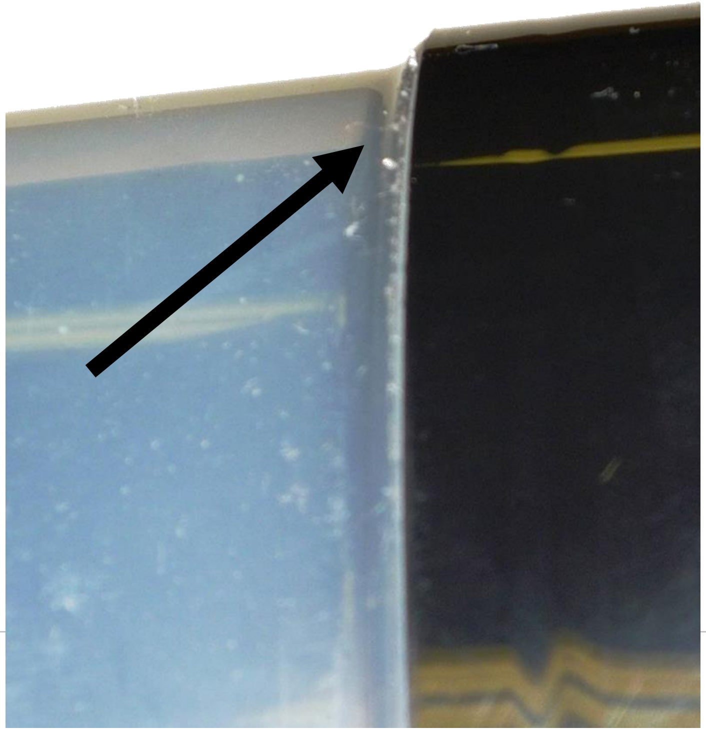
- Four primary factors affect the quality of a visual inspection:
  - Quality of the detector (eye or camera)
  - Lighting conditions
  - Capability to process the visual data
  - Level of training and attention to detail



Visual Examination, continued

- Go/No-Go gauges
- Calipers for rough measurements
- Inspection for particulate, flash, marking, burns, discoloration

