Servo-Driven Ultrasonic Welding of Semicrystalline Thermoplastics

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Outline

- Welding Engineering Program
- Plastics and Composites Joining Lab
- Fundamentals of Ultrasonic Welding
- Dual-Pressure Ultrasonic Welding
- Servo-Driven Ultrasonic Welding
- Summary and Future Work
- Acknowledgments

Welding Engineering Program

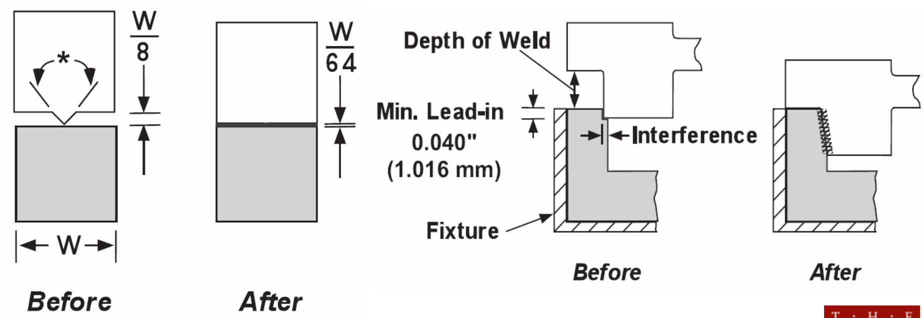
- The only ABET accredited Welding Engineering Program in US.
- Recently merged with Material Science and Eng.
- Located at the Edison Joining Technology Center housing both OSU Welding Engineering and EWI.
- Seven faculty specializing in processes, welding metallurgy, design, NDE and plastics and composites joining.
- Over 100 undergraduate students.
- About 50 graduate students.
- Student are in high demand with one of the highest starting pay in the college of engineering.

Plastics & Composites Joining Lab.

- The only academic group in the US specializing in joining of plastics and polymeric composites.
- Wide range of welding equipment including ultrasonic, hot plate, hot gas, spin, vibration, RF, microwave, induction, resistance, laser and laser diode, and infrared.
- Polymer and composite processing equipment.
- Material and joint characterization equipment.
- Mechanical testing, and more…
- Advanced computational analysis and design capabilities including FE modeling of viscoelastic material for thermal and residual stress prediction.

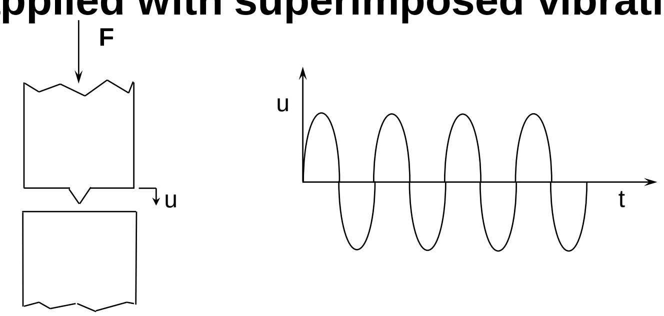
Fundamentals of Ultrasonic Welding

- Concentrate heating at weld interface with use of energy director or interference.



Fundamentals of Ultrasonic Welding

- Consider ultrasonic welding of energy director joint.
- During welding a static force is applied with superimposed vibration.

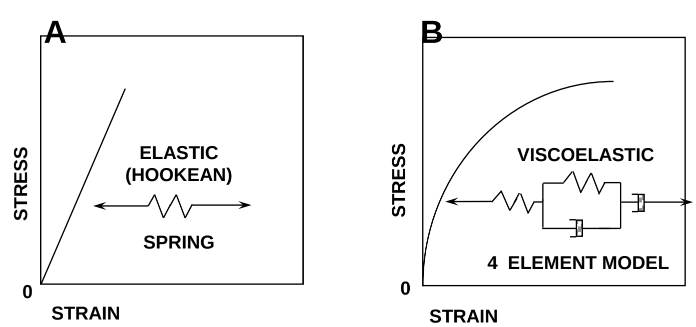


Fundamentals of Ultrasonic Welding

- Ultrasonic welding is a complex process made up of five distinct yet highly coupled subprocesses.
- Mechanics and vibration of the parts.
- Viscoelastic heating of thermoplastic and heat transfer.
- Squeeze flow of energy director.
- Intermolecular diffusion and chain entanglement.
- Cooling and resolification.

Mechanics and Vibration of Parts

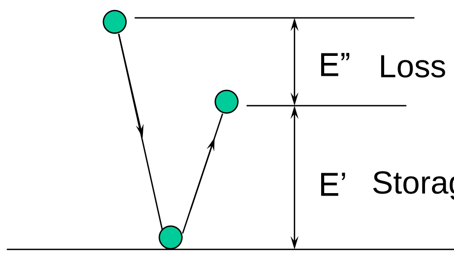
- Polymers are viscoelastic materials.



