Weldability of Linear Vibration Welded Dissimilar Amorphous Thermoplastics for Automotive External Lighting Applications

by
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ABSTRACT

This research paper analyzes the material compatibility, in terms of weld strength, of thermoplastics currently in use for external lighting applications. Signal lamps typically consist of a transparent lens welded to an opaque housing. The different types of polymers used in housing materials are polycarbonate (PC), acrylonitrile butadiene styrene (ABS), acrylonitrile styrene acrylate (ASA), and blends thereof. The different types of transparent lens materials are polymethyl methacrylate (PMMA) and PC. The specific thermoplastic material grades in this document are kept confidential.

The scope of the work is to determine plaque-level compatibility of materials as a function of weld strength performance and to create material-level weld strength guidelines regarding optimal welding parameters for component level design/development and quality. This is achieved through a parametric study, strength testing welds with dissimilar (chemically different) materials through a varying set of welding parameters.

Material combinations are found which can reach the weaker material's bulk strength and other combinations are found which have very poor compatibility, as confirmed by the weld factor. A great majority of the weld combinations' strengths increase with weld depth, and most dissimilar material welds continue to increase in strength with even further weld penetration. Optimal weld parameters are determined for each material combination.

DEDICATION

From the bottom of my heart, I would like to thank my parents, Danny and Angela for their unconditional love and support throughout these very intense academic years. Thank you to my sisters, Carla and Katrina, whose motivation and lighthearted attitudes kept me on task, especially during time sensitive deadlines. Your help and continuous support was critical to my success.

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LIST OF ABBREVIATIONS

ABS - Acrylonitrile Butadiene Styrene

ASA - Acrylonitrile Styrene Acrylate

ASTM – American Society for Testing and Materials

ESC – Environmental Stress Cracking

IR - Infrared

LVW – Linear Vibration Welding

M-PPO – Modified Polyphenylene Oxide

PBT – Polybutylene Terephthalate

PC - Polycarbonate

PEI – Polyetherimide

PMMA - Polymethyl Methacrylate / Acrylic

PP – Polypropylene

SEM – Scanning Electron Microscope

UTS – Universal Testing Machine

CHAPTER 1: INTRODUCTION

1.1 Purpose

This study uses physical testing and data analysis to determine the compatibility and optimal welding parameters of dissimilar amorphous polymers when vibration welded together. Throughout this research paper, the term ‘dissimilar materials’ refers to materials that are chemically different. This includes weld combinations of two different parent materials or two different grades of the same parent material.

With development of high-performance plastics beginning in the 1930s, plastics have become of interest for engineering applications. Plastics were not originally viewed as engineering materials since their mechanical properties are not as appealing as those of metals. Initially used for cosmetic parts, plastics are now also used as load-bearing parts [1]. Even with advanced plastic processing methods, the adoption of plastics could not have proceeded without new innovative welding processes [2].

As for plastic welding processes, the earliest trace can be tracked back to the 1920s where spin welding was used to create plastic compasses. Using frictional heat to join plastic components has been adopted in an industrial setting since the 1970s [3]. At this time, multi-component plastic bumpers, also known as fascias, were assembled using vibration welding. The advantage to these new fascias was their ability to absorb an impact of 5 mph. Other joining methods for the fascia were explored, however hot plate welding failed over time due to embrittlement, and induction bonding was too expensive. Due to the thermal cycling the fascia undergoes presumably from environmental conditions, adhesive bonding could not be used and also added weight to the part. Fasteners could not be used due to the stresses that the holes would induce on the bumper.

One barrier to vibration welding the bumper was the large part size (three times larger than any previously welded part) and the large welding face area (four times larger area than any previously welded part). Another barrier that vibration welding posed was the new desired part orientation necessary during the welding process. Since the clamping force was needed in the horizontal direction instead of the usual vertical direction, the part needed to be oriented differently. A new vibration welding machine was created for the application of vibration welding the fascia [4]. With minimal research until the 1990s, it seems that quality welds were determined by trial and error of welding parameter combinations.

Since the 1980s, the use of plastics has become increasingly more common for many engineering applications. The use of thermoplastics for engineering applications has become critical over the past decades in many different industries, including the automotive, medical, and aerospace industries. With the automotive industry becoming more competitive, automotive manufacturers are looking for creative ways to improve their designs over their competitors. Plastics have replaced many metal applications in the aerospace, structural, and transportation fields [5]. Thermoplastics are a cheaper and lighter alternative to metal. Different thermoplastics have different strengths and can be used in many different applications. Low weight, ease of manufacturing complicated geometries, and low cost are their main benefits.

LVW involves putting two thermoplastic pieces together under pressure and vibrating one piece relative to the other. The friction at the interface creates heat and melts the materials at their contact area. The materials mix at the interface and once the vibratory motion stops, the materials cool and join together at the weld interface.

Signal lamps in the automotive industry typically use vibration welding to join the PMMA lens to the housing material, enclosing the internal lighting source (e.g. bulb, LED) within the welded system. These welds are expected to create a consistent seal to prevent leakages which compromise the effectiveness of the lighting system.

Thermoplastics have the ability change from a solid to a molten-like state when heated to their glass transition temperature. Here, they can be forced to flow under pressure and can be shaped into complicated geometries. This enables the manufacturing process of injection moulding, which is used for lamp systems.

Figure 1: Thermoplastic lighting housing. The transparent thermoplastic lens is welded to the opaque housing to create an automotive lamp system. [6]

Figure 2: Thermoplastic lighting lens. The transparent thermoplastic lens is welded to the opaque housing to create an automotive lamp system. [6]

Automotive companies utilize different lens and housing materials. The materials of interest for this study are: acrylic (PMMA), polycarbonate (PC), acrylonitrile styrene acrylate (ASA), and acrylonitrile butadiene styrene (ABS), as well as blends of these materials. Each material has benefits for specific lighting applications. PMMA and PC are used as lens materials. Both have good optical properties. Some benefits of modified PMMA materials are its resistance to high heat, scratches, high impacts, or resistance to weathering. The PC is more resistant to higher temperatures and impacts than the PMMA. Since PC does not have good scratch or weather resistance, it usually needs a coating when used as a lens. PMMA is weatherable without a resistant coating. PC, a PC+ABS blend, an ABS+PC blend, ABS, ASA, and an ASA+PC blend are used as housing materials.

The PC housing is the most resistant to temperatures and impacts. ASA and ABS can be blended with PC to improve other properties while also reducing the amount of PC in the blend which tends to be more expensive. ABS does not typically weather well so ASA is used when weather resistance is needed.

This paper completes research of plaque-level material compatibility. The final goal is to determine the maximum strengths attainable and the optimal vibration welding parameters for each lighting material combination; and to gain an understanding of the limitations of LVW for each combination. In application, part design can influence the weld strength and can dictate how the weld is executed.

The study can be defined into six different sections:

1. Literature Review and Process Determination: discovering what past researchers have done, examining their results and how they are obtained, choosing the best methods to prepare and test weld samples, creating feasible tensile test fixture
2. Sample Preparation for Weld Trials: manufacturing plastic sample parts to be welded
3. Weld Trials: vibration welding the prepared samples together at varying welding parameters, following welding parameter matrix
4. Sample Preparation for Strength Testing: Manufacturing welded plastic samples for strength testing
5. Strength Testing: strength testing of welded samples on custom-designed fixture
6. Data Analysis: determining the maximum attainable strengths, material compatibility, and optimal welding parameters, analyzing the physical appearance of welds and their fractures

1.2 Motivation

The motivation of this project is to find the maximum weld strength (and its corresponding optimized welding parameters) for various material combinations. This strength data can then be used by design engineers.

Different vehicular applications may prioritize different outcomes. Some examples which welding parameters may want to achieve are: high strength, aesthetics, or geometric tolerance [7]. Automotive lamp applications prioritize high strength. Presently, engineers have access to material compatibility charts for plastic welding. These charts display which plastic materials can be welded to each other, in a general sense. These charts give no specific indication of the achievable quantitative maximum strength attainable or the optimal welding parameters for each material combination. Additionally, different grades of each material will act differently to other materials and welding parameters. A general guide, not accounting for plastic grades is displayed below.

	Amorphous								
Compatibility table for thermoplastics welding ● Ideal ○ Compatible	Styrol	A・S	A・B・S	Noryl	Acryl	Polycarbonate	Vinyl chloride	P E I	P E S
Styrol	●			○					
A・S		●	○		○				
A・B・S		○	●		○	○	○		
Noryl	○			●					
Acryl		○	○		●	○	○		
Polycarbonate			○		○	●	○		
Vinyl chloride			○		○	○	●		
P E I								●	
P E S									●

Figure 3: Plastic Welding Material Compatibility Table [8]. Note that the table only specifies the general compatibility for parent materials and not for specific grades thereof.

The chart above only indicates if welds can be made and has no indication of their strength. Past strength test data is either not publicly shared or not applicable to lamp applications. Past research has been conducted on linear vibration welding (LVW), however most often similar materials are welded together. In the automotive industry, many companies are interested in data regarding dissimilar materials being welded together, where the difference in melting temperature between materials causes complications during the linear vibration welding process. Therefore, it was decided to independently conduct a research study on the strength of different vibration welded material combinations.

The scope of the work is to determine plaque-level compatibility of materials as a function of weld strength performance and to create material-level weld strength guidelines regarding optimal welding parameters for component level design/development and quality. The goal of this study is to confirm material compatibility for LVW for thermoplastic external lighting materials currently in use by automotive manufacturers. Quantitative attainable strength values for each material combination and set of parameters will be determined. This way, optimal welding parameters can be known. Additional information such as a weld penetration threshold may also be determined.

This research study will contribute to the LVW material strength database for dissimilar materials. Additionally, future microscopic studies and environmental stress cracking (ESC) projects will deepen the understanding of these materials and their behaviours.

CHAPTER 2: LITERATURE SURVEY

2.1 General Information of Thermoplastics

There are two major classifications of plastics: thermosets and thermoplastics [2]. Thermosets cannot be welded, since they are chains of chemical molecules which have undergone an irreversible chemical reaction, creating a close-networked structure possessing covalent bonds. These materials will degrade instead of melting. A commonly used type of plastic for engineering applications are thermoplastics. These are advantageous since they can be melted and molded to different geometries without altering their chemical structure.

There are two different types of thermoplastics: amorphous resins and semi-crystalline resins. These resins differ in molecular arrangement. Amorphous resins display disorganized molecular chains, whereas semi-crystalline resins exhibit organized and closely arranged molecular chains with amorphous areas between the crystalline zones.

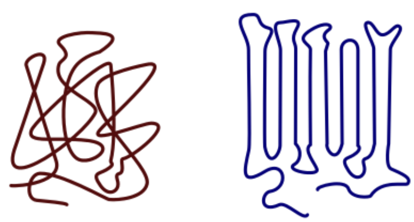

Figure 4: An amorphous molecular chain (left) and a semi-crystalline molecular chain (right). The semi-crystalline chain is ordered whereas the amorphous chain is not. [9]

Amorphous polymers do not have an exact melting point. They have a glass transition temperature which is normally a range where the polymer transitions from a solid material to a soft and molten-like material that can flow. At this temperature, the amorphous polymer’s molecular chains can wiggle freely. This wiggling or slithering motion is known as long-range segmental motion.

Amorphous plastics typically have better impact resistance, but a lesser resistance to fatigue cracking and stress cracking when compared to semi-crystalline plastics. The great majority of foamed, filled, and reinforced thermoplastics can also be vibration welded. Storing thermoplastics in certain environments can affect the strength of the material and therefore the strength of an eventual weld. For example, humid environments can cause plastic materials to absorb water, damaging their overall strength. Bubbles forming in the weld can have adverse effects on the weld and its strength. This paper studies amorphous resins since they are used in automotive lighting applications. Semi-crystalline polymers have separate crystalline and amorphous regions. For these polymers to melt and flow, the temperature must reach the crystalline melt temperature.

When thermoplastic pellets are heated, they soften; eventually they become soft enough that they can flow when put under pressure. Thermoplastics can be remolded and recycled and this process is reversible and chemical bonding does not take place. Thermoplastics have many different applications. The driving factor of using thermoplastics in the automotive industry is that they are lightweight materials. Therefore, their integration into the vehicle, replacing other components, could reduce the overall weight of the vehicle, increasing fuel efficiency. Thermoplastics are resistant to traditional vehicle corrosion. Their ability to be heated and shaped allows them to be shaped into complicated geometries that would not be possible with other materials. Their low processing costs, ability to be manufactured in high volume, and geometric precision makes them ideal for automotive applications. Thermoplastic have lower melting points when compared to traditional materials used within vehicles. Engineers must be mindful that the thermoplastics do not approach temperatures close to their melting point in the vehicle.

Regarding automotive applications, different thermoplastics have diverse beneficial physical properties. Their advantages include: their weight, low cost, their ability to be molded into complicated geometries, recyclability, energy absorption, solvent resistance, impact resistance, fracture toughness, damage tolerance, and long shelf life [10]. The materials in this study and their corresponding specific benefits and applications are described in Chapter 3.6.

2.2 Polymer Joining Processes

There are different methods for connecting thermoplastics. They can be attached together with the help of fasteners or physically joined together using adhesives or welding.

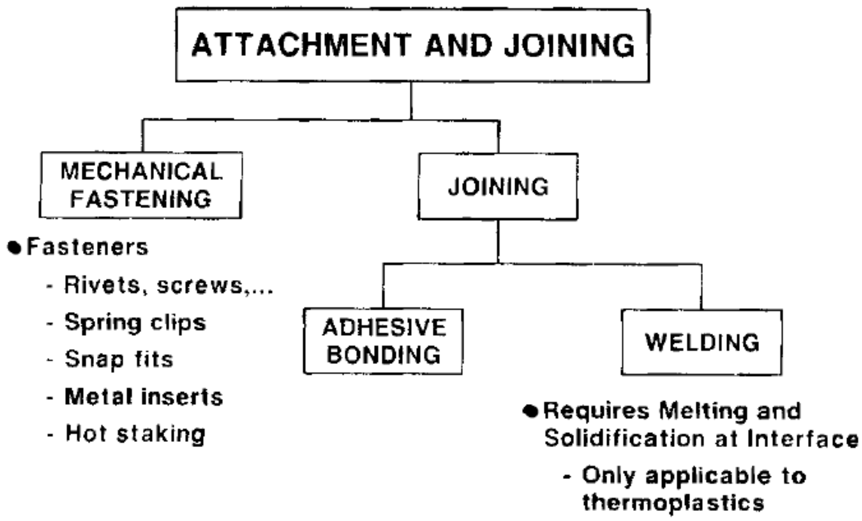

Figure 5: Methods of attaching and joining thermoplastics [1]

As shown below in Figure 6, there are many different types of welding for thermoplastics. This paper will focus on vibration welding.

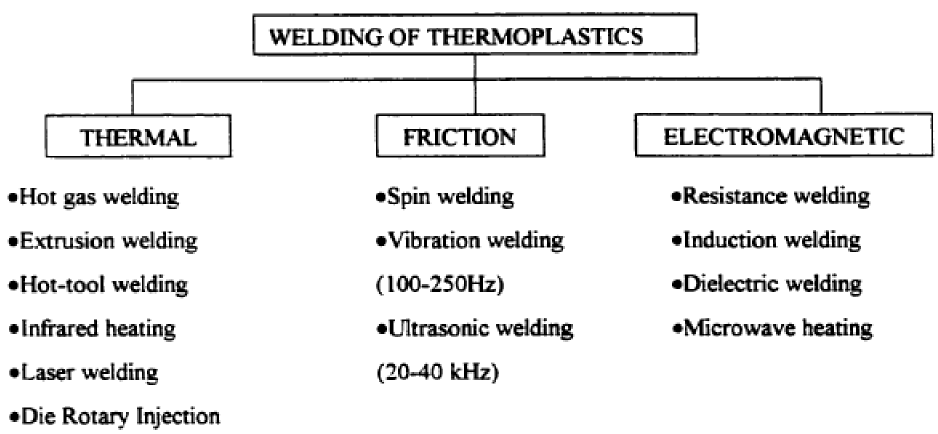

Figure 6: Classifications of types of welding for Thermoplastics [1]

2.3 Linear Vibration Welding

Linear vibration welding uses friction generated between two materials to join them together. The materials are pressed together with reciprocating motion parallel to the contact interface. This is displayed in Figure 2. The friction created at the weld interface melts the materials, which mix under pressure and once cooled, they bond together. The process parameters for linear vibration welding are the weld amplitude, weld frequency, weld pressure, and the weld depth [11, 12, 13] (or weld time, since they are related) as displayed in Figure 7 [12]). The frequency for vibration welding can be between 100-250 Hz, but is normally operated at 120 Hz or 240 Hz. Welds can be made outside of this range [12]. Typically, the vibrational amplitude is less than 5 millimeters and the weld time is between 1 and 10 seconds. In the past, majority of friction welding processes utilized LVW.

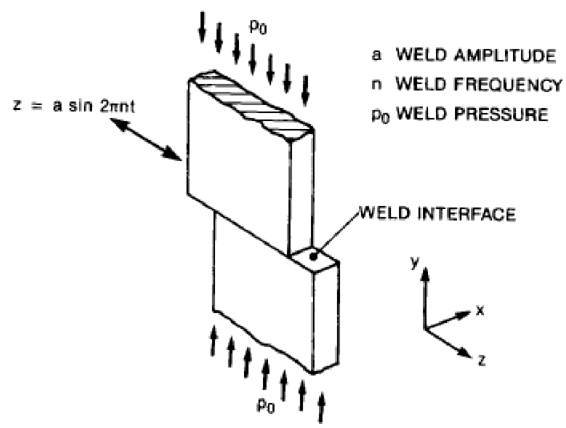

Figure 7: Schematic of Vibration Welding Process [12]

The weld amplitude is limited by the geometry of the parts and the welding machine. A general weld depth threshold cannot be chosen for all scenarios since the minimum weld depth varies greatly for different material combinations and weld parameters [7]. It is important to note that when using the weld depth as the process-terminating factor, the weld depth will always be slightly greater than the target depth. This is because the process may stop oscillating once the weld depth is reached. However, the liquid materials at the interface are still under pressure while cooling. This results in a larger weld depth than intended.

LVW has the capability to weld large parts, short cycle times, robustness, energy efficiency, and an insensitivity to surface preparation. Part geometries and the direction of motion must accommodate the constraints of vibration welding. The vibration welding machine's initial high cost typically does not outweigh its ability to quicken process times. Welds can be created on surfaces that were once contaminated, painted or vacuum metalized. Additional adhesives, lubricants, or implants need to be introduced to the weld. LVW is highly controllable and less likely to degrade the materials being welding due to overheating when compared to other welding techniques, such as hot plate welding where the heating is not localized. LVW also deals with warped parts better than other welding processes due to its use of higher pressures which flattens out the warpages. Quality vibration welds create strong hermetically sealed welds, regardless of the manufacturing process used to form the part. LVW machines have high sound levels during the welding process, between 90 and 95 dB [4]. Ear protection is necessary for workers to protect from harmful exposure to high sound levels.

Some defects from LVW are internal voids, cracks, high-residual stresses, and flash. Internal voids are more of a material manufacturing defect. LVW has a "self-cleaning" process, since the melted material rids the area of impurities and fills voids under pressure. Brittle plastics can experience cracks caused by stresses during welding. LVW has a minimal heat-affected zone which results in more localized residual stresses. These internal residual stresses can lead to environmental stress cracking during application. ESC occurs when a polymer is exposed to internal or external stress and a chemical agent simultaneously. It is an accelerated brittle failure of polymers, even for ductile polymers. ESC is not a focus for this study. However, subsequent testing is planned to test material combinations' resistance to ESC and how the welding parameters affect the strength when resisting ESC. Welding dissimilar materials can experience a lack of fusion at the weld interface when the materials’ glass transition temperatures are not alike, causing one material to melt well before the other, if at all. Flash is the most visible plastic welding defect. It is the hardened liquid material pushed out from the weld interface during the welding process, typically on the order of 0.13 mm in thickness [14]. It does not add to the effective weld area. Certain weld parameter combinations result in different flash behaviours. Minimal/no visible flash is ideal. To reduce flash on the outside of parts, engineers can design the plastic parts with energy directors or flash traps, to proactively design the parts to hide the weld areas within itself. Additionally, the welding surface can be preheated before friction welding for less harsh contact.

Figure 8: Weld flash on a sample. Different material combinations and welding parameters will yield different flash behavior - patterns and amounts.

Regarding applications, LVW is normally used for part sizes between 3x3 in and 24x60 in. Some automotive applications of LVW are lighting lamps, instrument panel assemblies, fluid reservoirs, dash-and-trim components, air conditioning and heater ducts, vacuum reservoirs, air intake manifolds, and more [4, 15]. Vibration welded components can be used on the interior and exterior of a vehicle, as well as for under-hood applications. For under-hood applications, the materials must withstand high temperatures. This study focuses solely on external lamp materials.

Large vibration welding machines are used in assembly lines, where parts are manually loaded. Vibration welding machines are large and heavy so that their vibratory motion does not displace the machine. The oscillating motion and vibration of the parts cause noise, with LVW machines reaching high sound levels between 85 and 95 dB during the welding process [4].

Figure 9: A Branson vibration welding machine used in automotive lighting assemblies [16]

2.4 Other Forms of Friction Welding

LVW is the simplest form of vibration welding, since the vibratory motion only occurs along one axis [3]. Some derivative forms of LVW are ultrasonic welding, orbital friction welding, angular friction welding, and LVW with infrared (IR) heating.

Ultrasonic welding is the most popular form of friction welding of thermoplastics. It uses a weld frequency much high than linear vibration welding, 20-40 kHz, with a very small vibratory amplitude, 1-25 μm. The oscillations are perpendicular to the joint surface. This welding process usually takes less than 1 s.

This high frequency process sends sinusoidal waves through the material to the weld interface, heating it up. Some energy is dissipated via intermolecular friction, heating up the part, making part design very important to accommodate for this. Obviously, less energy is lost when the ultrasonic welder is closer to the joint. If the joint is less than 6.4 mm away from the welder, it is designated as near-field welding, which is used for stiff materials and amorphous plastics. Energy directors can be used to focus the energy. During welding, the energy director will melt first and the displacement will rise quickly due to the focused material. Once the director is melted and spread out on the weld surface, the melting rate decreases. The process works generally the same as linear vibration welding. The limiting welding parameters for ultrasonic welding can be displacement, energy, power level, or weld time. Once this limiting factor is reached, the movement halts and the materials solidify together under pressure, creating a molecular bond [4].

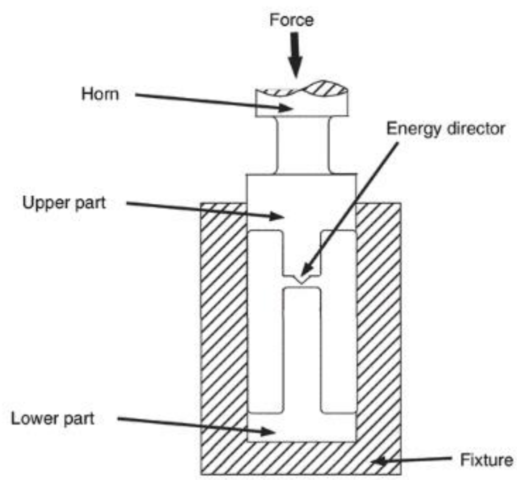

Figure 10: Ultrasonic welding diagram [4]. The high frequency welding process uses energy to melt the materials at the weld interface. Upon cooling, the materials join together.

Orbital welding is very similar to LVW except instead of a linear vibratory motion, one part is rubbed in an orbital motion relative to the other, while under axial pressure. This is geared towards special applications with parts having thin walls less than 2 mm or assemblies containing sensitive electrical components.

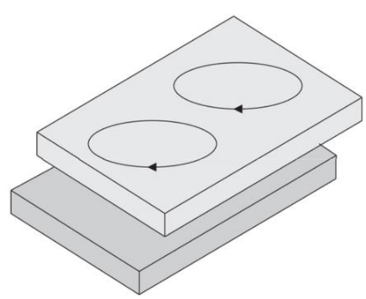

Figure 11: Orbital vibration welding [17]. Similar to LVW, except an orbital motion is used.

Angular friction welding also has parts under an axial force and they are rubbed together, rotating about a similar axis. This process is used for welding circular parts. This process has been eliminated from industrial use by spin welding.

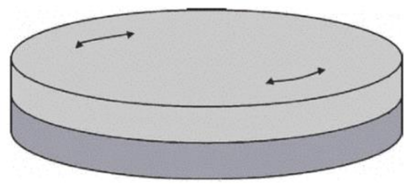

Figure 12: Angular friction welding [17]. Similar to LVW, except an angular rotation is used.

LVW with IR preheating is a process used to minimize the amount and rough appearance of flash. Preheating the parts where the LVW will take place softens the area, making the first phase less rough and drastic due to the shear forces at play. The material melts and softens before contact. Coil heaters, short-wave infrared emitters, and long-wave infrared emitters can be used. The preheat cycle is not a long process (a few seconds) so it does not impact LVW's benefit of short cycle times.

Figure 13: IR preheating before linear vibration welding softens the materials at the interface, making the first interaction of the materials less rough. This generally results in a more aesthetically appealing flash behaviour.

Spin welding can be used for thermoplastic pieces that have rotationally symmetric surfaces which can be joined under pressure [4]. Spin welding is used for its simplicity and energy efficiency. Majority of the heat created is used in the welding process. It is used in automotive assembly lines. Spin welding is a better option than ultrasonic welding for long and tall parts.

The parts are loaded into the welding machine and then the upper head begins rotating and lowers until it is in contact with the top part. This rotation speed typically ranges between 200 and 14000 rpm, but is normally used near 2000 rpm. The upper head spins the top part, creating frictional heat at the weld interface. This welding process has the four phases similar to linear vibration welding. The first three phases last 0.5-2 s while phase IV lasts 1-2 s.

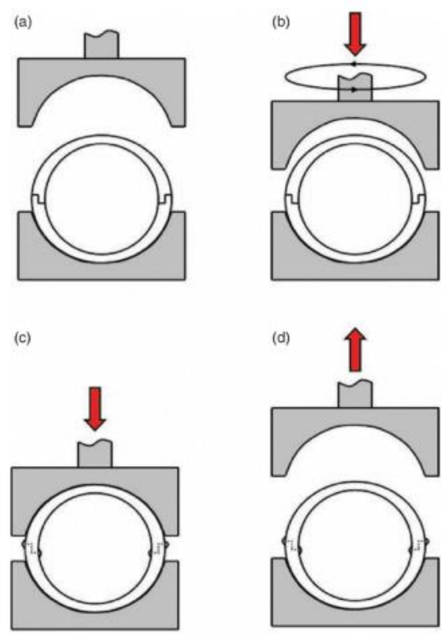

Figure 14: Spin welding: (a,b) the parts are loaded into the fixture and the upper head lowers while spinning, (c) welding process occurs while top part spins and creates melting at the weld interface due to friction, (d) upper head is lifted [17].

2.5 General Factors Affecting Weld Strength

Potente and Uebbing [7] presented factors that can affect the weld strength:

- Welding Parameters
    - There are several welding parameters that affect the weld strength, including: vibratory amplitude, pressure, clamp force, and tolerance limit (time or weld depth).

- Specimen Geometry
    - The variation in specimen will cause variation in strength value. For this particular study, the sample specimen sides needed to be parallel and machined flat. Either of these criteria not being met would result in a poor or compromised weld.
- Moisture
    - The storage of thermoplastics can affect the strength of the vibration weld, specifically the water absorption. Bubbles forming in the weld can have adverse effects on the weld and its strength. This paper studies amorphous resins since they are used in automotive lighting applications.
- Rate of Heating and Cooling (for Welding Dissimilar Materials)
    - Welding dissimilar materials can experience a lack of fusion due to the materials' dissimilar melting temperature. During the welding process, one material may reach its melting point much earlier than the other, not allowing the two to mix at the weld interface.
- Peak Temperature (Possible Material Degradation)
    - Vibration welding allows dissimilar materials to be joined. Typically, materials need a similar melting temperature to be welded together. If their melting temperatures are not similar, the material with the lower melting temperature will burn and its molecular structure will degrade as the temperature still rises to reach the other material's melting point. The general rule is that the dissimilar materials' difference in melt temperature should not be greater than 40°C to result in a quality weld [4].

Some additional factors not posed by the pair include:

- Joint Design
    - For T-joint welds of dissimilar materials, swapping the materials' orientations will yield different strengths [18].

- Weld Geometry
    - The geometry of the weld can influence the strength of a weld. It has been proven that a butt-joint weld is the best representation of a material combination's strength capabilities [19].
- Chemical Compatibility
    - Dissimilar materials must be chemically compatible to be welded together. This means that their polymer chains must be able to form secondary bonds, caused by molecular or atomic dipoles. Amorphous plastics are compatible with each other. For example, polypropylene (PP) is semi-crystalline and is compatible with very few other materials.
- Welding Defects
    - Examples of weld defects are: internal voids, cracks, high-residual stresses, and flash. Plastic welding defects are discussed in Chapter 2.3.

2.6 Welding Geometry

In application, the weld geometry is constrained by the clearance constraints of the welding machine, the clearance between the parts, and the necessary stiffness of the parts once they are joined. The two main weld geometries are the butt-joint weld and the T-joint weld. The most basic weld is the butt-joint, where as the name suggests, the sample's butts are welded together. The direction of motion can be longitudinal or transverse.

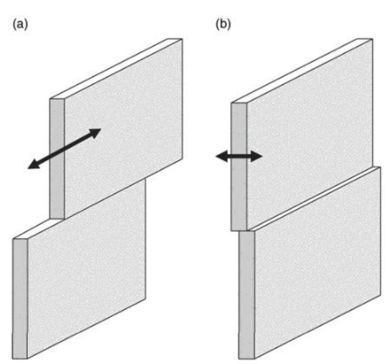

Figure 15: Butt joints for linear vibration welding: (a) longitudinal motion (b) transverse motion [17]

The type of weld geometry to be used for this study is the T-joint, since it is the most reflective of automotive lighting applications. This weld earns its name from the component's resulting post-weld shape. The T-joint's parts can be referred to as the web and flange, with the flange being the horizontal part of the 'T' and the web being the vertical part of the 'T'.

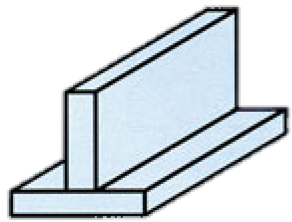

Figure 16: A T-joint weld. The vertical upper piece of this orientation is called the 'web' and the horizontal lower piece is called the 'flange'. [20]

For this study's application, the T-joint weld best simulates the production vibration welds. The welding supplier, Branson, manufactured their M-102H tabletop LVW machine which facilitates T-joint welds. The lens material for the project is chosen as the web of the T-joint and the housing is placed as the flange on the oscillating panel in the machine. The lens and housing combinations used in this study are the orientations that are reflective of their respective automotive lighting applications. Swapping their orientation may yield higher strengths [18], but cannot be applied to the lighting fixtures. The welded samples' shape, or "Type" as referred to by the ASTM standard, does not directly correlate to the standard since T-welds were used instead of butt welds due to a more accurate representation of their real-world application [21]. Stokes believes that the butt weld is the most representative of a weld materials strength, whereas T-joints have residual stresses that attribute to the underestimation of its strength [19].

2.7 Linear Vibration Welding Phenomenology

Stokes was a key contributor to the advanced understanding of vibration welding, presenting his work in the 1980s, where friction welding had already been in use for at least 20 years [12]. Up until his research, there had been minimal studies regarding vibration welding [22], as opposed to the heavily studied ultrasonic bonding and hot plate welding [12]. The closest relevant studies were regarding vibration spin welding. The strength of linear vibration welds had not been researched systematically at the time [12]. Stokes determined the phenomenology of the LVW process.

As previously stated, process parameters for LVW includes weld amplitude, weld pressure, weld depth, and weld frequency. Stokes was interested to find how these parameters affect the weld quality. He also wanted to explore which conditions yield the best welds for specific scenarios, the weldability of dissimilar plastics, and the effect of fillers on the weld. He fabricated a specialized vibration welding machine where he could control each welding parameter independently. The design and mechanics of this specially designed machine are presented in Stokes' paper [12].

A vibration weld needs a chosen parameter to limit the weld process. Therefore, the weld process can continue for a pre-specified time duration, a preset number of cycles, or a preset weld penetration. Once this preset value is achieved, the process terminates. Through vibration welding plastic specimen with the use of this machine, Stokes was able to study the parameters during the welding process.

Stokes found that the frictional force in the molten steady-state case is greater than the frictional force in the solid friction case. He determined that this occurs because the frictional force in the steady-state case depends on the shear rate and the viscosity of the melted plastic. The pressure applied during the weld process creates a thin layer of molten plastic which induces a high shear rate.

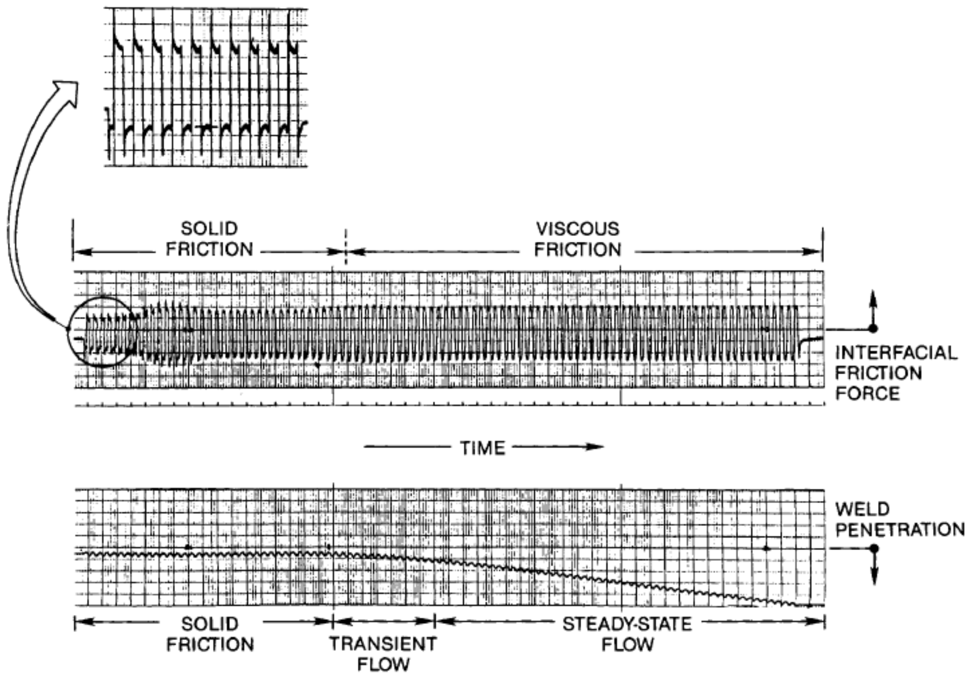

Figure 17: Frictional force (top) and weld penetration (bottom) over time during the LVW process [12]

With the use of this machine, the phases of the penetration-time curve could be defined. The vibration welding process of thermoplastics consists of four phases defined by Stokes, as shown in Figure 3. The work completed to determine this curve is outlined in Chapter 2.11.1.

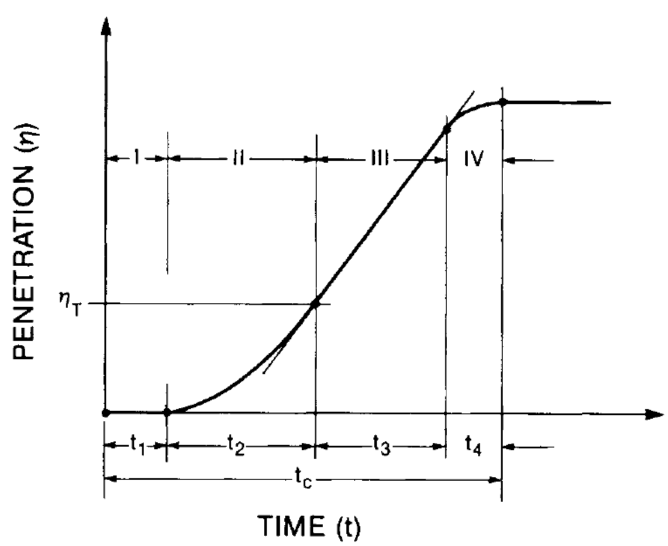

Figure 18: Penetration-time curve for the four phases of vibration welding [12]

In Phase I, the solid materials are pressured together and reciprocate motion. This creates heat through friction and raises the temperature at the contact interface. Since both materials are solid, there is no displacement/penetration depth during Phase I. Phase I ends when the temperature reaches the glass transition temperature for amorphous plastics or the melting point for semi-crystalline plastics. This phase is driven by Coulomb friction. The frictional force is not constant.

Phase II finds the material at the interface becoming viscoelastic. It melts and flows outward due to the contact pressure. The fluid film is initially not thick, resulting in a high melting rate. As the fluid layer thickens, the heating rate decelerates due to the reduction in shear rate. A thicker fluid layer promotes a larger flow rate. The weld depth is no longer zero and gradually increases.

Phase III is attained when the film thickness is constant, which occurs when the melting rate is equivalent to the rate of the melted material being forced out of the interfacial region. The weld depth increases linearly until the vibratory motion is stopped.

Phase IV is initiated when the motion is stopped and the interface is kept under pressure. The interface cools and the materials solidify together, completing the weld.

These four phases have been observed for the vibration welding of unfilled polymers, filled polymers, polymer blends, polymer foams, and dissimilar polymers [23].

2.8 Linear Vibration Welding Process Analysis

Stokes derived simple analytical models to represent the first three phases of the welding process, involving dynamic physics, heat transfer and fluid mechanics [13, 15]. Below, the behavior of the LVW process is outlined using basic relations, as shown by Qi. These relations were utilized in an attempt to use regression analysis to create a predictive numerical equation which calculates the strength of welds after inputting its specific process parameter values [15].

The displacement of the vibration welding can be described as:

$$x = a * sin(\omega t)$$

where *x* is the horizontal displacement of the moving part from its initial position, *a* is the amplitude of the weld, ω is the frequency of the weld and *t* is time. The derivative of this equation yields the equation for the relative velocity:

$$V = \frac{dx}{dt} = a * \omega * \cos(\omega t)td$$

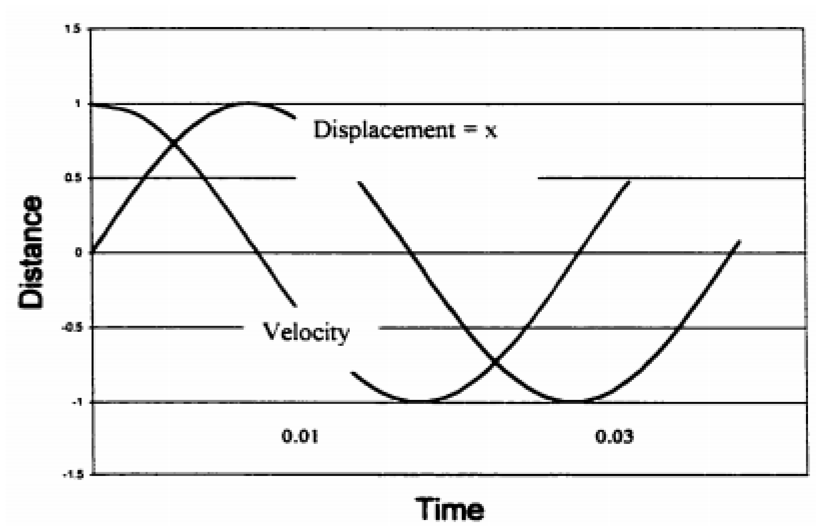

Figure 19: The relationship between the relative displacement and velocity [24]

There are two key forces during LVW [3]:

1. Working force

   The working force is caused by the frictional resistance to the vibrational displacements at the welding interface, releasing energy as heat.

2. Clamp force

   The clamp force is responsible for squeeze flow, molecular alignment, and out-gassing. It directly affects the working force.

With the welded components being pressured together and then one of them moving relative to the other causes friction at their interface. The amount of friction is dependent on the coefficient of friction and the normal force (clamping force in this case). The dynamic frictional working force can be described as:

$$f = \mu * F$$

Where *F* is the welding clamp force, and μ is the dynamic coefficient of friction.