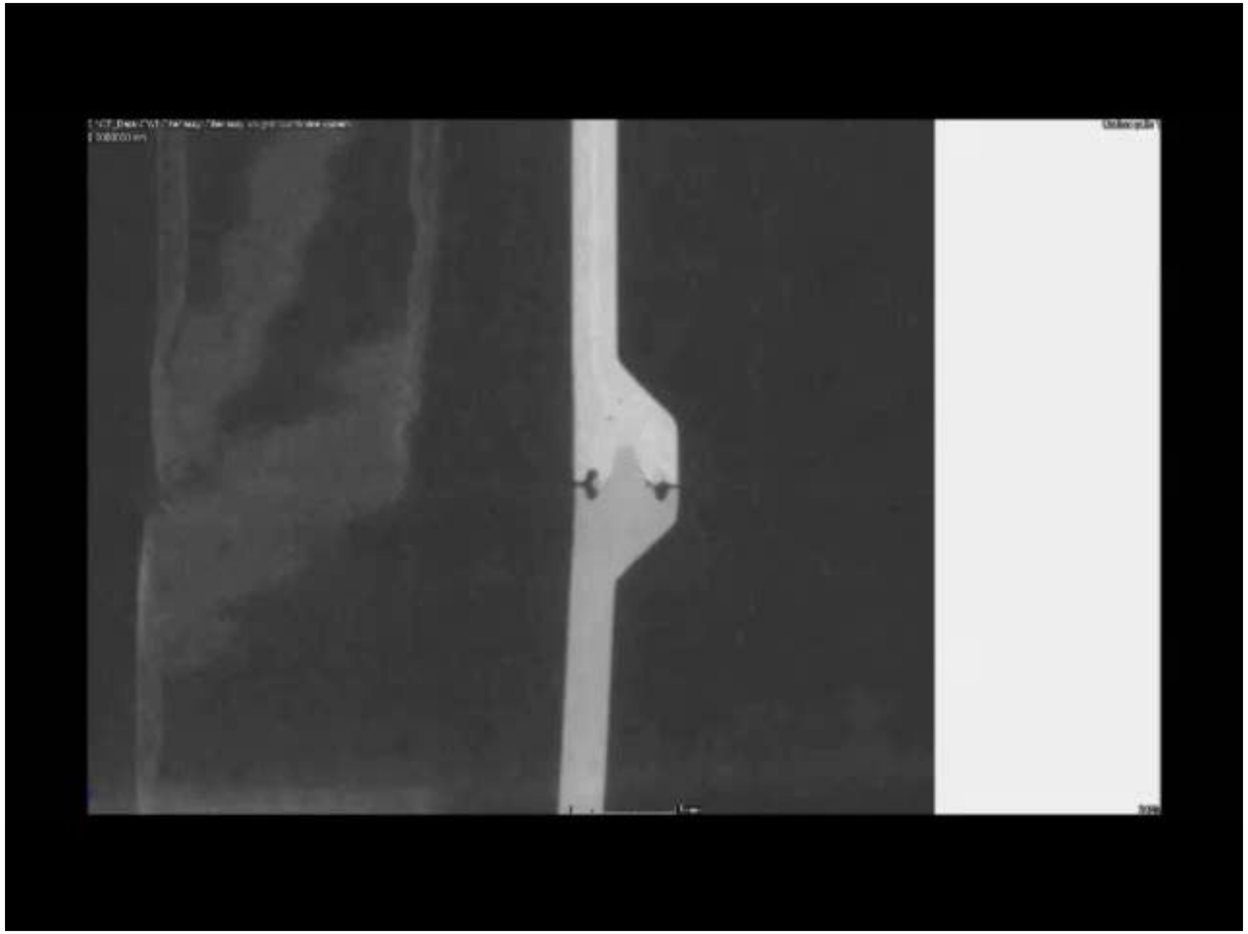




Computed Tomography Scan

- EWI Buffalo has a computed tomography (CT) scanner:
  - Ability to scan parts with low energy, high resolution, medium energy, and high energy (450 keV) with fan beam and LDA detection.
  - Allows scanning of application spaces from plastic to metal.

CT Scan of Spin Welded Part



Leak and Burst Testing

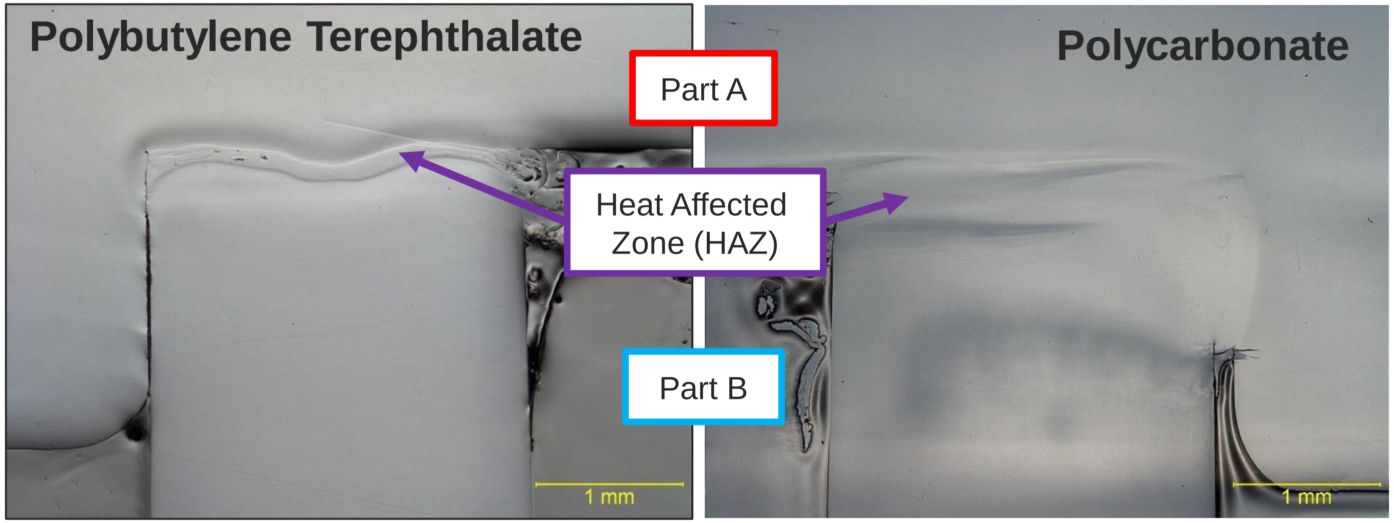
- Very common for plastic parts: water, air, helium
  - Pressurize part and hold under water to look for bubbles
    - Can use graduated cylinder to collect bubble and determine rough leak rate
    - Shows location of leak.
  - Pressurize part and monitor for leak decay rate.
  - Put parts in pressurized chamber and monitor for leak decay rate
    - Equipment will monitor to ensure that the appropriate amount of air is used to achieve the correct pressure, using more air indicates a gross leak.
  - Pressurize part until weld breaks
    - Must be performed in a safety enclosure.