Mechanics and Vibration of Parts

- **Polymers subjected to sinusoidal loading have a dynamic modulus.**

$$E^* = E' + iE''$$

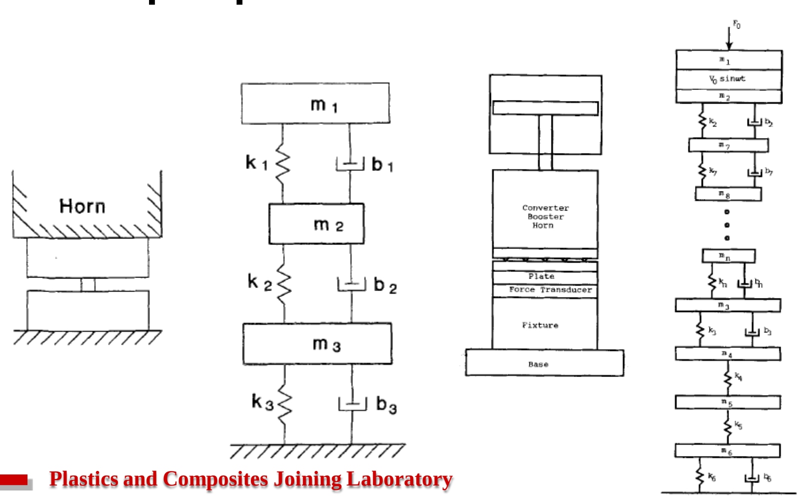


E”   Loss modulus - convert to heat

E’   Storage modulus - recovered energy

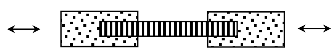
Mechanics and Vibration of Parts

- **Lumped parameter model**

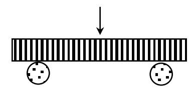


Viscoelastic Heating & Heat Transfer

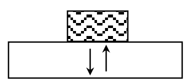
- **Heat dissipation due to loss modulus.**
- **Measure dynamic modulus.**



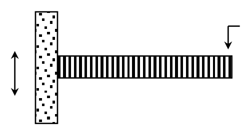
Rheovibron



Rheometrics
Dynamic Analyzer

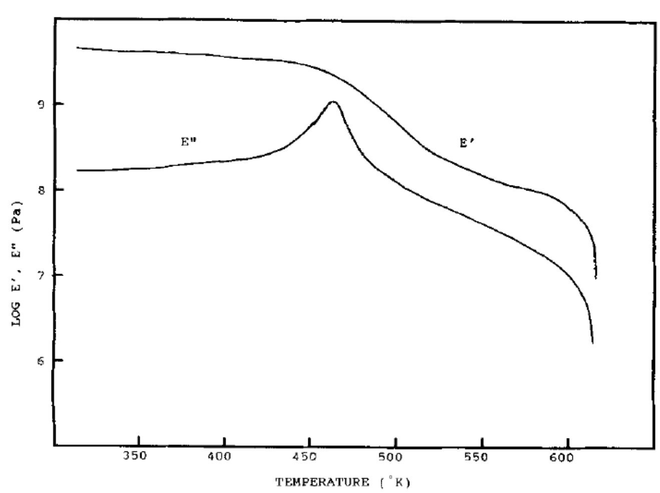


Non - Destructive Evaluation

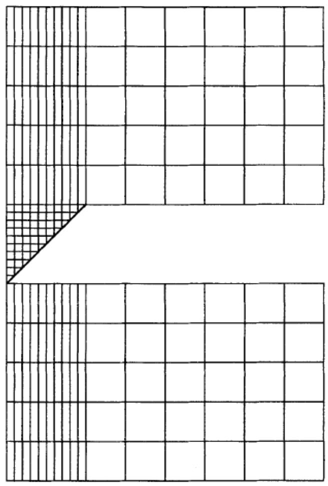


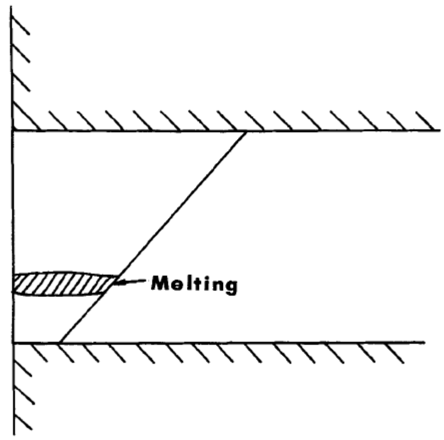
Resonant Frequency of Cantilever Beam

Viscoelastic Heating & Heat Transfer



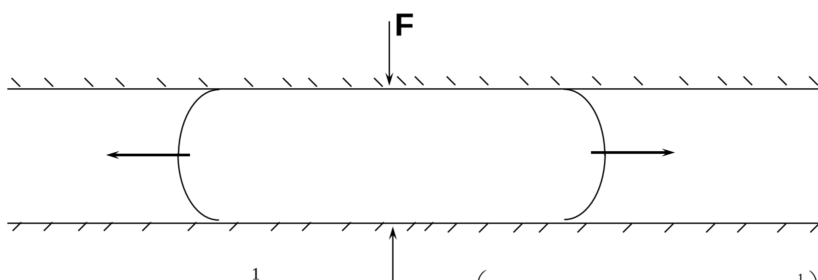
Viscoelastic Heating & Heat Transfer





Squeeze Flow

- Molten energy director flows due to the applied pressure/force.