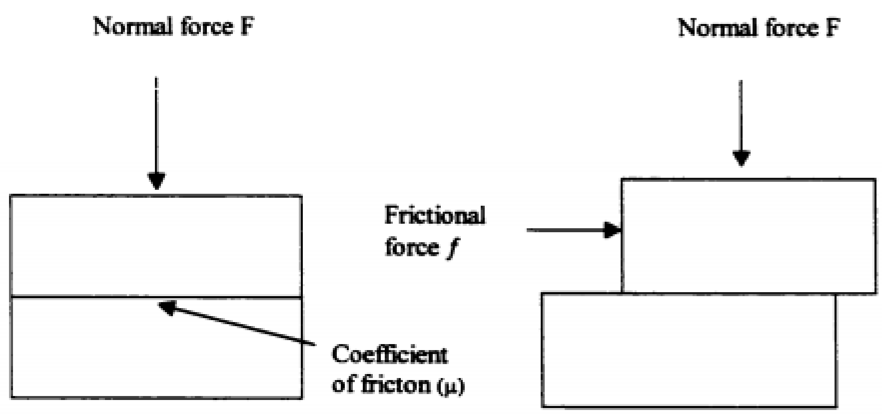

Figure 20: Definition of friction; displaying the normal force, frictional force, and the coefficient of friction. [24]

The amount of energy produced during the Coulomb friction phase (Phase I) can be calculated as:

$$P = V * f$$

Where *V* is the relative velocity and f is the dynamic frictional force. *P* is the power necessary to drive the process. Substituting the frictional force formula into the Power equation yields:

$$P = \mu * F * V$$

And substituting the relative velocity equation into this equation gives:

$$P = \mu * F * a * \omega * \cos(\omega t)$$

It is now clearly evident that the instantaneous power produced during the Coulomb friction phase is dependent on the coefficient of friction, the clamping force, the vibratory amplitude, the welding frequency, and the time. The average power can be defined as the power in one cycle divided by the radians in a cycle:

$$P_{av} = \frac{P_{1\,cycle}}{2\pi} = \frac{1}{2\pi}\int_0^{2\pi} \mu * F * a * \omega * \cos(\omega t) * d(\omega t)$$

$$P_{av} = \frac{\mu F\omega}{2\pi} * 4 * \int_0^{2\pi} a * cos(\omega t) * d(\omega t) = \frac{4\mu F\omega}{2\pi}$$

$$* {}_0^{2\pi}[a * \sin(\omega t)] = \frac{4\mu F\omega}{2\pi} * [a - 0]$$

$$P_{av} = \frac{2\mu F\omega A}{\pi}$$

Phase II has the melted material being continually heated by the generated friction. The outward flow of the liquid material allows the weld penetration depth to gradually increase. Phase III begins when steady-state flow is achieved and the weld penetration increases linearly with time. This occurs when the amount of molten material being produced is equivalent to the amount of material being squeezed out of the interface by the clamping pressure. The heating is now produced by shear instead of Coulomb friction. Viscoelastic heating is responsible for the generated heat during this phase. This phase ends when the weld motion halts and the material proceeds to cool.

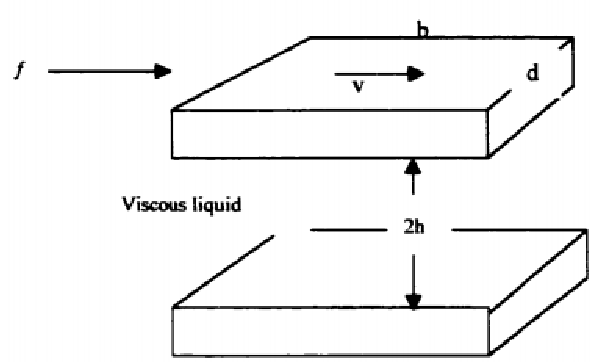

Figure 21: Diagram displaying the geometry used. The upper prism's bottom area is calculated by 'bd'. A viscous fluid exists between the two prisms. [15]

This diagram assumes a Newtonian fluid with a viscosity independent of temperature. Newton's law of viscosity gives the shear stress as the product between the dynamic viscosity and the shear rate:

$$\tau = \mathrm{v} * \dot{\gamma}$$

Where v is the viscosity of the molten material and $\dot{\gamma}$ is the shear rate.

The shear stress is defined by:

$$\tau = \frac{f_s}{A} = \frac{f_s}{bd}$$

Where f_s is the shear horizontal force on the upper plate, *A* is the area of the cross section, *b* is the length of the interface and *d* is the width of the interface.

The shear rate is defined as:

$$\dot{\gamma} = \frac{V}{2h}$$

Where *V* is the upper plate's velocity and *2h* is the thickness of the melted layer.

Using these relations, the shear force f_s can be shown as:

$$\tau = \mathrm{v} * \dot{\gamma} = \frac{f_s}{bd}$$

$$\frac{f_s}{bd} = \mathrm{v} * \dot{\gamma} = \frac{\mathrm{v} * V}{2h}$$

$$f_s = \frac{\mathrm{v} * V}{2h} bd$$

As previously defined, the Power can now be given as follows:

$$P = f_s * V = \frac{\mathrm{v} * V^2}{2h} ld$$

Unit analysis confirms that the unit after this calculation are in Watts. The power per unit area, also known as the intensity of radiant energy or the heat flux, can be defined as:

$$Q = \frac{P}{A} = \frac{P}{ld} = \frac{\mathrm{v} * V^2}{2h}$$

And using the first basic equation describing the relative velocity, the heating/energy exerted in Phase III is explained using the expression:

$$Q = \frac{\mathrm{v}A^2\omega^2 cos^2(\omega\tau)}{2h * ld} = \frac{\mathrm{v}A^2\omega^2}{4h}$$

Phase IV begins when the vibratory motion ceases and the weld interface is allowed to cool under pressure. The weld penetration continues to increase slightly during cooling due to this existing clamping force.

2.9 Factors Affecting Material Compatibility

There are three main factors affecting material compatibility for vibration welding of plastics: material compatibility, similar melt flow indexes, and similar melting temperatures.

One of the main requirements to ensure high quality vibration welds is material compatibility. Material compatibility is dependent on if the chosen materials are chemically compatible. Chemically compatible materials are able to form secondary bonds. Polymers contain internal primary and secondary bonds. Plastic grades are created by slightly modifying the chains of the material, resulting in beneficial outcomes for a specific area of application.

Secondly, materials should have similar melt flow indexes to ensure mixing at the weld interface. These materials should be within 10% of each other for a quality weld. Material grades can have a wide range of values for the melt flow index, sometimes even resulting in incompatibility for two materials with the same parent polymer. For example, a melt flow for ABS can be anywhere within the range of 0.08-80 g/10 min, depending on the grade.

Lastly, the weld materials need a similar melting temperature because the temperature at the weld interface is the same for both materials and their molten states must be mixed during the welding process. As previously explained, amorphous polymers do not have a clear melting point. They have a glass transition temperature range. Here, the polymer changes from a brittle and solid glass-like structure to its molten state. This temperature range can be modified between grades.

2.10 Polymer Chain Behaviour During Welding

The word ‘reptation’ is based off of the Latin verb ‘raptare’, which means to creep. Researcher de Gennes chose this term to describe the movement of the molecular chains which he believed to move like snakes, after experimental review. The reputation model is commonly used to display the behaviours of molecule chains during healing. With molecules diffusing across the interface, strength can be obtained. The build-up of this strength has been referred to as tack or autohesion.

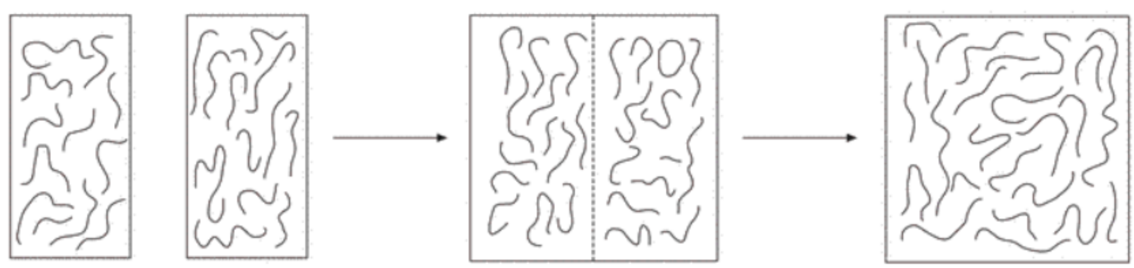

Figure 22: Interdiffusing polymer chains across an interface [25]

Wool used the reputation theory and created a model describing welding. Wool and O’Connor [26] describe five important molecular steps that occur while welding thermoplastics: surface rearrangement, surface approach, wetting, diffusion, and randomization.

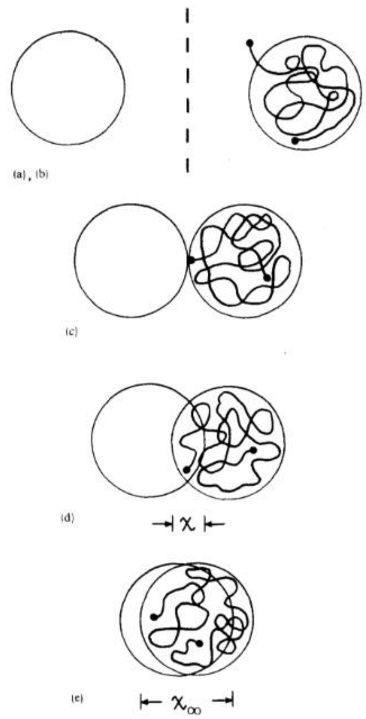

Figure 23: Two polymer chains from different crack surfaces during the five crack healing stages: (a) rearrangement of molecular chains, (b) approaching of two welding surfaces, (c) wetting, (d) molecular chain interdiffusion, (e) molecular chain randomization [26]. The dotted line represents the crack plane. Only one molecular chain is shown for simplicity.

They comment that crack healing in polymers is critical to the strength of the materials. It is concluded that diffusion and randomization are the most critical steps that affect the weld strength. Their findings are based on previous studies of crack healing, which includes previous experimental testing of independent amorphous and semi-crystalline polymers separately.

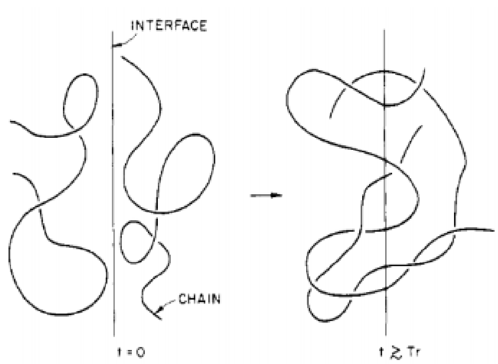

Figure 24: Two polymer chains at a crack or weld interface before and after interdiffusion and randomization [27]

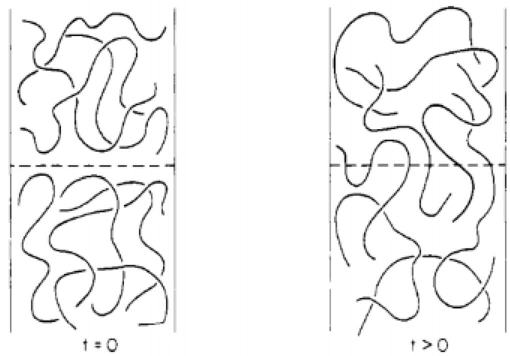

Figure 25: Side view of many chains at a weld interface post-interdiffusion [27]

The idea of crack healing involves a material being transformed from a damaged state to a healed state, which typically results in only partial healing. This means that the healed material only reaches a fraction of its typical physical property values. This is accomplished by putting the material under a healing temperature and a healing pressure, for a set healing time. The welding interface of a linear vibration weld can therefore be treated as a crack in a material which is put under a healing pressure, temperature, and time to heal.

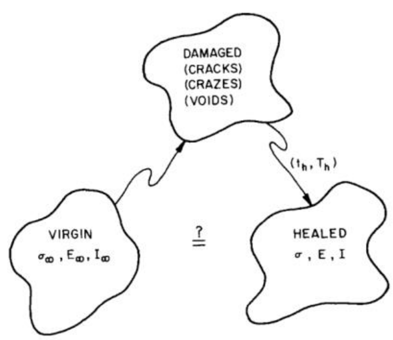

Figure 26: A damaged virgin material is healed and its resulting physical properties are compared to its bulk material values as a function of temperature and healing time [26].

Experimental testing displayed that cracks, voids, and crazes disappeared after healing. Some cracks only healed at the tip of the crack, which is referred to as point mode healing, while other cracks healed consistently along the entire crack, referred to as line mode healing.

Wool eventually created a general welding function:

$$G = W(t, T, P, M)$$

Using this theory, Wool determines that larger molecules take a greater amount of time to diffuse. Therefore, the weld time of these materials should be increased. Also, over half of a molecule must crossweld to achieve the maximum weld properties. A more intuitive conclusion is that higher temperatures do create welds at a quicker rate.

Experimental results and the reputation theory implicate:

Table 1: Effect of Welding Parameters Regarding Crack Healing [28]

	High	Low
Temperature	Faster welding time Possible thermal degradation	Slow or no weld
Pressure	Chain diffusion inhibited	Insufficient surface wetting
Weld Time	Oxidative degradation, flash	Insufficient diffusion, weak weld
Molecular Weight	Very long weld times and high pressures required Slow diffusion weak parent materials and welds	Rapid weld times and low pressures required

An optimal set of parameters must be found that satisfies all scenarios to create a strong weld. Diffusion of molecules and randomization of the molecular chains are the main steps that determine the weld strength. The diffusion capabilities depend on material compatibility. LVW is essentially the same process as healing, except healing process parameters are based on a specific material and the main purpose is to heal. With LVW, the welding parameters are chosen, which may not be cohesive to the healing parameters.

Haire and Windle studied the motion of polymer chains using Monte Carlo simulation [29] on the mesoscale. This gave the ability to determine weld completion times and explain the material diffusion. This model has been proven successful for similar linear amorphous polymers. It does not account for material flow or non-isothermal heating affect polymer chain diffusion. It is hoped to be extended to semi-crystalline and branched polymers, as well as modified for all plastics welding processes.

Amorphous polymer chains' movements are constrained by the other chains surrounding them. Since the chains are so randomly tangled, each chain acts as if it is restrained in a tunnel region. The reputation model is a method of describing their movement. When the temperature is increased to the glass transition temperature, the chains are able to wiggle with very small amplitudes in one dimension. The ends of the chain will wiggle and find new paths which disentangle the chain from its previous tunnel position, finding a new position. The portions of the chain that have moved from their initial position are called the minor chains. These progressively get longer with time, until the chain is fully in a new position/tunnel.

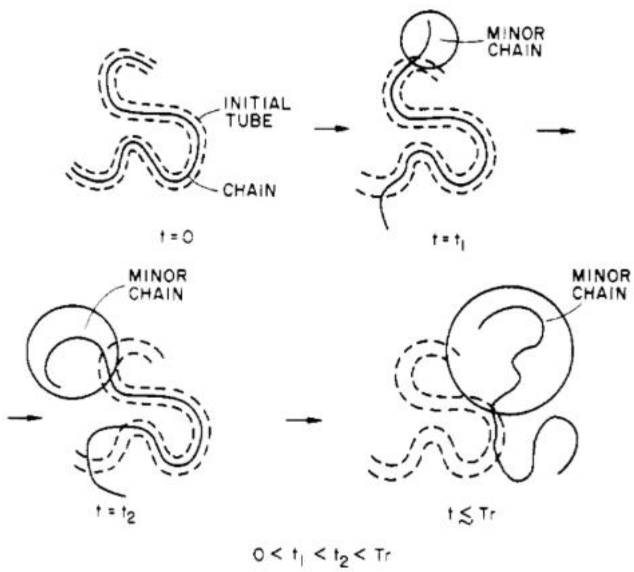

Figure 27: The disengagement of a molecular chain from its tunnel. The dotted line outlines its initial starting position in its tunnel. The minor chains are also shown [27].

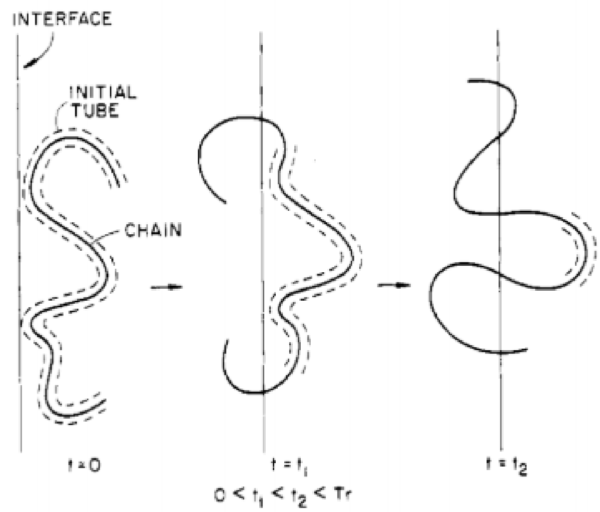

Figure 28: The disengagement of a singular chain from its tunnel near a crack or weld interface. The dotted line shows the tunnel that contains the portion of the chain still in its initial position [27].

Relating back to LVW, this all occurs above the glass transition temperature and the mixing is typically accelerated by the oscillatory motion at the interface. Once the welding stops, a strong weld will have a good engagement of molecules intertwined and crossing the interface plane once cooled. Jud et al. [30] determines that this intertwinement (or as they refer to the process, 'polymer interdiffusion') of molecules determines the strength of the weld. They also note that additional research must be completed on the influence of material compatibility, molecular weight, and chain structure, and how they affect the diffusion.

2.11 Previous Work on Welding Similar and Dissimilar Thermoplastic Materials and Strength Testing

2.11.1 Impact of welding parameters on the welding penetration-time curve for similar material welds

As previously explained, Stokes created his own sensitive controllable linear vibration welding machine. With his state of the art machine, Stokes explored the weldability of similar plastics and the effects of the varying parameters on the penetration-time graph. This curve is dependent on the weld pressure, the weld frequency, and the weld amplitude. In the study examining the penetration-time curves, Stokes chose polycarbonate (PC), polyetherimide (PEI), polybutylene terephthalate (PBT), and a modified polyphenylene oxide (M-PPO). Polycarbonate and polyethermide are amorphous polymers, which are of interest to this research paper. While studying these curves, similar material welds are used.

Stokes presents PC data [12] for the relationship between the penetration and time, using butt welded specimens that are 5.84 mm in thickness at a weld frequency of 120 Hz with a weld pressure of 0.9 MPa. The weld amplitude is varied. Rectangular specimens were used which were 76 mm in height and 25.4 mm in width, with machined edges.

Stokes collected the time-penetration data using a constant frequency of 120 Hz and a weld pressure of 0.9 MPa, with the weld amplitude varying for different welds. Each weld scenario's Phase I is clear, with the transient zone following and then reaching a steady state. For these similar butt welded samples, it is clear that Phase I takes less time to complete when the amplitude is greater. Note that Phase IV is not shown in Stokes' diagrams. He references the weld amplitude as 'a', the weld pressure as 'p', and the weld frequency as 'n'. These will be adopted in the diagram descriptions for brevity.

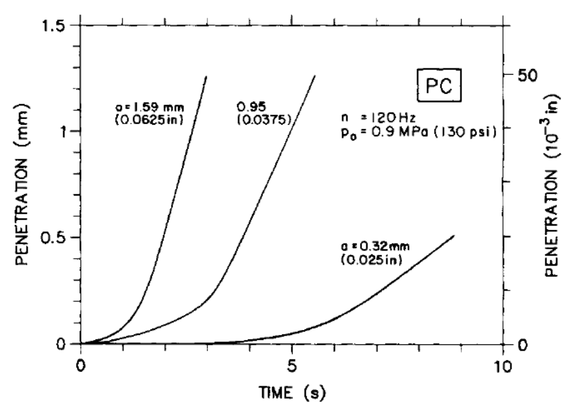

Figure 29: Effects on the penetration-time curve when varying the weld amplitude for PC welds at n = 120 Hz and p = 0.9 MPa [12]. A larger weld amplitude results in a shorter Phase I for dissimilar welds.

Next, Stokes completed the same testing, but varied the pressure instead of the amplitude, keeping the amplitude constant at 1.59 mm.

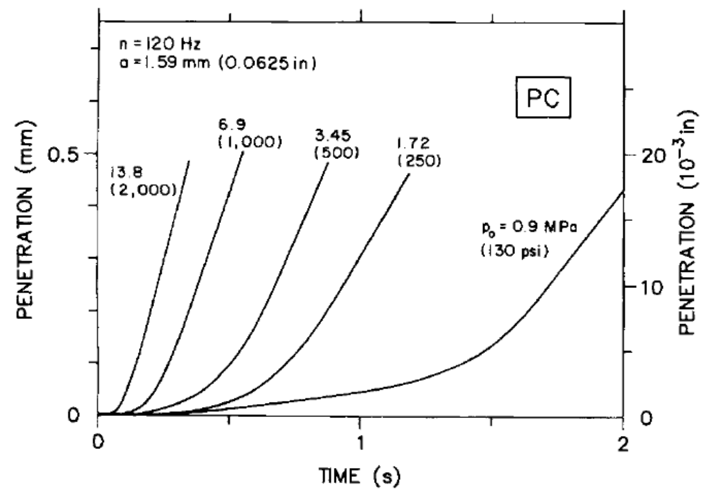

Figure 30: Effects on the penetration-time curve when varying the weld pressure for PC welds at n = 120 Hz and a = 1.59 mm. A larger pressure results in a larger unsteady transient portion. The penetration which initiates the steady-state increases with a decreasing weld pressure.

The unsteady transient portion grows larger and the penetration at which the steady-state is reached increases as the weld pressure decreases. A second steady-state was observed for certain conditions, appearing after the Coulomb-friction and transient portions of the curve. Stokes presents varying pressure data, for different amplitudes.

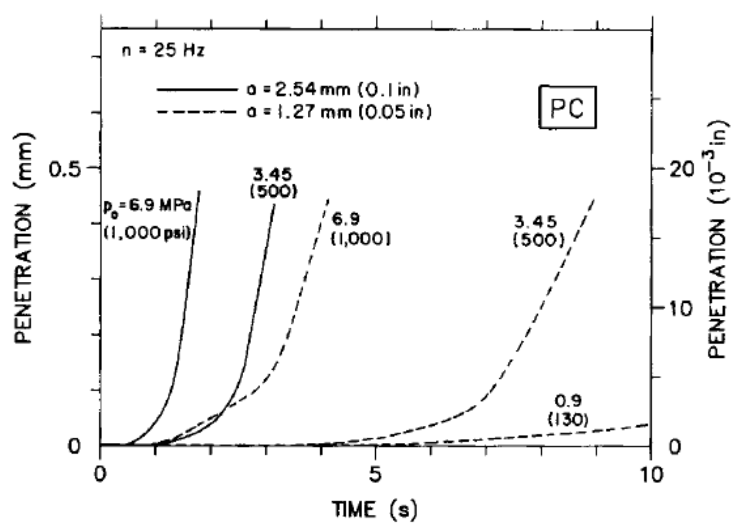

Figure 31: PC penetration-time curves for varying pressures at different weld amplitudes.

Stokes presents many more graphs solidifying his findings. Through widely varying welding process parameters, Stokes proves that the PC time-penetration curves displayed the three phases of the welding process. He also found that a second steady state phase is apparent for some parameter combinations. It is clear that Phase I reduces with increasing weld frequency, weld amplitude, weld pressure. Stokes determines that increasing the width of the sample extends the length of Phase II [31]. These results are summarized by Patham and Foss [23] in the figure below.

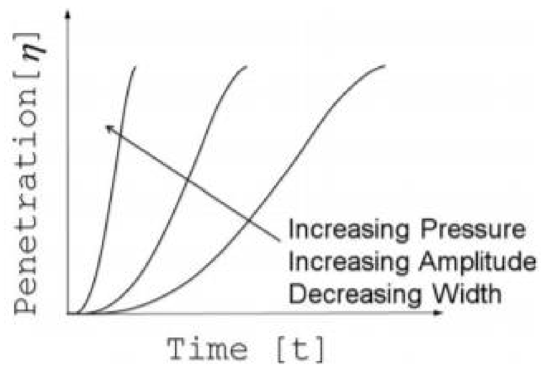

Figure 32: The typical effects of weld parameters and sample width on the weld penetration-time curve [23]

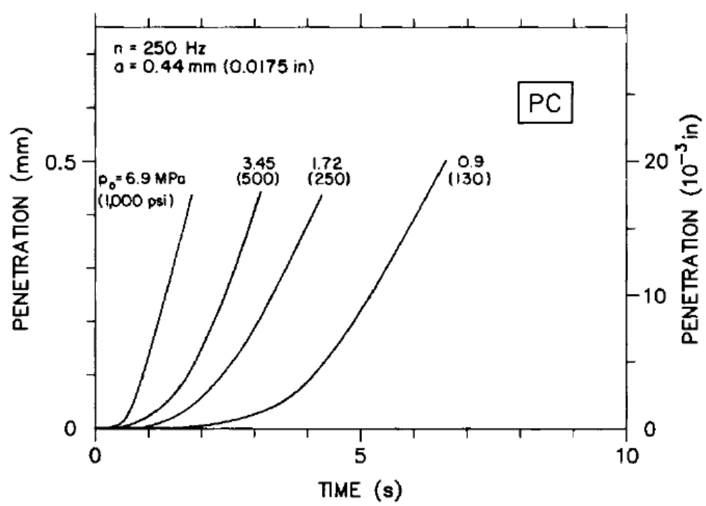

Figure 33: Penetration-time curve for PC with varying pressure at n = 250 Hz and a = 0.44 mm [12]. A larger weld pressure decreases the amount of time it takes to reach the desired weld depth.

The same penetration-time curves were created for PBT, PEI, and M-PPO, and the same overall trends were found. The plastics' phases can be directly compared when welded at the same conditions and using the same sized samples, as shown below.

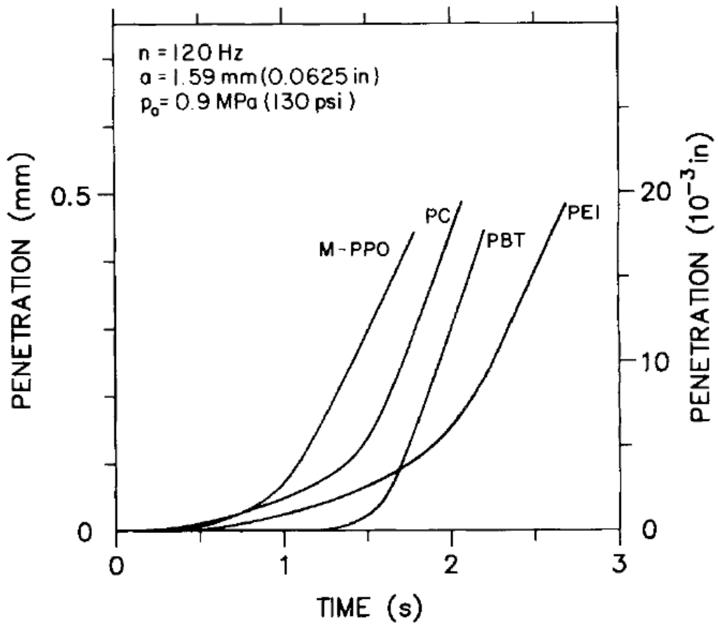

Figure 34: The penetration-time curves for different similar material welds using welding parameters of n = 120 Hz, a = 1.59 mm, and p = 0.9 MPa [12].

All four plastics exhibited the three phases of the welding process at different combinations of the parameters. The initial Coulomb-friction phase decreases with increasing weld frequency, increasing weld pressure, and increasing weld amplitude. Also, an increase in weld amplitude and frequency causes a decrease in the penetration where the steady state is attained.

Since these materials all displayed similar behavior, showing the three phases, Stokes generalized the welding process using the penetration-time curve. These four phases have been observed for the vibration welding of unfilled polymers, filled polymers, polymer blends, polymer foams, and dissimilar polymers [23].

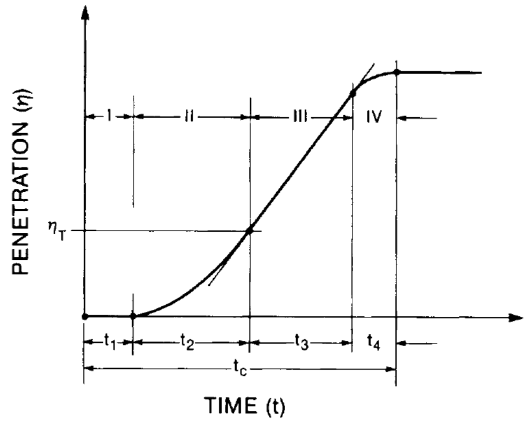

Figure 35: Penetration-time curve for the four phases of linear vibration welding [12].

In Phase I, the solid materials are pressured together and reciprocate motion. This creates heat through friction and raises the temperature at the contact interface. Since both materials are solid, there is no displacement/penetration during Phase I ($\eta = 0$). The penetration rate ($\dot{\eta}$) during Phase I is zero. Phase I ends at $t = t_1$ when the temperature reaches the glass transition temperature for amorphous plastics or the melting point for semi-crystalline plastics. The first phase is dominated by Coulomb-type friction.

Phase II finds the material at the interface melting and flowing outward due to the contact pressure. The fluid film is initially not thick, allowing a high melting rate. As the fluid layer thickens, the heating rate decelerates due to the reduction in shear rate. A thicker fluid layer promotes a larger flow rate. The weld depth is no longer zero ($\eta = \eta_T$) and the penetration rate ($\dot{\eta}$) is increasing.

Phase III is initiated at $t = t_2$, when the film thickness is constant, which occurs when the melting rate is equivalent to the rate of flow of the melted material. The penetration rate ($\dot{\eta}$) during Phase III is a constant non-zero value ($\dot{\eta} = \dot{\eta}_o$). The weld depth increases linearly until the vibratory motion is stopped.

Phase IV is initiated when the vibratory motion is stopped and the interface is kept under pressure. The interface cools and the materials solidify together, completing the weld.

The total weld time (t_c) is equal to the sum of the time taken for each individual phase, $t_1 + t_2 + t_3 + t_4$.

For modelling, the most important variables are: t_1, t_2, η_T, $\dot{\eta}_o$. As seen previously from the experimental results, t_1 is typically small and problematic to measure, as is t_2 and therefore η_T.

Stokes' experimental data determines that the different plastics all have similar trends for the variations of t_1, t_2, η_T, and $\dot{\eta}_o$, as a function of the process parameters. With increasing amplitude and pressure, t_1, t_2, and η_T decrease while the penetration rate, $\dot{\eta}_o$, increases.

Stokes proceeded to write three companion papers, studying the welding process and how it is affected by the welding parameters, as well as their effect on the strength of similar PC, PBT, M-PPO, and PEI welds.

2.11.2 Similar material vibration welds - Impact of welding parameters on the weld strength

Stokes studied the effects of varying weld parameters on the strength of PC butt welds [32] using rectangular samples, 76.2 mm by 25.4 mm (3 in by 1 in). The samples' edges were machined to confirm alignment during the welding process.

One of Stokes' main findings in his successive paper studying the strength of PC butt welds is the existence of a weld penetration threshold. This is defined as the minimum penetration needed to achieve a quality high strength weld and is the penetration during Phase III of the welding process. Welds not attaining this minimum penetration are much weaker. For PC, the minimum penetration threshold was found to be 0.25 mm, with pressures ranging from 0.9 MPa to 6.9 MPa not having an effect on the strength of the weld. This displays that the weld depth is a highly influential key welding parameter for LVW strength. This weld penetration threshold increases with part thickness. Stokes then introduces the weld factor; the ratio of the weld strength of a specific set of weld parameters to the strength of the weaker base material.

At the high weld pressure of 13.8 MPa, the weld strength is relatively small even with a penetration of 0.5 mm, larger that the weld threshold. Welds with relatively low weld pressure can create strong welds with drastically large weld depths.

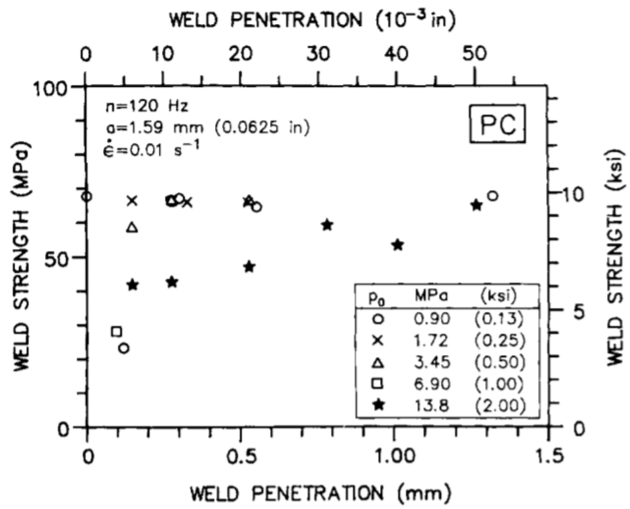

Figure 36: PC strength vs penetration with n = 120 Hz and a = 1.59 mm with weld pressure as parameter [32]. A weld penetration threshold is discovered at 0.25 mm. The relatively high weld pressure of 13.8 MPa has an adverse impact on the weld strength.

Stokes determined that high welding pressures cause the slightly heated material to be pushed out of the weld interface laterally, while the material is at a lower temperature and its viscosity is still high. Therefore, instead of the material flowing as a more of a liquid, the material is being forced and pushed out of the weld interface instead of mixing at the interface to form a weld.

A similar phenomenon occurs at very large pressures, except the liquid plastic is pushed out of the weld face laterally. Stokes shows this experimentally at a pressure of 13.8 MPa, where all strength values decreased from using a lower pressure at the same weld depth. Only the largest weld depth of 1.295 mm could hold its strength value at the highest weld pressure.

Additionally, Stokes found that similar PC welds display a strength equivalent to the material pre-weld. Some welds failed outside of the weld area, indicating the weld stronger than the location of failure. It is found that the weld strength is not affected by the amplitude of the vibratory motion or the strain rate. He noted that the weld time depends on the welding parameters. Therefore, the weld depth should be used as the variable for controlling the duration of the weld and not the weld time. Additionally, with other weld parameters constant, the weld time will not be consistent or comparable between different materials and can be affected by material imperfections. Clearly, the weld penetration is a superior measure of the weld strength than the weld time.

While exploring the effects that the weld pressure has on weld strength, Stokes found that at 6.9 MPa, the strength at an amplitude of 3.18 mm was peak strength while the strength at an amplitude of 1.59 mm halved this peak. Stokes hypothesizes that the lower amplitude cannot generate enough heat at a quick enough rate. This smaller area is subjected to localized frictional heat, causing a thicker heat affected zone. This viscous layer is then pressed out of the interface by the pressure, so even with a large penetration depth, a healthy weld cannot be formed.

In summary, Stokes defines a weld penetration threshold for PC and confirms that when PC achieves steady-state conditions, it can produce strong welds over a variety of parameters and combinations. Stokes' study is the first to present strength data for LVW.

Stokes proceeds to investigate similar weld strength data of PBT, M-PPO, and PEI welds. He concludes that all of the similar welds for these materials can create welds just as strong as the original material. Just as with PC, the most important weld parameter affecting the weld strength is the penetration. The weld penetration threshold is also 0.25 mm for these materials. The next most important parameter is the pressure, which each material responds to differently. Like PC, PBT weld strength is insensitive to the weld pressure, unlike PEI whose strength increases with pressure. M-PPO welds have highest strengths at the lowest pressures. It is unknown why PEI and M-PPO react differently to the pressure parameter, but it is assumed to be related to the material orientations. All materials were insensitive to the weld frequency, except PEI, which performed better at higher frequencies. The reasoning is unknown. Weld amplitude had the least effect on the weld strength for these materials. Past hot-plate welding testing methods and research results from other researchers are presented as well, but cannot be compared to Stokes' data due to the different welding process and materials. It is clear that each material has different optimal weld parameters, and material behavior is unpredictable which is why physical strength testing is necessary.

2.11.3 Dissimilar material vibration welds - Impact of welding parameters on the weld strength and morphology

Stokes was interested in reviewing the bonding mechanisms of linearly vibration welded dissimilar plastics, PC and PEI [14]. Stokes notes that the only other literature at the time regarding welding dissimilar materials was focused on hot-tool welding. He uses the same sample sizes and welding procedures as in his previous studies. This is a relevant study as both materials are amorphous plastics, similar to those used for external lighting lamps. Since the welding materials are different, the flange and web of the T-joint have different thermophysical properties, such as the heating rate and melting temperature. Therefore, one material may melt well before the other or in some cases, one material may melt while the other does not. This type of weld could display a steady-state phase on the time-penetration curve, but may not be the proper representation of the actual behavior. This steady-state does not have the same significance as it does with welding similar materials. Stokes refers to interchain diffusion as a critical bonding mechanism for similar material welds and concludes that this mechanism is limited when welding dissimilar materials. The PC/PEI welds can be compared to the similar PC and PEI welds at the same set of welding parameters. The past data displayed that PEI took a longer duration of time than PC to reach steady-state, while PC took longer than the PC/PEI weld other than the weld with a frequency of 120 Hz and a pressure of 2.45 MPa. Stokes is surprised by this last result and believes that it is due to the different rates of heat transfer at the weld interfaces.

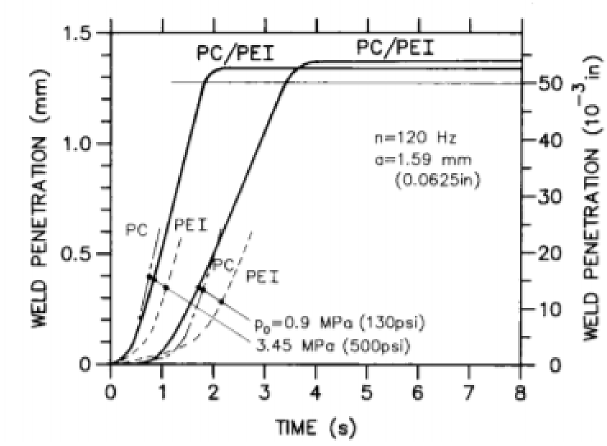

Figure 37: Penetration-time curves for PC/PEI, similar PC, and similar PEI welds at n = 120 Hz and a = 1.59 mm for two different weld pressures, P = 0.9 MPa and P = 3.45 MPa. [14]

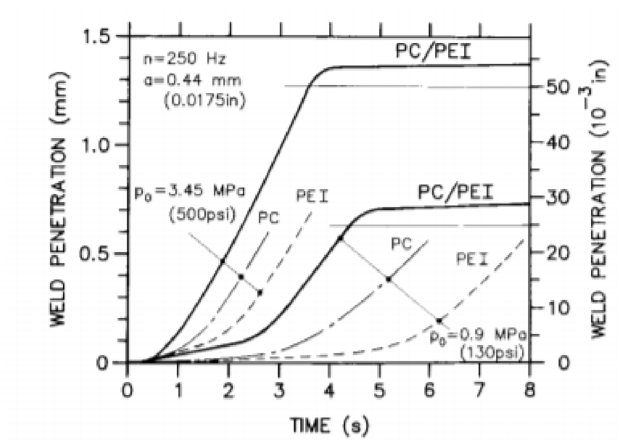

Figure 38: : Penetration-time curves for PC/PEI, similar PC, and similar PEI welds at n = 250 Hz and a = 0.44 mm for two weld pressures, P = 0.9 MPa and P = 3.45 MPa. [14]

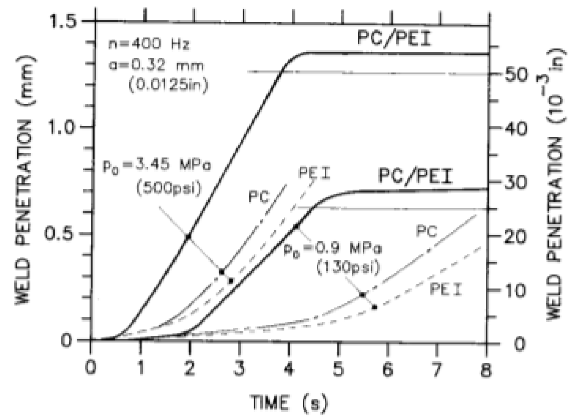

Figure 39: Penetration-time curves for PC/PEI, similar PC, and similar PEI welds at n = 400 Hz and a = 0.32 mm for two weld pressures, P = 0.9 MPa and P = 3.45 MPa. [14]

Stokes then examined weld strength data. The penetration-strength graph below displays that the weld strengths increase gradually after similar materials' weld penetration threshold of 0.25 mm. This is different from similar material welds which approach their maximum weld strength at this special weld depth, for most parameter settings. It appears that dissimilar welds continue to get stronger as the penetration increases past this value. The variability in the graph should also be noted. Welds using the same welding parameters can result in quite different weld strength values.

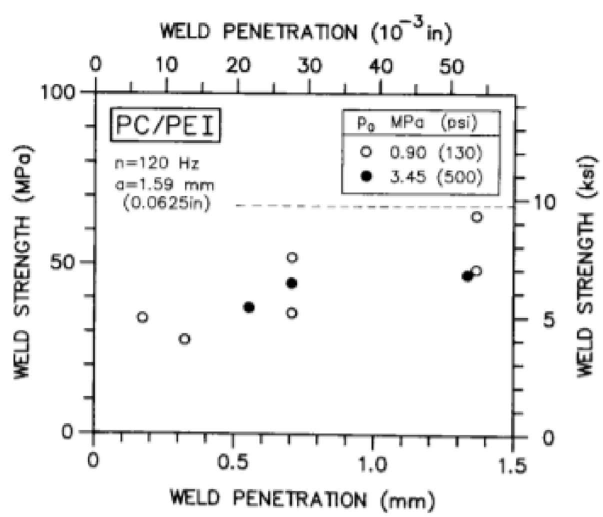

Figure 40: PC/PEI strength vs penetration with n = 120 Hz and a = 1.59 mm, for two weld pressures of P = 0.9 MPa and P = 3.45 MPa [14]

Stokes discovered that at some welding parameter settings, higher pressures yielded higher strength welds. As expected, deeper weld penetrations yielded stronger welds. Through all tests, the PC/PEI weld was found to reach a maximum strength of 95% of PC's base strength, but is assumed to be able to reach PC's strength at optimal welding parameters.