Leak Decay Testing

- Air leak decay tester (shown here):
  - Uses shop air
  - Can be portable
  - Automated on production line
- Helium tester:
  - Can put part in chamber
  - Can create vacuum in part, move helium line around joint and check for helium getting into part, provides information on location of leak.

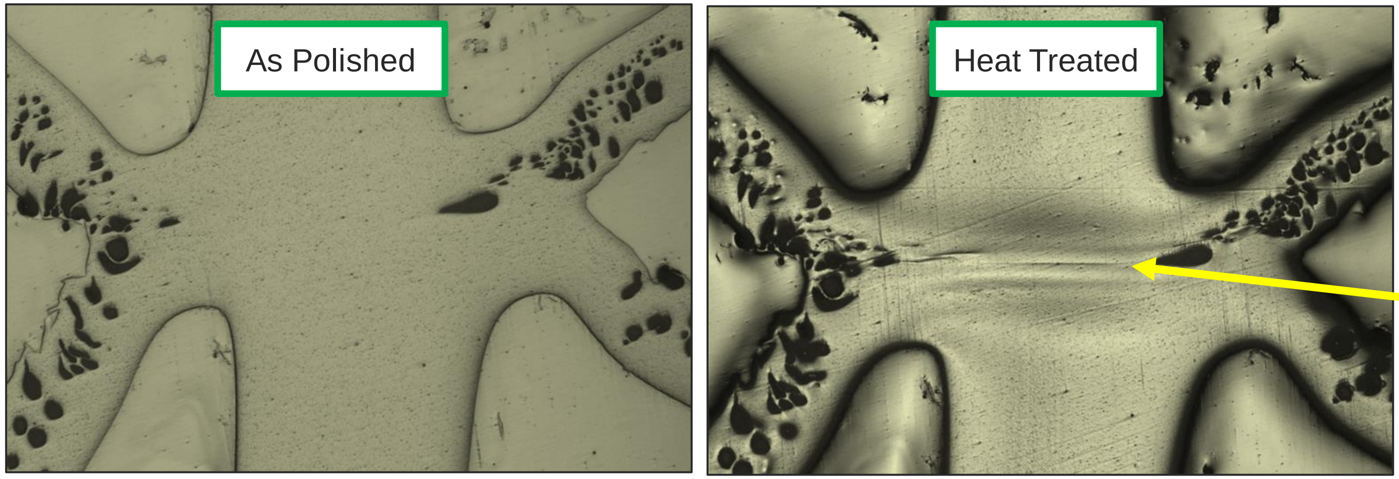
Cross-section Analysis

Semi-crystalline polymers show the heat affected zone(HAZ) lines due to a change in crystallinity in the heated area.



Good welds with intermolecular diffusion (no separation line across joint)

Amorphous polymers show the HAZ lines due to a change in polymer chain orientation in the heated area.



No intermolecular diffusion (separation line across joint)

Cross-section Preparation

- Samples were cut in the desired location, then mounted into an epoxy.
- Sample surface was ground using 400-grit paper.
- Sample surface was polished using 3-micron to 0.05-micron diamond polish.
  - Polishing varies based on the polymer and is frequently checked as too much polishing can be as damaging as too little.
- Cross-section surface is heat treated.
- Photographed using microscope.

Heat-treat Procedure

- Cross-section surfaces are heated using a Puhui infrared (IR) reflow system
  - 20 seconds at 240°C
- Allows the polymer chains on the surface which have been displaced due to mechanical grinding and polishing to thermally recover.

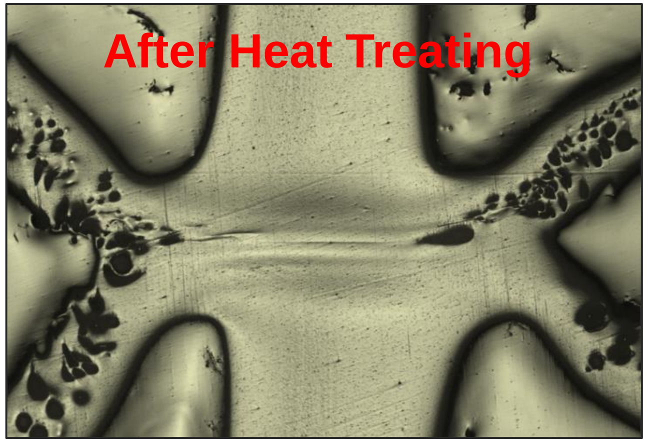
Weld Defects Detectable via Cross-section

- Lack of Diffusion
- Voids
  - Humidity
  - Degradation
  - Shrinkage
- Cracking
- Uneven or Misaligned Weld

Lack of Diffusion Example

After heating, the melt surfaces were allowed to cool below the critical flow temperature of the polymer causing a “cold skin” effect.