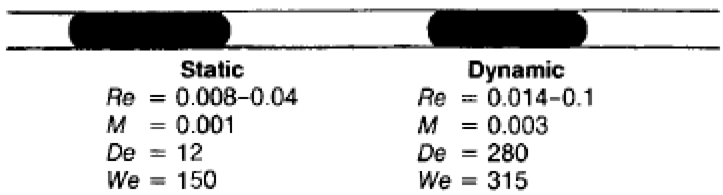


$$\frac{h_0}{h} = \left(1 + \frac{5 \cdot F \cdot t \cdot h_0^2}{4 \cdot \eta \cdot L \cdot b_0^3}\right)^{\frac{1}{5}}$$

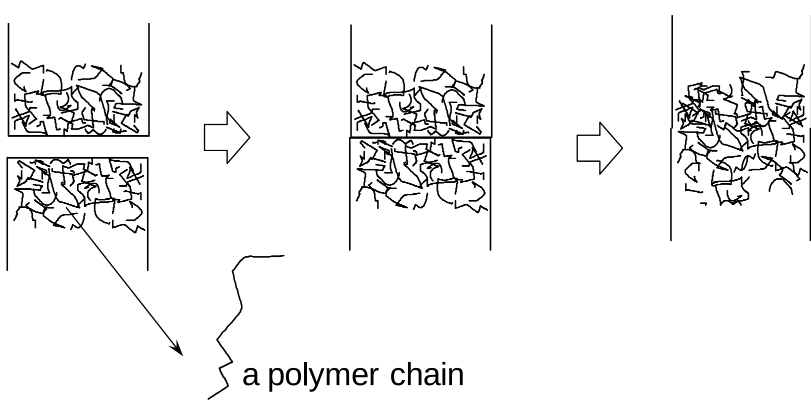
$$\frac{h_0}{h} = \left(1 + t\frac{2n+3}{4n+2}\left(\frac{(4h_0 b_0)^{n+1} \cdot F \cdot (n+2)}{(2b_0)^{2n+3} \cdot L \cdot m}\right)^{\frac{1}{n}}\right)^{\frac{n}{2n+3}}$$

Squeeze Flow

- However, polymer melts are also viscoelastic resulting in elongational flow, similar to elastic materials.
- Flow is complex with static force and dynamic force affecting the flow.



Intermolecular Diffusion



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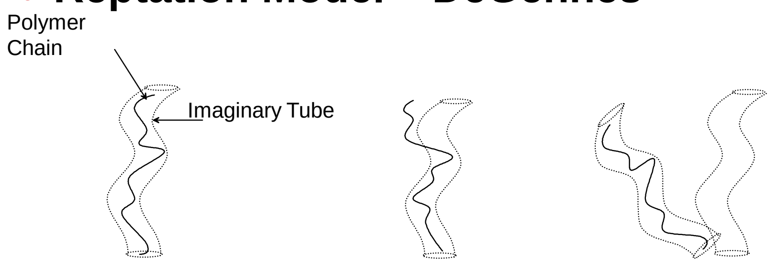
Intermolecular Diffusion

- **Reptation Model – DeGennes**

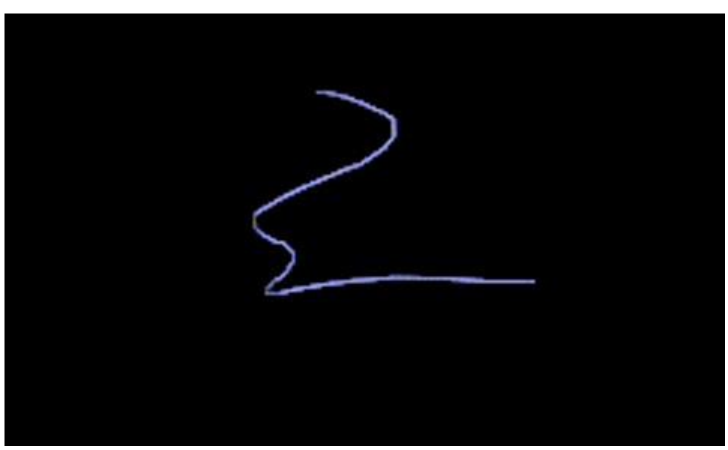


t < Te | Te < t < TR | t > TR

t - time
T_e - time for motion within the imaginary tube
T_R - time to generate new imaginary tube

Segmental motion is sufficient to achieve complete healing

Intermolecular Diffusion



Cooling and Resolidification

- **Formation of residual stresses.**
- **Final microstructure – spherulite formation for semicrystalline polymers.**

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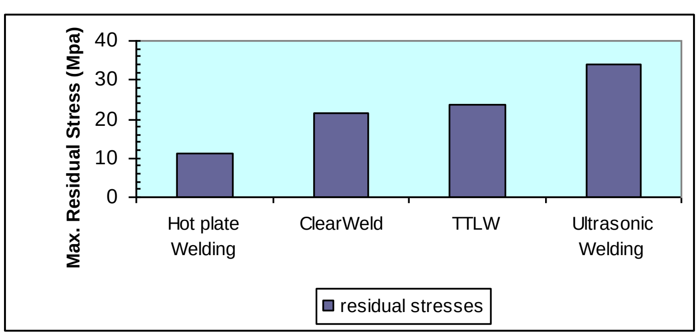
Cooling and Resolidification

- **Ultrasonic welding is a rapid cooling process resulting in high residual stresses and amorphous structure.**