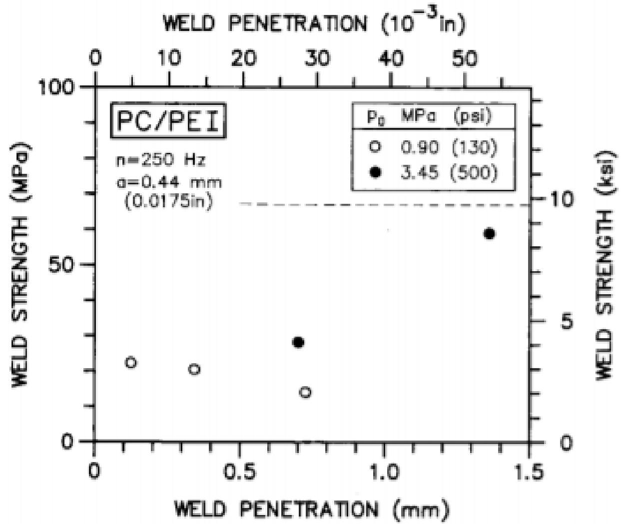

Figure 41: PC/PEI strength vs penetration with n = 250 Hz and a = 0.44 mm, for two different weld pressure, P = 0.9 MPa and P = 3.45 MPa [14]

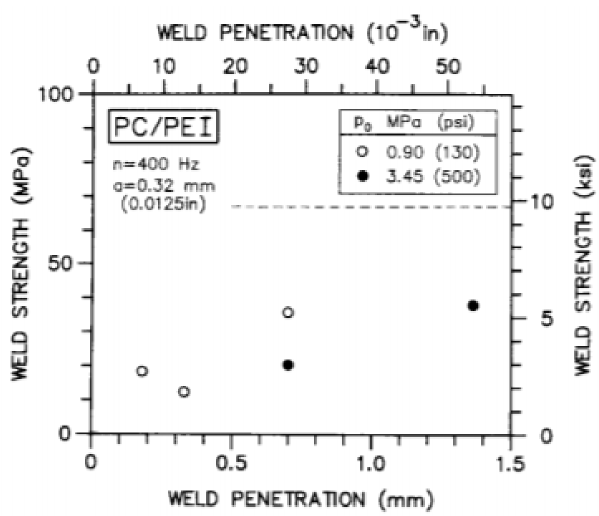

Figure 42: PC/PEI strength vs penetration with n = 400 Hz and a = 0.32 mm for two different weld pressure, P = 0.9 MPa and P = 3.45 MPa. [14]

The flash is more abundant on the PC side of the butt welds, since PC has a lower melt viscosity and glass transition temperature.

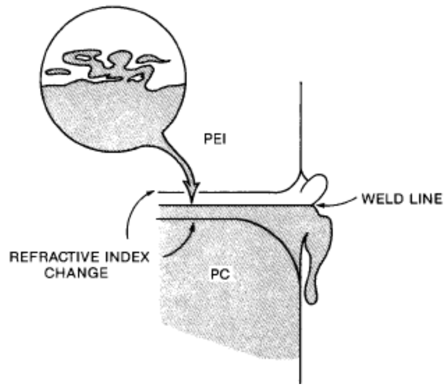

Figure 43: Diagram of the flash created for PC/PEI butt-welds, where the PC side has more flash due to its lower melt viscosity. [14]

Stokes utilized a scanning electron microscope (SEM) to study the cross sections of the weld zones [14] and view the mixing at the interface, referred to by Stokes as the interfascial morphology. More information on the sample preparation for microscopy is included in the paper [14].

The weld zones become smaller and flatter as the weld depth increases, as seen below.

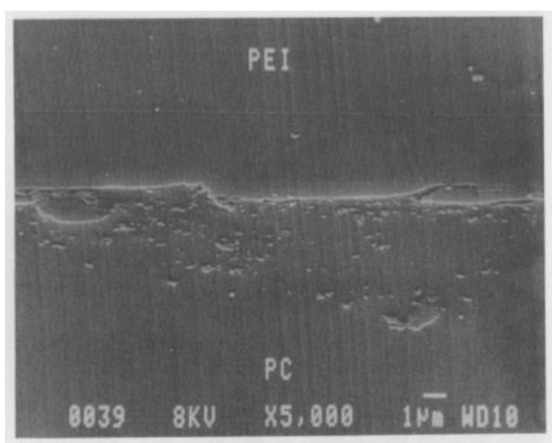

Figure 44: SEM side view (through direction of vibratory motion) displaying the planar weld line between PC and PEI at n = 400 Hz and a weld depth of 2 mm. [14]

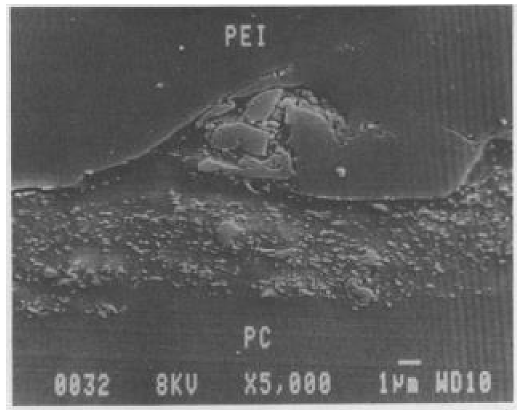

Figure 45: SEM side view (through direction of vibratory motion) displaying the planar weld line between PC and PEI at n = 400 Hz and a weld depth of 0.64 mm. [14]

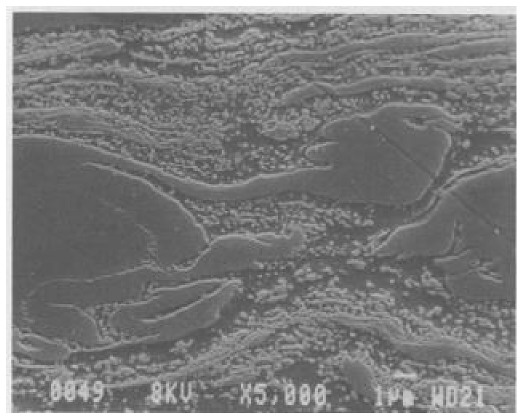

Figure 46: The top view of the cross section of a PC/PEI weld, highlighting the turbulent mixing at the weld interface. Turbulent mixing aids in creating stronger welds. [14]

Welds using higher frequency weld parameters yielded smooth fractures at the weld after pull tests, since the weld zone is less thick. Welding PC to PEI can create strong welds, comparable to the strength of the weaker base material PC. Obviously, the PC material would break first if the weld was stronger and therefore, the PC base material is the maximum strength that the welded piece can possess.

Stokes expresses that the time-penetration curve is inadequate for determining the conditions for a strong weld of dissimilar materials. Due to the dissimilar melting temperatures and viscosities, finding where the penetration rate attains a steady state is difficult. This specific material combination is dictated by PC's higher melting rate and flow rate. Therefore, to optimize the weld's parameters, more testing must be completed. It is also concluded that mixing of the materials at the weld interface due to shear forces benefits the weld strength greatly. Longer and deeper welds allow for molecular material diffusion even though the materials do not look mixed. Even though the weld zone progressively moves towards planarity with increasing weld depth and looks unmixed at the interface, the weld strength increases. This is possible due to the elimination of material defects as the material is liquified and expelled during the welding process. Stokes assumes that a second bonding mechanism, segmental diffusion, is in action to help determine the strength. Lastly, the fracture surfaces of high strength welds appear to have waves with deep ridges, which Stokes contributes to flow instabilities during welding. The ridges' depths increase with weld pressure and at low frequencies, the ridges are perpendicular to the welding vibration direction and at high frequencies, they are parallel.

Stokes then completed a similar paper vibration welding PC to PBT [14]. PBT is semi-crystalline, which is not a type of polymer of interest for this study. Microscopic assessment of semi-crystalline polymer welds is simpler. This is because semi-crystalline polymers, unlike amorphous polymers, have a spherulitic microstructure.

Due to the unpredictability of LVW strengths, physical testing is still highly recommended and most often, necessary. Stokes has expressed that researchers must work together to create a global database for the strength of plastic welds, which solidifies the importance and novelty of this chosen research.

More recently, Stokes completed strength testing of PC/ABS blends to themselves and to other polymers [34]. He summarizes that through his previous studies, it is determined that any weld penetration past the weld penetration threshold does not affect the weld strength for neat resins, blends, chopped glass-filled and particulate filled resins, and in structural foam. This is not true for welds of dissimilar materials, which continue to increase after the weld penetration threshold. This is due to the difference in melting temperatures between the materials, causing one material to melt slower than the other. Therefore, dissimilar materials that do not increase in strength after the weld-threshold can be assumed to have similar melt and viscosity characteristics. It should be noted that for dissimilar welds, even with an increase in only weld penetration, the weld strength may decrease. This is assumed to be due to variability. Stokes tested many different material weld combinations and found relative weld strengths between 83% and 20%. This shows how dissimilar welds can act unpredictably. The presentation of the data in Stokes' specific table format will be adopted and utilized in this research paper.

Tensile testing has been completed by Leblanc [18] on dissimilar nylon welds and it was found that the peak strength was found when the horizontal (flange) specimen was the material possessing the higher melting temperature. The fracture loads were not as great when the material orientations were swapped, with the higher melting temperature material as the web. The greatest weld strength between nylons yielded 29.2 MPa and swapping the material orientations dropped the strength by 26%. Nylons are not of interest for this study, but the welding of dissimilar materials is relevant. When tensile testing T-samples, Qi [15] cut welded samples T-joint and butt welded samples into multiple pieces; using some for testing and some for cross-sectional examination. The tensile tests were completed on an Instron screw driven tensile machine using a 1000lb or 20000lb load cell, with a cross-head speed of 2.54 mm/min. The ultimate tensile fracture strength is found by dividing the load applied during fracture by the weld area. If the weld strength is greater than both of the materials' base strengths, then the materials will fail before the weld does [33]. Note that the weld depth is always slightly greater than intended because of the weld pressure and leftover heat during Phase IV causing slightly further penetration [23, 32]. Using penetration as the limiting factor makes more sense than using time when the goal is to compare weld strengths. Qi found no correlation between the shape or amount of flash produced and the strength of the weld [15].

Qi remarks that the materials in a T-welded sample are assumed to be perfectly perpendicular, however this is not the case. Often, the flange becomes curved after the welding process due to residual stresses. Qi determines that the bending is in the region near the weld junction with the web. When the flange is the high temperature material, the molten material can flow out of the sides of the weld interface easily. The thin liquid layer will create small tensile forces causing slight bending. The web can penetrate further into the flange when the flange is the lower melting temperature material, making it harder for the molten material to escape. This case has a thicker liquid layer. When the material solidifies, it creates stronger tensile forces creating more drastic bending. Bending is more prominent when more liquid material freezes in the weld interface. There is a direct correlation between the flange material and the curvature.

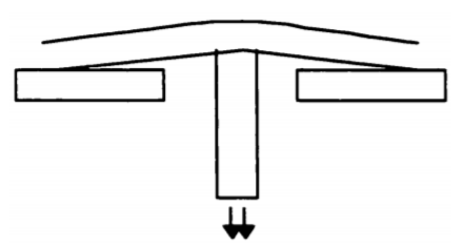

Figure 47: A welded sample with a curved flange, caused by the residual stresses during the welding process [15]

Qi explored whether flattening the flange has an effect on the strength of the weld. It is noted that a previous study stated that straightening the flange using clamps does not affect the strength results, while other researchers have experienced the opposite.

Qi shows the vibration welding process analysis and relations, as explained previously in Chapter 2.8. The relations shown can be used for regression analysis to create a numerical equation estimating the Ultimate Tensile Strength (UTS) of the weld by varying parameters for each combination of materials. Obviously there is a maximum strength each weld can possess, so these linear relations have a limit. These interpolative tools are also only achievable after physical testing of specific materials, and only predict between physically tested data points [15]. Small-scale trial and error testing to find optimal welding parameters is acceptable due to the vibration welding process' relatively low operation costs and plastic's cheap material costs. No additional research was found studying the predictive strength modelling of linear vibration welding plastics. Much more effort has been put into predictive modelling regarding ultrasonic vibration welding, focusing on metals and composites.

Pal et al. [10] also found that high weld strengths could be achieved when welding similar plastic and also dissimilar amorphous plastics at the optimal welding parameters. The amorphous materials studied are PC, ABS, and PMMA. They concluded that welding any of these amorphous plastics to PBT, a semi-crystalline plastic, resulted in large reductions of weld strength between 40% and 55%. It is believed that this occurs due to the poor bonding between the two different types of plastic, resulting in a poor quality weld.

Weglowskas and Pietras [11] studied the butt welding of dissimilar nylons and found that quality joints could be made. The influence of welding parameters was determined. Like other studies, they utilized tensile testing and microscopy examinations, utilizing light microscopy and scanning electron microscopy. The key difference between their study and this research is the materials used. The materials in this study do not have glass fibers or fillers, however the processes and experimentation procedures are similar. A Branson M-112H LVW machine was used. It was concluded that the thickness of the heat affected zone increased as the weld pressure decreased, and after strength testing on an INSTRON 4210, it was concluded that the strength also increased with decreasing weld pressure. Low pressures result in a larger heat affected zone due to the extended welding process before reaching the pre-specified depth limit, displaying as a thicker weld. The width of the weld zone increases with larger welding amplitudes and longer weld time. The maximum strength of the welds proved to be 60-75% of the base materials.

Potente and Uebbing explored the friction welding of polyamides [7]. They proved that material combinations, part geometry and welding process parameters all affect the strength of the weld and therefore, optimized welding parameters exist for each specific material combination. A parametric study was completed, using a frequency of 240 Hz, a welding pressure of 7 MPa, and an amplitude of 0.75 mm. Potente and Uebbing introduced a weld factor, the ratio of the weld strength of a specific set of weld parameters to the strength of the weaker base material. They found that increasing the amplitude helps achieve the welding limit quicker. The pair took an interesting approach regarding quality assurance. Tests were completed to simulate the mass production of a vibration welded shell component, using burst pressure as the quality determining factor. The pair proved that the quality of the joints is dependent on the processing conditions, not solely the welding conditions. It is critical to control processing conditions. This could be a potential quality assurance test adopted by OEMs.

Nonhof [35] reiterates that high clamping pressures can be counterproductive to the weld strength, causing the molten material to be squeezed out of the interface and the interface's low temperature would not be conducive for interdiffusion between the materials.

2.11.4 Common fracture mechanics for plastic welds and past predictive modelling efforts

A common fracture mechanic for plastic vibration welds occurs at the weld zone, starting at a notch located between the initial material and the heat affected zone. This is assumed to be caused by the shearing of the material, which orients the material's molecules in the direction of the flow. This weakens the weld. If the molten weld interface is cooled slowly, the molecules can become reoriented. This is enabled by low welding pressures to reduce the shear rate as well as a minimal temperature gradient. Nonhof shows different failure mechanisms for butt welded joints.

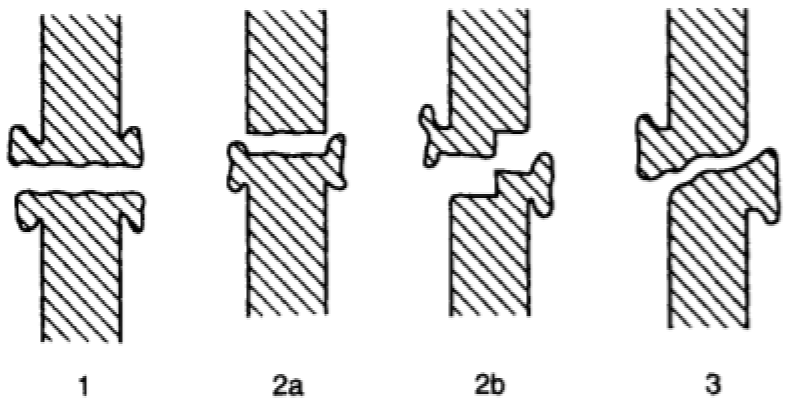

Figure 48: Failure mechanisms for butt welded joints. 1) fracture through centre of the weld, 2a/2b) fracture begins at a notch and runs in the plane between the weld zone and bulk material, 3) fracture begins at notch and continues through the material randomly. [35]

When the weld is weaker than the base material, T-joint welds will fail at the same notch area and progress through the weakest areas of the weld interface until it reaches the notch on the other side, similar to 2a in the diagram since the bottom piece would be the horizontal flange.

The material viscosity is an important variable for welding, which affects the flow patterns and heat generation. This is the reason that predictions cannot be made using logic or by extrapolating data from previous tests. Nonhof proceeds to attempt to use finite element calculations to predict the effect that the viscosity has on Phase III and Phase IV of the welding process. There are many limitations to his process since the viscosity's behavior is dependent on the amplitude and frequency, and is therefore unpredictable.

Schlarb and Ehrenstein discuss the intrinsic properties of amorphous and semi-crystalline polymer vibration welded test samples [36]. They explain that the temperature is highest at the welding interface, generating different structures in the material, annealing zones next to the melt region. The vibratory motion shears the material, deforming the macromolecules. For semi-crystalline polymers, their molecules orient along the direction of motion during the welding process. For these resulting orientations to remain, the area must be cooled quickly before they relax and realign.

High cooling rates are generally present for LVW due to the small interface area. This process is similar to how orientation occurs during injection moulding processes. This does not affect amorphous polymers.

Internal stresses are stored as potential energy until they are relaxed. At the time of the paper, only theoretical consideration had been made regarding internal stresses in welds. The authors compare the welding of plastic to that of metal. They discuss the shrinkage of plastic when cooling at the weld interface, causing an internal strain distribution. Additionally, the shrinkage processes are affected by the previously annealed zones which cool slower. These stresses will occur at the base of the weld bead. This stands for thin welded samples. These internal changes affect the overall mechanical properties, causing multi-axial stresses when loaded uni-axially perpendicular to the weld interface. These stresses are caused by the varying internal stiffness between the weld layers. The effect on the strength of weld is different for different materials and welding parameters. Schlarb and Ehrenstein have also completed impact strength testing of butt welded vibration welds outlined in a separate paper [37].

Benham and Foss [38] studied the creep of thermoplastics under uniaxial tensile loading to test correlation procedures. Creep can be predicted through uniaxial testing. Decades later, Patham and Foss [23] outline different physical models of the phenomenology of linear vibration welding, which can hopefully be of use for creating linear vibration welding predictive models in the future.

Many industrial welders use the Handbook of Joining Plastics [4] as a set of rules for welding. This should simply be used as a guideline for new plastic welders since information is given on few materials. It can be used as a reference to review general topical knowledge of plastic welding and materials.

2.11.5 Environmental Stress Cracking

Environmental stress cracking (ESC) is a topic of interest after this research project. The end pieces of each 5 in welded sample are being saved for future ESC testing. One end will be annealed and their resistance to environmental stressors will be evaluated. Jansen reviews the basics of ESC [39]. ESC is when a chemical agent degrades a plastic under stress and was responsible for approximately 25% of plastic part failures at the time of the paper's publication. The chemical reaches the molecular structure and inhibits the molecular forces keeping the polymer chains together. The paper also outlines the characteristics and elements of ESC, resin types, chemical agents and stress effects. Although an in-depth understanding of ESC is not necessary for this study, this topic will be relevant for future developments on this project.

CHAPTER 3: MATERIALS AND EXPERIMENTAL PROCEDURE

3.1 LVW Sample Preparation

The plastic housing plaques were received from suppliers with dimensions of 4 in by 6 in, and a thickness of 0.125 in (3.175 mm). This sample complies with the American Society for Testing and Materials (ASTM) standard (ASTM Standard D638) for tensile testing plastics, which states that test samples must be between 1 mm and 14 mm in thickness [21].

The final size of the lens and houses sample pieces needed to be 5 in by 2 in. A singular plaque is shown below, marked to display where the bandsaw cuts will take place, creating two usable housing pieces.

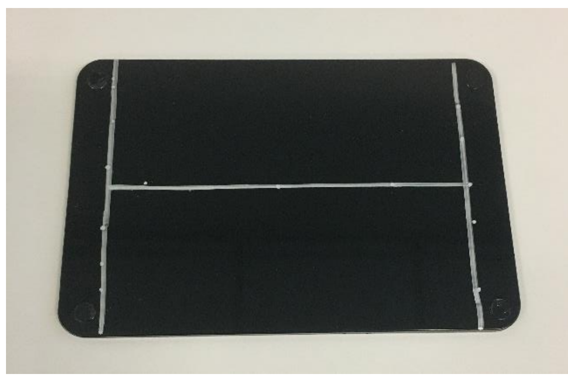

Figure 49: A housing plaque received from suppliers with marks designating where it will be cut to create housing sample pieces for the welds.

Each plaque would be cut to sample size using a bandsaw. The chosen welding supplier is Branson. Sample size was chosen to accommodate for the sizing constraints presented by their welding machine. Also when choosing the size that the plaques needed to be cut down to, it was crucial to ensure that three tensile testing samples could be taken from them, and that there would be enough room for the tensile testing grip to secure the sample. It is noted that the 2 in x 5 in size is a constraint of the welding supplier’s machine. The materials displayed through trial welds that taller lens pieces resonated during welding, creating the lens to slide sideways instead of penetrating at the interface, creating an imperfect and non-perpendicular weld, as shown below:

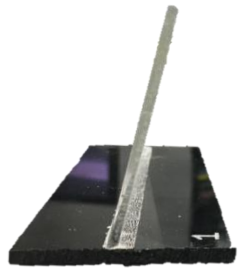

Figure 50: A crooked weld caused by improper sizing of the lens sample piece

Lens materials require an extra step before the welding process. The lens plaques needed to be cut with a bandsaw and then machined to 2in by 5in. Stokes [12] and others machined their sample pieces [40]. It is important that the sides cut by the bandsaw (one being the weld interface) are parallel to each other, facilitating a proper welding interface. This is a constraint of using the specific welding machine, and will be explained in the welding process section. The machine process ensured parallel sides of the lens samples. Precautions were taken and tests trials were completed to find machining settings that would not crack each lens material.

Figure 51: The rectangular lens plaques are machined to ensure the longitudinal sides are parallel. This aids in facilitating close contact during the welding process.

Test runs and improper welds also needed to be accounted for at the welding trials. Therefore, extra pieces were cut. Well over 540 plaques, sized 2 in by 5, were created to ensure that all of the proper welds could be made.

3.2 LVW Welding Process

The T-joint vibration welding of samples was completed at Branson Ultrasonics, in Sterling Heights, Michigan. The samples were welded on Branson's own M-102H linear vibration welding machine. Similar to the vibration welding machine used by Stokes and others [12, 13, 32, 41, 40, 42, 15], the welding parameters can be independently controlled. For this study, all welds were completed using a frequency of 236 Hz, with the weld penetration as the process control variable, as recommended by Stokes [32].

The opaque housing piece sits on the base, which vibrates during the welding process. The transparent lens plaque is loaded and fixed into the upper fixture of the machine and then lowered to meet the bottom housing plaque. The housing sits on sandpaper and is under pressure during the welding to ensure it does not move out of place. Once aligned, the necessary pressure is applied and the bottom plaque oscillates at the given frequency until the weld depth is reached. The welding machine setup is displayed below:

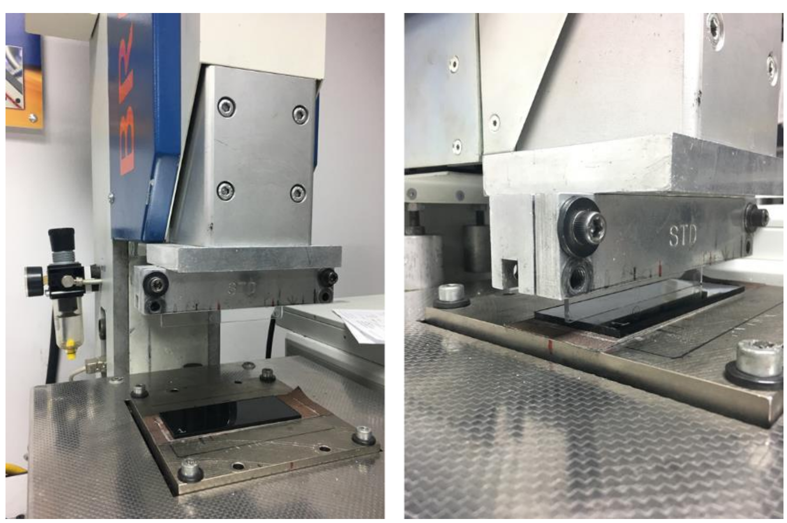

Figure 52: (Left) The lens is loaded into the upper fixture and the housing is placed below it. Right: The upper fixture lowers and the lens and housing meet at the weld interface.

As shown, the transparent lens piece is loaded into the top portion of the machine before it is lowered to create the weld. This is why it was so important that the lens' long sides were parallel. The top side aligns the piece into the machine. Therefore, if the sides are not parallel, the lens will come down and not be in full contact along the weld interface. This would result in an impartial weld, which is insufficient for an application for a system that needs to be hermetically sealed.

3.3 Tensile Test Sample Preparation

Using a waterjet to cut the samples was considered for this stage. A waterjet fixture was created in CATIA software. Upon testing, it was deemed too complicated for the initial cuts, and also displayed to be very time consuming as each singular piece would need to be placed and fixed before the cuts, and removed after the cuts. This was not ideal due to the large number of samples. It was also proving difficult to cut through the depth of the samples, while also creating cracks.

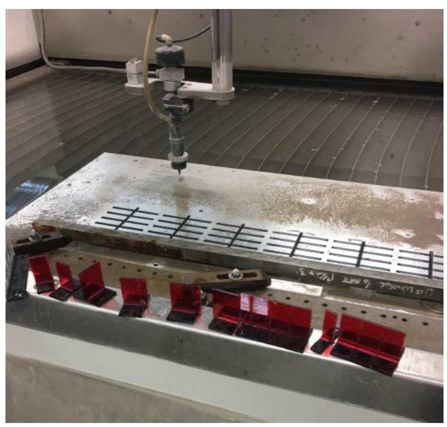

Figure 53: The waterjet fixture with failed sample cuts.

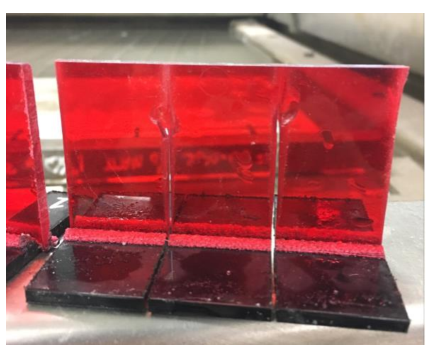

Figure 54: A failed sample cut using the waterjet method.

Therefore, instead of using a waterjet, each welded sample was then cut into three separate 1 in pieces using the bandsaw again. Qi [15] also cut down longer welded pieces to create more samples for tensile testing.

It is realized that using the bandsaw is not the most precise method to cut the weld samples, especially when basing the strength off of the small weld interface area. Bandsaws also remove material while cutting and will overcut the desired size. This distance will vary much more than the thickness of the samples, which vary from the tolerance of the injection molding manufacturing process. Therefore, each sample was remeasured after using a caliper, with an accuracy of +/- 0.02 mm, to use more accurate measurements when calculating the interfacial area. The weld strength value is sensitive due to the differences in area between samples.

Figure 55: A weld sample's section interface

These cut pieces were labelled and sorted into categorized bags. The labelling process kept track of the material combination, weld parameters, and the strength of each welded sample. The reference/labelling notation is described fully in Chapter 3.7.

Figure 56: (Left) A 5 inch weld sample. (Right) Three samples taken from the 5 in samples.

Each sample would eventually be tensile tested. This would give three strength values for each set of welding parameters, where the average could be calculated. The end pieces of the 5 in long samples were saved for future environmental stress cracking testing outside of the scope of this project.

3.4 Manufacturing Tensile Test Fixture

A fixture was manufactured to hold the welded sample during testing. A computer animated design model was created in CATIA and was wirecut from an aluminum block. Knurling was added to the fixture interface where the testing machine's grips would clamp. Adequate room was left for the sample so it could be easily inserted and removed, also accounting for any flash buildup from the welding process.

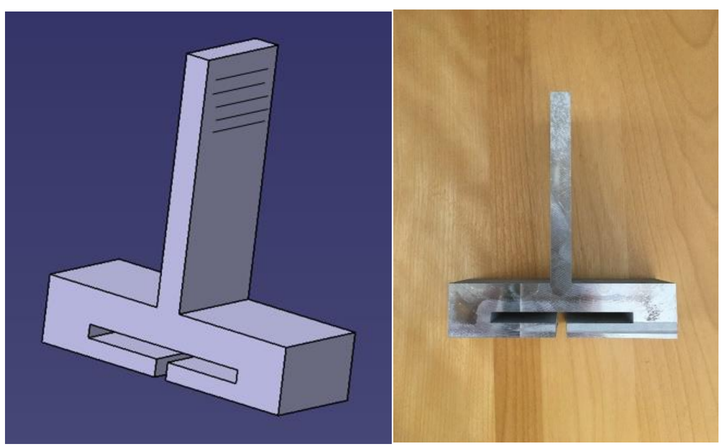

Figure 57: (Left) The tensile test fixture CAD design. (Right): The wirecut aluminum test fixture manufactured.

Figure 58: Grip texture added to the fixture.

3.5 Tensile Testing

The ASTM D638-03 and ISO 527-2 test standards for tensile properties of plastics were consulted [21, 43]. The use of ASTM or ISO standard varies by geographic region. The ASTM D638 standard is typically used in North America, whereas the ISO 527 standard is typically used in in Europe and Asia [21], excluding China. The ASTM standard was used since the project's tensile testing was completed in North America, at the University of Windsor. Additionally, the ASTM standard notes that itself and ISO 527 are technically equivalent. The ASTM standard outlines how to execute tensile tests to find the tensile properties of plastics. With this range of thicknesses, for data results to be compared, material samples used must be the exact same thickness. Test data achieved using this standard is pertinent and can be used for engineering applications, but should not be used for applications where the environment is drastically different from test conditions or load-time scales [21].

The testing machine was an MTS Criterion Model 45 Electromechanical Universal Test System (UTS) with a constant-rate-of-crosshead-movement type, as required by the ASTM standard. There is not an official standard for tensile testing T-joint samples. The chosen crosshead speed is 2.54 mm/min, as used by Qi [24]. The ASTM standard and advisors were also consulted. This was verified as an appropriate testing speed to use for all materials [21]. This machine has a fixed member (lower), a moveable member (upper), and grips to secure the test specimen. The loads are recorded during testing on the attached computer monitor [21]. A 50 kN load cell was used with a sensitivity of 2.099 mV/V. The machine was verified to be calibrated before every tensile test session. Metal shims can be placed between the sample flange and the custom test fixture during testing to decrease any bending.

Figure 59: A sample loaded in the aluminum test fixture and clamped by the UTS grips.

3.6 Materials of Interest – Housing and Lens

The amorphous materials to be studied are used for automotive lighting applications, specifically for lamp systems. Lamps consist of a housing and a transparent lens, which are vibration welded together.

Figure 60: Thermoplastic lighting housing. [6]

Figure 61: Thermoplastic lighting lens. [6]

Five lens materials and six housing materials, which are currently used in production, are studied. The general parent materials of interest are:

- Acrylic (PMMA), a transparent thermoplastic. It is generally a cheaper alternative than PC, but it is typically lower temperature and shatter resistant. It is also weather resistant. Acrylic has replaced glass in many applications since it is light and does not shatter hazardously like glass.
- Polycarbonate (PC), used for its stiffness, hardness, and toughness. Typically, it has an advantageous impact strength and is temperature resistance.
- Acrylonitrile Styrene Acrylate (ASA), also known as acrylic-styrene-acrylonitrile, known for its toughness and rigidity, and weather resistance.
- Acrylonitrile Butadiene Styrene (ABS), used for its cost-effectiveness. ABS is can be modified to improve impact resistance and heat resistance, but does not outperform PC and PMMA. Without modification, it has the lowest temperature and impact capabilities. Its weatherability is poor compared to ASA.

Blending these polymers can enhance properties, giving new opportunities for use in application. Additionally, different grades of each polymer can be used which may have properties that may be beneficial for specific applications.

The lens materials used in this study are summarized below in Table 2:

Table 2: Lens materials for parametric study

Reference ID	*Material*	*Information*	*Strength (MPa)*	*Vicat Softening Point (°C)*
A	PMMA	High heat PMMA	70	104
B	PMMA	Light impact PMMA	63	102
C	PMMA	High impact PMMA	48	90
D	PMMA	Higher heat PMMA	70.3	116
E	PC	High-clarity PC	62	141

Note that a secondary material supplier provided the lens material for some 'A' weld combinations due to time constraints of the project and availability of the product. Additionally, slightly different lens thicknesses are used during testing due to the large number of plaques needed in a short time frame.

A lens thickness of 2.5 mm is used for the following weld combinations:

i. A1, A2, A3 (1,2,7-18), A4(7-18), A5 (7-18)
ii. B1(1-12), B2(1-12), B3(1-12), B4(1-12), B5(1-12), B6(1-12)

A lens thickness of 3 mm is used for the following weld combinations and samples:

i. E1-6

A lens thickness of 3.2 mm is used for the following weld combinations and samples:

i. A3(3-6), A5(1-6), A4(1-6), A6
ii. B1(13-18), B2(13-18), B3(13-18), B4(13-18), B5(13-18), B6(13,14)
iii. C1-6
iv. D1-6

The housing materials used in this study are summarized below in Table 3:

Table 3: Housing materials for parametric study

Reference ID	*Material*	*Information*	*Strength (MPa)*	*Vicat Softening Point (°C)*
1	PC	General grade PC	68	154
2	PC+ABS	High impact / high heat	56	127
3	ABS+PC	General purpose blend	44	111
4	ABS	General purpose	36	98
5	ASA	High heat ASA	33	98
6	ASA+PC	Higher-heat, impact, excellent weatherability	62.1	113

The material suppliers for this study are Evonik, Arkema, and Sabic. It was necessary that Evonik and Arkema both provided comparable grades due to time constraints of this project. Both were used for this study, as specified in the following section. For confidentiality of the research, the material grades researched are omitted from this document. It is verified that their strengths have been determined using the ASTM standards.

3.7 Welding Process Matrix

For reference, each confidential material is given a reference character. Lens materials are given letters and housing materials are given numbers, as shown below.

Table 4: Lens Reference ID Table

Reference ID	Material
A	PMMA
B	PMMA
C	PMMA
D	PMMA
E	PC

Table 5: Housing Reference ID Table

Reference ID	Material
1	PC
2	PC+ABS
3	ABS+PC
4	ABS
5	ASA
6	ASA+PC

Each lens grade is welded to each housing grade. The material combinations are shown below:

Table 6: Material Combinations

Lens/Housing	***1***	***2***	***3***	***4***	***5***	***6***
A	*A1*	*A2*	*A3*	*A4*	*A5*	*A6*
B	*B1*	*B2*	*B3*	*B4*	*B5*	*B6*
C	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*
D	*D1*	*D2*	*D3*	*D4*	*D5*	*D6*
E	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*

Adopting this naming convention allows specific material combinations to be referenced, (i.e. A1). Each material combination is welded at a set of varying welding parameters. There are three welding parameters being studied: pressure, weld amplitude, and weld penetration at the interface. Different levels of each parameter are chosen based on the range of their values currently used in the manufacturing process:

- Pressure (1, 3, 5 MPa)
- Weld amplitude (1.78mm [High] / 1.5mm [Low])
- Weld penetration at interface (0.3, 0.5, 0.7 mm)

The methodology is explained further. Regarding welding parameters, three pressure settings (1 MPa, 3 MPa, 5 MPa), two amplitude settings (High = 1.5 mm, Low = 1.78 mm), and three weld depth settings (0.3 mm, 0.5 mm, 0.7 mm) yields 18 different testable combinations. These are values chosen based on common parameter levels used in the manufacturing of automotive external lamps. Since LVW of dissimilar materials is unpredictable, different values are examined. A range of high and low parameter values is used so their effects can later be examined. Each combination of parameters is tested to ensure interactions are not masked. It is already known that the LVW data will be volatile due to unforeseen welding parameter interactions. Therefore, it is important to test all possible combinations of materials and weld parameters. All 18 variations of the welding parameters are shown below:

Table 7: Weld parameter combinations using a pressure of 1 MPa

Pressure (1 MPa)					
Amplitude (High)			Amplitude (Low)		
Depth (0.3mm)	Depth (0.5mm)	Depth (0.7mm)	Depth (0.3mm)	Depth (0.5mm)	Depth (0.7mm)

Table 8: Weld parameter combinations using a pressure of 3 MPa

Pressure (3 MPa)					
Amplitude (High)			Amplitude (Low)		
Depth (0.3mm)	Depth (0.5mm)	Depth (0.7mm)	Depth (0.3mm)	Depth (0.5mm)	Depth (0.7mm)

Table 9: Weld parameter combinations using a pressure of 5 MPa

Pressure (5 MPa)					
Amplitude (High)			Amplitude (Low)		
Depth (0.3mm)	Depth (0.5mm)	Depth (0.7mm)	Depth (0.3mm)	Depth (0.5mm)	Depth (0.7mm)

A reference system was necessary to be able to label each weld to identify its welding parameters. This numbering will be called the Trial ID. The Trial ID parameters are consistent for each weld material combination (for recording purposes) to allow them to be compared.

Table 10: Numeric reference system for weld parameter combinations

Trial ID	Pressure (MPa)	Amplitude (mm)	Depth (mm)
1	1	1.78	0.3
2	1	1.78	0.5
3	1	1.78	0.7
4	1	1.5	0.3
5	1	1.5	0.5
6	1	1.5	0.7
7	3	1.78	0.3
8	3	1.78	0.5
9	3	1.78	0.7
10	3	1.5	0.3
11	3	1.5	0.5
12	3	1.5	0.7
13	5	1.78	0.3
14	5	1.78	0.5
15	5	1.78	0.7
16	5	1.5	0.3
17	5	1.5	0.5
18	5	1.5	0.7

Below is a table displaying the weld trial combinations for welding Lens A to Housing 1 only. This table is repeated for each lens to housing combination. Note all welds were completed using a frequency of 236 Hz.

Table 11: Full weld table for weld material combination A1

Lens	Housing	Trial ID	Pressure (MPa)	Amplitude (mm)	Depth (mm)
A	1	1	1	1.78	0.3
A	1	2	1	1.78	0.5
A	1	3	1	1.78	0.7
A	1	4	1	1.5	0.3
A	1	5	1	1.5	0.5
A	1	6	1	1.5	0.7
A	1	7	3	1.78	0.3
A	1	8	3	1.78	0.5
A	1	9	3	1.78	0.7
A	1	10	3	1.5	0.3
A	1	11	3	1.5	0.5
A	1	12	3	1.5	0.7
A	1	13	5	1.78	0.3
A	1	14	5	1.78	0.5
A	1	15	5	1.78	0.7
A	1	16	5	1.5	0.3
A	1	17	5	1.5	0.5
A	1	18	5	1.5	0.7

Consistently using this table for each material combination allows the adoption of a naming convention to reference not only the material combination, but also the weld parameters. For example, a weld between lens A and housing 1, with the settings from Trial ID 18, can now be simply referred to as “A1-18”. And since each of the three welded samples for each material combination were also labelled (A, B, or C), we can refer to a specific singular sample if needed (i.e. A1-18C).

Figure 62: Sorted welded samples at a weld trial

In summary, each material lens is welded to each material housing, and each combination of lens to housing has a welding parameter set of 18 different combinations, involving the weld depth, weld pressure, and weld amplitude. Therefore, each material combination (A1, A2, A3… etc.) is welded under each of the 18 weld parameter combinations. Additionally, three samples from each combination is tested. That leads to 1620 individual welded samples and therefore, 1620 tensile tests in total.

CHAPTER 4: STRENGTH TESTING RESULTS AND DISCUSSION

The ASTM D638 standard defines the tensile strength, also known as the ultimate strength, as the maximum load on the test sample by the average area of the original cross section, reported to three significant digits. In this specific case, the area of interest is the weld interface [21]. The stress-strain curve of sample A from the weld combination E1-2 is shown below, with the location of the ultimate strength outlined:

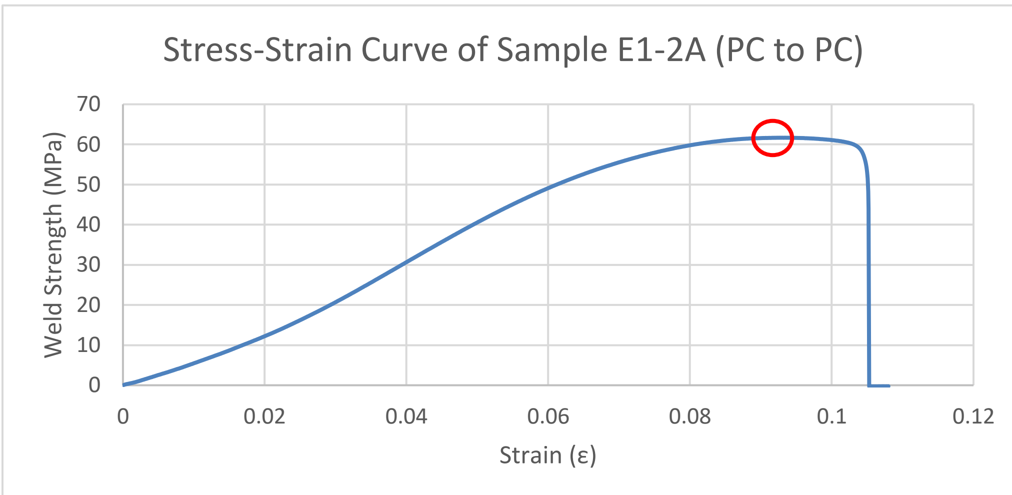

Figure 63: Stress-strain curve of sample E1-2A, with the location of the ultimate strength identified. This sample is PC welded to PC with welding parameters of a = 1.78 mm, d = 0.5 mm, P = 1 MPa.