When the surfaces were pressed together, the still molten material behind the surface was still deformed and produced flash, giving a false “good” weld appearance.

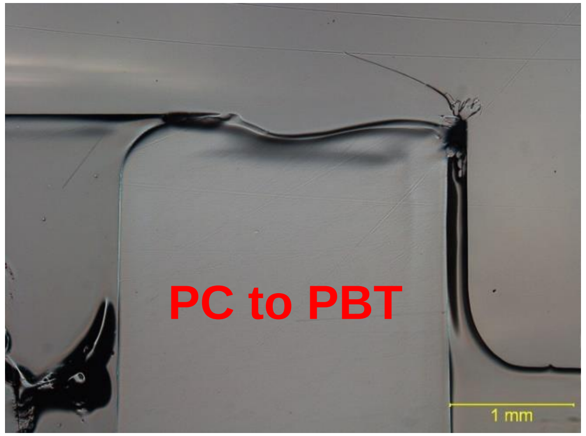


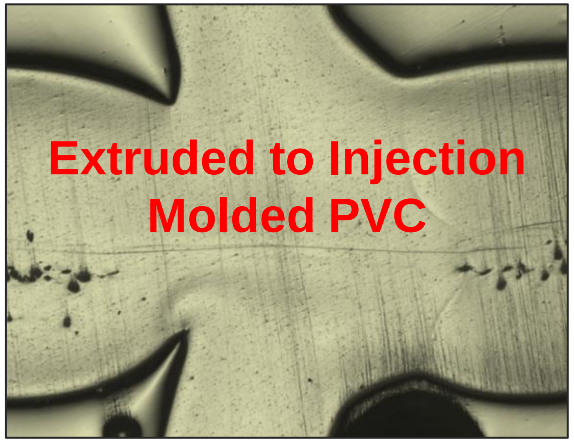
Lack of Diffusion Example

Each side of the assembly is a different material.

Due to a viscosity mismatch between the materials, there is no diffusion across the joint.

Because both polymers melt and flash is generated, the weld appears good from external inspection.