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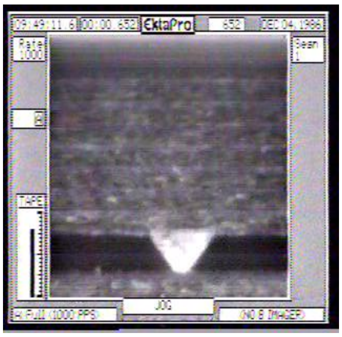
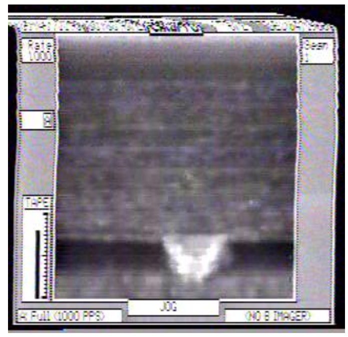
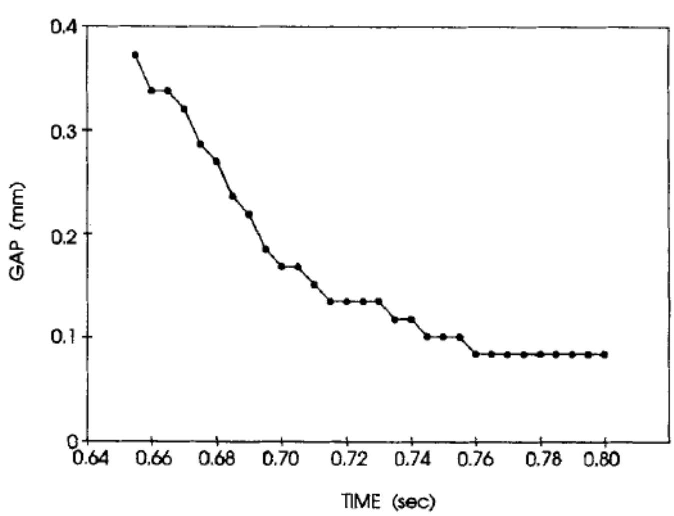
Fundamentals of Ultrasonic Welding

- **High speed video shows that flow occurs in stepwise fashion.**



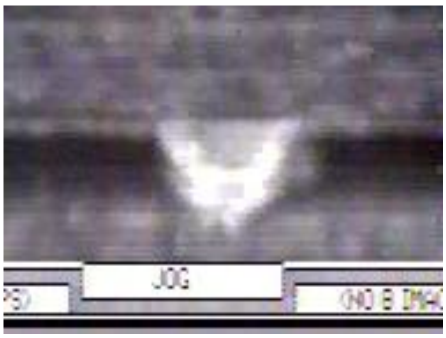


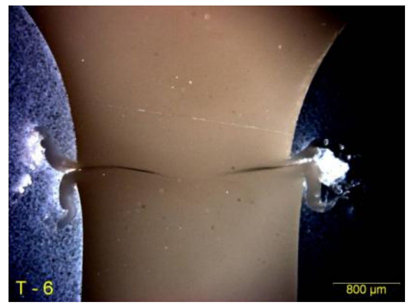
Fundamentals of Ultrasonic Welding



Fundamentals of Ultrasonic Welding

- From high speed video it was also observed that melt streams out rather than flow regularly.



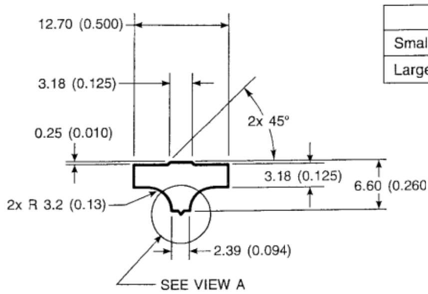


Fundamentals of Ultrasonic Welding

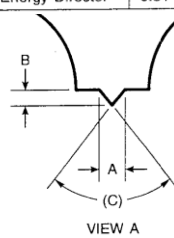
- Semicrystalline polymers experience abrupt transition at melting resulting in ejection of melt during US Welding (observed using high speed video).
- With dual-pressure ultrasonic welding it may be possible to reduce the pressure once melting occurs to reduce melt ejection.
- Servo-driven US welder using velocity control may be used to regulate squeeze flow of molten energy director.

Dual-Pressure Ultrasonic Welding

- **Ultrasonic welding using single pressure and dual-pressure of polyamide 6 was studied using AWS G1.2 standard test sample.**

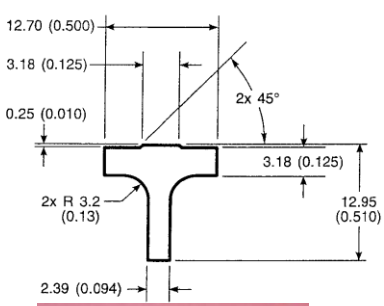


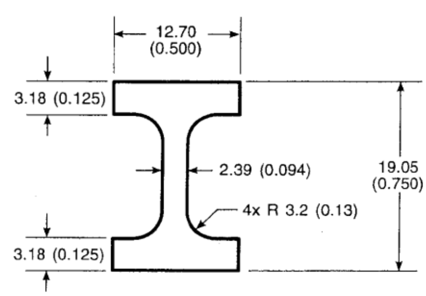
Profile	A	B	Ref. C
Small Energy Director	0.61 (0.024)	0.30 (0.012)	90°
Large Energy Director	0.81 (0.032)	0.51 (0.020)	77°

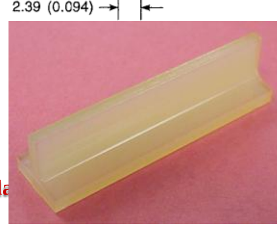


Dual-Pressure Ultrasonic Welding

- **Samples dried at 70°C for 24 hours.**







Dual-Pressure Ultrasonic Welding

- **Dukane 40 kHz (model 40A700) dual-pressure ultrasonic welder with UltraCom Microcomputer System (model 43A300).**
- **Single pressure welding conditions:**

	Weld Time	Vibration Amplitude	Cylinder Pressure	Weld Force
	(sec)	(µm-pp)	(kPa)	(N)
Case 1	0.2 - 1.0	5.9	207	258
Case 2	0.8	4.1 - 9.4	207	258
Case 3	0.8	9.4	138 - 345	182 - 409
For all Cases: Hold time = 2 sec.				