Stokes notes that tensile samples may neck during tensile testing, resulting in the true stress at failure being larger than the recorded stress using the original cross sectional area [32]. This point is the maximum stress that the material combination weld can endure before eventually leading to a failure. Any welded samples that broke during transportation or during sectioning with the bandsaw were considered insufficient welds. Blatant strength outliers are ignored, assumed to be weakened by incorrect sample processing, defects, cracks or during international transport.

Three samples of each scenario were tested so slight variabilities are expected, but general expected trends should hold and be considered. Stokes' previous study of many dissimilar material welds shows the slight variations that may occur [34].

The strength results will be presented below graphically using the weld factor, f_w. The weld factor is the ratio of the weld strength to the strength of the weaker parent material involved in the weld [7, 32]. This factor therefore ranges from 0-1 in theory. In reality, it can reach a value greater than one since the given strength of materials on datasheets is an average value. The weld factor will be the measure of weldability. Each scenario's optimal welding parameters (from the tested values) can easily be determined by evaluating the weld factor or the weld strength. The optimal parameters correspond to the best performing welds, based on their strength achieved from tensile testing.

Each material combination's strength is also displayed as a function of its weld depth, which previous researchers have found as the most important welding parameter. Irregularities can easily be identified from this graph and can be explored further. Trends of increasing strength with increasing weld depth occur for dissimilar materials, caused by their difference in melting temperature. Dissimilar materials that have a constant strength after a weld penetration threshold can be assumed to have similar melt and viscosity characteristics, acting as similar materials.

The specific weld strength results for each material combination are displayed and discussed in the following sections and the overall trends and results are summarized in Chapter 5.

4.1 Lens A (PMMA) Combinations - Weld Strength Testing Results

4.1.1 Tensile Test Results – A1 (PMMA to PC)

Material A is PMMA and material 1 is PC. The strength testing results for 236 Hz Vibration Welds of Lens Material A to Housing Material 1 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 12. The weld factors are based off of Material 1's tensile strength, 68 MPa.

Table 12: Strength of 236 Hz Vibration Welds of Lens Material A (PMMA) to Housing Material 1 (PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations.

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	16.185	0.238
1	0.5	20.965	0.308
1	0.7	15.043	0.221
3	0.3	7.744	0.114
3	0.5	19.891	0.293
3	0.7	6.541	0.096
5	0.3	8.517	0.125
5	0.5	0.031	0.000
5	0.7	11.571	0.170

The strength testing results for 236 Hz Vibration Welds of Lens Material A to Housing Material 1 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 13.

Table 13: Strength of 236 Hz Vibration Welds of Lens Material A (PMMA) to Housing Material 1 (PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations.

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	10.422	0.153
1	0.5	7.175	0.106
1	0.7	24.825	0.365
3	0.3	11.122	0.164
3	0.5	7.926	0.117
3	0.7	14.387	0.212
5	0.3	5.991	0.088
5	0.5	9.880	0.145
5	0.7	6.212	0.091

The maximum weld strength achieved is 24.825 MPa, corresponding to a weld factor of 0.365. This is accomplished with a welding pressure of 1 MPa, a depth of 0.7 mm, and an amplitude of 1.5 mm.

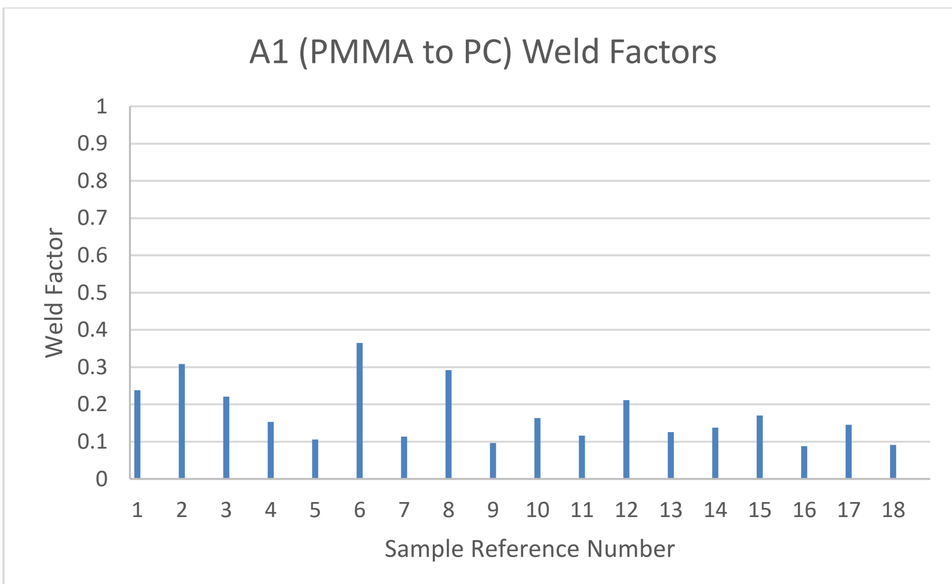

Figure 64: A1 (PMMA to PC) Weld Factors. Weld 6 achieved the highest weld factor of 0.365 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The weldability of these materials is mediocre, reaching a maximum weld factor of 0.365 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The results appear to be quite random and inconsistent in which sample achieves the strongest point, regarding pressure, weld depth, or amplitude. The material combination appears to be insensitive to weld depth, as shown in the previous tables. Although the general trend of the strength data does not increase with weld penetration, the graph below does display that the maximum achievable strength increases with weld depth.

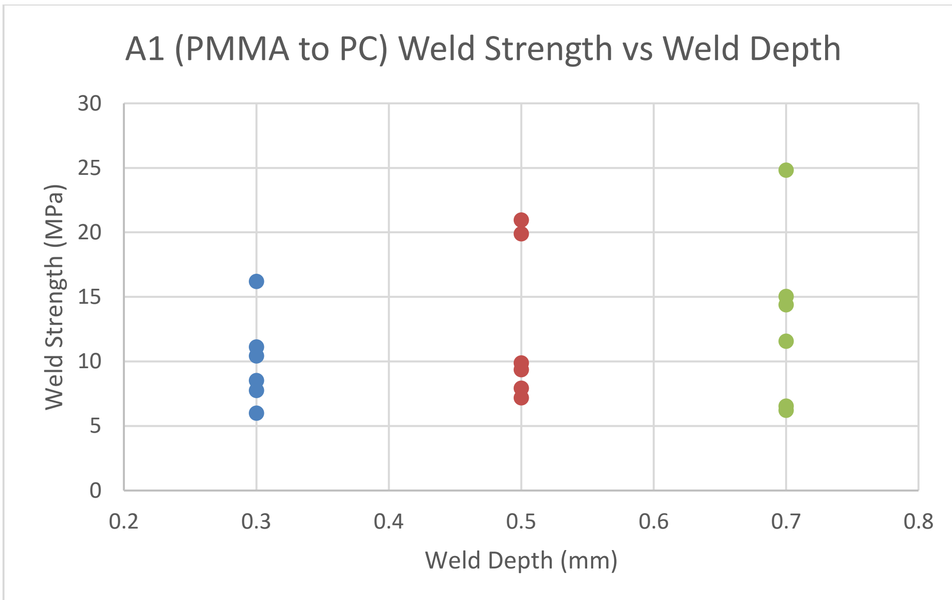

Figure 65: A1 (PMMA to PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 24.825 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The weld strength increases with increasing weld depth.

This strength trend is common for dissimilar material welds, whose strengths continually increase with penetration instead of passing a general weld threshold and maintaining a maximum weld strength.

4.1.2 Tensile Test Results – A2 (PMMA to PC+ABS)

Material A is PMMA and material 2 is a PC+ABS blend. The strength testing results for 236 Hz Vibration Welds of Lens Material A to Housing Material 2 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 14. The weld factors are based off of Material 2’s tensile strength, 56 MPa.

Table 14: Strength of 236 Hz Vibration Welds of Lens Material A (PMMA) to Housing Material 2 (PC+ABS) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations.

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	8.630	0.154
1	0.5	9.886	0.177
1	0.7	14.687	0.262
3	0.3	4.532	0.081
3	0.5	9.099	0.162
3	0.7	11.415	0.204
5	0.3	3.029	0.054
5	0.5	1.630	0.029
5	0.7	2.785	0.050

The strength testing results for 236 Hz Vibration Welds of Lens Material A to Housing Material 2 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 15.

Table 15: Strength of 236 Hz Vibration Welds of Lens Material A (PMMA) to Housing Material 2 (PC+ABS) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations.

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	9.900	0.177
1	0.5	10.075	0.180
1	0.7	17.588	0.314
3	0.3	5.682	0.101
3	0.5	4.928	0.088
3	0.7	8.364	0.149
5	0.3	2.983	0.053
5	0.5	5.347	0.095
5	0.7	3.323	0.059

For pressures of 1 MPa and 3 MPa, the strength increases with depth.

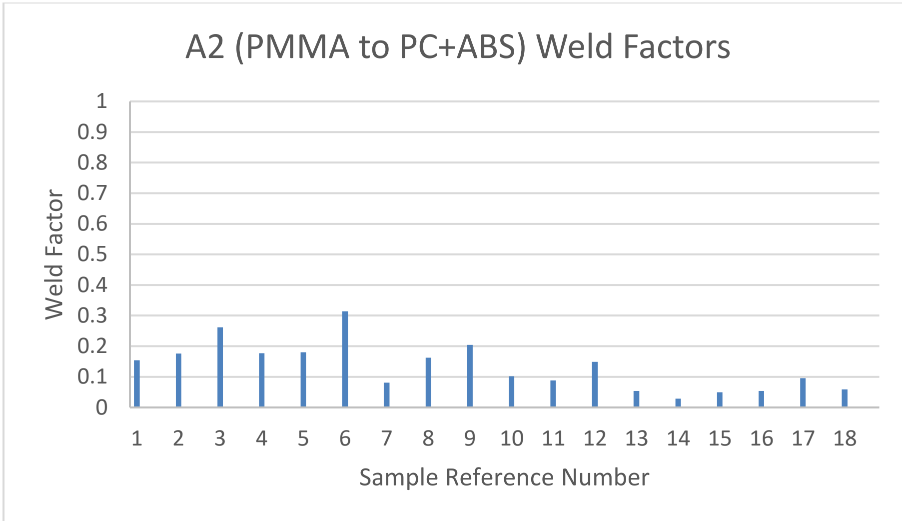

Figure 66: A2 (PMMA to PC+ABS) Weld Factors. Sample 6 achieved the highest weld factor of 0.314. Weld 6 achieved the highest weld factor of 0.365 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The sixth sample is observed to have the highest weld strength, giving optimal welding parameters of a pressure of 1 MPa, a weld depth of 0.7 mm, and a weld amplitude of 1.5 mm. The maximum weld strength achieved is 17.558 MPa. The greatest weld factor achieved is 0.314. These materials demonstrate very poor material compatibility.

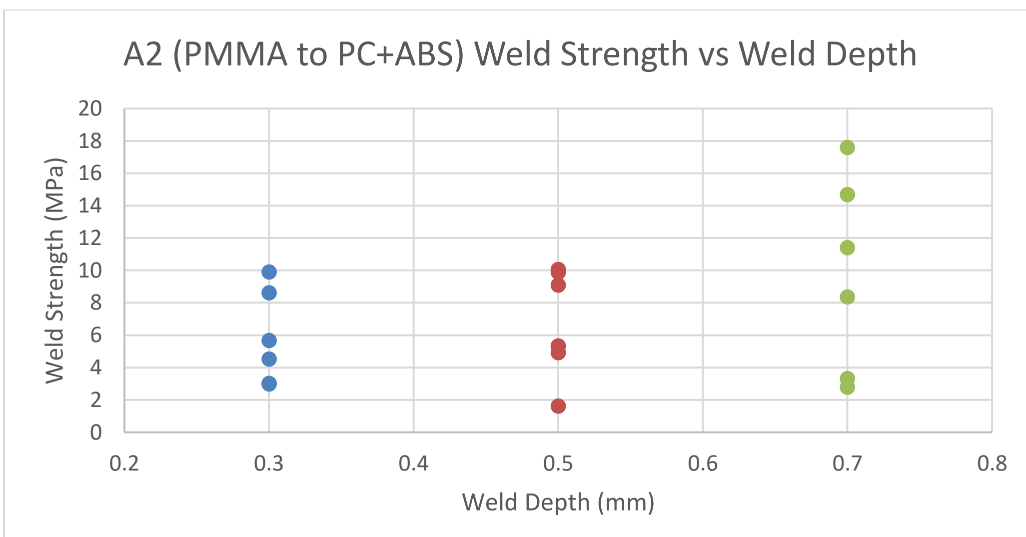

Figure 67: A2 (PMMA to PC+ABS) Weld Strength vs Weld Depth. The maximum weld strength achieved is 17.588 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The weld strength increases with increasing weld depth. An increase in weld depth increases the weld strength greatly. The recommended minimum weld depth is greater than 0.5 mm.

The strength does not increase between 0.3 and 0.5 mm depths, but 0.7 mm deep welds almost double the overall achievable strength. It is clear that the weld strength decreases with increasing pressure for both the high and low amplitudes tested.

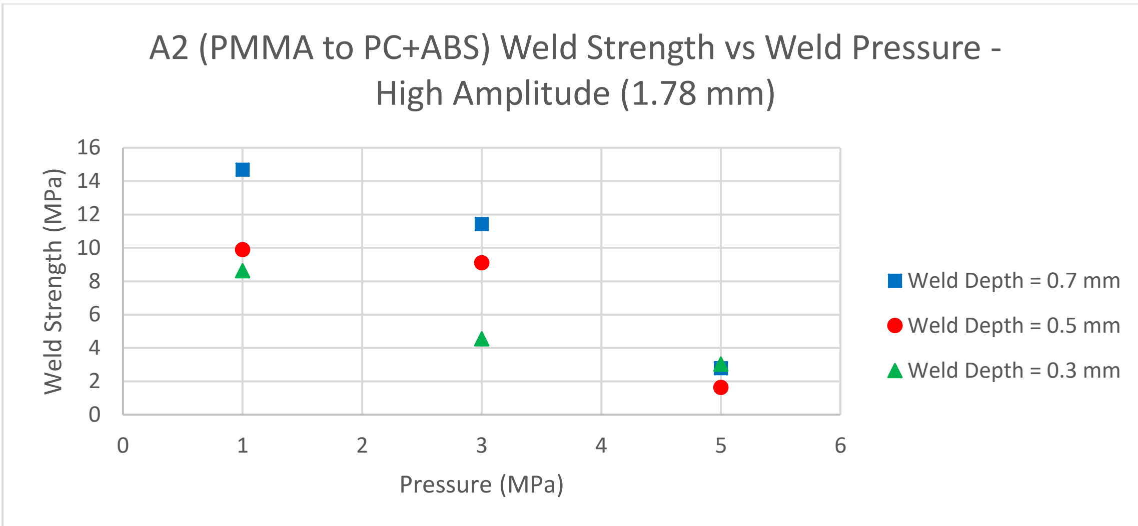

Figure 68: A2 (PMMA to PC+ABS) Weld Strength-Pressure for High Amplitude (1.78 mm) with varying weld depth. For this amplitude, the weld strength clearly decreases with increasing weld pressure.

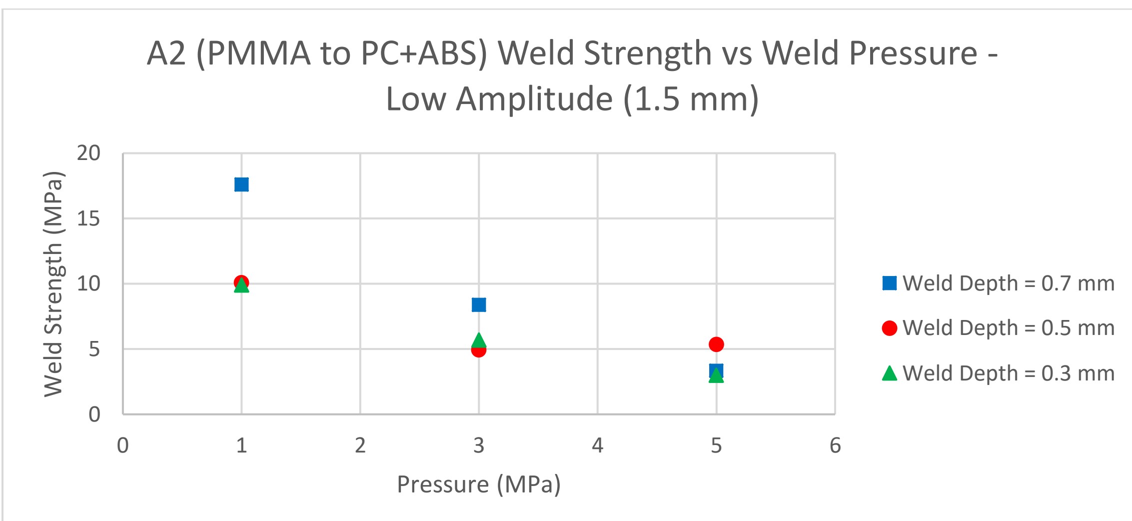

Figure 69: A2 (PMMA to PC+ABS) Weld Strength-Pressure for Low Amplitude (1.5 mm) with varying weld depth. For this amplitude, the weld strength clearly decreases with increasing weld pressure.

4.1.3 Tensile Test Results – A3 (PMMA to ABS+PC)

Material A is PMMA and material 3 is an ABS+PC blend. The strength testing results for 236 Hz Vibration Welds of Lens Material A to Housing Material 3 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 16. The weld factors are based off of Material 3's tensile strength, 44 MPa.

Table 16: Strength of 236 Hz Vibration Welds of Lens Material A (PMMA) to Housing Material 3 (ABS+PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	12.659	0.288
1	0.5	13.249	0.301
1	0.7	19.952	0.453
3	0.3	6.375	0.145
3	0.5	8.994	0.204
3	0.7	12.693	0.288
5	0.3	4.796	0.109
5	0.5	9.033	0.205
5	0.7	13.737	0.312

The strength testing results for 236 Hz Vibration Welds of Lens Material A to Housing Material 3 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 17.

Table 17: Strength of 236 Hz Vibration Welds of Lens Material A (PMMA) to Housing Material 3 (ABS+PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	14.179	0.322
1	0.5	20.997	0.477
1	0.7	20.175	0.459
3	0.3	8.805	0.200
3	0.5	8.520	0.194
3	0.7	9.188	0.209
5	0.3	5.181	0.118
5	0.5	4.991	0.113
5	0.7	11.806	0.268

At low pressure, the low amplitude welds consistently create stronger welds than using a higher amplitude.

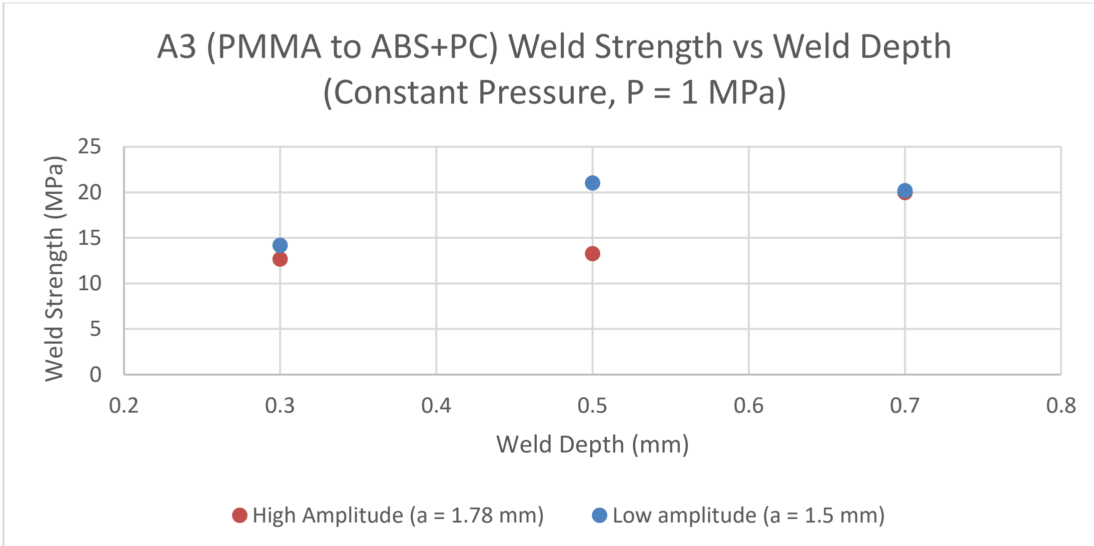

Figure 70: A3 (PMMA to ABS+PC) weld strength vs weld penetration for both amplitudes at low pressure (P = 1 MPa). The weld strength increases with increasing weld depth.

Additionally, the weld strengths generally decrease with increasing pressure for both low and high amplitude welds.

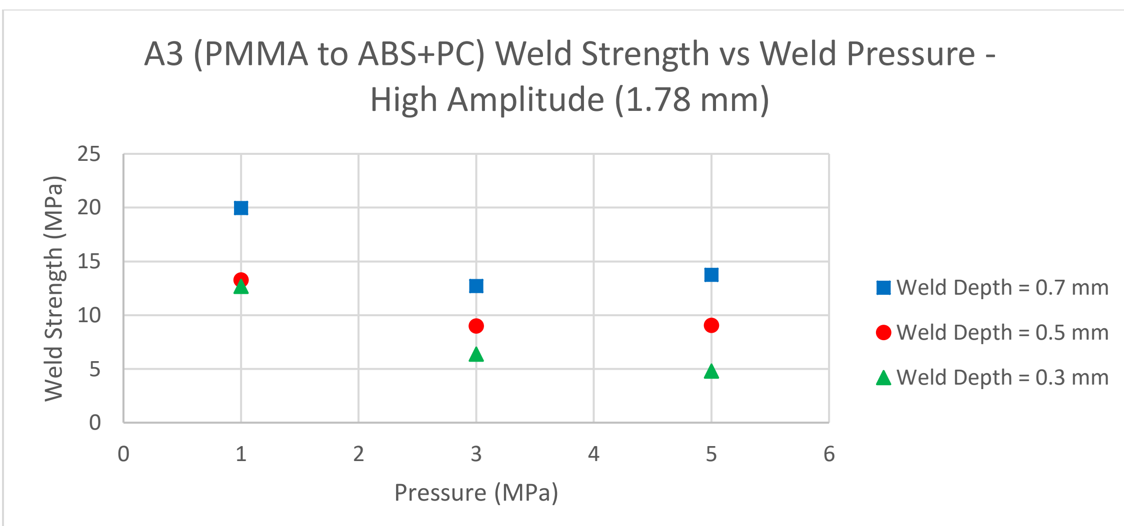

Figure 71: A3 (PMMA to ABS+PC) weld strength vs weld pressure at high amplitude for different weld depths. The weld strength generally decreases with increasing pressure at the high welding amplitude, a = 1.78 mm.

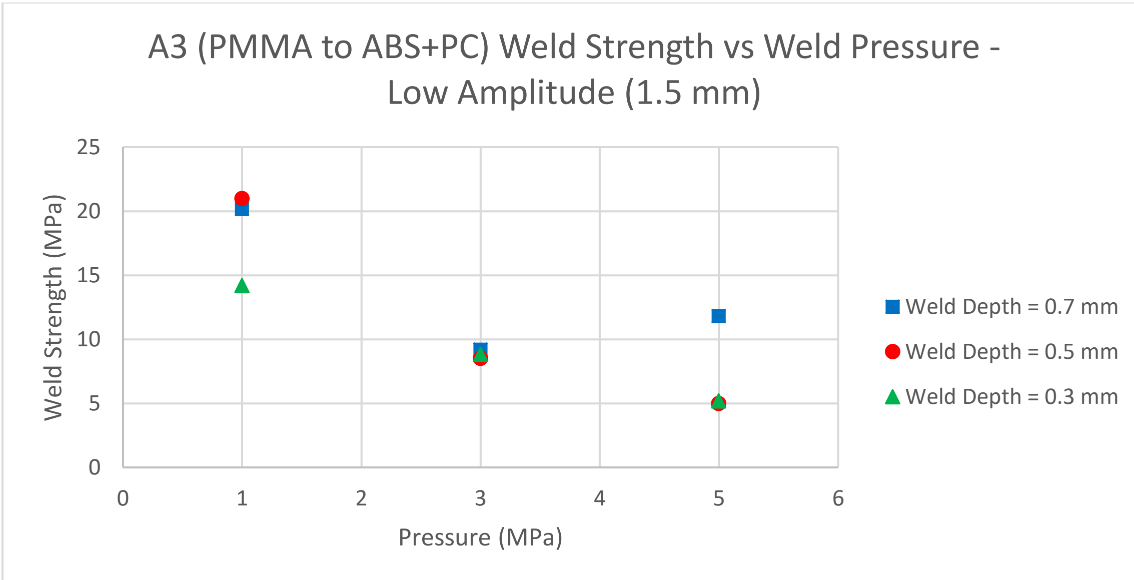

Figure 72: A3 (PMMA to ABS+PC) weld strength vs weld pressure at low amplitude for different weld depths. The weld strength generally decreases with increasing pressure at the low welding amplitude, a = 1.5 mm.

The optimal weld parameters are observed at sample 5. This is unexpected since typically larger weld depths at the same parameters perform better.

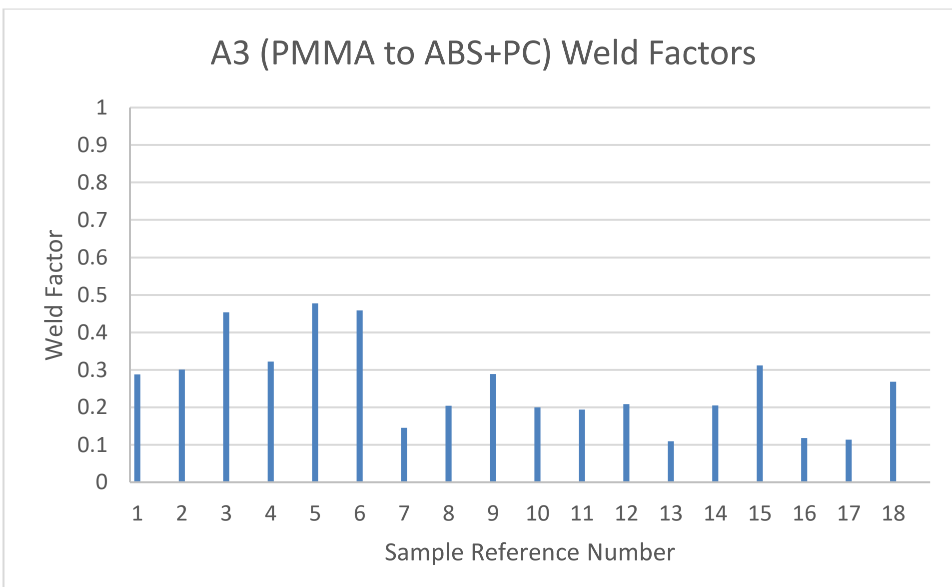

Figure 73: A3 (PMMA to ABS+PC) Weld Factors. Weld sample 5 achieved the highest weld factor of 0.477 at a welding depth of 0.5 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The small difference between sample 5 and sample 6 may be due to variability. It is likely that they achieve the same strength value on average. The sample reference numbers refer to the trial ID welding parameters in Table 10.

These materials can only reach a weld factor of 0.477, which is calculated using the weld strength of 20.997 MPa. The small difference between sample 5 and sample 6 may be due to variability. It is likely that they achieve the same strength value on average, the maximum achievable at a pressure of 1 MPa and an amplitude of 1.5 mm. This can be verified by the graph below, where the weld penetration threshold is likely somewhere between 0.3 mm and 0.5 mm in depth. Additional testing on this material combination can confirm if the similarities between sample 5 and sample 6 are due to a weld penetration threshold or a variability causing sample 5 to be stronger. If sample 5's strength is on average lower than sample 6's strength, then it is inspected that at these welding parameters, increasing depth will increase the strength of the weld.

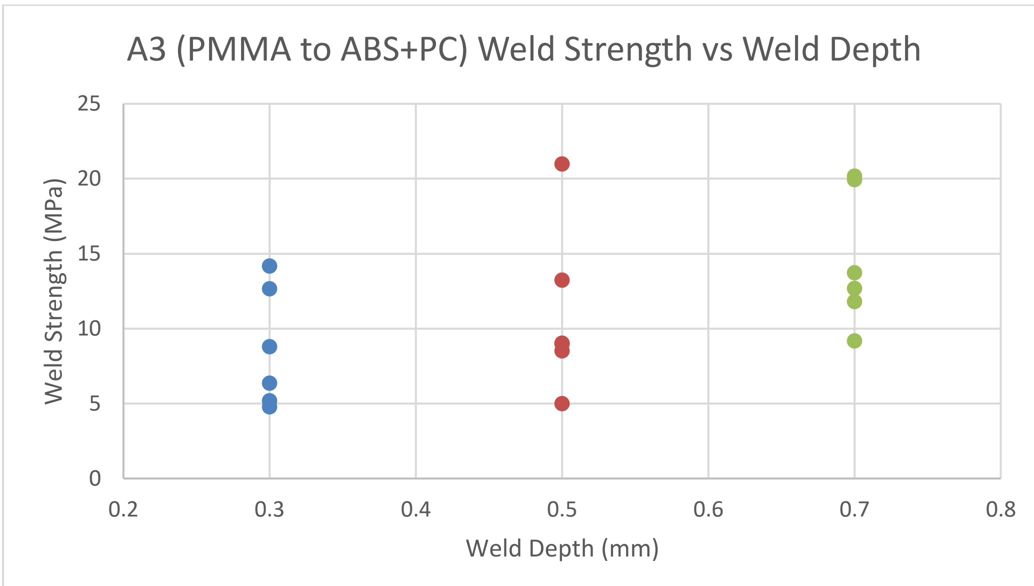

Figure 74: A3 (PMMA to ABS+PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 20.996 MPa. This weld was created using a welding depth of 0.5 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The weld strength increases with increasing weld depth.

4.1.4 Tensile Test Results – A4 (PMMA to ABS)

Material A is PMMA and material 4 is ABS. The strength testing results for 236 Hz Vibration Welds of Lens Material A to Housing Material 4 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 18. The weld factors are based off of Material 4's tensile strength, 36 MPa.

Table 18: Strength of 236 Hz Vibration Welds of Lens Material A (PMMA) to Housing Material 4 (ABS) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	13.715	0.381
1	0.5	13.394	0.372
1	0.7	12.813	0.356
3	0.3	15.224	0.423
3	0.5	11.613	0.323
3	0.7	11.701	0.325
5	0.3	14.327	0.398
5	0.5	14.053	0.390
5	0.7	7.170	0.199

At the high amplitude, the weld factor decreases with increasing weld penetration. At the low amplitude, the same general phenomenon occurs for pressures of 3 MPa and 5 MPa. At 1 MPa, the intuitive trend occurs where an increase in weld depth causes an increase in strength.

The strength testing results for 236 Hz Vibration Welds of Lens Material A to Housing Material 4 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 19.

Table 19: Strength of 236 Hz Vibration Welds of Lens Material A (PMMA) to Housing Material 4 (ABS) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	17.341	0.482
1	0.5	17.784	0.494
1	0.7	20.110	0.559
3	0.3	13.167	0.366
3	0.5	12.793	0.355
3	0.7	8.442	0.235
5	0.3	11.962	0.332
5	0.5	4.461	0.124
5	0.7	7.855	0.218

At the lower pressure, the lower amplitude welds outperform the higher amplitude welds. An increase in pressure seems to generally also decrease the weld strength.

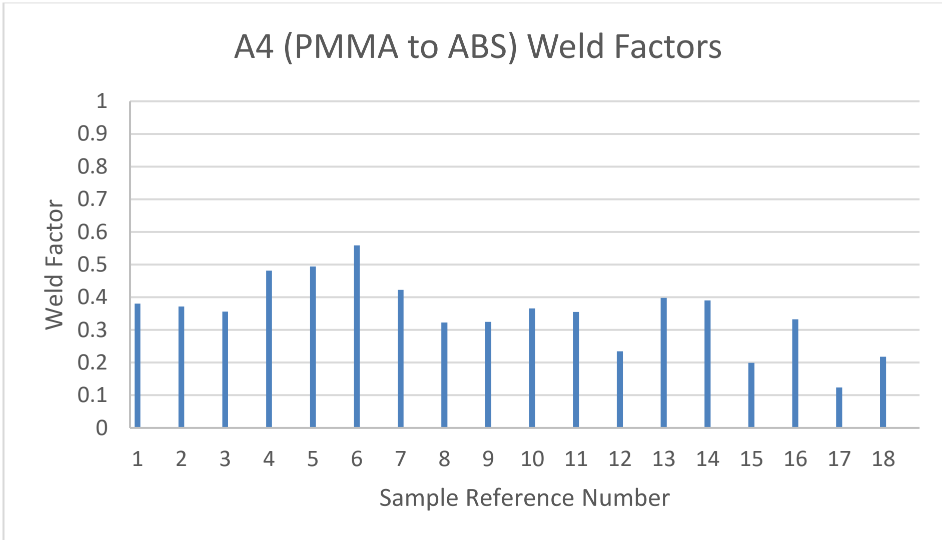

Figure 75: A4 (PMMA to ABS) Weld Factors. Weld sample 6 achieved the highest weld factor of 0.559 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

These materials are somewhat compatible for welding, reaching a maximum weld strength of 20.110 MPa, corresponding to a weld factor of 0.558. This is achieved using a pressure of 1 MPa, a weld depth of 0.7 mm, and a weld amplitude of 1.5 mm.

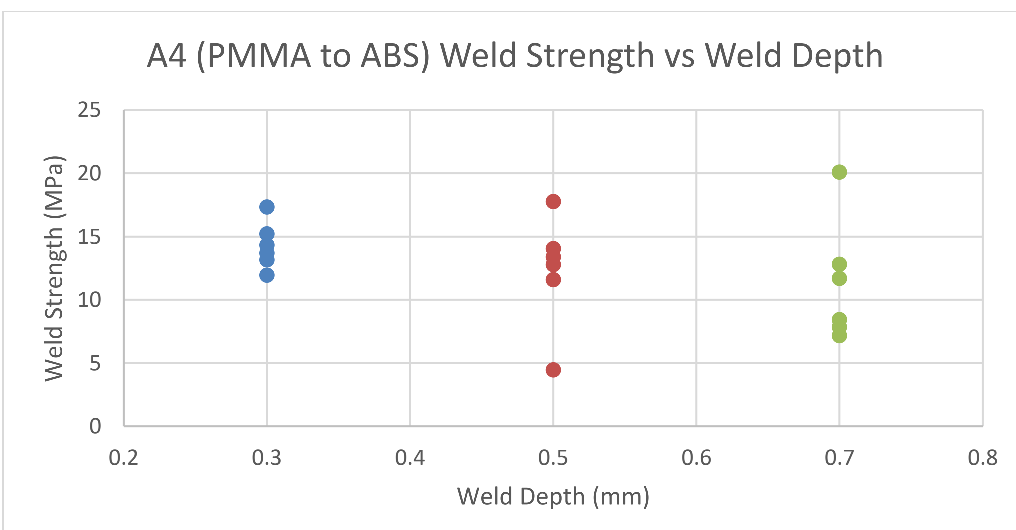

Figure 76: A4 (PMMA to ABS) Weld Strength vs Weld Depth. The maximum weld strength achieved is 20.110 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The weld strength increases with increasing weld depth.

It is seen that the maximum attainable weld strength can be increased with weld depth when using the optimal weld parameters. These maximum values all occur at a pressure of 1 MPa, and an amplitude of 1.5 mm. These are the only weld depth values that follow the logical progression of strength regarding weld depth. The data seems to become more unstable as the weld depth is increased.

Seeing weld strength consistently fall off with increasing weld depth at the same parameters is very strange and is opposite to the general consensus regarding vibration welding. For this combination of materials, the increasing weld depth must severely impede mixing at the weld interface. It is known that greater weld depths cause the weld depth to become smaller and flatter. It has also been determined tha higher pressures cause the molten material out of the interface before mixing can occur. The interaction of weld pressure and weld depth together must obstruct mixing. This material combination is perplexing and should be studied further to confirm findings.

4.1.5 Tensile Test Results – A5 (PMMA to ASA)

Material A is PMMA and material 5 is ASA. The strength testing results for 236 Hz Vibration Welds of Lens Material A to Housing Material 5 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 20. The weld factors are based off of Material 5’s tensile strength, 33 MPa. It can be seen that the weld strengths increase with weld depth.

Table 20: Strength of 236 Hz Vibration Welds of Lens Material A (PMMA) to Housing Material 5 (ASA) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	6.553	0.199
1	0.5	8.153	0.247
1	0.7	16.906	0.512
3	0.3	5.990	0.182
3	0.5	5.139	0.156
3	0.7	9.506	0.288
5	0.3	0.000	0.000
5	0.5	4.873	0.148
5	0.7	8.030	0.243

The strength testing results for 236 Hz Vibration Welds of Lens Material A to Housing Material 5 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 21.

Table 21: Strength of 236 Hz Vibration Welds of Lens Material A (PMMA) to Housing Material 5 (ASA) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	9.631	0.292
1	0.5	14.242	0.432
1	0.7	12.232	0.371
3	0.3	6.459	0.196
3	0.5	8.737	0.265
3	0.7	6.983	0.212
5	0.3	0.000	0.000
5	0.5	4.691	0.142
5	0.7	4.961	0.150

For both high and low amplitudes, the increase in pressure consistently causes a decrease in weld strength.

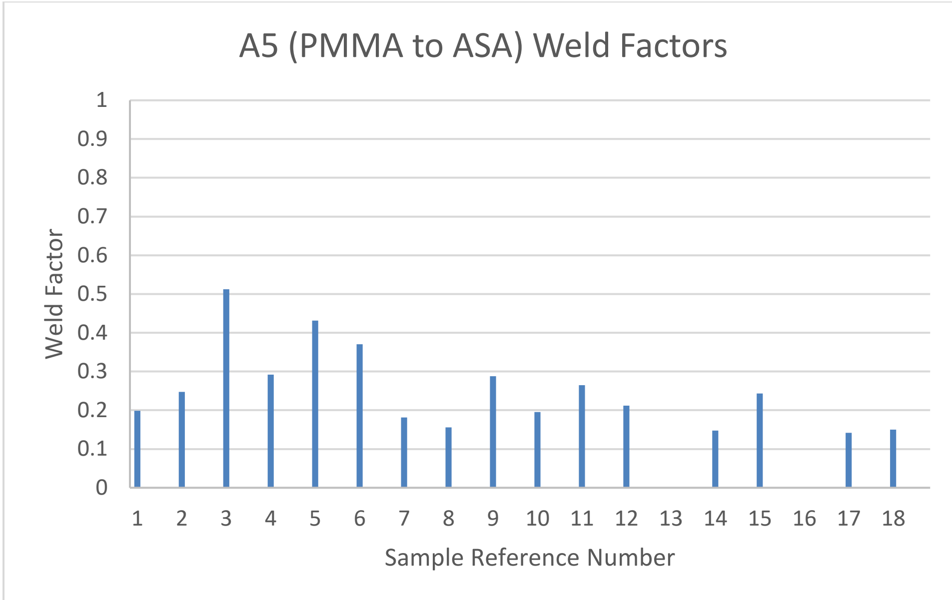

Figure 77: A5 (PMMA to ASA) Weld Factors. Weld sample 5 achieved the highest weld factor of 0.512 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum weld strength of 16.906 MPa occurs at a weld amplitude of 1.78 mm, a weld pressure of 1 MPa, and a weld depth of 0.7 mm. This material combination has mediocre material compatibility, with the weld factor peaking at 0.512.

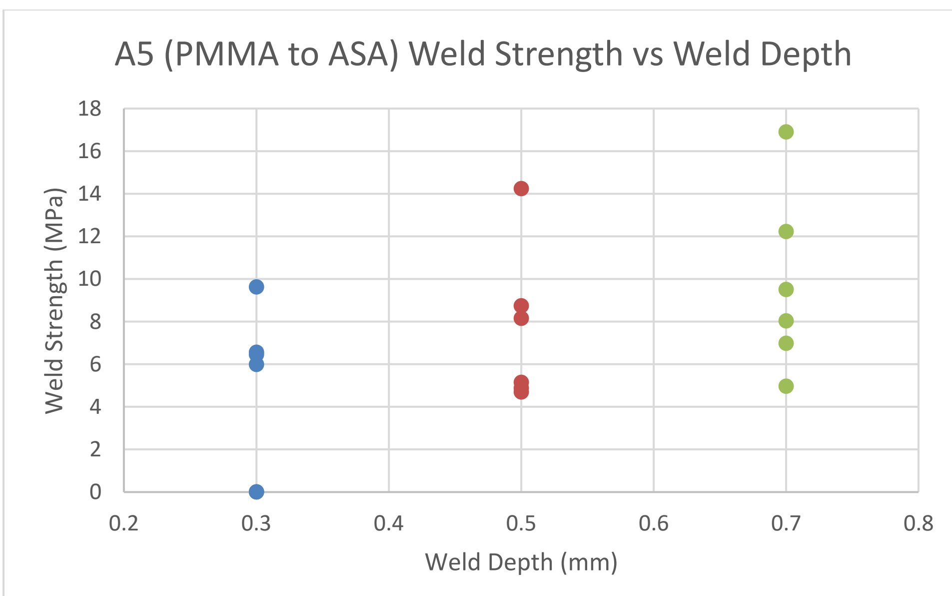

Figure 78: A5 (PMMA to ASA) Weld Strength vs Weld Depth. The maximum weld strength achieved is 16.906 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The weld strength increases with increasing weld depth.