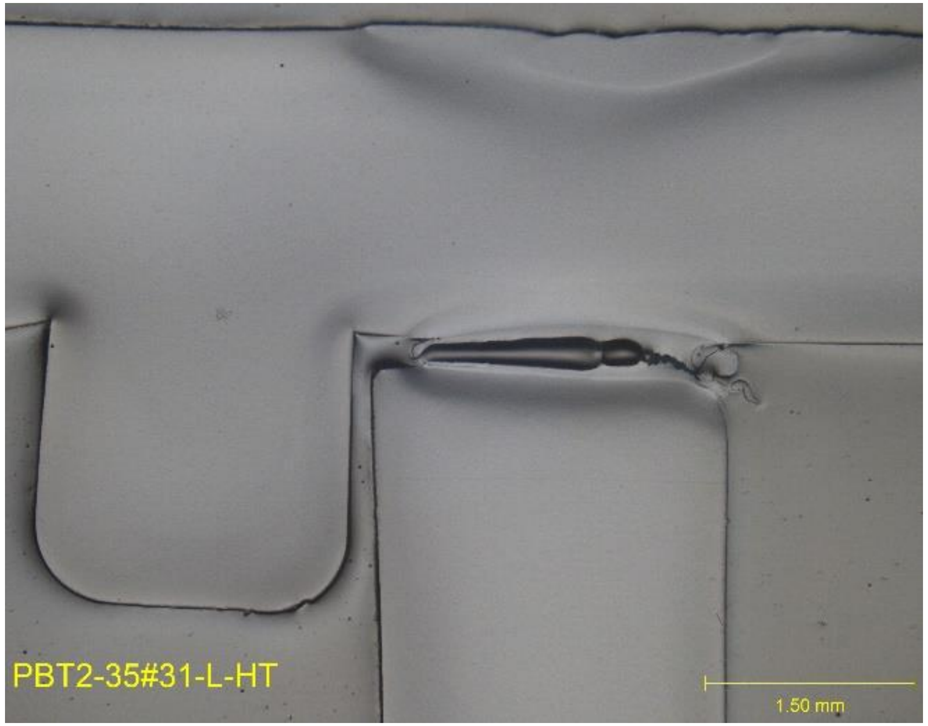


PC = Polycarbonate PBT = Polybutylene Terephthalate PVC = Polyvinyl chloride

Void from Shrinkage Example

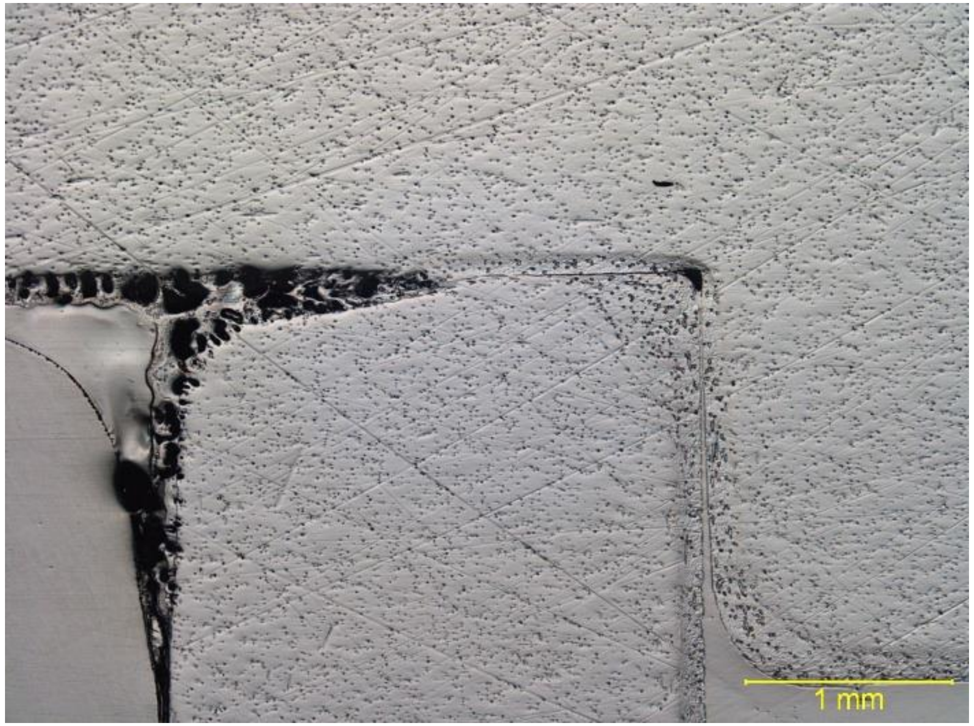
During cooling, insufficient pressure was applied to the weld.

When the part cooled, it shrunk and pulled open creating a void in the weld material.



Uneven Heating Example

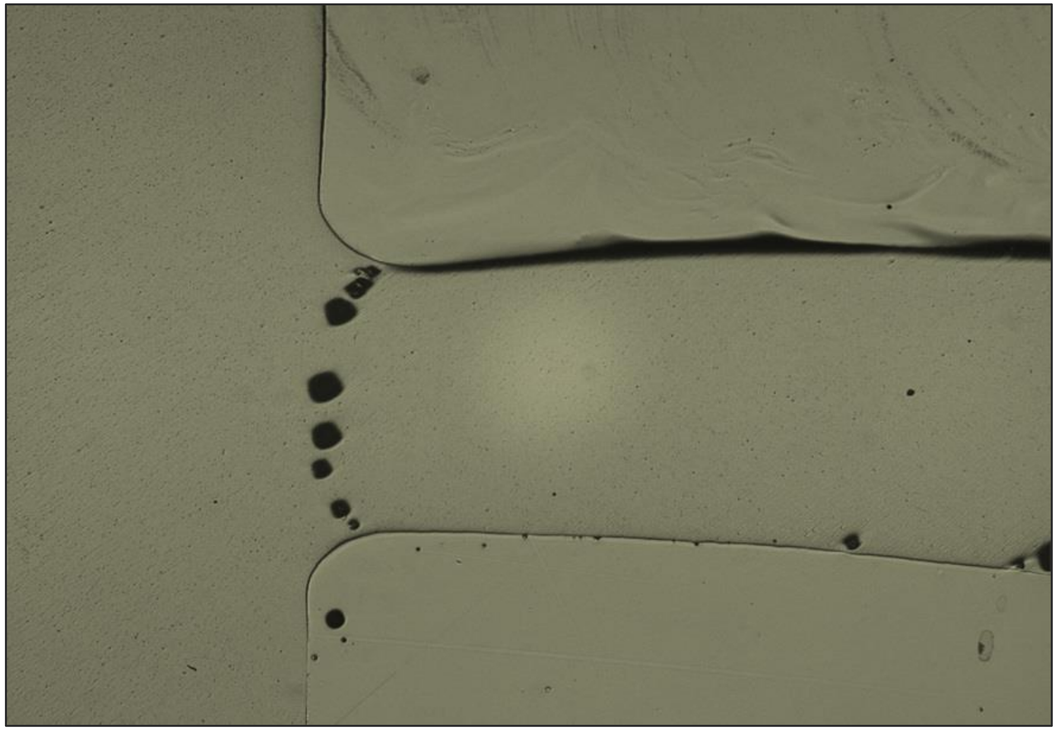
During laser welding, the beam was offset on the weld wall, causing uneven heating.