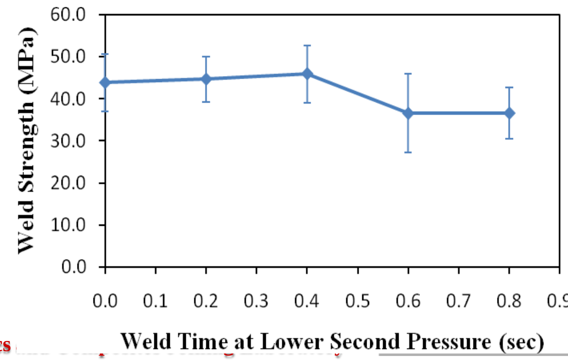
Dual-Pressure Ultrasonic Welding

- **Dual-pressure welding conditions:**

	Pressure-2	Force-2	Weld Time-2
	(kPa)	(N)	(sec)
Case 1	172	220	0 - 0.8
Case 2	379	447	0 - 0.4
For all Cases	Pressure-1 = 310 kPa, (Force-1 of 371 N), Weld Time-1 = 0.7 sec, Vibration Amplitude = 9.4 µm-pp, Hold Time = 2 sec.		

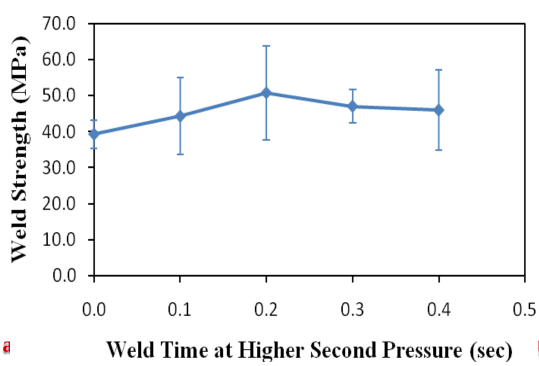
Dual-Pressure Ultrasonic Welding

- **Effect of weld time at the second lower pressure on weld strength for cylinder pressure-1 of 310 kPa with weld time-1 of 0.7 sec. and cylinder pressure-2 of 172 kPa with vibration amplitude of 9.4 µm-pp, and hold time of 2 sec.**



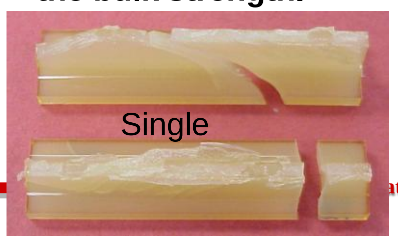
Dual-Pressure Ultrasonic Welding

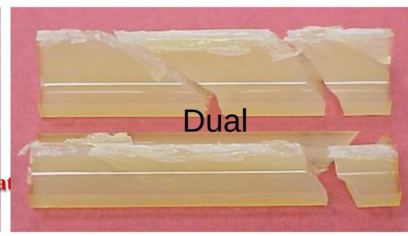
- **Effect of weld time at the second higher pressure on weld strength for cylinder pressure-1 of 310 kPa, weld time-1 of 0.7 sec., cylinder pressure-2 of 379 kPa, vibration amplitude of 9.4 µm-pp, and hold time of 2 sec.**



Dual-Pressure Ultrasonic Welding

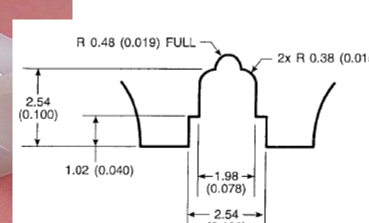
- For single pressure ultrasonic welding, a maximum weld strength of 74% of the bulk strength could be achieved.
- For dual-pressure using a lower second cylinder resulted in slightly lower weld strength than single pressure ultrasonic welding.
- For dual-pressure using a higher second cylinder pressure the maximum weld strength was 70% of the bulk strength.





Servo-Driven Ultrasonic Welding

- Servo-Driven ultrasonic welding of HDPE was studied using AWS G1.2 standard test sample.

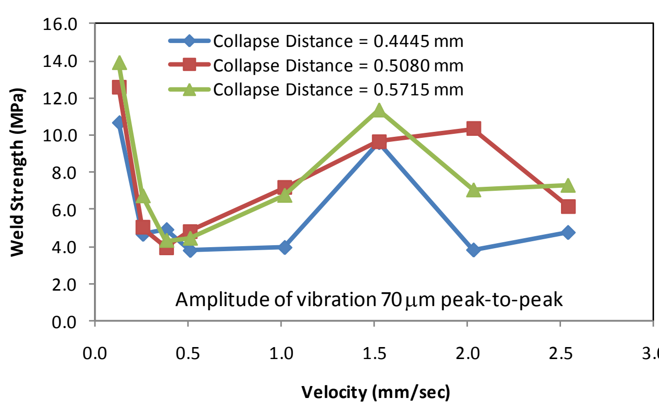


Servo-Driven Ultrasonic Welding

- Dukane 20 kHz iQ Servo-Driven Ultrasonic Welder to weld energy director and shear joints.
- For energy directors, studied effects of velocity, amplitude of vibration and collapse on weld strength.
- Preliminary work with velocity profiling.