It is very clear that at optimal parameters, an increase in weld strength will occur while continuing to increase the weld depth.

4.1.6 Tensile Test Results – A6 (PMMA to ASA+PC)

Material A is PMMA and material 6 is an ASA+PC blend. The strength testing results for 236 Hz Vibration Welds of Lens Material A to Housing Material 6 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 22. The weld factors are based off of Material 6's tensile strength, 62.1 MPa.

Table 22: Strength of 236 Hz Vibration Welds of Lens Material A (PMMA) to Housing Material 6 (ASA+PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	11.63108	0.187296
1	0.5	14.1763	0.228282
1	0.7	12.47067	0.200816
3	0.3	2.888734	0.046517
3	0.5	6.237717	0.100446
3	0.7	8.918105	0.143609
5	0.3	4.338165	0.069858
5	0.5	5.355528	0.08624
5	0.7	3.92249	0.063164

The strength testing results for 236 Hz Vibration Welds of Lens Material A to Housing Material 6 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 23.

Table 23: Strength of 236 Hz Vibration Welds of Lens Material A (PMMA) to Housing Material 6 (ASA+PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	7.4703	0.120295
1	0.5	9.754466	0.157077
1	0.7	11.46706	0.184655
3	0.3	4.605995	0.074171
3	0.5	5.689141	0.091613
3	0.7	10.36988	0.166987
5	0.3	3.615953	0.058228
5	0.5	2.679685	0.043151
5	0.7	4.162738	0.067033

Increasing welding pressure has a negative effect on the strength of this material combination.

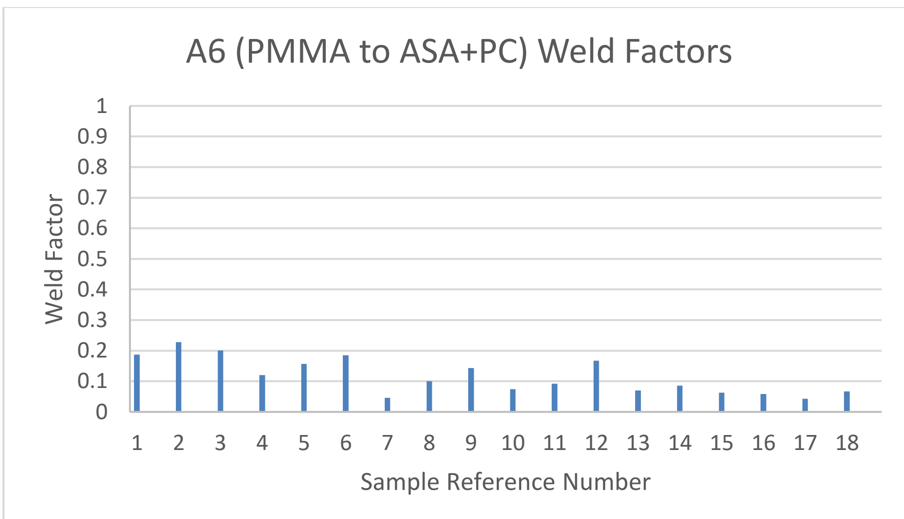

Figure 79: A6 (PMMA to ASA+PC) Weld Factors. Weld sample 2 achieved the highest weld factor of 0.228 at a welding depth of 0.5 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The greatest weld strength attained during the tensile tests is 14.176 MPa. The weldability of these two materials is low, with all combinations yielding weld factors less than 0.3. The weld factor is maximum at 0.228.

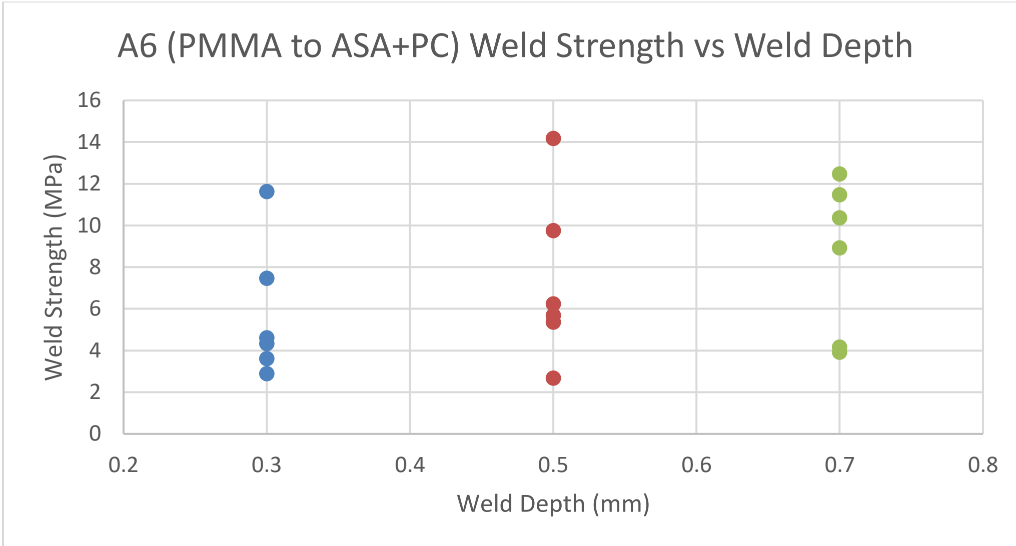

Figure 80: A6 (PMMA to ASA+PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 14.176. This weld was created using a welding depth of 0.5 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm.

The maximum achievable strengths at the weld depths is basically consistent. Increasing weld depth for this combination should not greatly increase the weld strength.

4.2 Lens B (PMMA) Combinations - Weld Strength Testing Results

4.2.1 Tensile Test Results – B1 (PMMA to PC)

Material B is PMMA and material 1 is PC. The strength testing results for 236 Hz Vibration Welds of Lens Material B to Housing Material 1 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 24. The weld factors are based off of Material B’s tensile strength, 63 MPa.

Table 24: Strength of 236 Hz Vibration Welds of Lens Material B (PMMA) to Housing Material 1 (PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations.

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	27.339	0.434
1	0.5	33.020	0.524
1	0.7	33.952	0.539
3	0.3	14.892	0.236
3	0.5	19.473	0.309
3	0.7	25.543	0.405
5	0.3	39.021	0.619
5	0.5	47.156	0.749
5	0.7	40.186	0.638

The strength testing results for 236 Hz Vibration Welds of Lens Material B to Housing Material 1 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 25.

Table 25: Strength of 236 Hz Vibration Welds of Lens Material B (PMMA) to Housing Material 1 (PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations.

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	24.149	0.383
1	0.5	29.194	0.463
1	0.7	40.775	0.647
3	0.3	12.054	0.191
3	0.5	15.729	0.250
3	0.7	24.757	0.393
5	0.3	22.744	0.361
5	0.5	35.327	0.561
5	0.7	53.842	0.855

The weld strength generally increases with weld penetration. This combination of materials is insensitive to the weld pressure.

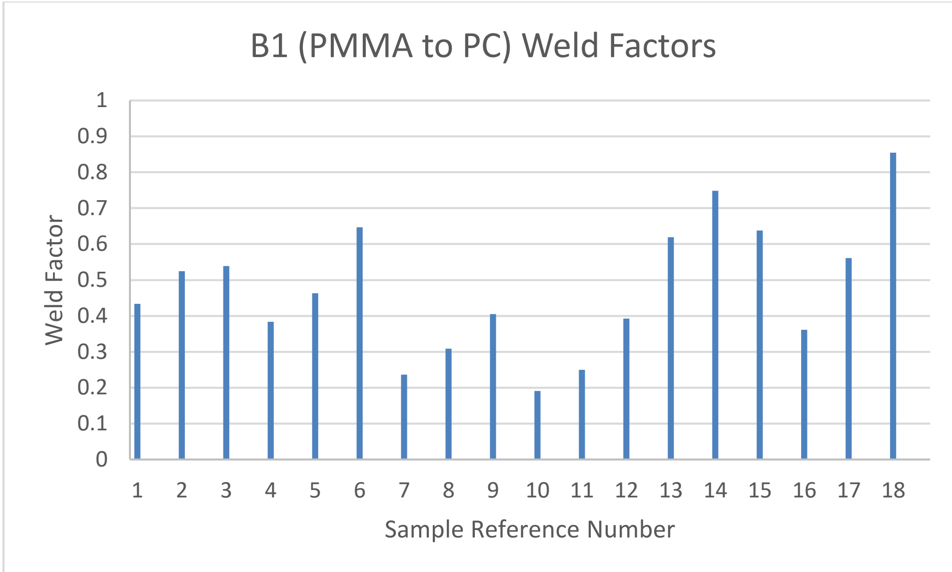

Figure 81: B1 (PMMA to PC) Weld Factors. Weld sample 14 achieved the highest weld factor of 0.854 at a welding depth of 0.7 mm, welding pressure of 5 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum weld factor achieved is 0.854 using a weld amplitude of 1.5 mm, a weld pressure of 5 MPa, and a weld depth of 0.7 mm. This is derived from the maximum weld strength of 53.842 MPa. It is seen that the maximum achievable weld strength increases with the weld depth.

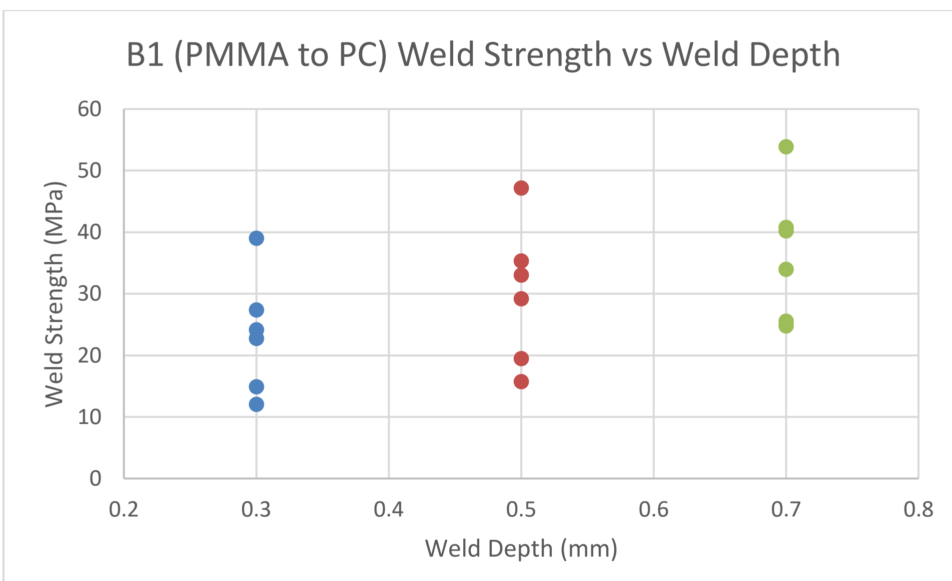

Figure 82: B1 (PMMA to PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 53.842 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The weld strength increases with increasing weld depth.

4.2.2 Tensile Test Results – B2 (PMMA to PC+ABS)

Material B is PMMA and material 2 is a PC+ABS blend. The strength testing results for 236 Hz Vibration Welds of Lens Material B to Housing Material 2 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 26. The weld factors are based off of Material 2's tensile strength, 56 MPa.

Table 26: Strength of 236 Hz Vibration Welds of Lens Material B (PMMA) to Housing Material 2 (PC+ABS) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	8.916	0.159
1	0.5	13.297	0.237
1	0.7	12.949	0.231
3	0.3	9.554	0.171
3	0.5	9.399	0.168
3	0.7	12.411	0.222
5	0.3	11.909	0.213
5	0.5	20.451	0.365
5	0.7	17.563	0.314

The strength testing results for 236 Hz Vibration Welds of Lens Material B to Housing Material 2 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 27.

Table 27: Strength of 236 Hz Vibration Welds of Lens Material B (PMMA) to Housing Material 2 (PC+ABS) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	9.609	0.172
1	0.5	10.958	0.196
1	0.7	14.603	0.261
3	0.3	7.464	0.133
3	0.5	9.745	0.174
3	0.7	8.466	0.151
5	0.3	11.466	0.205
5	0.5	13.691	0.244
5	0.7	8.299	0.148

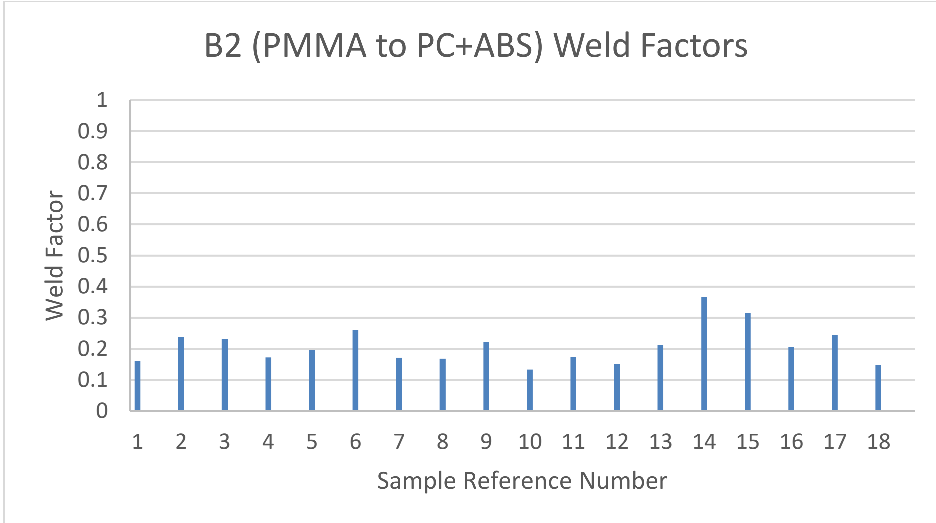

Figure 83: B2 (PMMA to PC+ABS) Weld Factors. Weld sample 14 achieved the highest weld factor of 0.365 at a welding depth of 0.5 mm, welding pressure of 5 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

Sample 14 demonstrated the highest weld strength, 20.451. The maximum weld factor is 0.4, found using a weld pressure of 5 MPa, a weld amplitude of 1.78 mm, a weld depth of 0.5 mm.

The lack of trends is assumed to be due to the random mixing of these incompatible materials. This leaves strength results volatile and unpredictable. This can be seen in the strength vs weld depth graph.

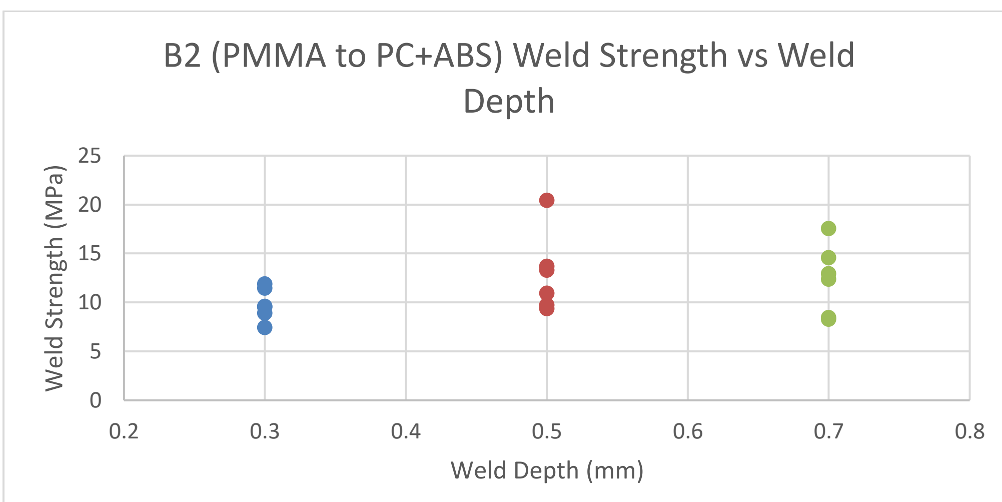

Figure 84: B2 (PMMA to PC+ABS) Weld Strength vs Weld Depth. The maximum weld strength achieved is 20.451 MPa. This weld was created using a welding depth of 0.5 mm, welding pressure of 5 MPa, and a welding amplitude of 1.78 mm.

This peak of achievable weld strength at 0.5 mm in depth is odd. It is assumed to be an outlier and that the weld penetration will typically increase with weld depth like the majority of dissimilar material combinations.

4.2.3 Tensile Test Results – B3 (PMMA to ABS+PC)

Material B is PMMA and material 3 is an ABS+PC blend. The strength testing results for 236 Hz Vibration Welds of Lens Material B to Housing Material 3 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 28. The weld factors are based off of Material 3's tensile strength, 44 MPa.

Table 28: Strength of 236 Hz Vibration Welds of Lens Material B (PMMA) to Housing Material 3 (ABS+PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	21.373	0.486
1	0.5	19.212	0.437
1	0.7	23.834	0.542
3	0.3	15.307	0.348
3	0.5	11.475	0.261
3	0.7	16.223	0.369
5	0.3	9.785	0.222
5	0.5	10.446	0.237
5	0.7	15.843	0.360

The strength testing results for 236 Hz Vibration Welds of Lens Material B to Housing Material 3 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 29.

Table 29: Strength of 236 Hz Vibration Welds of Lens Material B (PMMA) to Housing Material 3 (ABS+PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	16.962	0.386
1	0.5	19.445	0.442
1	0.7	25.679	0.584
3	0.3	12.843	0.292
3	0.5	13.230	0.301
3	0.7	16.017	0.364
5	0.3	8.242	0.187
5	0.5	13.335	0.303
5	0.7	17.046	0.387

The weld strength values decrease with pressure. This material combination seems insensitive to the welding amplitude.

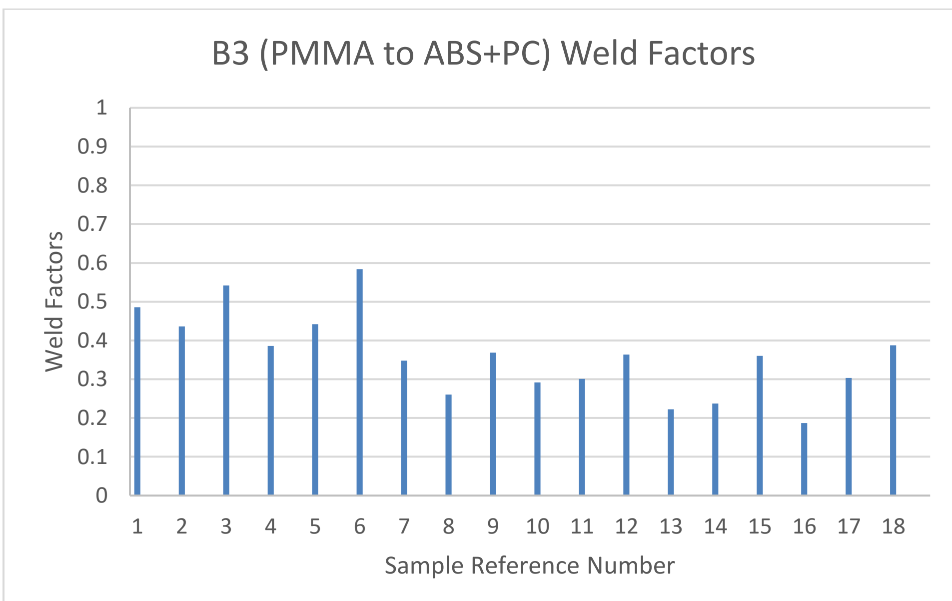

Figure 85: B3 (PMMA to ABS+PC) Weld Factors. Weld sample 6 achieved the highest weld factor of 0.583 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The best weld strength is 25.679 MPa, achieving a weld factor of 0.583. This was accomplished using a weld pressure of 1 MPa, a weld amplitude of 1.5 mm, and a weld depth of 0.7 mm.

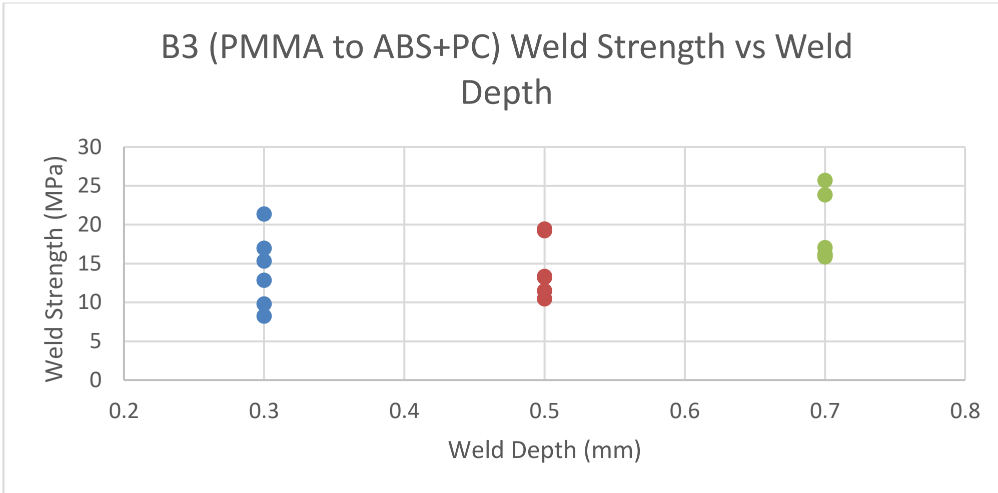

Figure 86: B3 (PMMA to ABS+PC)Weld Strength vs Weld Depth. The maximum weld strength achieved is 25.679 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The weld strength increases with increasing weld depth.

The weld strength will increase with weld depth. There may be some type of weld penetration threshold between 0.5 mm and 0.7 mm.

4.2.4 Tensile Test Results – B4 (PMMA to ABS)

Material B is PMMA and material 4 is ABS. The strength testing results for 236 Hz Vibration Welds of Lens Material B to Housing Material 4 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 30. The weld factors are based off of Material 4's tensile strength, 44 MPa.

Table 30: Strength of 236 Hz Vibration Welds of Lens Material B (PMMA) to Housing Material 4 (ABS) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	20.381	0.566
1	0.5	22.036	0.612
1	0.7	24.021	0.667
3	0.3	18.128	0.504
3	0.5	18.889	0.525
3	0.7	18.650	0.518
5	0.3	5.058	0.140
5	0.5	16.960	0.471
5	0.7	14.102	0.392

The strength testing results for 236 Hz Vibration Welds of Lens Material B to Housing Material 4 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 31.

Table 31: Strength of 236 Hz Vibration Welds of Lens Material B (PMMA) to Housing Material 4 (ABS) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	23.849	0.662
1	0.5	23.579	0.655
1	0.7	13.386	0.372
3	0.3	17.877	0.497
3	0.5	17.270	0.480
3	0.7	13.587	0.377
5	0.3	13.724	0.381
5	0.5	11.650	0.324
5	0.7	16.486	0.458

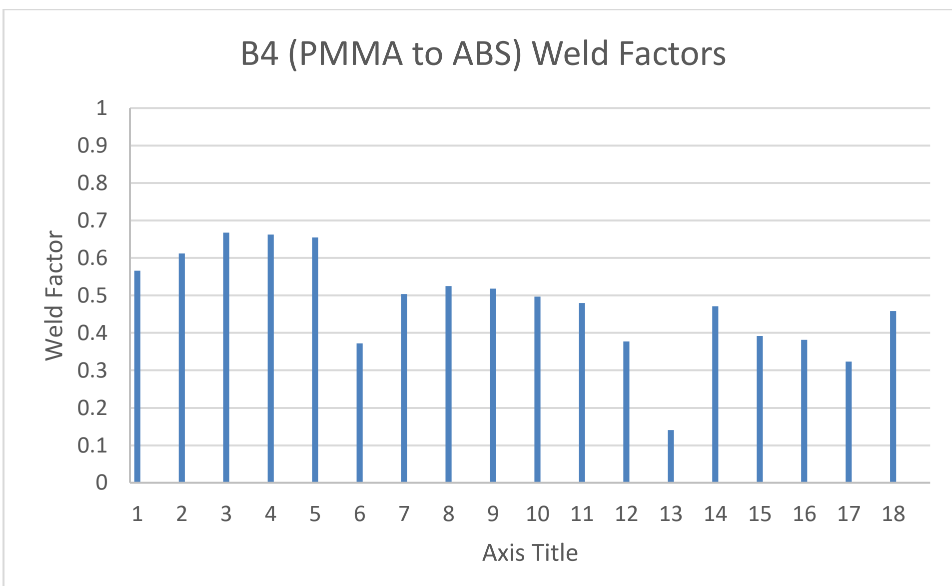

Figure 87: B4 (PMMA to ABS) Weld Factors. Weld sample 3 achieved the highest weld factor of 0.667 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The greatest weld factor was found at a weld pressure of 1 MPa, a weld depth of 0.7 MPa, and a weld amplitude of 1.78 mm. The weld strength is 24.021 MPa. This weld combination experienced two unexpected strength falloffs at weld depths of 0.7 mm. Both drops occurred at the lower weld amplitude of 1.5 mm. It is assumed that the lower amplitude does not create enough heat at the weld interface and negatively impacts the weld interface, not allowing the welds to fuse together when penetrating deeper in the material.

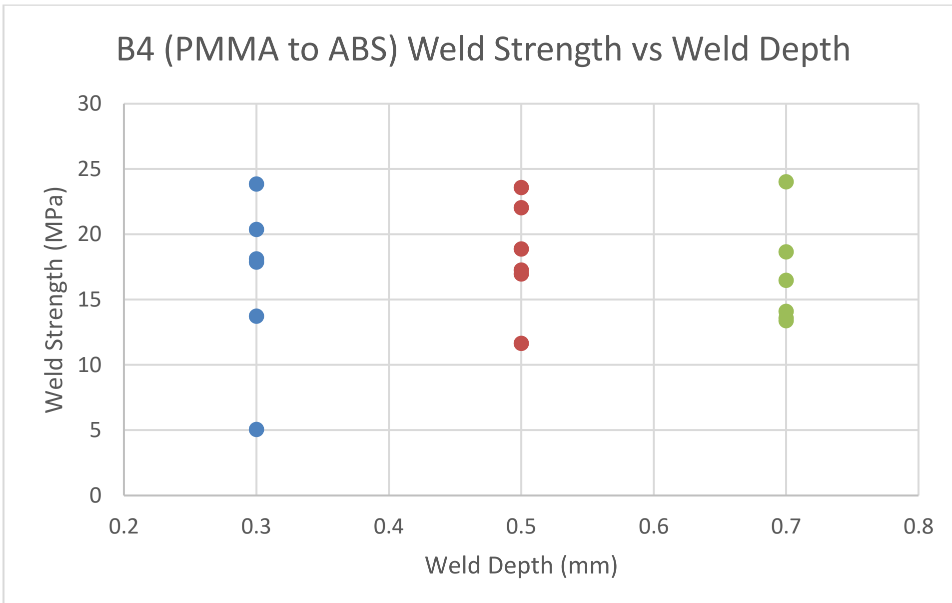

Figure 88: B4 (PMMA to ABS) Weld Strength vs Weld Depth. The maximum weld strength achieved is 24.021 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The weld strength appears to have reached the maximum attainable value. Increasing the weld depth will not increase the weld strength.

It appears that this material combination has a weld penetration threshold less than or equal to 0.3 mm. Further weld penetration does not increase the maximum achievable strength.

4.2.5 Tensile Test Results – B5 (PMMA to ASA)

Material B is PMMA and material 5 is ASA. The strength testing results for 236 Hz Vibration Welds of Lens Material B to Housing Material 5 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 32. The weld factors are based off of Material 5's tensile strength, 33 MPa.

Table 32: Strength of 236 Hz Vibration Welds of Lens Material B (PMMA) to Housing Material 5 (ASA) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	8.756	0.265
1	0.5	8.981	0.272
1	0.7	12.789	0.388
3	0.3	6.722	0.204
3	0.5	10.753	0.326
3	0.7	9.891	0.300
5	0.3	2.944	0.089
5	0.5	7.341	0.222
5	0.7	7.948	0.241

The strength testing results for 236 Hz Vibration Welds of Lens Material B to Housing Material 5 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 33.

Table 33: Strength of 236 Hz Vibration Welds of Lens Material B (PMMA) to Housing Material 5 (ASA) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	9.476	0.287
1	0.5	9.480	0.287
1	0.7	12.839	0.389
3	0.3	7.377	0.224
3	0.5	7.372	0.223
3	0.7	9.472	0.287
5	0.3	3.951	0.120
5	0.5	9.311	0.282
5	0.7	6.925	0.210

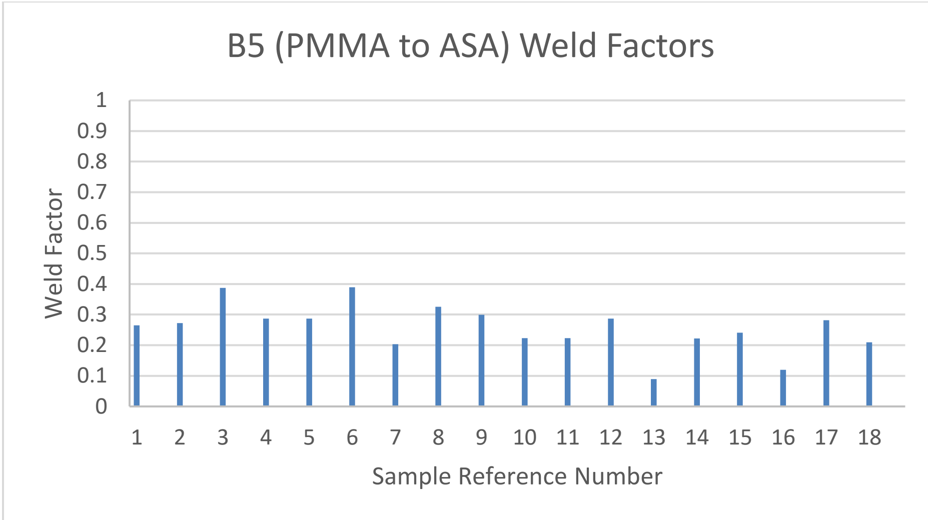

Figure 89: B5 (PMMA to ASA) Weld Factors. Weld sample 6 achieved the highest weld factor of 0.389 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The largest weld factor experienced is sample 6, with sample 3 almost equal, yielding 0.389 and 0.387 respectively. Their corresponding weld strengths are 12.839 and 12.789 MPa. Both welds were under a pressure of 1 MPa and had a weld depth of 0.7, with the only difference being their respective weld depths of 1.5 mm and 1.78 mm. It seems that at this low pressure, they are insensitive to the weld amplitude and act similarly.

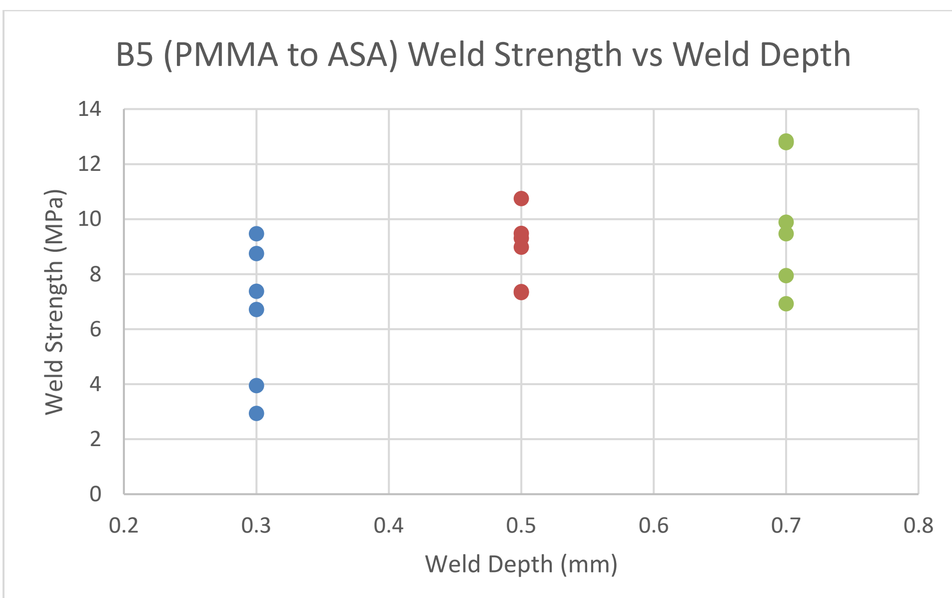

Figure 90: B5 (PMMA to ASA) Weld Strength vs Weld Depth. The maximum weld strength achieved is 12.789 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The weld strength increases with increasing weld depth.

The highest achievable weld strength can be increased by increasing the weld depth at the optimized parameters.

4.2.6 Tensile Test Results – B6 (PMMA to ASA+PC)

Material B is PMMA and material 6 is an ASA+PC blend. The strength testing results for 236 Hz Vibration Welds of Lens Material B to Housing Material 6 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 34. The weld factors are based off of Material 6's tensile strength, 62.1 MPa.

Table 34: Strength of 236 Hz Vibration Welds of Lens Material B (PMMA) to Housing Material 6 (ASA+PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	8.382	0.135
1	0.5	7.641	0.123
1	0.7	10.254	0.165
3	0.3	6.319	0.102
3	0.5	6.271	0.101
3	0.7	7.823	0.126
5	0.3	3.720	0.060
5	0.5	2.855	0.046
5	0.7	N/A	N/A

The strength testing results for 236 Hz Vibration Welds of Lens Material B to Housing Material 6 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 35.

Table 35: Strength of 236 Hz Vibration Welds of Lens Material B (PMMA) to Housing Material 6 (ASA+PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	7.840	0.126
1	0.5	6.121	0.099
1	0.7	10.012	0.161
3	0.3	4.641	0.075
3	0.5	6.671	0.107
3	0.7	7.518	0.121
5	0.3	N/A	N/A
5	0.5	N/A	N/A
5	0.7	N/A	N/A

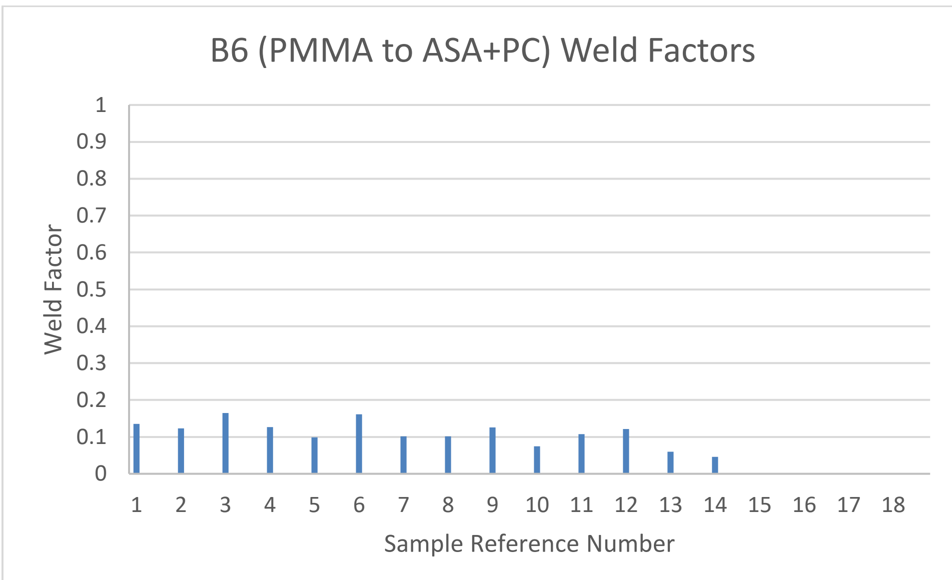

Figure 91: B6 (PMMA to ASA+PC) Weld Factors. Weld sample 6 achieved the highest weld factor of 0.161 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

Samples 15-18 could not be tested since they broke during transport, implying a very weak weld strength. It is clear that this combination of materials is not compatible. The maximum weld strength determined is 10.254 MPa, with a weld factor of 0.165. This implies that the materials are not joining/fusing together. This is likely due to a difference in melt temperature, where the meltdown of one material gives the perception of a steady-state and weld depth. Material B's glass transition temperature is not available. The weak weld strengths could also be caused by material incompatibility.

It seems that the weld strengths are random and do not follow a logic controlled by the welding parameters. The strength then depends on the small amount of random mixing at the interface. This type of incompatibility is erratic and unreliable for certain applications.

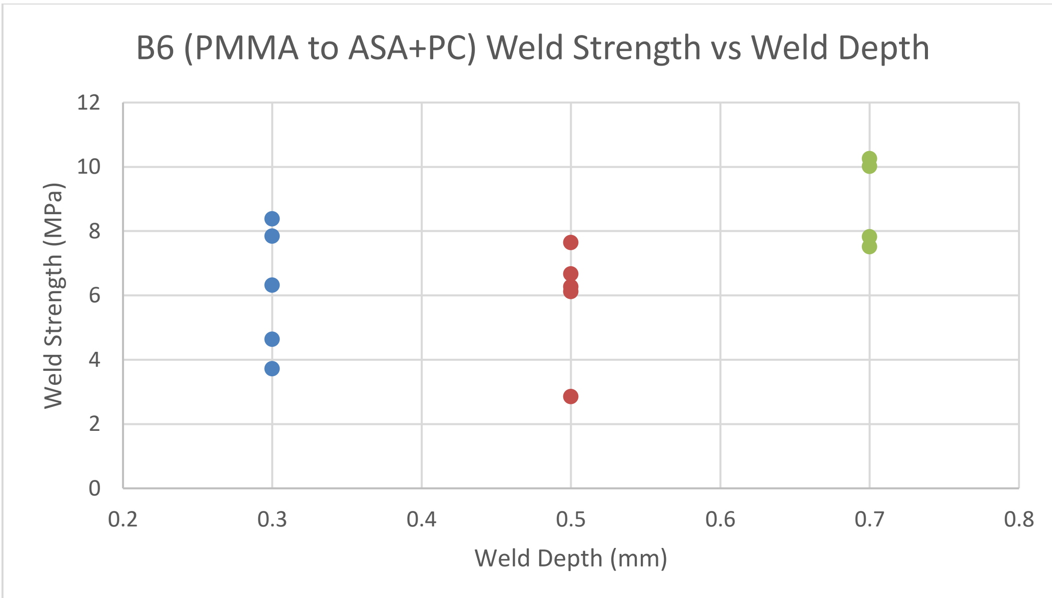

Figure 92: B6 (PMMA to ASA+PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 10.012 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm.

This weld strength pattern is likely the maximum achievable weld strength. Since one material is melting much more than the other, the increase in perceived weld depth will not influence the strength of the weld in a quantifiable gain.

4.3 Lens C (PMMA) Combinations - Weld Strength Testing Results

4.3.1 Tensile Test Results – C1 (PMMA to PC)

Material C is PMMA and material 1 is PC. The strength testing results for 236 Hz Vibration Welds of Lens Material C to Housing Material 1 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 36. The weld factors are based off of Material C's tensile strength, 48 MPa.

Table 36: Strength of 236 Hz Vibration Welds of Lens Material C (PMMA) to Housing Material 1 (PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	30.993	0.645
1	0.5	48.309	1.006
1	0.7	38.426	0.800
3	0.3	30.908	0.643
3	0.5	25.491	0.531
3	0.7	38.331	0.798
5	0.3	6.520	0.135
5	0.5	29.515	0.614
5	0.7	26.590	0.553

The strength testing results for 236 Hz Vibration Welds of Lens Material C to Housing Material 1 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 37.

Table 37: Strength of 236 Hz Vibration Welds of Lens Material C (PMMA) to Housing Material 1 (PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	3.4057	0.070
1	0.5	10.154	0.211
1	0.7	46.998	0.979
3	0.3	30.456	0.634
3	0.5	27.699	0.577
3	0.7	34.584	0.720
5	0.3	9.895	0.206
5	0.5	17.925	0.373
5	0.7	30.819	0.642

All sample sets are insensitive to weld pressure and amplitude.

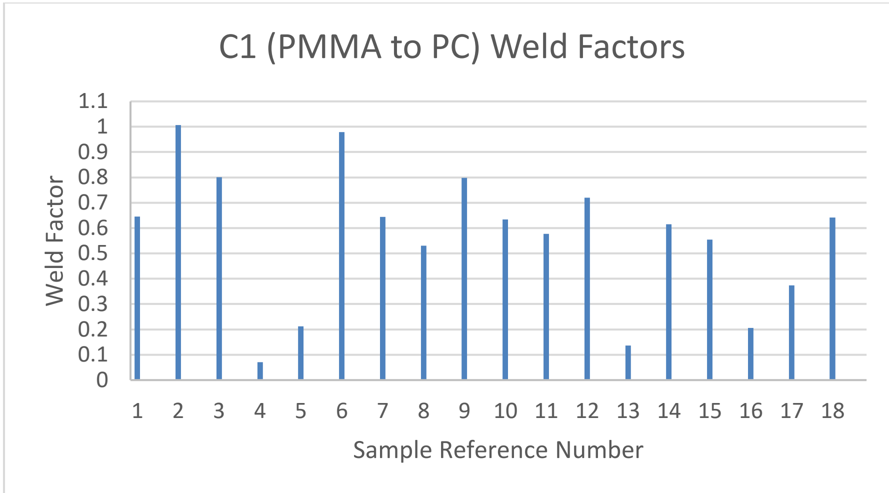

Figure 93: C1 (PMMA to PC) Weld Factors. Weld sample 1 achieved the highest weld factor of unity at a welding depth of 0.5 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The greatest weld strength achieved reaches the weaker parent material's strength of 48 MPa, yielding a weld factor of unity. This quality weld occurs at a high weld amplitude of 1.78 mm, a weld pressure of 1 MPa, and a weld depth of 0.5 mm. It is odd that increasing the weld depth at these parameters decreases the weld strength. An almost equivalent strength can be achieved using a low weld amplitude of 1.5 mm, a weld pressure of 1 MPa, and a weld depth of 0.7 mm.