Void from Shrinkage Example (in molded part)

During injection molding, the polymer may not fill well at transitions in the geometry.

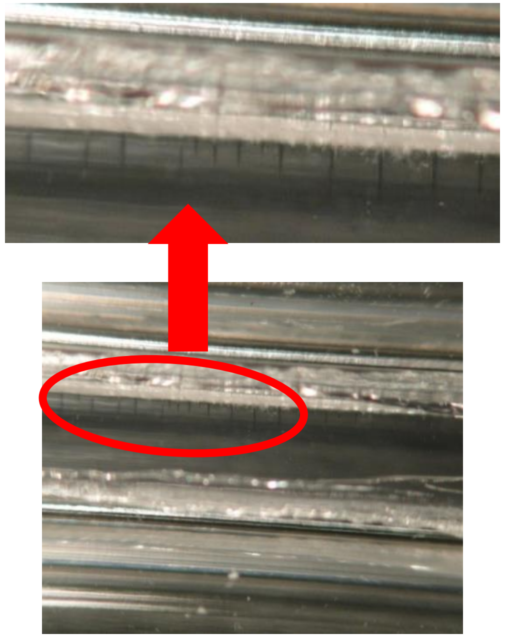
These voids can be seen on the cross-section.

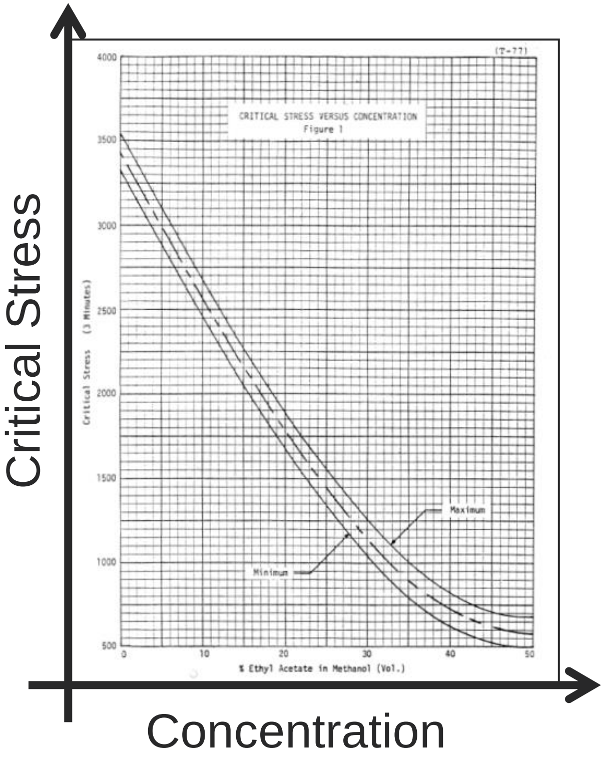


Residual Stress Analysis

- GE solvent stress test (for PC):
  - Parts exposed to mixes of methanol and ethyl acetate.
  - Examine for crack formation.

Stress
Cracks





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Residual Stress Analysis

- Weld parts
- Pull test half of the welded parts
- Expose the other half to a known aggressive chemical
- Pull test the second half of the parts
- The difference in weld strength before and after treatment will show the level of stress in the parts:
  - Environmental stress cracking.

Questions?

THANK YOU

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