Servo-Driven Ultrasonic Welding

- Effects of collapse and velocity on weld strength for energy director joints.



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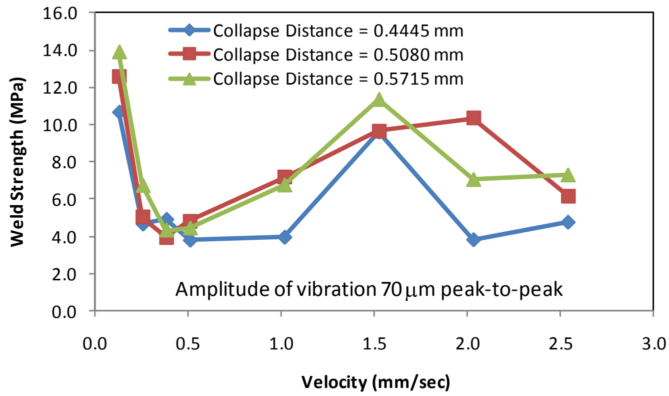
Servo-Driven Ultrasonic Welding

- **Low velocity results in strongest joints – squeeze flow is more gradual resulting in less ejection from joint area.**



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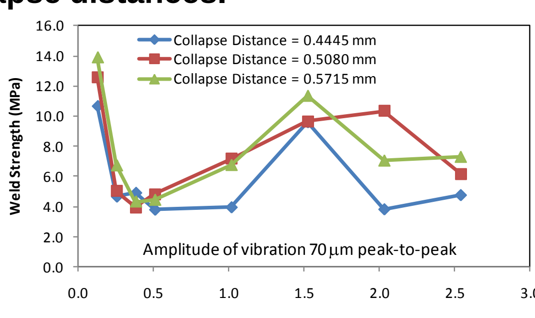
Servo-Driven Ultrasonic Welding

- **For the applied amplitude of vibration of 70 μm peak-to-peak, a velocity of 1.5 mm/sec provides, on average, the best match with melting and flow of energy director resulting in a peak in strength for all collapse distances.**



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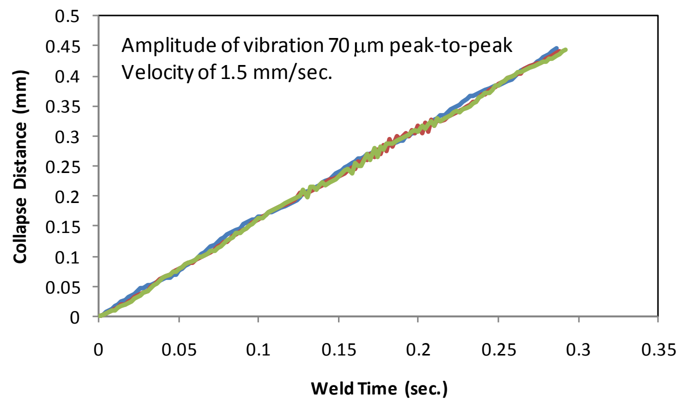
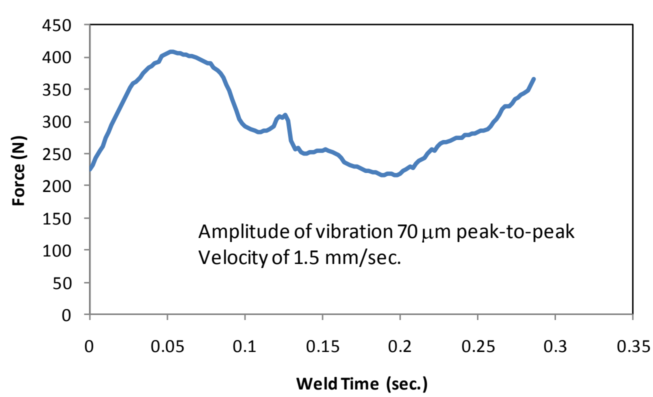
Servo-Driven Ultrasonic Welding

- Excellent repeatability of collapse distance from sample to sample.



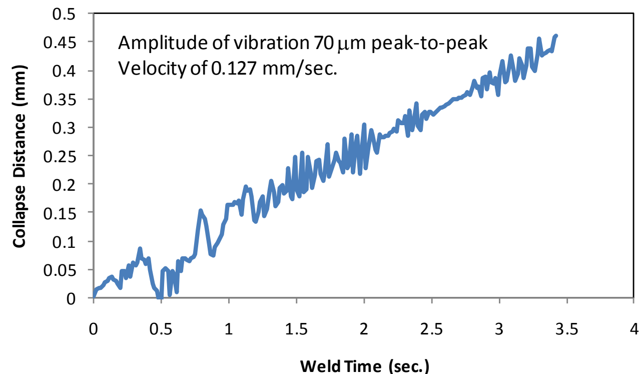
Servo-Driven Ultrasonic Welding

- Applied force varies in order to maintain constant velocity.



Servo-Driven Ultrasonic Welding

- Lower velocity results in longer weld time, lower forces and more part marking. May require modification of control algorithm.