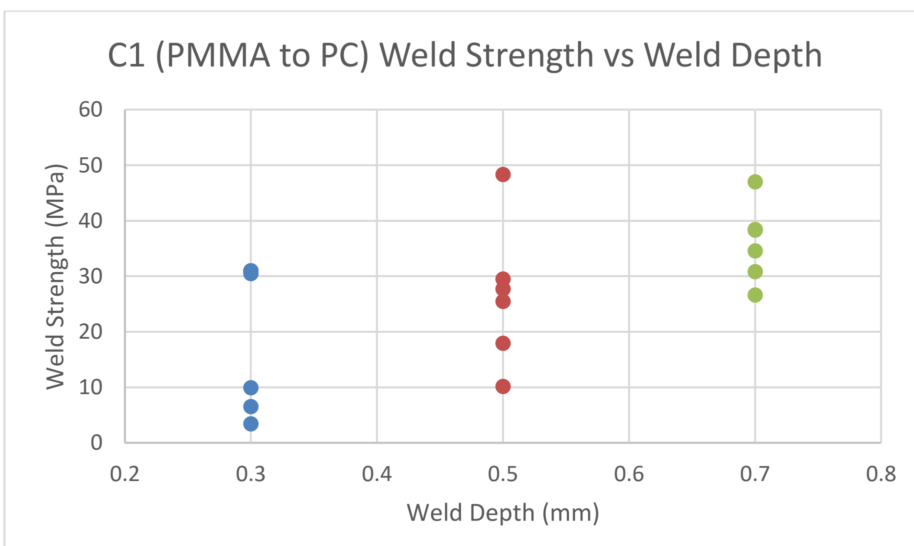

Figure 94: C1 (PMMA to PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 48.310 MPa. This weld was created using a welding depth of 0.5 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The weld strength likely increases with increasing weld depth as the high strength value at a depth of 0.5 mm seems like an outlier based on the spread of the other strength values at the same depth.

This graph shows that there is a weld penetration threshold present between a depth of 0.3 mm and 0.5 mm. Increasing the weld depth past this value does not increase the weld strength and could potentially cause adverse effects.

4.3.2 Tensile Test Results – C2 (PMMA to PC+ABS)

Material C is PMMA and material 2 is a PC+ABS blend. The strength testing results for 236 Hz Vibration Welds of Lens Material C to Housing Material 2 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 38. The weld factors are based off of Material C's tensile strength, 48 MPa.

Table 38: Strength of 236 Hz Vibration Welds of Lens Material C (PMMA) to Housing Material 2 (PC+ABS) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	10.525	0.219
1	0.5	10.165	0.212
1	0.7	19.949	0.416
3	0.3	4.201	0.088
3	0.5	10.324	0.215
3	0.7	17.854	0.372
5	0.3	4.555	0.095
5	0.5	4.206	0.088
5	0.7	10.526	0.219

The strength testing results for 236 Hz Vibration Welds of Lens Material C to Housing Material 2 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 39.

Table 39: Strength of 236 Hz Vibration Welds of Lens Material C (PMMA) to Housing Material 2 (PC+ABS) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	13.377	0.279
1	0.5	14.399	0.300
1	0.7	18.410	0.384
3	0.3	3.997	0.083
3	0.5	11.027	0.230
3	0.7	17.287	0.360
5	0.3	0.000	0.000
5	0.5	5.763	0.120
5	0.7	4.648	0.097

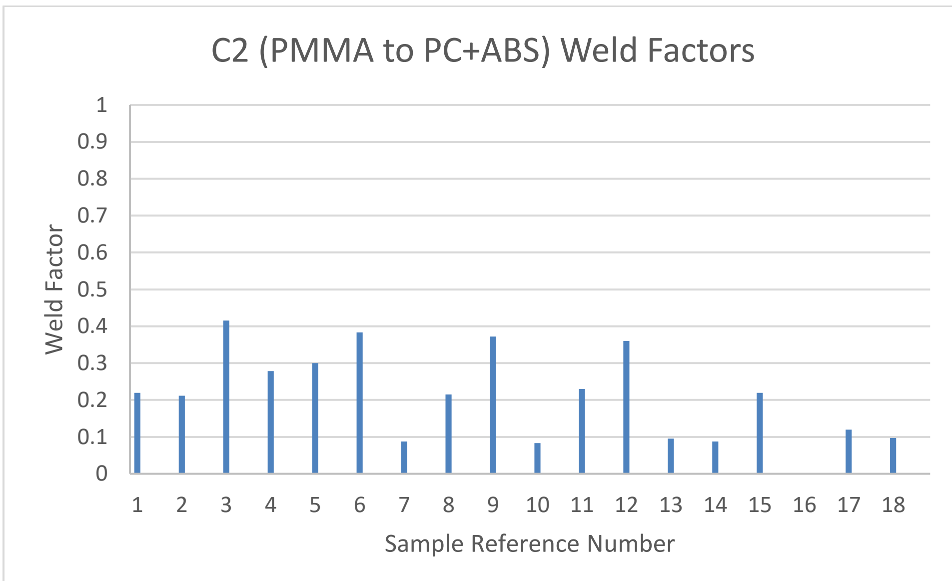

Figure 95: C2 (PMMA to PC+ABS) Weld Factors. Weld sample 3 achieved the highest weld factor of 0.416 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

Sample 3 yielded the best strength results, with 19.949 MPa as the maximum attainable strength. This correlates to a weld factor of 0.416. Its welding parameters are a weld pressure of 1 MPa, a weld amplitude of 1.78 mm, and a weld depth of 0.7 mm. The results are comparable at the high and low amplitude for 1 MPa and 3 MPa.

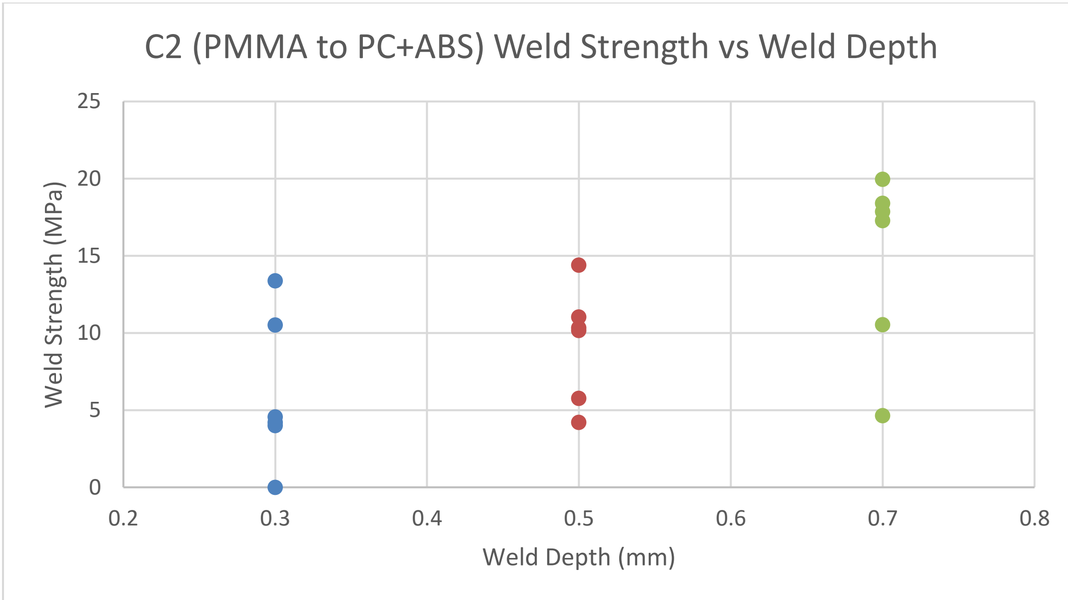

Figure 96: C2 (PMMA to PC+ABS) Weld Strength vs Weld Depth. The maximum weld strength achieved is 19.949 MPa. This weld was created using a welding depth of 0.5 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The weld strength increases with increasing weld depth.

It is clear that increasing the weld depth increases the achieved strength. As typical for dissimilar material welds, continuing to increase the weld depth, will continue to increase the weld strength

4.3.3 Tensile Test Results – C3 (PMMA to ABS+PC)

Material C is PMMA and material 3 is an ABS+PC blend. The strength testing results for 236 Hz Vibration Welds of Lens Material C to Housing Material 3 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 40. The weld factors are based off of Material C’s tensile strength, 44 MPa.

Table 40: Strength of 236 Hz Vibration Welds of Lens Material C (PMMA) to Housing Material 3 (ABS+PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	20.089	0.457
1	0.5	25.773	0.586
1	0.7	20.751	0.472
3	0.3	10.678	0.243
3	0.5	17.161	0.390
3	0.7	18.625	0.423
5	0.3	9.403	0.214
5	0.5	10.136	0.230
5	0.7	13.590	0.309

The strength testing results for 236 Hz Vibration Welds of Lens Material C to Housing Material 3 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 41.

Table 41: Strength of 236 Hz Vibration Welds of Lens Material C (PMMA) to Housing Material 3 (ABS+PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	21.514	0.489
1	0.5	26.936	0.612
1	0.7	29.067	0.661
3	0.3	15.966	0.363
3	0.5	18.302	0.416
3	0.7	18.472	0.420
5	0.3	8.741	0.199
5	0.5	13.456	0.306
5	0.7	15.022	0.341

The weld strengths decrease with increasing weld pressure. Almost all of the welds perform better at the lower amplitude of 1.5 mm than the higher weld amplitude of 1.78 mm, except when comparing sample 3 to sample 6 and comparing sample 13 to sample 16.

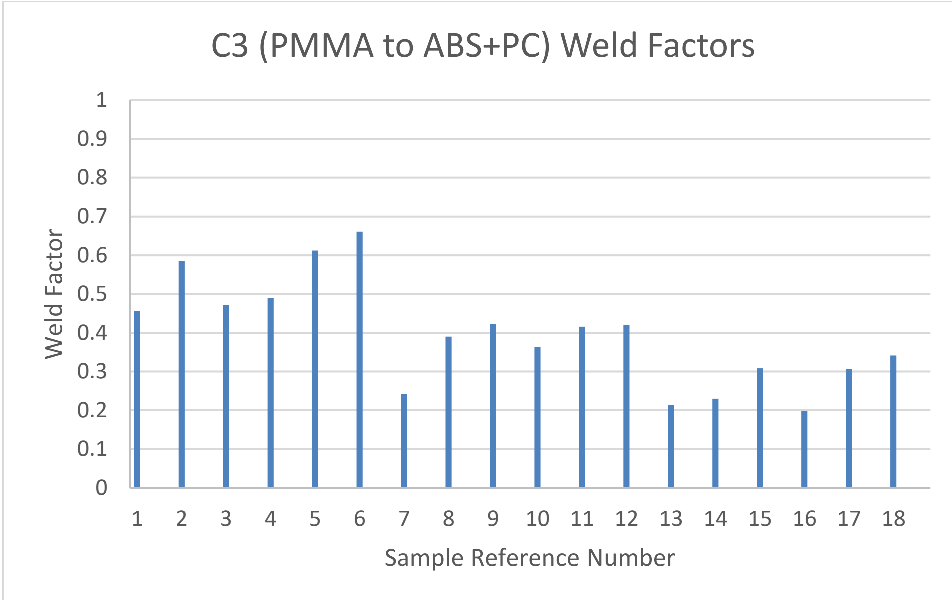

Figure 97: C3 (PMMA to ABS+PC) Weld Factors. Weld sample 6 achieved the highest weld factor of 0.661 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum attainable weld strength is given by sample 6, with a strength of 29.067 MPa and a weld factor of 0.661. The optimal weld parameters for the tested data are a pressure of 1 MPa, a weld amplitude of 1.5 mm, and a weld depth of 0.7 mm.

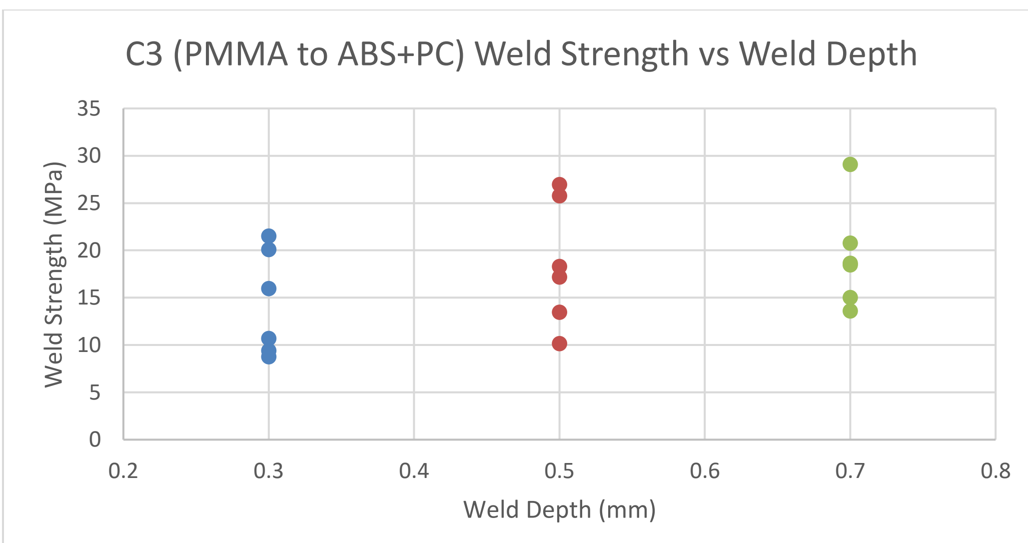

Figure 98: C3 (PMMA to ABS+PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 29.067 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The weld strength increases with increasing weld depth.

The maximum attainable weld strength increases with increasing weld depth.

4.3.4 Tensile Test Results – C4 (PMMA to ABS)

Material C is PMMA and material 4 is ABS. The strength testing results for 236 Hz Vibration Welds of Lens Material C to Housing Material 4 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 42. The weld factors are based off of Material 4's tensile strength, 36 MPa.

Table 42: Strength of 236 Hz Vibration Welds of Lens Material C (PMMA) to Housing Material 4 (ABS) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	31.772	0.883
1	0.5	32.690	0.908
1	0.7	34.994	0.972
3	0.3	14.765	0.410
3	0.5	16.008	0.445
3	0.7	24.901	0.692
5	0.3	9.450	0.263
5	0.5	10.181	0.283
5	0.7	14.471	0.402

The strength testing results for 236 Hz Vibration Welds of Lens Material C to Housing Material 4 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 43.

Table 43: Strength of 236 Hz Vibration Welds of Lens Material C (PMMA) to Housing Material 4 (ABS) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	13.756	0.382
1	0.5	31.967	0.888
1	0.7	33.261	0.924
3	0.3	21.717	0.603
3	0.5	15.406	0.428
3	0.7	21.922	0.609
5	0.3	6.712	0.186
5	0.5	15.506	0.431
5	0.7	22.620	0.628

Welds at the same parameters became stronger as the weld depth increased. The high amplitude welds reacted negatively to increases in pressure, whereas the low amplitude welds seemed insensitive to pressure changes.

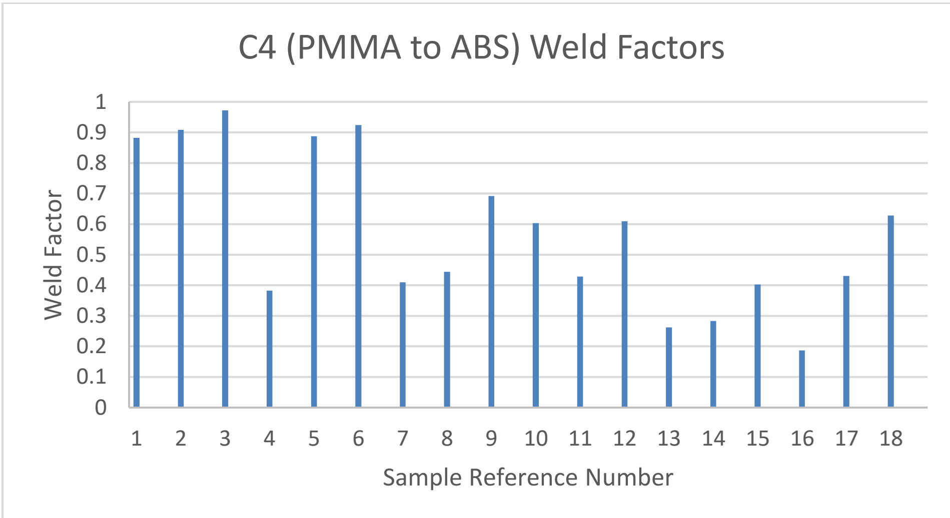

Figure 99: C4 (PMMA to ABS) Weld Factors. Weld sample 3 achieved the highest weld factor of 0.972 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum weld strength, 34.994 MPa, is achieved with a weld pressure of 1 MPa, a weld depth of 0.7 mm, and a weld amplitude of 1.78 mm. Its weld factor is 0.972.

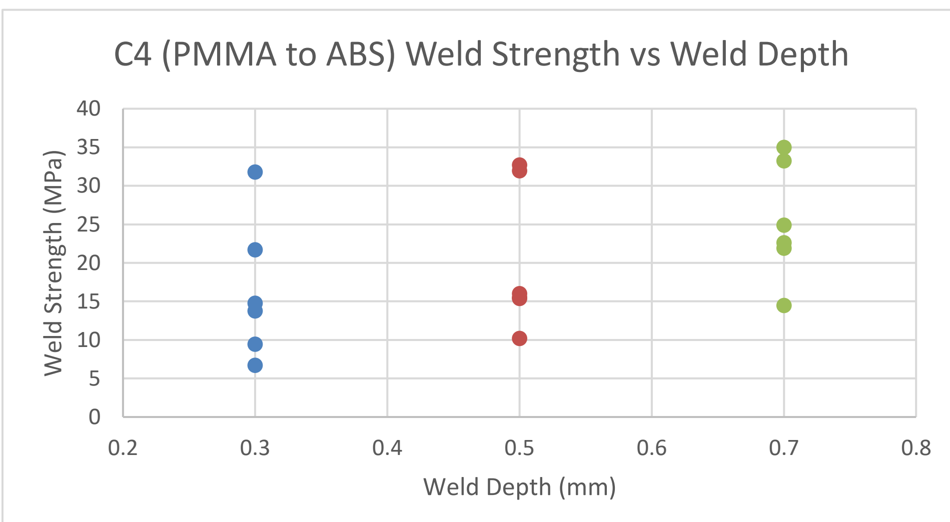

Figure 100: C4 (PMMA to ABS) Weld Strength vs Weld Depth. The maximum weld strength achieved is 20.996 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The weld strength slowly increases with increasing weld depth.

The maximum achievable weld strength increases slightly with the weld depth, almost reaching the base material's strength.

4.3.5 Tensile Test Results – C5 (PMMA to ASA)

Material C is PMMA and material 5 is ASA. The strength testing results for 236 Hz Vibration Welds of Lens Material C to Housing Material 5 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 44. The weld factors are based off of Material 5's tensile strength, 33 MPa.

Table 44: Strength of 236 Hz Vibration Welds of Lens Material C (PMMA) to Housing Material 5 (ASA) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	10.383	0.315
1	0.5	19.058	0.578
1	0.7	26.428	0.801
3	0.3	13.106	0.397
3	0.5	15.852	0.480
3	0.7	17.539	0.531
5	0.3	4.252	0.129
5	0.5	7.603	0.230
5	0.7	10.883	0.330

The strength testing results for 236 Hz Vibration Welds of Lens Material C to Housing Material 5 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 45.

Table 45: Strength of 236 Hz Vibration Welds of Lens Material C (PMMA) to Housing Material 5 (ASA) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	18.944	0.574
1	0.5	24.923	0.755
1	0.7	31.259	0.947
3	0.3	11.627	0.352
3	0.5	17.163	0.520
3	0.7	20.565	0.623
5	0.3	3.911	0.119
5	0.5	4.186	0.127
5	0.7	13.722	0.416

Majority of the low amplitude welds outperform the high amplitude welds at the same settings. An increase in weld pressure causes a decrease in strength for almost all of the tested parameter sets, as shown below.

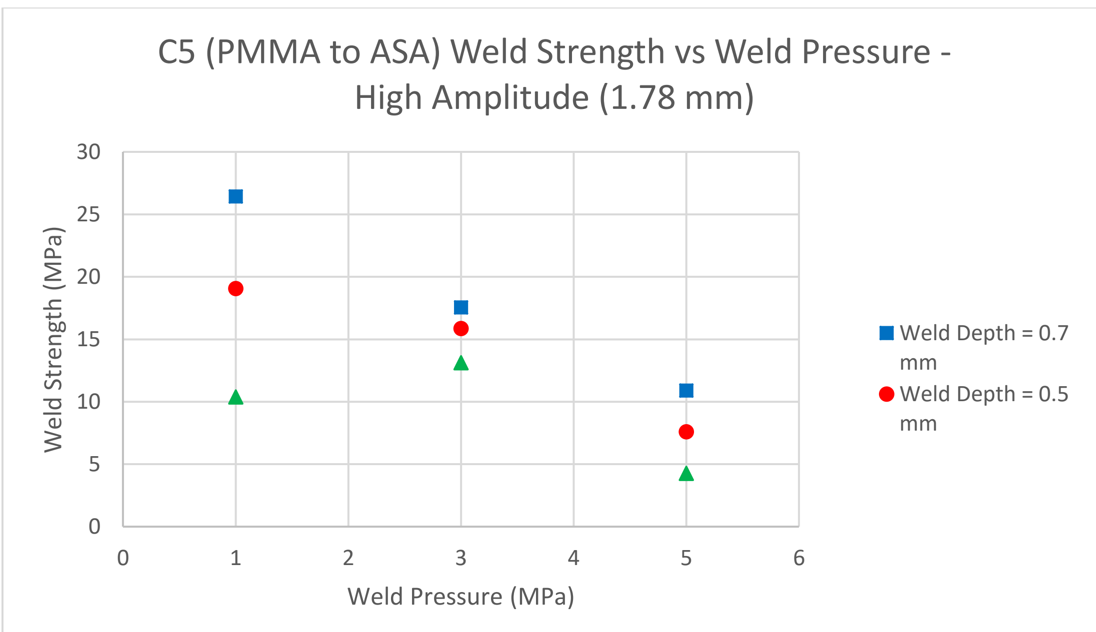

Figure 101: C5 (PMMA to ASA) weld strength vs weld pressure at high amplitude (a = 1.78 mm) for varying weld depths. The weld strength decreases with increasing weld pressure.

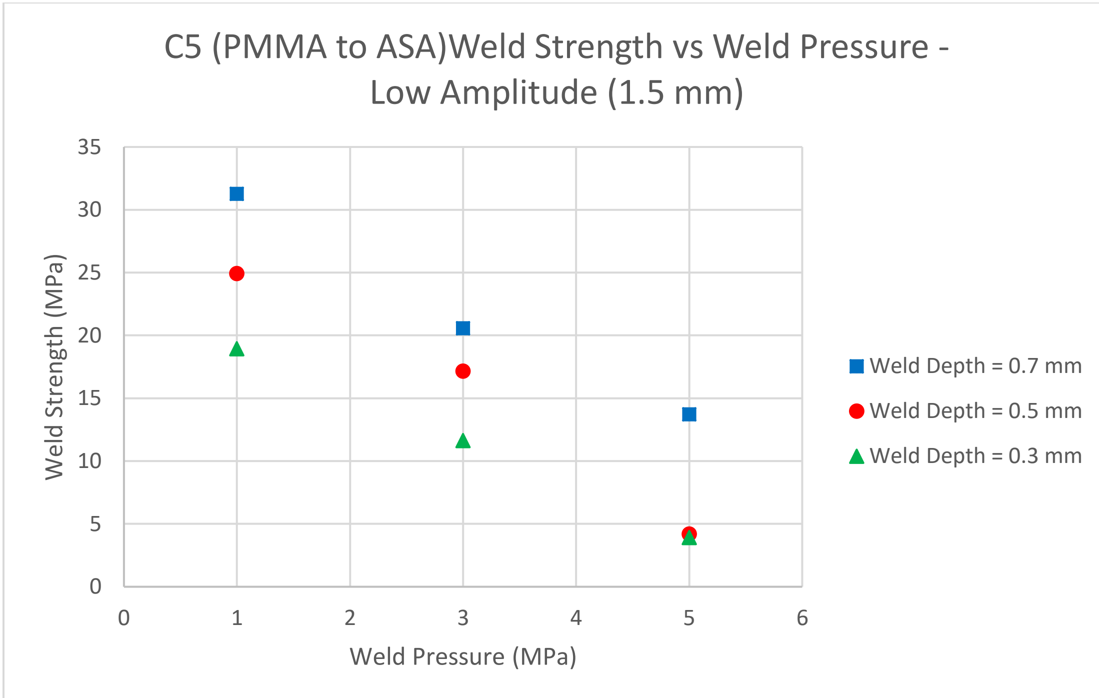

Figure 102: C5 (PMMA to ASA) weld strength vs weld pressure at low amplitude (a = 1.5 mm) for varying weld depths. The weld strength decreases with increasing weld pressure.

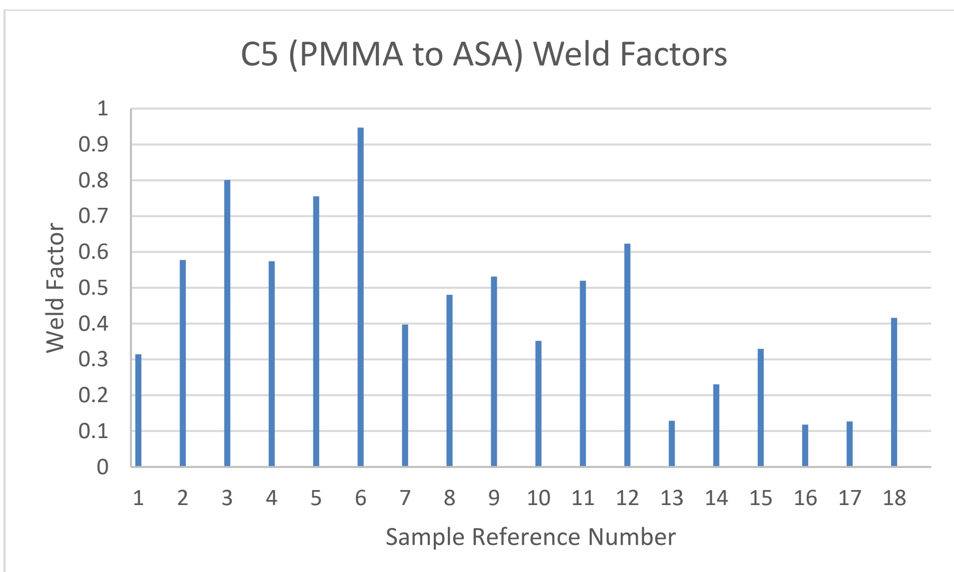

Figure 103: C5 (PMMA to ASA) Weld Factors. Weld sample 6 achieved the highest weld factor of 0.947 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

Sample 6 produced the best weld factor of 0.947 with a weld pressure of 1 MPa, a weld depth of 0.7 MPa, and a weld amplitude of 1.5 mm. Its strength is 31.259 MPa.

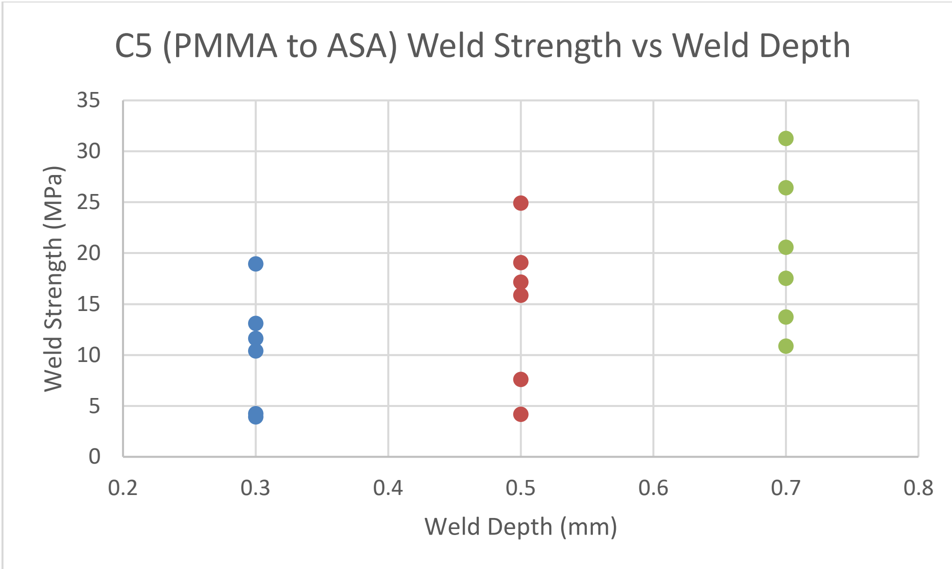

Figure 104: C5 (PMMA to ASA) Weld Strength vs Weld Depth. The maximum weld strength achieved is 31.259 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The weld strength increases with increasing weld depth.

This weld demonstrates the expected response of a LVW. The individual weld strengths increase with weld depth, as do the overall maximum achievable weld strengths at each depth. The weld strength is expected to increase further and approach the material's base strength if the weld depth is also additionally increased.

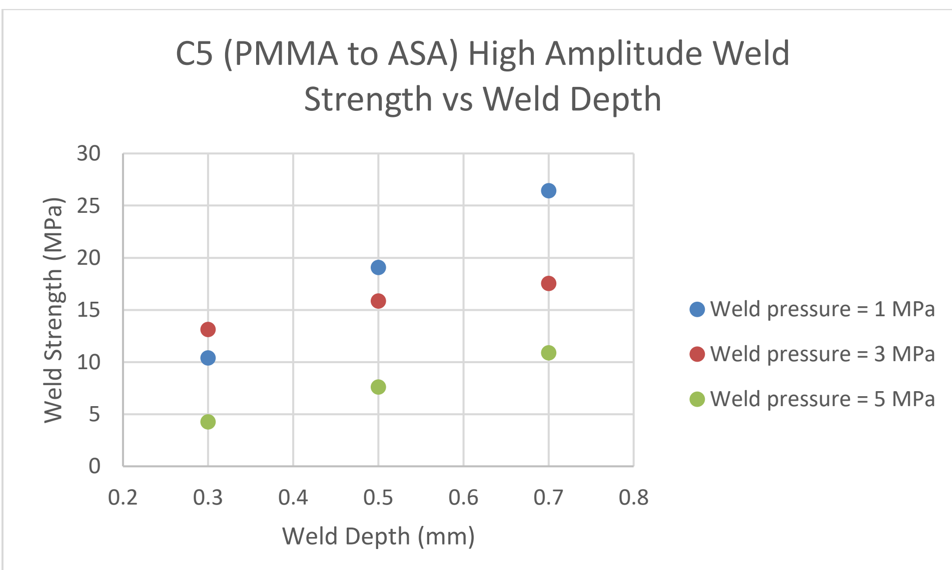

Figure 105: C5 (PMMA to ASA) Weld Strength vs Weld Depth for high amplitude (a = 1.78 mm) welds, with varying weld pressure. The weld strength increases with increasing weld depth.

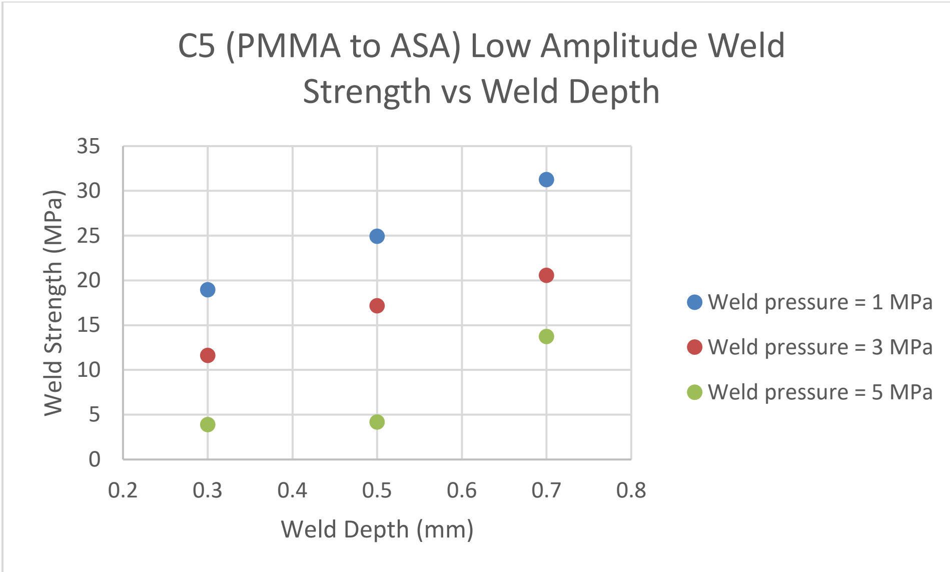

Figure 106: C5 (PMMA to ASA) Weld Strength vs Weld Depth for low amplitude (a = 1.5 mm) welds, with varying weld pressure. The weld strength increases with increasing weld depth.

4.3.6 Tensile Test Results – C6 (PMMA to ASA+PC)

Material C is PMMA and material 6 is an ASA+PC blend. The strength testing results for 236 Hz Vibration Welds of Lens Material C to Housing Material 6 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 46. The weld factors are based off of Material C's tensile strength, 48 MPa.

Table 46: Strength of 236 Hz Vibration Welds of Lens Material C (PMMA) to Housing Material 6 (ASA+PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	10.286	0.214
1	0.5	10.343	0.215
1	0.7	16.016	0.334
3	0.3	3.352	0.070
3	0.5	9.328	0.194
3	0.7	10.733	0.224
5	0.3	2.380	0.050
5	0.5	3.819	0.080
5	0.7	5.416	0.113

The strength testing results for 236 Hz Vibration Welds of Lens Material C to Housing Material 6 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 47.

Table 47: Strength of 236 Hz Vibration Welds of Lens Material C (PMMA) to Housing Material 6 (ASA+PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	8.788	0.183
1	0.5	13.463	0.280
1	0.7	17.173	0.358
3	0.3	6.166	0.128
3	0.5	6.816	0.142
3	0.7	11.130	0.232
5	0.3	0.000	0.000
5	0.5	5.304	0.111
5	0.7	7.240	0.151

The weld strengths increase with increasing weld depth and decrease with increasing pressure. Every weld at a depth of 0.7 mm was stronger when using the lower weld amplitude of 1.5 mm.

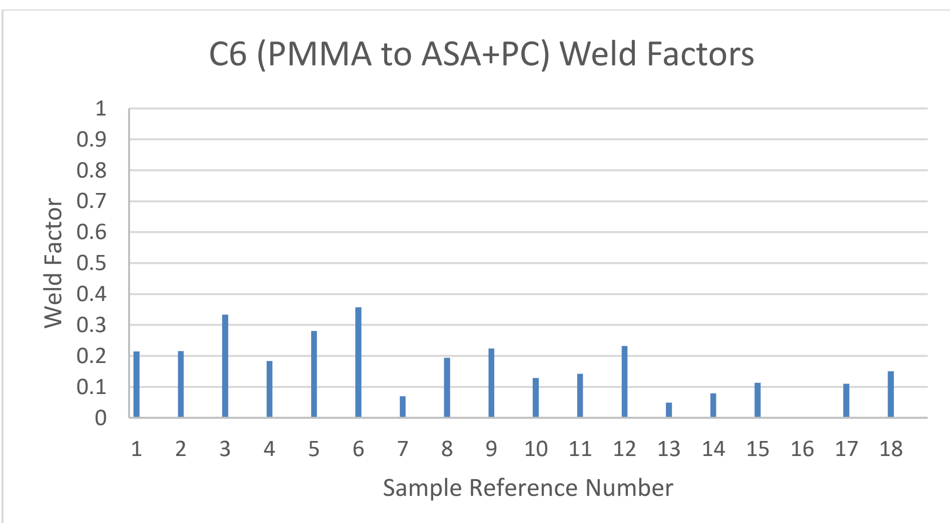

Figure 107: C6 (PMMA to ASA+PC) Weld Factors. Weld sample 6 achieved the highest weld factor of 0.358 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum weld factor is 0.358, using a weld pressure of 1 MPa, a weld amplitude of 1.5mm, and a weld depth of 0.7 mm. A maximum weld strength of 17.173 MPa is achieved.

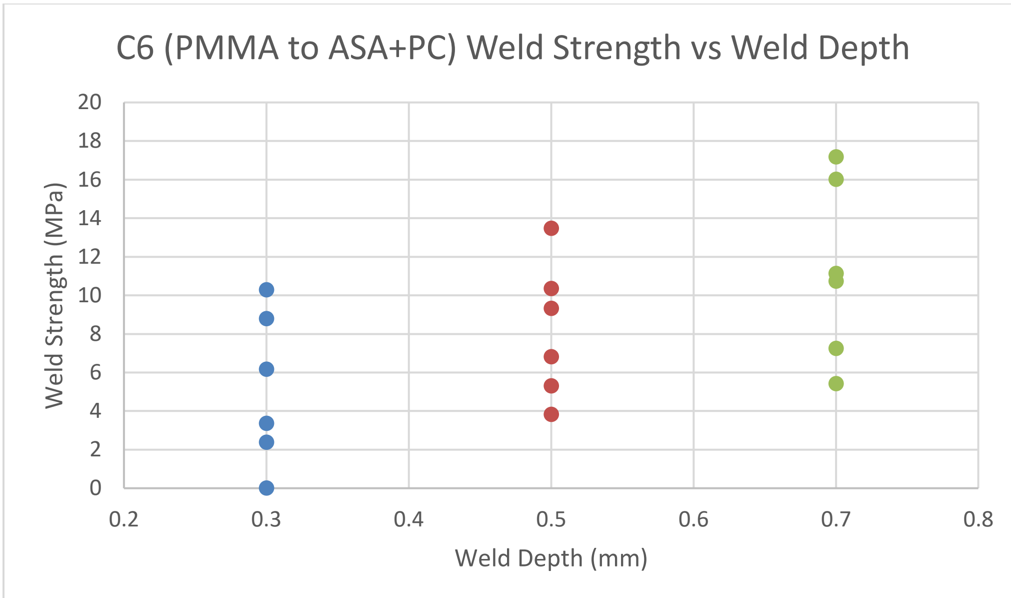

Figure 108: C6 (PMMA to ASA+PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 17.173 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The weld strength increases with increasing weld depth.

The maximum achievable weld strengths continually increase with increasing weld depth.

4.4 Lens D (PMMA) Combinations – Weld Strength Testing Results

4.4.1 Tensile Test Results – D1 (PMMA to PC)

Material D is PMMA and material 1 is PC. The strength testing results for 236 Hz Vibration Welds of Lens Material D to Housing Material 1 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 48. The weld factors are based off of Material 1’s tensile strength, 68 MPa.

Table 48: Strength of 236 Hz Vibration Welds of Lens Material D (PMMA) to Housing Material 1 (PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	5.985	0.088
1	0.5	12.153	0.179
1	0.7	10.752	0.158
3	0.3	5.762	0.085
3	0.5	7.223	0.106
3	0.7	11.340	0.167
5	0.3	10.497	0.154
5	0.5	9.871	0.145
5	0.7	10.892	0.160

The strength testing results for 236 Hz Vibration Welds of Lens Material D to Housing Material 1 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 49.

Table 49: Strength of 236 Hz Vibration Welds of Lens Material D (PMMA) to Housing Material 1 (PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	8.746	0.129
1	0.5	11.134	0.164
1	0.7	9.114	0.134
3	0.3	4.659	0.069
3	0.5	7.605	0.112
3	0.7	9.208	0.135
5	0.3	10.350	0.152
5	0.5	8.775	0.129
5	0.7	14.626	0.215

The weld strengths appear insensitive to the weld pressure and the weld amplitude.