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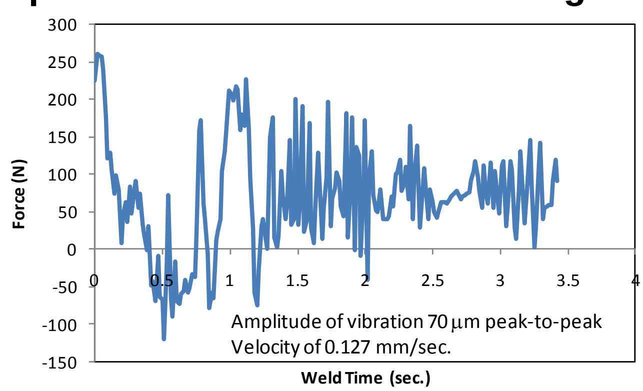
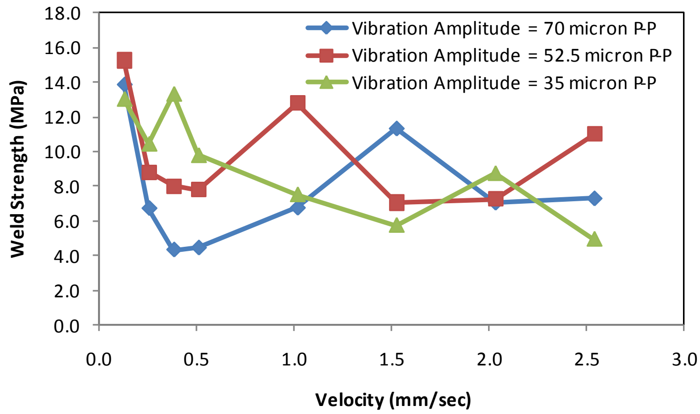


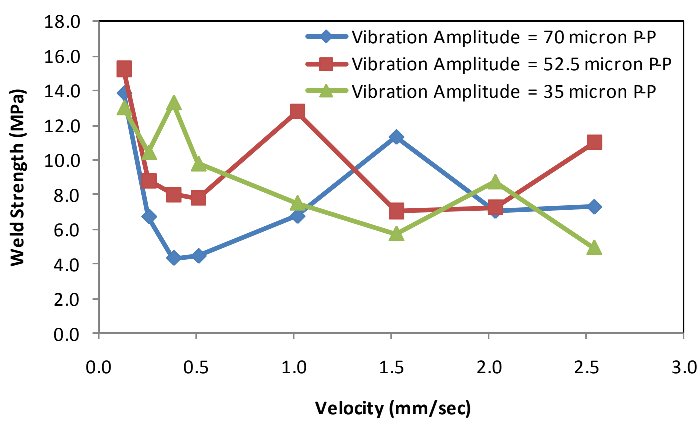
Servo-Driven Ultrasonic Welding

- **Effects of amplitude of vibration and velocity on weld strength for energy director joints.**



Servo-Driven Ultrasonic Welding

- **Low velocity results in strongest joints.**



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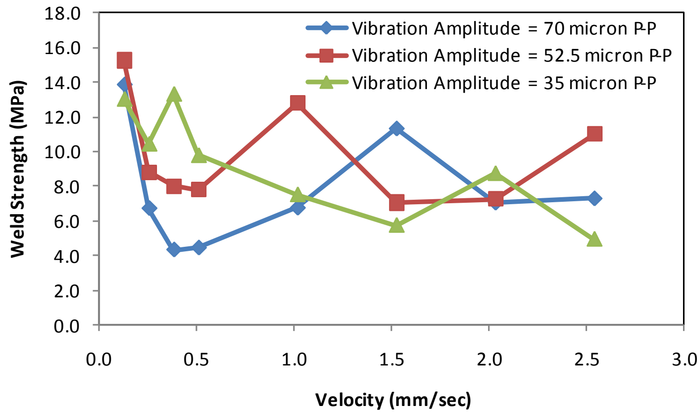
Servo-Driven Ultrasonic Welding

- For every amplitude of vibration there is an average velocity with peak strength.



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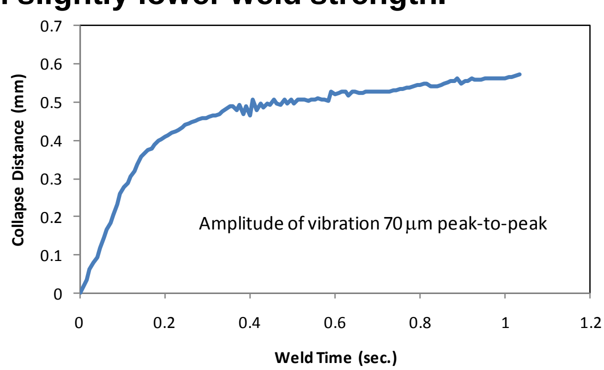
Servo-Driven Ultrasonic Welding

- There is an infinite number of possible amplitude profiles that can be used for energy director joints.
- Preliminary work with decreasing velocity resulted in slightly lower weld strength.



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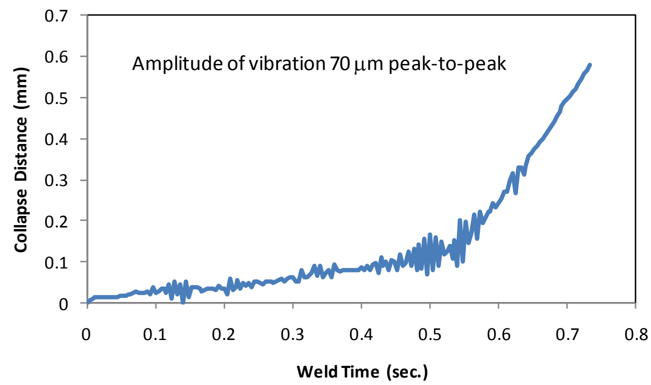
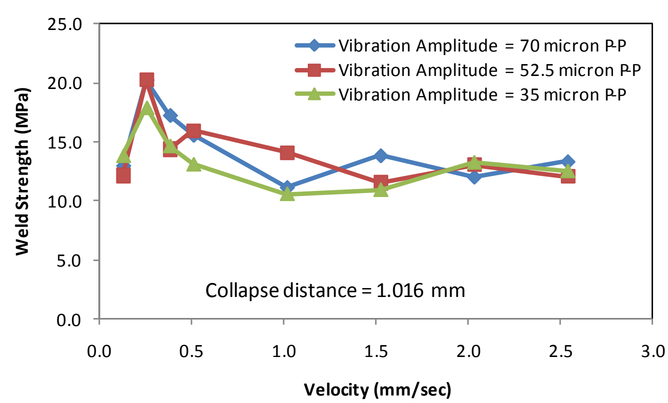
Servo-Driven Ultrasonic Welding

- Preliminary work with increasing velocity resulted in about the same weld strength as with constant velocity.



Servo-Driven Ultrasonic Welding

- Effects of amplitude of vibration and velocity on weld strength for shear joints.



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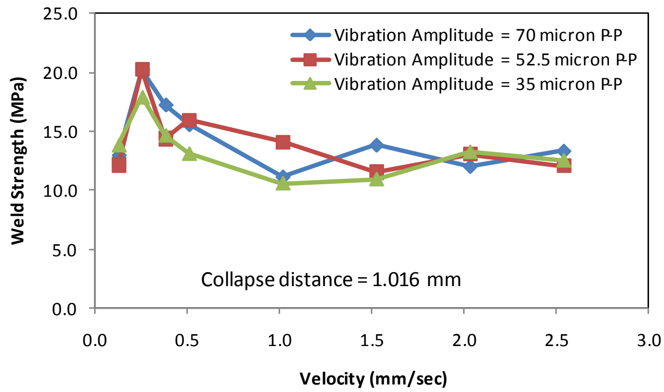
Servo-Driven Ultrasonic Welding

- Constant velocity of 0.254 mm/sec results in consistent melt and flow and strongest joint.



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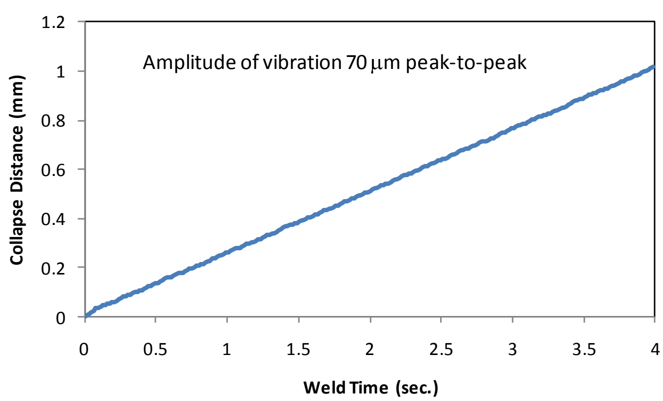

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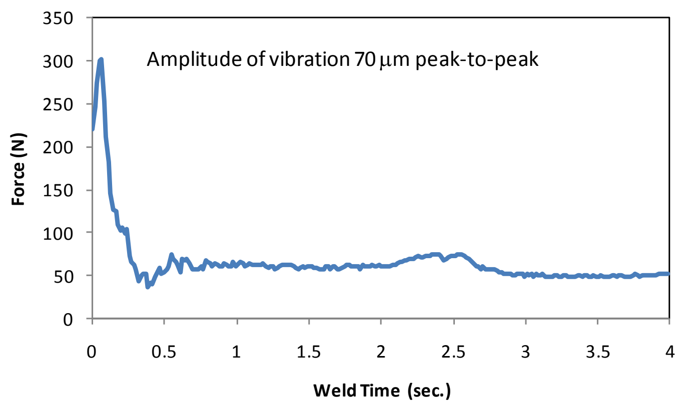
Servo-Driven Ultrasonic Welding

- **Constant velocity of 0.254 mm/sec results in consistent force after initial peak.**



Servo-Driven Ultrasonic Welding

- **There is an infinite number of possible amplitude profiles that can be used for shear joints.**
- **Preliminary work with decreasing velocity resulted in slightly lower weld strength.**
- **Preliminary work with increasing velocity also resulted in slightly lower weld strength.**

Summary and Future Work

- Semicrystalline polymers experience abrupt transition at melting resulting in ejection of melt during US Welding (observed using high speed video).
- Dual-pressure ultrasonic welding with either higher or lower second pressure results in no improvement in weld strength.
- Servo-driven ultrasonic welder allows precise control of velocity and an infinite number of velocity profiles.

Summary and Future Work

- For energy director joints, lower velocity results in stronger welds.
- For energy director joints, for each amplitude of vibration there is a velocity that best matches, on average, melting and flow of energy director.
- For energy director joints, collapse distance is very repeatable from sample to sample indicating potential for higher final collapse precision and more consistent weld quality – future work.

Summary and Future Work

- For shear joints, a constant velocity of 0.254 mm/sec. resulted in strongest welds and appears to be optimum for melting at the interface and flow of melt.
- For energy director and shear joints, more work is needed to understand and evaluate the effects of velocity profiling.
- More work is needed to evaluate other materials – melt and flow are material dependent.

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