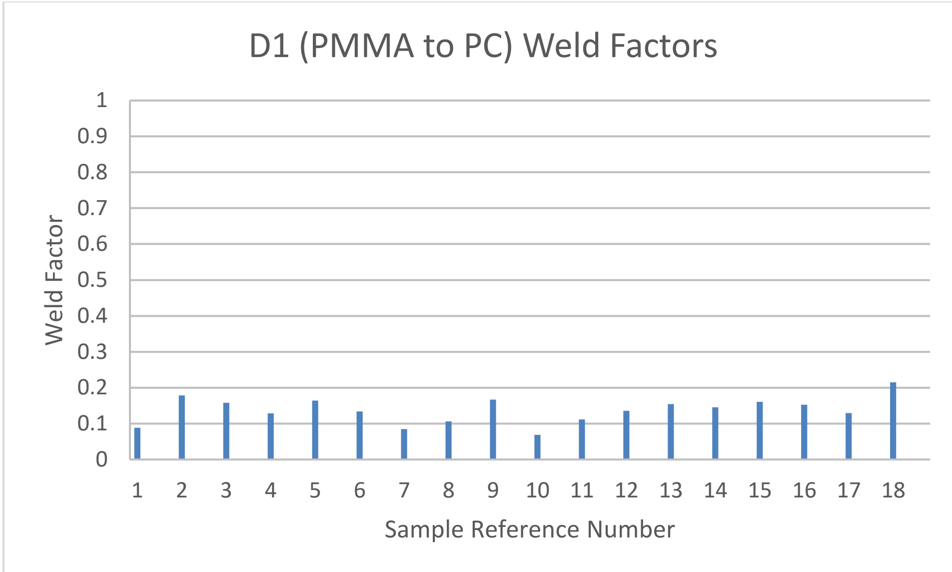

Figure 109: D1 (PMMA to PC) Weld Factors. Weld sample 18 achieved the highest weld factor of 0.215 at a welding depth of 0.7 mm, welding pressure of 5 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum strength achieved is 14.626 MPa, with a weld factor of 0.215. This was determined using a pressure of 5 MPa, a weld depth of 0.7 mm, and a weld amplitude of 1.5 mm. This low weld factor translates to poor welds.

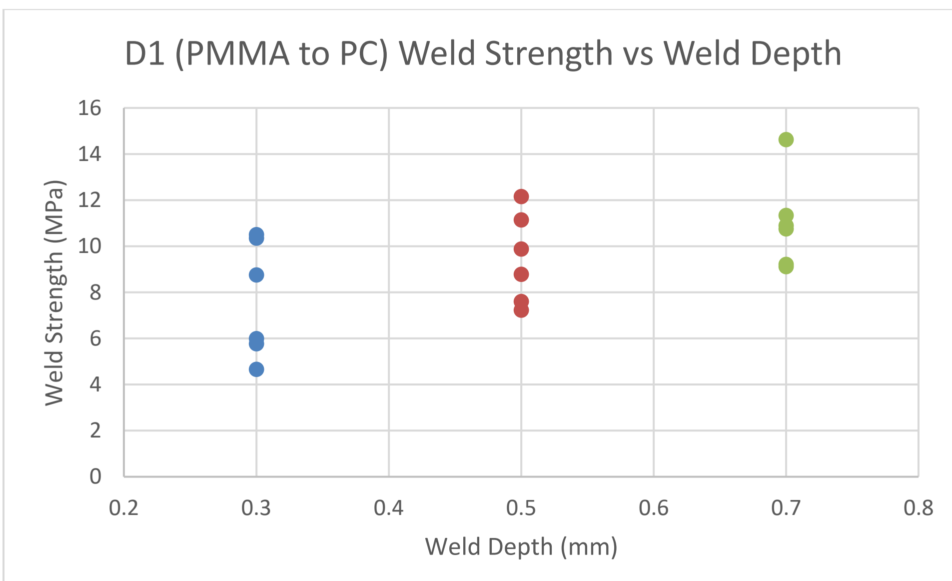

Figure 110: D1 (PMMA to PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 14.626 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 5 MPa, and a welding amplitude of 1.5 mm. The weld strength increases with increasing weld depth.

The graph above does prove that although the weld results were poor, the maximum attainable strength can be improved by increasing the weld depth.

4.4.2 Tensile Test Results – D2 (PMMA to PC+ABS)

Material D is PMMA and material 2 is a PC+ABS blend. The strength testing results for 236 Hz Vibration Welds of Lens Material D to Housing Material 2 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 50. The weld factors are based off of Material 2's tensile strength, 56 MPa.

Table 50: Strength of 236 Hz Vibration Welds of Lens Material D (PMMA) to Housing Material 2 (PC+ABS) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	6.328	0.113
1	0.5	14.089	0.252
1	0.7	8.655	0.155
3	0.3	8.110	0.145
3	0.5	10.564	0.189
3	0.7	6.199	0.111
5	0.3	7.540	0.135
5	0.5	9.827	0.175
5	0.7	6.697	0.120

The strength testing results for 236 Hz Vibration Welds of Lens Material D to Housing Material 2 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 51.

Table 51: Strength of 236 Hz Vibration Welds of Lens Material D (PMMA) to Housing Material 2 (PC+ABS) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	8.668	0.155
1	0.5	8.692	0.155
1	0.7	9.289	0.166
3	0.3	3.548	0.063
3	0.5	7.244	0.129
3	0.7	9.093	0.162
5	0.3	10.284	0.184
5	0.5	10.489	0.187
5	0.7	10.519	0.188

The weld strengths appear to be independent of weld depth, amplitude, and pressure.

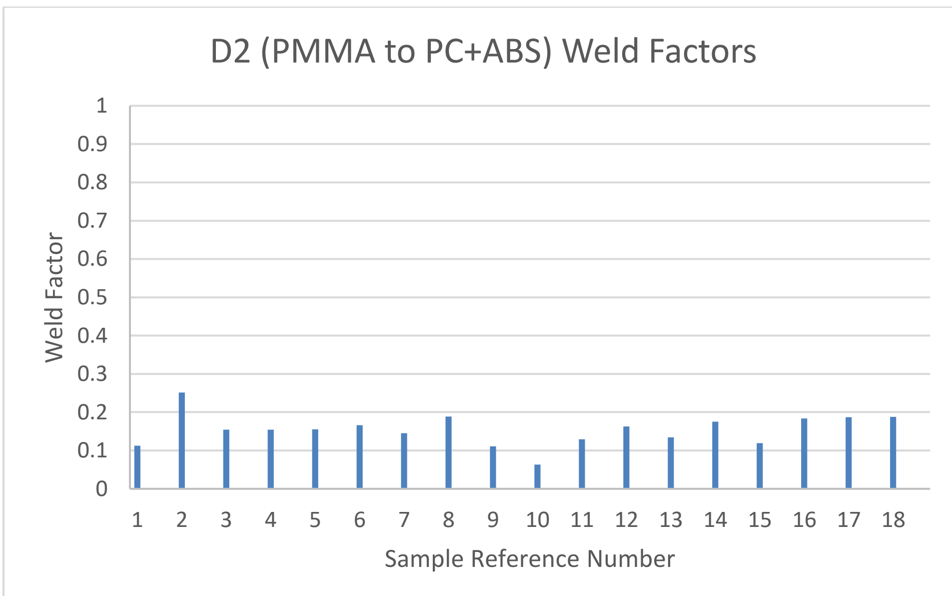

Figure 111: D2 (PMMA to PC+ABS) Weld Factors. Weld sample 2 achieved the highest weld factor of 0.252 at a welding depth of 0.5 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The highest weld strength is 14.089 MPa, corresponding to a weld factor of 0.252. This weld uses a weld pressure of 1 MPa, a weld amplitude of 1.78 mm, and a weld depth of 0.5 mm.

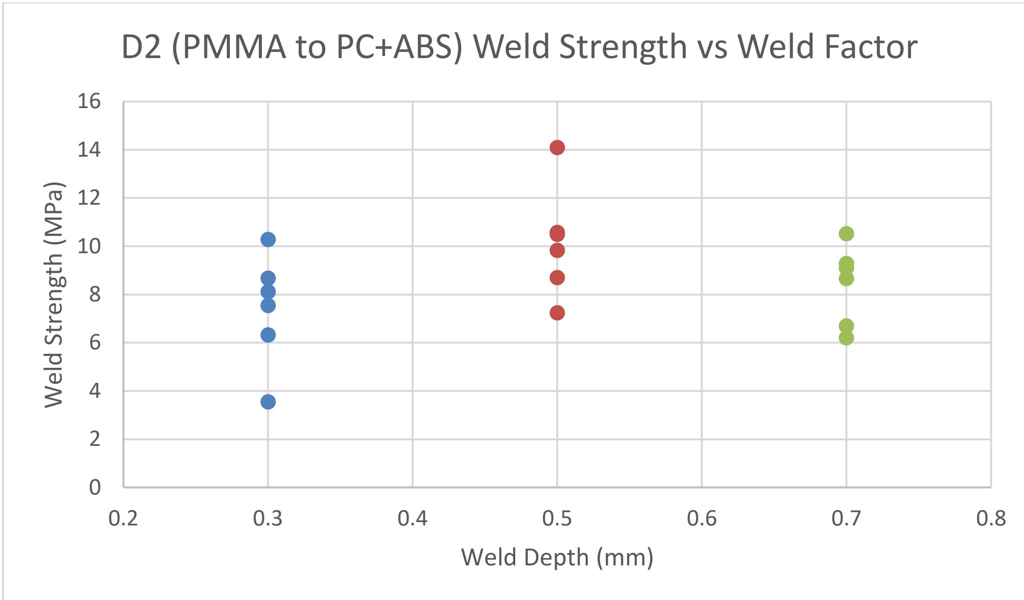

Figure 112: D2 (PMMA to PC+ABS) Weld Strength vs Weld Depth. The maximum weld strength achieved is 14.089 MPa. This weld was created using a welding depth of 0.5 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. This trend can be assumed to be caused by random mixing and interactions between the welding parameters, but the exact cause cannot be surely determined.

The highest strength was achieved using a weld depth of 0.5 mm. This is surprising since typically welds become stronger with deeper weld penetration. This leads to believe that there may be unpredictable interactions between parameters. More likely, material combinations that create low weld factors may just depend on the randomness of the mixing at the weld interface.

4.4.3 Tensile Test Results – D3 (PMMA to ABS+PC)

Material D is PMMA and material 3 is an ABS+PC blend. The strength testing results for 236 Hz Vibration Welds of Lens Material D to Housing Material 3 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 52. The weld factors are based off of Material 3's tensile strength, 44 MPa.

Table 52: Strength of 236 Hz Vibration Welds of Lens Material D (PMMA) to Housing Material 3 (ABS+PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	12.934	0.294
1	0.5	15.142	0.344
1	0.7	10.847	0.247
3	0.3	14.281	0.325
3	0.5	15.377	0.349
3	0.7	13.452	0.306
5	0.3	12.241	0.278
5	0.5	9.150	0.208
5	0.7	14.338	0.326

The strength testing results for 236 Hz Vibration Welds of Lens Material D to Housing Material 3 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 53.

Table 53: Strength of 236 Hz Vibration Welds of Lens Material D (PMMA) to Housing Material 3 (ABS+PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	13.873	0.315
1	0.5	10.677	0.243
1	0.7	12.281	0.279
3	0.3	14.531	0.330
3	0.5	12.365	0.281
3	0.7	11.661	0.265
5	0.3	13.428	0.305
5	0.5	13.519	0.307
5	0.7	11.796	0.268

In almost all parameter sets, the weld strength attained a higher value at a weld depth of 0.5 rather than the logical 0.7. The welds seem insensitive to the welding pressure, weld amplitude, and weld depth.

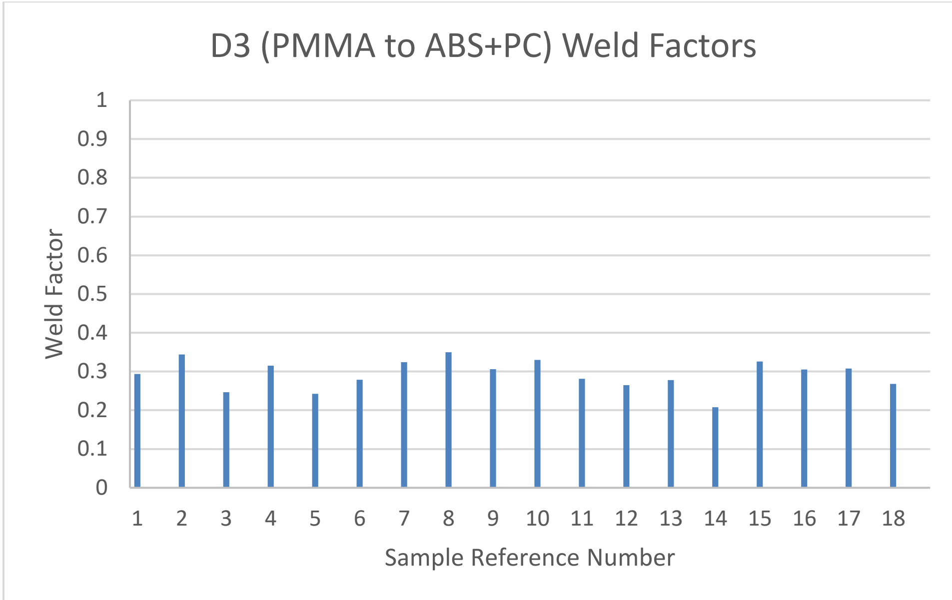

Figure 113: D3 (PMMA to ABS+PC) Weld Factors. Weld sample 8 achieved the highest weld factor of 0.349 at a welding depth of 0.5 mm, welding pressure of 3 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum weld factor is 0.349 calculated using the maximum weld strength of 15.377 MPa. This weld uses a welding pressure of 3 MPa, a weld depth of 0.5 mm, and a weld amplitude of 1.78 mm.

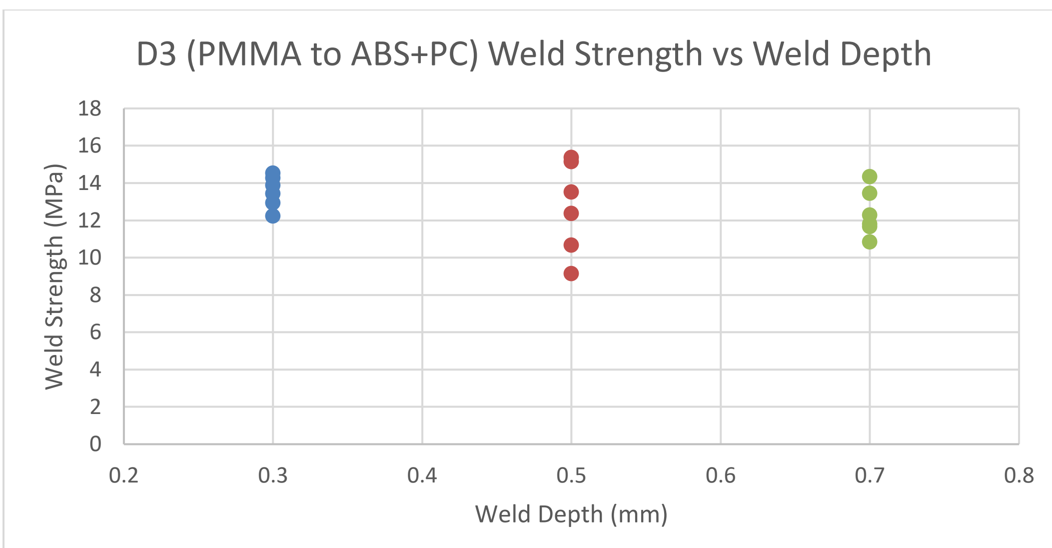

Figure 114: D3 (PMMA to ABS+PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 15.377 MPa. This weld was created using a welding depth of 0.5 mm, welding pressure of 3 MPa, and a welding amplitude of 1.78 mm. The weld strength does not increase with increasing weld depth. This material combination is insensitive to the welding parameters.

The highest strength attained is at a weld depth of 0.5 mm.

4.4.4 Tensile Test Results – D4 (PMMA to ABS)

Material D is PMMA and material 4 is ABS. The strength testing results for 236 Hz Vibration Welds of Lens Material D to Housing Material 4 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 54. The weld factors are based off of Material 4's tensile strength, 36 MPa.

Table 54: Strength of 236 Hz Vibration Welds of Lens Material D (PMMA) to Housing Material 4 (ABS) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	9.374	0.260
1	0.5	14.076	0.391
1	0.7	12.257	0.340
3	0.3	14.839	0.412
3	0.5	6.146	0.171
3	0.7	10.416	0.289
5	0.3	17.112	0.475
5	0.5	8.230	0.229
5	0.7	10.819	0.301

The strength testing results for 236 Hz Vibration Welds of Lens Material D to Housing Material 4 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 55.

Table 55: Strength of 236 Hz Vibration Welds of Lens Material D (PMMA) to Housing Material 4 (ABS) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	15.018	0.417
1	0.5	10.674	0.297
1	0.7	16.243	0.451
3	0.3	12.509	0.347
3	0.5	12.175	0.338
3	0.7	9.892	0.275
5	0.3	17.355	0.482
5	0.5	14.708	0.409
5	0.7	8.625	0.240

This material combination is insensitive to weld pressure, weld frequency, and weld depth.

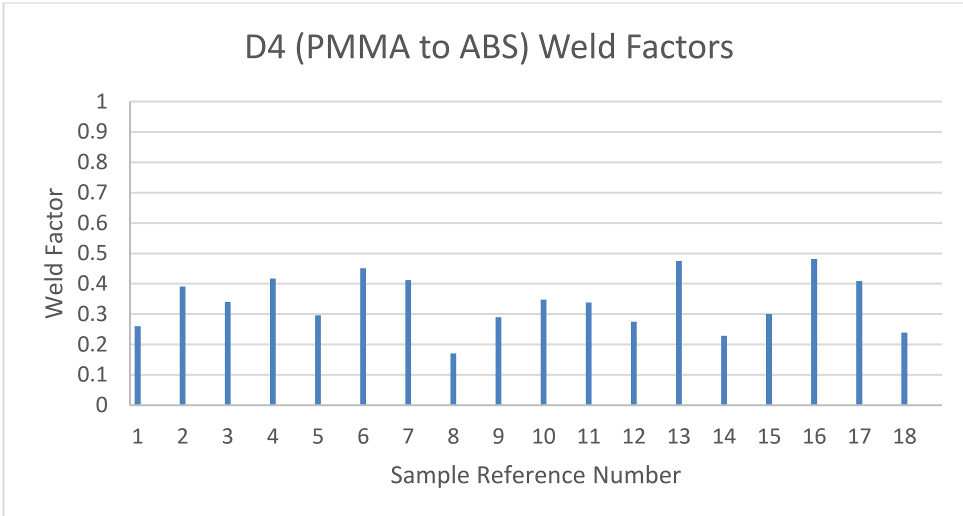

Figure 115: D4 (PMMA to ABS) Weld Factors. Weld sample 16 achieved the highest weld factor of 0.482 at a welding depth of 0.3 mm, welding pressure of 5 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum weld strength is 17.354 MPa and its weld factor is 0.482. The weld parameters are a pressure of 5 MPa, a weld depth of 0.3 mm, and a weld amplitude of 1.5 mm.

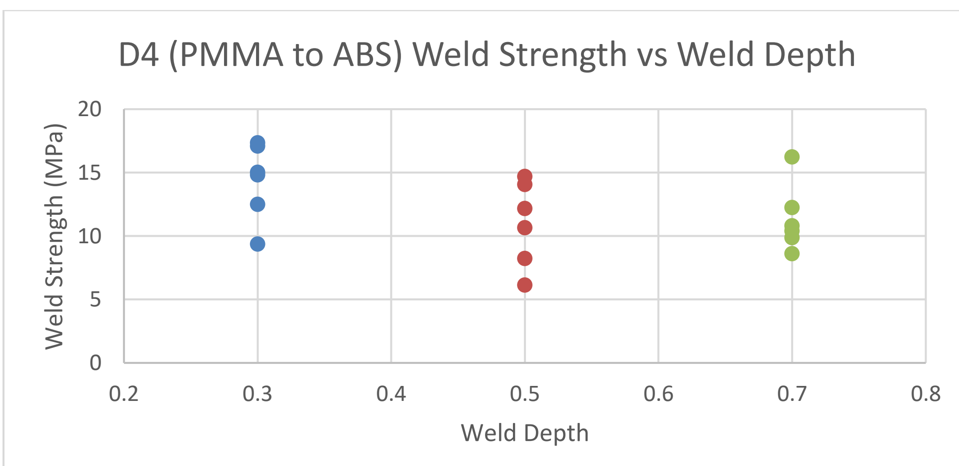

Figure 116: D4 (PMMA to ABS) Weld Strength vs Weld Depth. The maximum weld strength achieved is 17.355 MPa. This weld was created using a welding depth of 0.3 mm, welding pressure of 5 MPa, and a welding amplitude of 1.5 mm. This material combination is insensitive to the weld parameters.

The maximum achievable weld strength occurred at a weld depth of 0.3 mm.

4.4.5 Tensile Test Results – D5 (PMMA to ASA)

Material D is PMMA and material 5 is ASA. The strength testing results for 236 Hz Vibration Welds of Lens Material D to Housing Material 5 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 56. The weld factors are based off of Material 5's tensile strength, 33 MPa.

Table 56: Strength of 236 Hz Vibration Welds of Lens Material D (PMMA) to Housing Material 5 (ASA) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	9.224	0.280
1	0.5	9.881	0.299
1	0.7	9.346	0.283
3	0.3	9.349	0.283
3	0.5	6.217	0.188
3	0.7	7.758	0.235
5	0.3	12.451	0.377
5	0.5	7.583	0.230
5	0.7	10.840	0.328

The strength testing results for 236 Hz Vibration Welds of Lens Material D to Housing Material 5 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 57.

Table 57: Strength of 236 Hz Vibration Welds of Lens Material D (PMMA) to Housing Material 5 (ASA) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	12.450	0.377
1	0.5	8.203	0.249
1	0.7	12.014	0.364
3	0.3	7.658	0.232
3	0.5	10.072	0.305
3	0.7	10.245	0.310
5	0.3	15.077	0.457
5	0.5	13.231	0.401
5	0.7	6.855	0.208

The weld is insensitive to weld pressure, and weld amplitude.

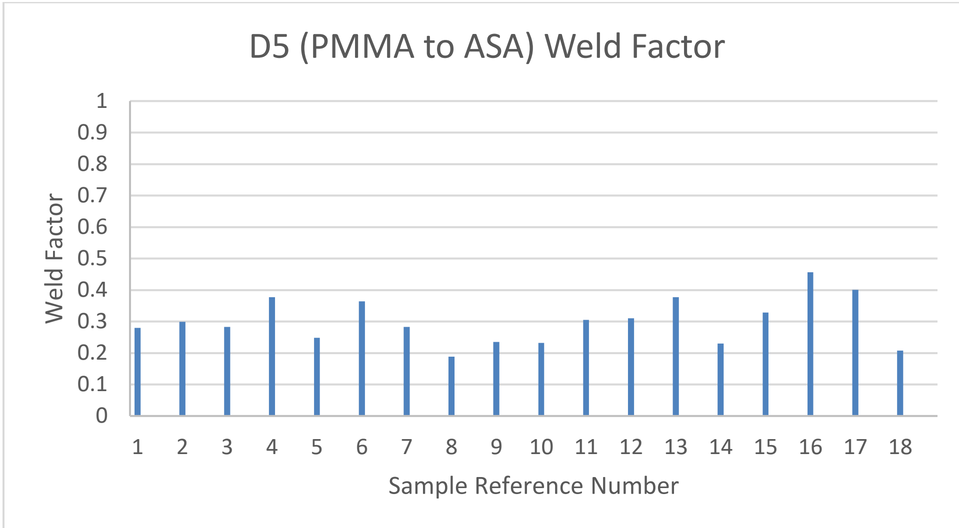

Figure 117: D5 (PMMA to ASA) Weld Factors. Weld sample 16 achieved the highest weld factor of 0.457 at a welding depth of 0.3 mm, welding pressure of 5 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum weld strength is 15.076 MPa, with a weld factor of 0.457. This is given from sample 16. The weld settings are a pressure of 5 MPa, a weld depth of 0.3 mm, and a weld amplitude of 1.5 mm.

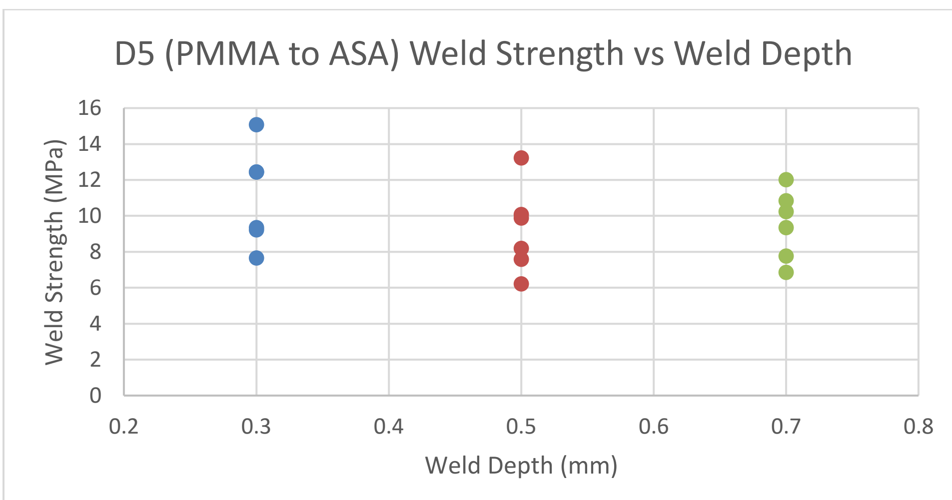

Figure 118: D5 (PMMA to ASA) Weld Strength vs Weld Depth. The maximum weld strength achieved is 15.077 MPa. This weld was created using a welding depth of 0.3 mm, welding pressure of 5 MPa, and a welding amplitude of 1.5 mm. The weld strength decreases with increasing weld depth.

The maximum achievable weld strength occurred at a weld depth of 0.3 mm. The weld strength decreases with increasing weld depth.

4.4.6 Tensile Test Results – D6 (PMMA to ASA+PC)

Material D is PMMA and material 6 is an ASA+PC blend. The strength testing results for 236 Hz Vibration Welds of Lens Material D to Housing Material 6 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 58. The weld factors are based off of Material 5's tensile strength, 62.1 MPa.

Table 58: Strength of 236 Hz Vibration Welds of Lens Material D (PMMA) to Housing Material 1 (PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	8.495	0.137
1	0.5	9.406	0.151
1	0.7	11.808	0.190
3	0.3	5.825	0.094
3	0.5	7.956	0.128
3	0.7	5.189	0.084
5	0.3	7.561	0.122
5	0.5	8.640	0.139
5	0.7	12.629	0.203

The strength testing results for 236 Hz Vibration Welds of Lens Material D to Housing Material 6 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 59.

Table 59: Strength of 236 Hz Vibration Welds of Lens Material D (PMMA) to Housing Material 6 (ASA+PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	8.681	0.140
1	0.5	10.347	0.167
1	0.7	6.160	0.099
3	0.3	6.704	0.108
3	0.5	6.948	0.112
3	0.7	7.836	0.126
5	0.3	10.963	0.177
5	0.5	8.667	0.140
5	0.7	7.875	0.127

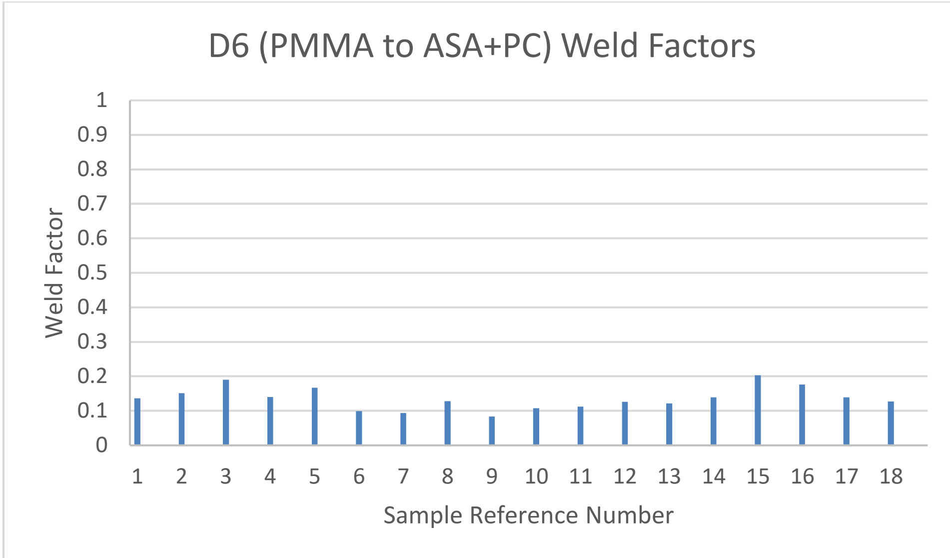

Figure 119: D6 (PMMA to ASA+PC) Weld Factors. Weld sample 15 achieved the highest weld factor of 0.203 at a welding depth of 0.7 mm, welding pressure of 5 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum weld strength is 12.629 MPa and its weld factor is 0.203. The weld parameters used to attain this value are a weld pressure of 5 MPa, a weld depth of 0.7 mm, and a weld amplitude of 1.78 mm.

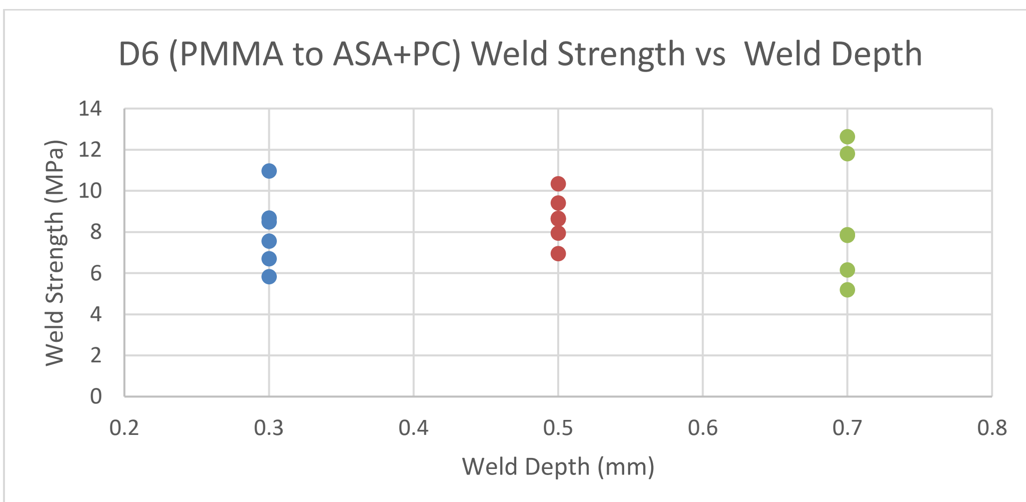

Figure 120: D6 (PMMA to ASA+PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 12.629 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 5 MPa, and a welding amplitude of 1.78 mm. The maximum weld strength may be attained. If not, the weld strength will slowly increase with increasing weld depth.

The maximum strength may have been attained. If not, it will slightly increase by increasing the weld depth.

4.5 Lens E (PC) Combinations – Weld Strength Testing Results

4.5.1 Tensile Test Results – E1 (PC to PC)

Both material E and material 1 are PC. The strength testing results for 236 Hz Vibration Welds of Lens Material E to Housing Material 1 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 60. The weld factors are based off of Material 5's tensile strength, 62 MPa.

Table 60: Strength of 236 Hz Vibration Welds of Lens Material E (PC) to Housing Material 1 (PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	41.901	0.676
1	0.5	62.137	1.002
1	0.7	69.647	1.123
3	0.3	32.287	0.521
3	0.5	46.263	0.746
3	0.7	42.394	0.684
5	0.3	28.569	0.461
5	0.5	47.440	0.765
5	0.7	58.882	0.950

The strength testing results for 236 Hz Vibration Welds of Lens Material E to Housing Material 1 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 61.

Table 61: Strength of 236 Hz Vibration Welds of Lens Material E (PC) to Housing Material 1 (PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	44.281	0.714
1	0.5	45.814	0.739
1	0.7	59.325	0.957
3	0.3	26.326	0.425
3	0.5	29.874	0.482
3	0.7	37.206	0.600
5	0.3	28.503	0.460
5	0.5	54.517	0.879
5	0.7	61.787	0.997

The weld strength increases with increasing weld depth. The higher amplitude welds generally yielded stronger results.

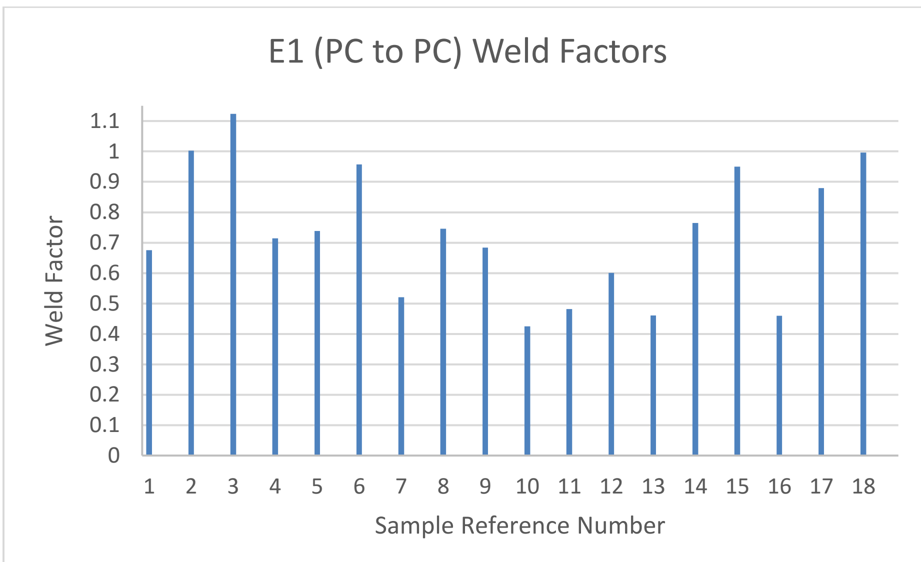

Figure 121: E1 (PC to PC) Weld Factors. Weld sample 2 and 3 both achieve a weld factor of unity using a welding depth of 0.5 or 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. Sample 18 reaches a weld factor of 0.997 using a welding depth of 0.7 mm, a weld pressure of 5 MPa, a weld amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The base material strength of 62 MPa can be reached at multiple different welding parameters. Using a pressure of 1 MPa, a weld amplitude of 1.78 mm, and a weld depth of 0.5 mm or 0.7 mm.

The weld strength is 61.787 and the weld factor is 0.997 at a welding pressure of 5 MPa, a weld depth of 0.7 mm, and a weld amplitude of 1.5 mm.

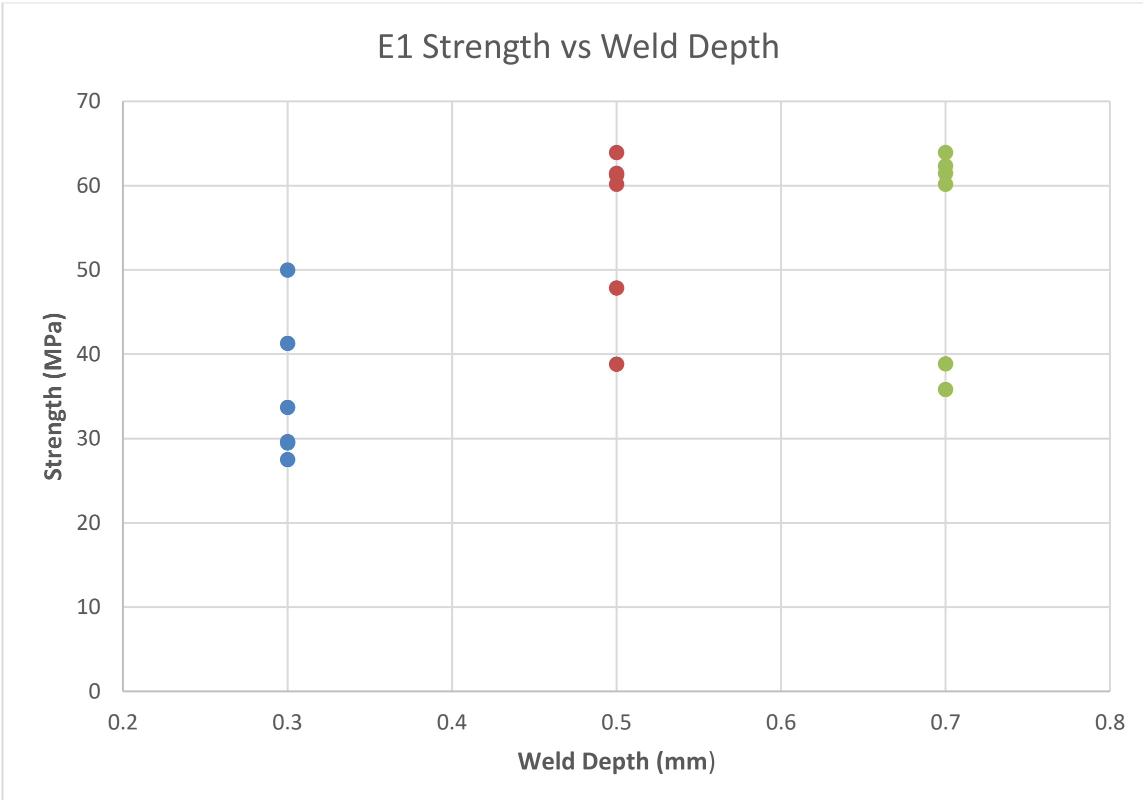

Figure 122: E1 (PC to PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 62 MPa, the strength of the weld's weaker parent material. The weld strength therefore cannot be increased with a further increase in weld depth. This weld strength is achieved created using a welding depth of 0.5 mm or 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm.

The material's base strength can be reached. This means there is a weld penetration threshold somewhere between the depth of 0.3 and 0.5 mm.

4.5.2 Tensile Test Results – E2 (PC to PC+ABS)

Material E is PC and material 2 is a PC+ABS blend. The strength testing results for 236 Hz Vibration Welds of Lens Material E to Housing Material 2 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 62. The weld factors are based off of Material 2's tensile strength, 56 MPa.

Table 62: Strength of 236 Hz Vibration Welds of Lens Material E (PC) to Housing Material 2 (PC+ABS) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	11.472	0.205
1	0.5	20.246	0.362
1	0.7	15.963	0.285
3	0.3	7.684	0.137
3	0.5	12.820	0.229
3	0.7	14.145	0.253
5	0.3	12.118	0.216
5	0.5	14.967	0.267
5	0.7	18.592	0.332

The strength testing results for 236 Hz Vibration Welds of Lens Material E to Housing Material 2 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 63.

Table 63: Strength of 236 Hz Vibration Welds of Lens Material E (PC) to Housing Material 2 (PC+ABS) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	14.085	0.252
1	0.5	20.706	0.370
1	0.7	21.260	0.380
3	0.3	7.568	0.135
3	0.5	14.225	0.254
3	0.7	14.156	0.253
5	0.3	15.368	0.274
5	0.5	20.487	0.366
5	0.7	19.778	0.353

The weld strength appears insensitive to weld pressure and weld amplitude.

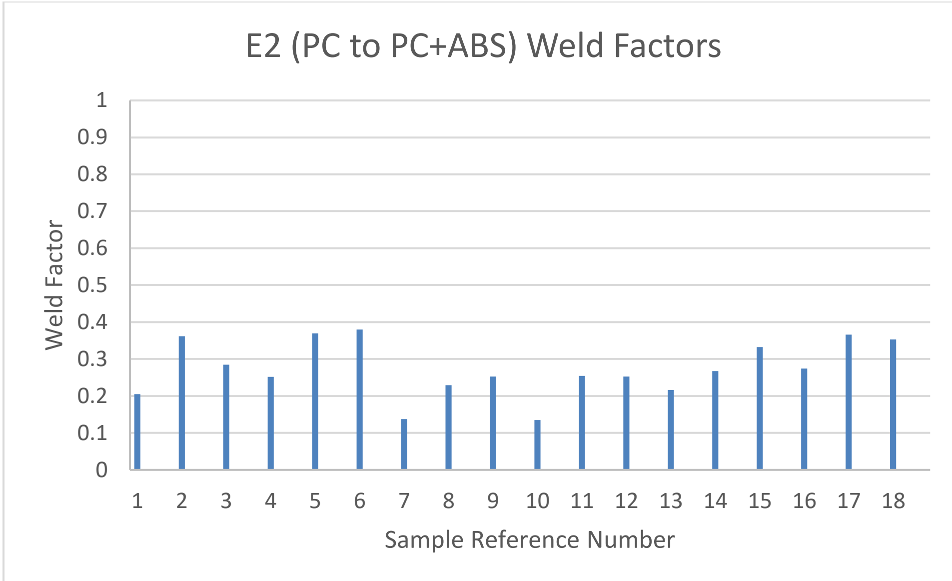

Figure 123: E2 (PC to PC+ABS) Weld Factors. Weld sample 6 achieved the highest weld factor of 0.380 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum weld strength achieved is 21.216 MPa, with a corresponding weld factor of 0.38. This is determined using a weld pressure of 1 MPa, a weld depth of 0.7 mm, and a weld amplitude 1.5 mm.

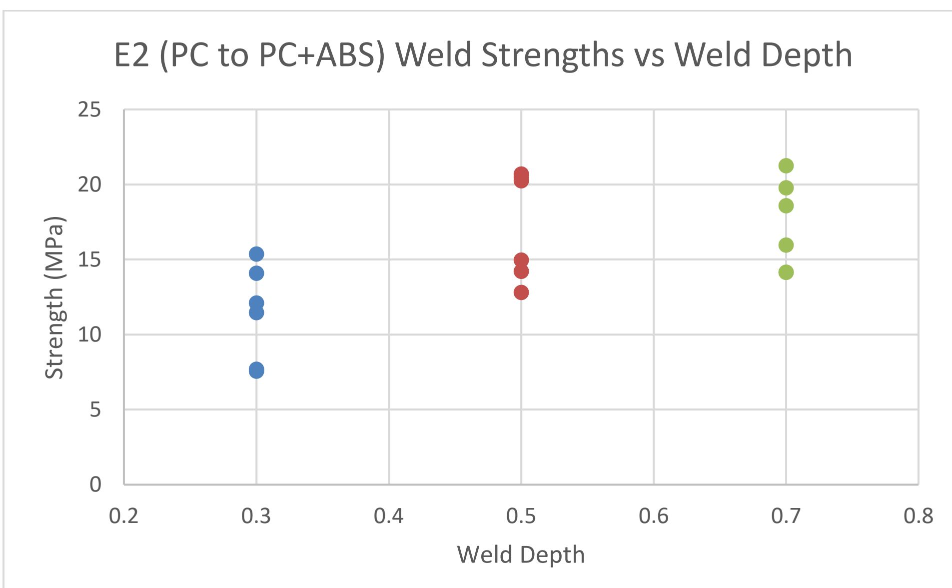

Figure 124: E2 (PC to PC+ABS) Weld Strength vs Weld Depth. The maximum weld strength achieved is 21.260 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. It is unclear if the maximum attainable strength has been obtained.

The maximum achievable weld strength appears to have a weld penetration threshold between 0.3 mm and 0.5 mm. If the maximum strength at a weld depth of 0.5 mm was an outlier, then the weld strength will continue to grow with further weld penetration.

4.5.3 Tensile Test Results – E3 (PC to ABS+PC)

Material E is PC and material 3 is an ABS+PC blend. The strength testing results for 236 Hz Vibration Welds of Lens Material E to Housing Material 3 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 64. The weld factors are based off of Material 3's tensile strength, 44 MPa.

Table 64: Strength of 236 Hz Vibration Welds of Lens Material E (PC) to Housing Material 3 (ABS+PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	28.755	0.654
1	0.5	30.026	0.682
1	0.7	31.407	0.714
3	0.3	19.148	0.435
3	0.5	18.404	0.418
3	0.7	21.592	0.491
5	0.3	23.265	0.529
5	0.5	17.355	0.394
5	0.7	29.337	0.667

The strength testing results for 236 Hz Vibration Welds of Lens Material E to Housing Material 3 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 63.

Table 65: Strength of 236 Hz Vibration Welds of Lens Material E (PC) to Housing Material 1 (PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	27.727	0.630
1	0.5	27.980	0.636
1	0.7	29.053	0.660
3	0.3	21.576	0.490
3	0.5	16.950	0.385
3	0.7	20.096	0.457
5	0.3	26.656	0.606
5	0.5	29.149	0.662
5	0.7	30.164	0.686

For pressures of 1 MPa and 3 MPa, the decrease in weld amplitude seems to decrease the weld strength at comparable parameter settings.

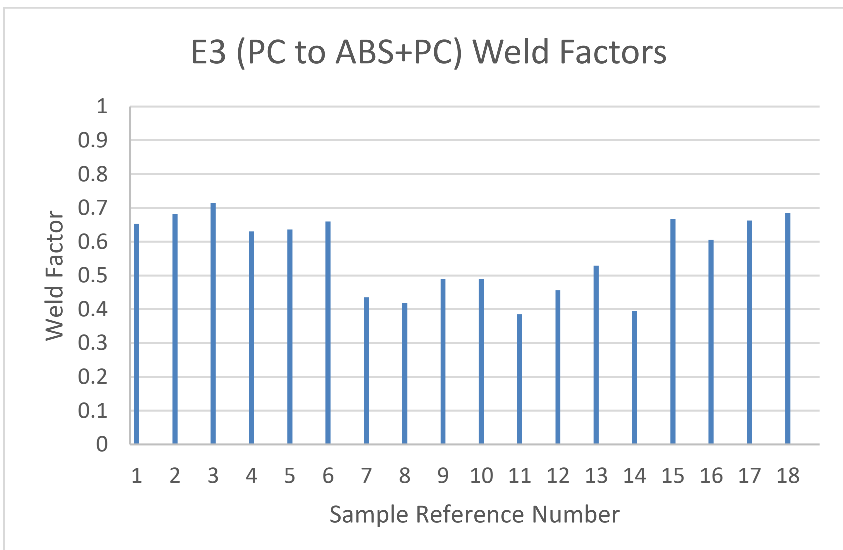

Figure 125: E3 (PC to ABS+PC) Weld Factors. Weld sample 3 achieved the highest weld factor of 0.714 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum weld strength is 31.407 MPa, with a weld factor of 0.713. The optimal welding parameters are found to be a weld pressure of 1 MPa, a weld depth of 0.7 mm, and a weld amplitude of 1.5 mm.

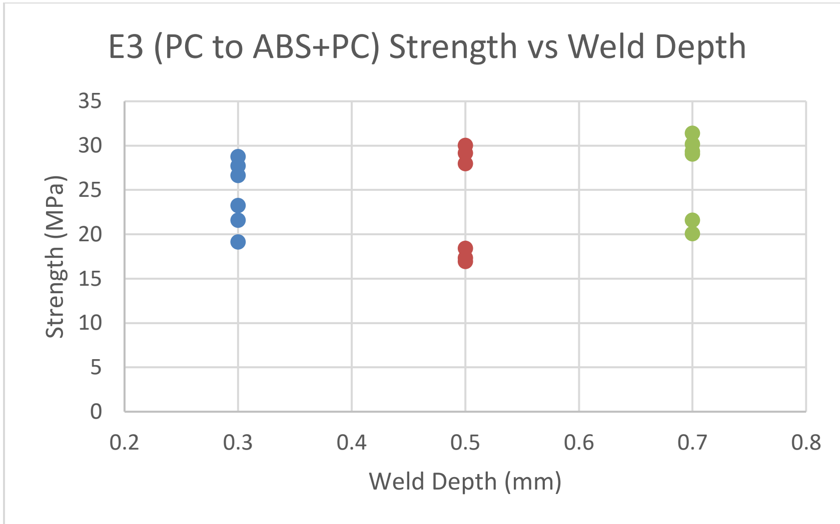

Figure 126: E3 (PC to ABS+PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 31.407 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The weld strength increases with increasing weld depth.

The maximum achievable weld strength slightly increases with further weld penetration.

4.5.4 Tensile Test Results – E4 (PC to ABS)

Material E is PC and material 4 is ABS. The strength testing results for 236 Hz Vibration Welds of Lens Material E to Housing Material 4 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 66. The weld factors are based off of Material 4's tensile strength, 36 MPa.

Table 66: Strength of 236 Hz Vibration Welds of Lens Material E (PC) to Housing Material 4 (ABS) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	19.740	0.548
1	0.5	33.270	0.924
1	0.7	37.332	1.037
3	0.3	16.156	0.449
3	0.5	23.820	0.662
3	0.7	28.025	0.778
5	0.3	22.449	0.624
5	0.5	23.986	0.666
5	0.7	14.861	0.413

The strength testing results for 236 Hz Vibration Welds of Lens Material E to Housing Material 4 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 67.

Table 67: Strength of 236 Hz Vibration Welds of Lens Material E (PC) to Housing Material 4 (ABS) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	19.870	0.552
1	0.5	29.964	0.832
1	0.7	29.931	0.831
3	0.3	22.241	0.618
3	0.5	24.959	0.693
3	0.7	11.837	0.329
5	0.3	15.996	0.444
5	0.5	22.669	0.630
5	0.7	26.008	0.722

The weld is insensitive to weld amplitude and weld pressure.

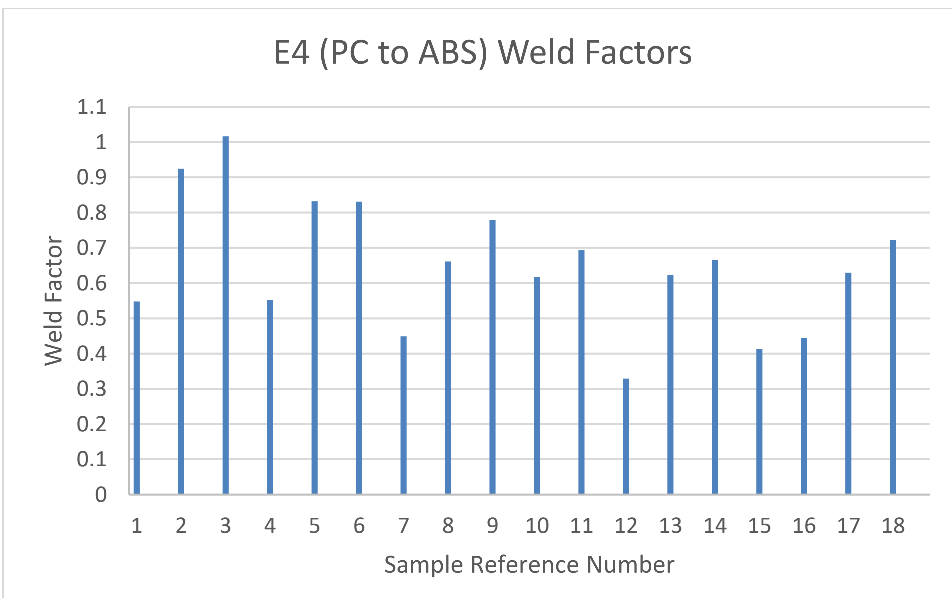

Figure 127: E4 (PC to ABS) Weld Factors. Weld sample 3 achieved a weld factor of unity at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

A weld strength equivalent to the parent base material, 36 MPa, is accomplished at a weld depth of 0.7 mm, a weld pressure of 1 MPa, and a weld amplitude of 1.78 mm.

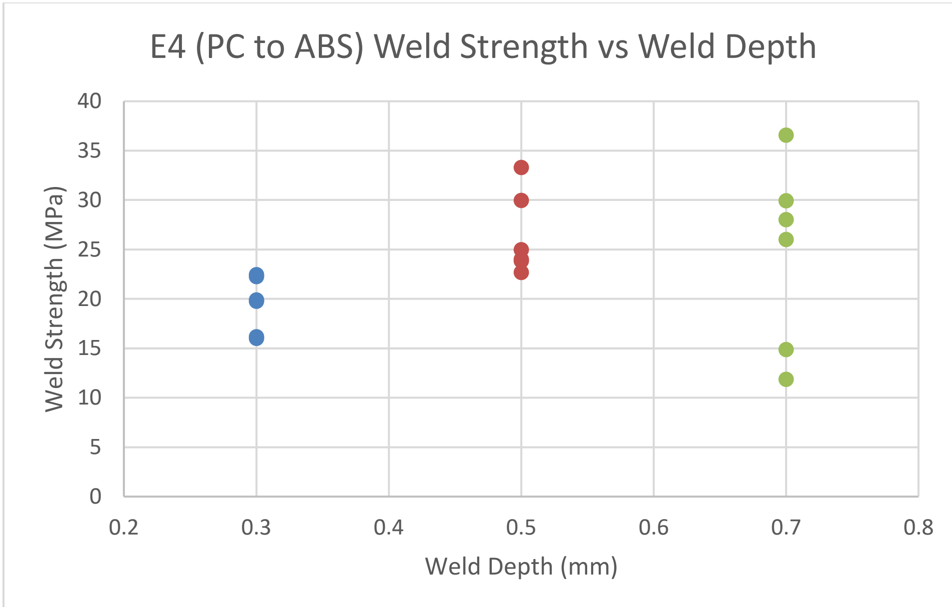

Figure 128: E4 (PC to ABS) Weld Strength vs Weld Depth. The maximum weld strength achieved is 36 MPa. This is the weld strength of the weld's weaker parent material. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The weld strength cannot increase past this value. The maximum strength is obtained at a weld depth between 0.5 mm and 0.7 mm.

The maximum weld strength of unity is achieved at a weld threshold between 0.5 mm and 0.7 mm.

4.5.5 Tensile Test Results – E5 (PC to ASA)

Material E is PC and material 5 is ASA. The strength testing results for 236 Hz Vibration Welds of Lens Material E to Housing Material 5 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 68. The weld factors are based off of Material 5's tensile strength, 33 MPa.

Table 68: Strength of 236 Hz Vibration Welds of Lens Material E (PC) to Housing Material 5 (ASA) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	15.006	0.455
1	0.5	18.616	0.564
1	0.7	25.508	0.773
3	0.3	6.320	0.192
3	0.5	12.161	0.369
3	0.7	15.673	0.475
5	0.3	2.607	0.079
5	0.5	7.877	0.239
5	0.7	1.063	0.032

The strength testing results for 236 Hz Vibration Welds of Lens Material E to Housing Material 5 for a weld amplitude of a = 1. mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 69.

Table 69: Strength of 236 Hz Vibration Welds of Lens Material E (PC) to Housing Material 5 (ASA) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	13.704	0.415
1	0.5	21.634	0.656
1	0.7	29.274	0.887
3	0.3	4.724	0.143
3	0.5	9.002	0.273
3	0.7	17.623	0.534
5	0.3	3.067	0.093
5	0.5	4.009	0.121
5	0.7	5.322	0.161

This material combination is sensitive to the weld pressure and insensitive to the weld amplitude. The weld strength decreases with increasing weld pressure. For all parameter combinations except the high amplitude and high pressure scenario, the weld strength clearly increases with weld depth. The differences in weld strength due to the weld depth are more drastic at the lower pressures.

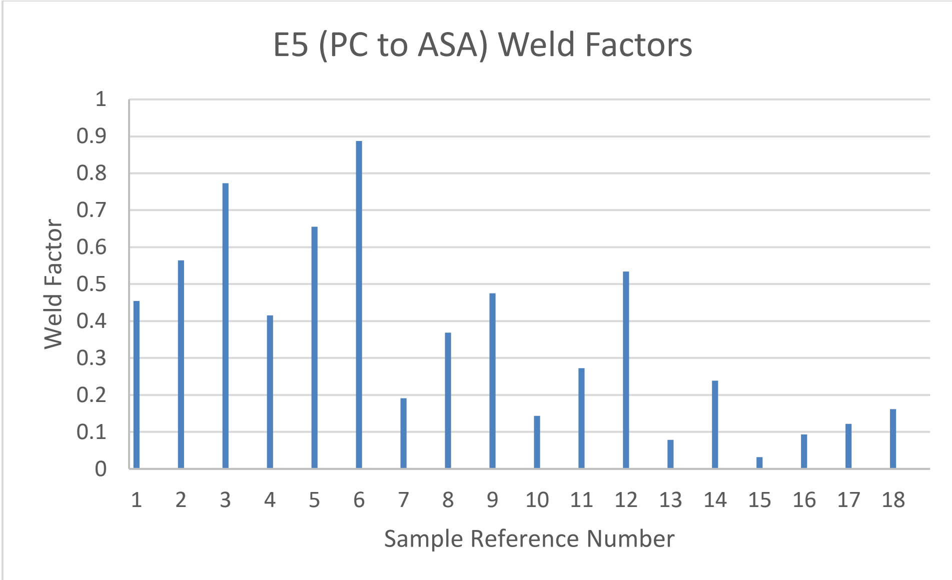

Figure 129: E5 (PC to ASA) Weld Factors. Weld sample 6 achieved the highest weld factor of 0.887 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The maximum weld strength is 29.274 MPa. This corresponds to a weld factor of 0.887. This is achieved at a weld pressure of 1 MPa, a weld amplitude of 1.5 mm, and a weld depth of 0.7 mm.

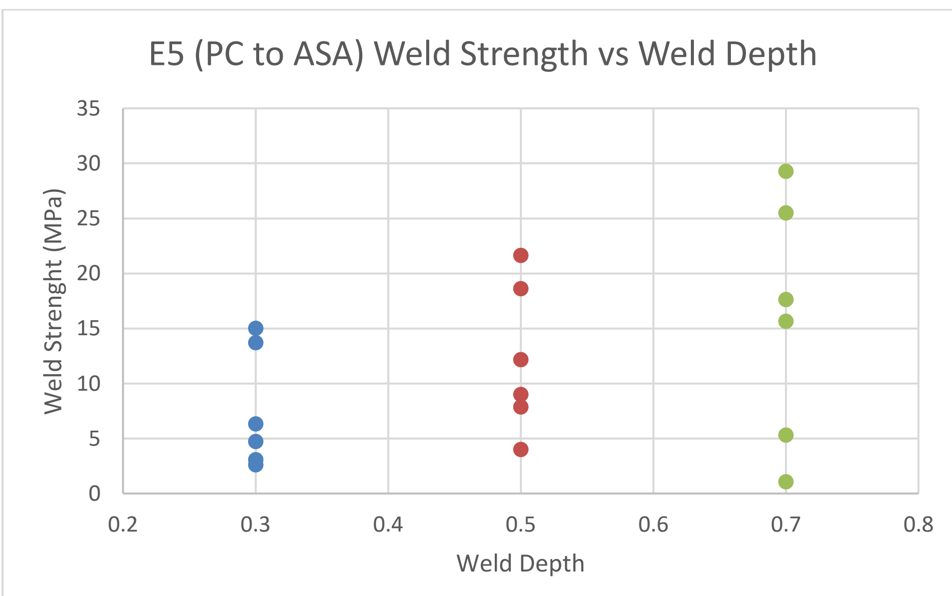

Figure 130: E5 (PC to ASA) Weld Strength vs Weld Depth. The maximum weld strength achieved is 29.274 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.5 mm. The weld strength increases with increasing weld depth.

The maximum attainable weld strength increases with weld depth, and will continue to do so past 0.7 mm in depth.

4.5.6 Tensile Test Results – E6 (PC to ASA+PC)

Material E is PC and material 6 is an ASA+PC blend. The strength testing results for 236 Hz Vibration Welds of Lens Material E to Housing Material 6 for a weld amplitude of a = 1.78 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 70. The weld factors are based off of Material 5's tensile strength, 62.1 MPa.

Table 70: Strength of 236 Hz Vibration Welds of Lens Material E (PC) to Housing Material 6 (ASA+PC) for a weld amplitude of a = 1.78 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	11.184	0.180
1	0.5	15.391	0.248
1	0.7	16.931	0.273
3	0.3	4.882	0.079
3	0.5	5.767	0.093
3	0.7	8.424	0.136
5	0.3	2.226	0.036
5	0.5	6.232	0.101
5	0.7	5.850	0.094

The strength testing results for 236 Hz Vibration Welds of Lens Material E to Housing Material 6 for a weld amplitude of a = 1.5 mm, with three varying weld pressures (1 MPa, 3 MPa, and 5 MPa) and three weld penetrations (0.3 mm, 0.5 mm, and 0.7 mm) are displayed below in Table 71.

Table 71: Strength of 236 Hz Vibration Welds of Lens Material E (PC) to Housing Material 6 (ASA+PC) for a weld amplitude of a = 1.5 mm, with three varying weld pressures and weld penetrations

Weld Pressure (MPa)	Weld Penetration (mm)	Weld Strength (MPa)	Weld Factor
1	0.3	6.521	0.105
1	0.5	14.334	0.231
1	0.7	4.858	0.078
3	0.3	7.242	0.117
3	0.5	8.040	0.130
3	0.7	13.815	0.223
5	0.3	0.000	0.000
5	0.5	3.672	0.059
5	0.7	6.059	0.098

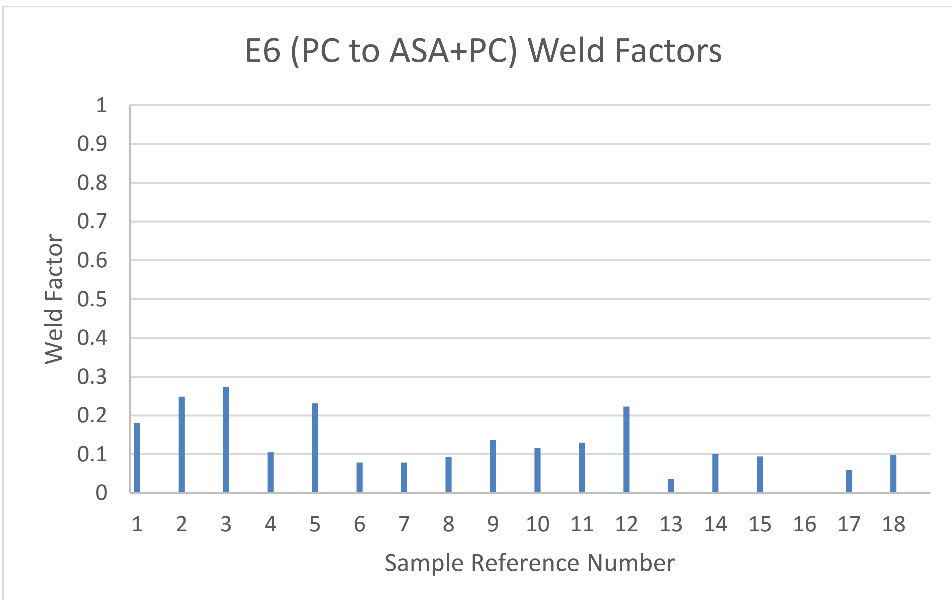

Figure 131: E6 (PC to ASA+PC) Weld Factors. Weld sample 3 achieved the highest weld factor of 0.273 at a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The sample reference numbers refer to the trial ID welding parameters in Table 10.

The greatest weld strength, 16.931 MPa, occurs from sample 3. Its weld factor is 0.273. The weld settings for this sample are a pressure of 1 MPa, a weld depth of 0.7 mm, and a weld amplitude of 1.78 mm.

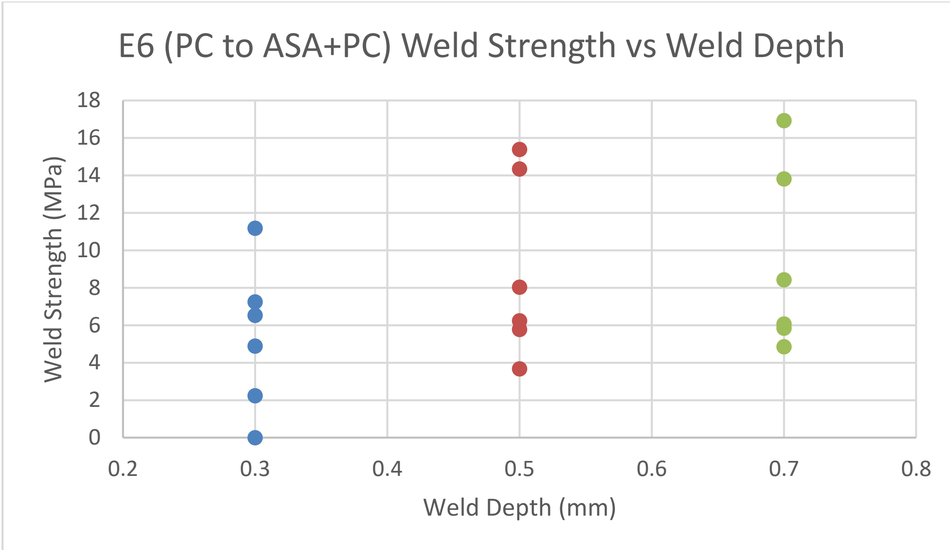

Figure 132: E6 (PC to ASA+PC) Weld Strength vs Weld Depth. The maximum weld strength achieved is 16.931 MPa. This weld was created using a welding depth of 0.7 mm, welding pressure of 1 MPa, and a welding amplitude of 1.78 mm. The weld strength increases with increasing weld depth.

The maximum weld strength seems to increase with weld penetration.

As expected, the general trend of increasing weld strength with increasing weld depth holds true. In the great majority of cases, weld depth is the overwhelming factor of creating quality welds. Additionally, the optimal welds of each scenario were typically achieved at the lowest weld pressure of 1 MPa. This finding is not surprising as high weld pressures during the welding process tend to push the molten material out of the interface laterally. This results in much less molten material at the interface to mix and eventually solidify, resulting in overall weaker welds.

The strength values are calculated by dividing the maximum load by the cross-sectional area of the weld. The attained maximum strengths are listed below in Table 72. Values without three significant digits have been rounded down since their weld factors exceeded unity during testing.

Table 72: Maximum Achievable Strength (MPa) Summary Table

	1 (PC)	***2 (PC+ABS)***	***3 (ABS+PC)***	***4 (ABS)***	***5 (ASA)***	***6 (ASA+PC)***
A (PMMA)	24.825	17.558	20.997	20.110	16.906	14.176
B (PMMA)	53.842	20.451	25.679	24.021	12.839	10.254
C (PMMA)	48	19.949	29.067	34.994	31.259	17.173
D (PMMA)	14.626	14.089	15.377	17.354	15.076	12.629
E (PC)	62	21.260	31.407	36	29.274	16.931

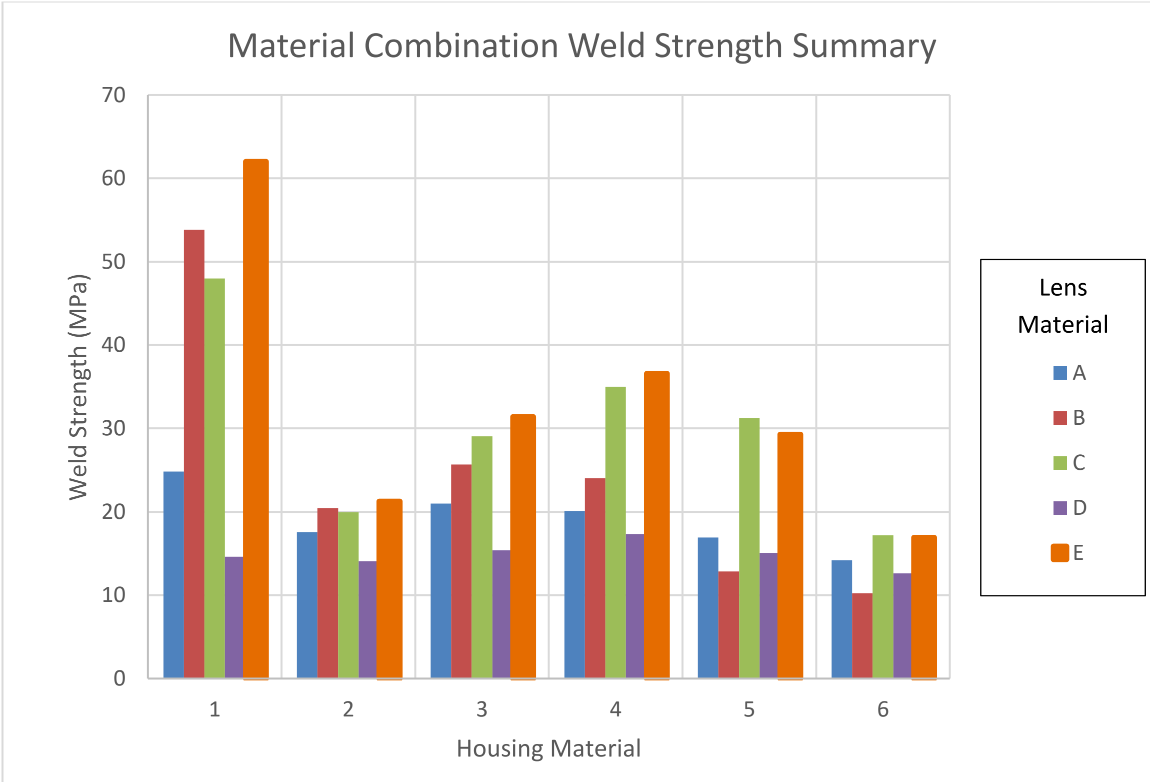

Figure 133: Material Combination Weld Strength Summary Chart. Material B (PMMA) and E (PC) are among the majority of the combinations which create the strongest welds. Material A (PMMA) and B (PMMA) are among the less compatible combinations and their strength values do not vary greatly when paired with different lens materials. The strengths do follow the same general trend of increasing or decreasing when paired with the same lens material. Housing material 1 (PC) is able to create the strongest welds overall, with a maximum of 62 MPa, whereas housing material 6 (ASA+PC) created the weakest overall welds for each lens combination.

The weld factor is used as a measure of material compatibility. The weld factor is the attained experimental strength value divided by the weaker material's independent base strength. The maximum attainable weld factors are summarized below.

Table 73: Weld Factor Summary Table

	1 (PC)	*2 (PC+ABS)*	*3 (ABS+PC)*	*4 (ABS)*	*5 (ASA)*	*6 (ASA+PC)*
A (PMMA)	0.365	0.314	0.477	0.482	0.512	0.253
B (PMMA)	0.855	0.365	0.542	0.667	0.389	0.161
C (PMMA)	1	0.416	0.661	0.972	0.947	0.358
D (PMMA)	0.215	0.252	0.349	0.482	0.457	0.203
E (PC)	1	0.379	0.714	1	0.887	0.273

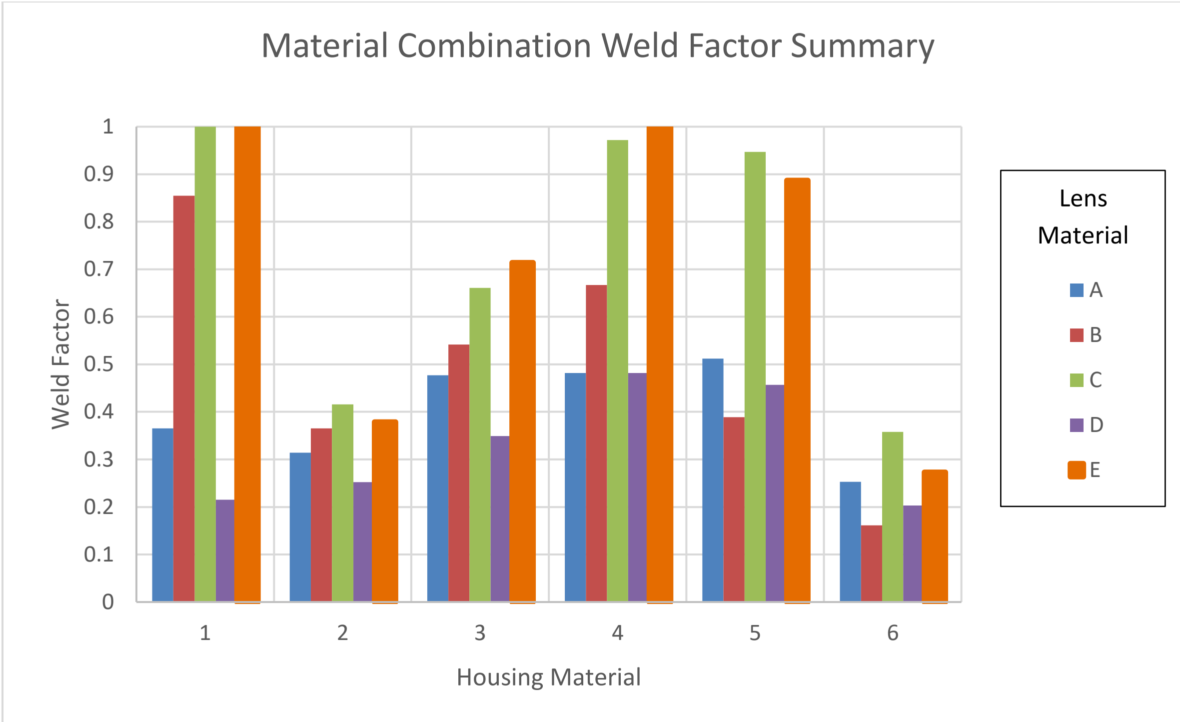

Figure 134: Material Combination Weld Factor Summary Chart. Lens materials C (PMMA) and E (PC) consistently create the strongest welds for each combination. . Housing materials 2 (PC+ABS) and 6 (ASA+PC) are generally incompatible with the tested lens materials, with material 2's weld factors ranging between 0.25 and 0.42 and material 6's (ASA+PC) weld factors ranging between 0.15 and 0.36. Combinations C1 (PMMA to PC), E1 (PC to PC), and E4 (PC to ABS) reach a weld factor of unity.

The weldability is dependent not only on the parent materials, but also the specific material grades. Exceptional welds with a weld factor of unity can reach the weaker parent material's independent base strength. This includes material combinations: C1 (PMMA to PC), E1 (PC to PC), and E4 (PC to ABS). C1 and E1 both display strength-penetration graphs which resemble that of the welding of similar materials, but with a larger weld penetration threshold. Additional compatible combinations include: B1 (PMMA to PC), C4 (PMMA to ABS), C5 (PMMA to ASA), and E5 (PC to ASA). These material combinations can reach over 80% of their base material's strength, with C4 and C5 close to unity. C4's weld strength appears to be less sensitive to an increasing weld depth than the other combinations mentioned. It is assumed that C4's weld-strength gradually increases with increasing weld depth and reaches a weld factor of unity at a depth shortly after 0.7 mm.

Lens materials B (PMMA), C (PMMA), and E (PC), and housing materials 1 (PC), 4 (ABS), and 5 (ASA) can create quality welds under the right circumstances. It is interesting to note that none of the mentioned housing materials here are blends. Material 6 (ASA+PC) is generally incompatible with all materials, not being able to generate strong welds, with its strongest weld approaching 36% of its base material's independent strength. Lens material D (PMMA) and housing materials 2 (PC+ABS) and 6 (ASA+PC) consistently create welds with low weld factors. Material A (PMMA) consistently contributes to welds with mediocre weld factors. Combinations with very low weld factors seem to have no strong dependence on any weld parameters. The effects seem random and volatile.

Table 74 below shows the optimal weld parameters for each combination. For combinations with multiple high weld factors, more than one set of parameters will be listed, with the stronger set listed first. All welds used a frequency of f = 236 Hz. The weld parameters listed are: pressure, P, weld depth, D, and amplitude, A. The graph is coloured to display the weldability in terms of the weld factor. The ranges are chosen subjectively. Green boxes represent welds which have a maximum weld factor greater than 0.9. Yellow Boxes represent welds with maximum weld factors between 0.9 and 0.7. Orange Boxes represent welds with maximum weld factors between 0.7 and 0.4 Red boxes represent welds which have a maximum weld factor less than 0.4.

Table 74: Optimal weld parameters for each material combination. Green boxes represent welds which have a maximum weld factor greater than 0.9, representing very high material compatibility which can result in quality welds. Yellow Boxes represent welds with maximum weld factors between 0.9 and 0.7. Orange Boxes represent welds with maximum weld factors between 0.7 and 0.4 Red boxes represent welds which have a maximum weld factor less than 0.4, displaying material incompatibility.

	1 (PC)	***2 (PC+ABS)***	***3 (ABS+PC)***	***4 (ABS)***	***5 (ASA)***	***6 (ASA+PC)***
A (PMMA)	P = 1 MPa D = 0.7 mm A = 1.5 mm	P = 1 MPa D = 0.7 mm A = 1.5 mm	P = 1 MPa D = 0.5 mm A = 1.5 mm	P = 1 MPa D = 0.7 mm A = 1.5 mm	P = 1 MPa D = 0.7 mm A = 1.78 mm	P = 1 MPa D = 0.5 mm A = 1.78 mm
B (PMMA)	P = 5 MPa D = 0.7 mm A = 1.5 mm	P = 5 MPa D = 0.5 mm A = 1.78 mm	P = 1 MPa D = 0.7 mm A = 1.5 mm	P = 1 MPa D = 0.7 mm A = 1.78 mm	P = 1 MPa D = 0.7 A = 1.5 mm P = 1 MPa D = 0.7 A = 1.78 mm	P = 1 MPa D = 0.7 mm A = 1.78 mm

C (PMMA)	P = 1 MPa D = 0.5 mm A = 1.78 mm P = 1 MPa D = 0.7 A = 1.5 mm	P = 1 MPa D = 0.7 mm A = 1.78 mm	P = 1 MPa D = 0.7 A = 1.5 mm	P = 1 MPa D = 0.7 mm A = 1.78 mm	P = 1 MPa D = 0.7 mm A = 1.5 mm	P = 1 MPa D = 0.7 mm A = 1.5 mm
D (PMMA)	P = 5 MPa D = 0.7 mm A = 1.5 mm	P = 1 MPa D = 0.5 mm A = 1.78 mm	P = 3 MPa D = 0.5 mm A = 1.78 mm	P = 5 MPa D = 0.3 mm A = 1.78 mm	P = 5 MPa D = 0.3 mm A = 1.78 mm	P = 5 MPa D = 0.7 mm A = 1.78 mm
E (PC)	P = 1 MPa D = 0.7 mm A = 1.78 mm P = 1 MPa D = 0.5 mm A = 1.78 mm P = 5 MPa D = 0.7 mm A = 1.5 mm	P = 5 MPa D = 0.7 mm A = 1.5 mm	P = 1 MPa D = 0.7 mm A = 1.78 mm P = 5 MPa D = 0.7 mm A = 1.5 mm	P = 1 MPa D = 0.7 mm A = 1.78 mm	P = 1 MPa D = 0.7 mm A = 1.5 mm	P = 1 MPa D = 0.7 mm A = 1.78 mm

To reiterate, material combination welds reaching weld factors of unity or close to unity include: C1 (PMMA to PC), C4 (PMMA to ABS), C5 (PMMA to ASA), E1 (PC to PC), and E4 (PC to ABS). This confirms LVW material compatibility. All of the highest weld factors use a pressure of 1 MPa, solidifying that low pressures help facilitate strong welds for compatible materials. This is true of similar material welds. C1 is the only mentioned combination to reach its maximum strength as a weld depth of 0.5 mm instead of 0.7 mm. C1's parameters should be tested again using the weld depth of 0.7 mm to confirm if the increase in weld depth truly consistently has adverse effects.

For dissimilar material combinations, a weld penetration threshold typically does not exist and increasing the weld depth continually should increase the overall weld strength. This trend is common for dissimilar materials, whose strengths continually increase with penetration instead of passing a general weld threshold and maintaining a maximum weld strength.

Excluding material combinations that were able to reach a weld factor of 1, majority of the combinations could increase their weld strength with further weld penetration. The material combinations clearly excluded from this are: D2 (PMMA to PC+ABS), D3 (PMMA to ABS+PC), D4 (PMMA to ABS), whose maximum achievable weld strength seemed to hit the same peak value at any weld depth. Material combination D5 (PMMA to ASA) appeared to decrease in strength with increasing weld depth.

For material combinations where a weld depth of 0.5 mm yielded the maximum attainable strength, it is not entirely clear if they are outliers caused by material imperfections or if an increasing weld depth truly has adverse effects. These welds should be tested again to confirm that these are their maximum welding parameters, and to solidify the ideology if increasing weld depth increases their maximum achievable weld strength, or if it has already been reached. This includes material combinations: D2 (PMMA to PC+ABS), D3 (PMMA to ABS+PC), B2 (PMMA to PC+ABS), C1 (PMMA to PC), A3 (PMMA to ABS+PC), A6 (PMMA to ASA+PC).

It is determined that the maximum weld strength possible has been determined for combinations: D2 (PMMA to PC+ABS), D3 (PMMA to ABS+PC), B2 (PMMA to PC+ABS), and B3 (PMMA to ABS+PC). Their strength graphs plateau with increasing weld depth. B2 may slowly increase with weld depth if its highest strength achieved is an outlier. This can be confirmed with additional strength testing.

Material combination D4 (PMMA to ABS) has a strange reaction to increasing weld depth, with a maximum at 0.3 mm in depth and a minimum at 0.5 mm in depth. Material combinations with a maximum strength at a depth of 0.5 mm are only a few MPa stronger than the maximum value at 0.7 mm. It is assumed that this is due to variability and that the maximum weld strength has already been achieved. Literature was reviewed and the existence of material combinations insensitive to weld depth is confirmed [42]. It is assumed that the maximum strength values have been reached for material combinations: D4 (PMMA to ABS), C1 (PMMA to PC), A3 (PMMA to ABS+PC), and A6 (PMMA to ASA+PC). For these combinations, the housing material has a lower strength. Almost all of these combinations that did not follow the expected patterns corresponding to weld parameters have poor weldability, meaning they are not subjectively ‘compatible’. The use of the term “compatible” in this paper refers to their relative strength compared to their base strength. The use of these so-called incompatible materials can still be applied if they meet the strength required per application.

CHAPTER 6: CONCLUSIONS

The goal of this research is to determine the plaque-level compatibility of materials as a function of the weld strength performance and to determine material-level weld strength guidelines regarding the optimal welding parameters for component level design/development and quality. This is achieved through a parametric study analyzing the strength of different material combination welds at varying weld parameters. There are many important findings regarding the compatibility of materials for LVW:

- An increasing weld depth most often results in an increasing weld strength for the tested welds of dissimilar materials and grades.
- Different material combinations react differently to a change in weld pressure
- Majority of the material combinations display that a further increase in weld depth, greater than 0.7 mm, would increase the maximum achieved weld strength.
- All of the highly compatible material combinations had optimal welding conditions using the lowest weld pressure of 1 MPa. Majority of the remaining material combinations also have optimal weld parameters using 1 MPa.
- Lens materials B (PMMA), C (PMMA), and E (PC), and housing materials 1 (PC), 4 (ABS), and 5 (ASA) can create quality welds under the right circumstances. Material combinations C1 (PMMA to PC), E1 (PC to PC), and E4 (PC to ABS) reached the strength of the weld's weaker parent material, yielding a weld factor of unity. Additional highly compatible combinations, reaching over 80% of their weaker parent material's strength, include: B1 (PMMA to PC), C4 (PMMA to ABS), C5 (PMMA to ASA), and E5 (PC to ASA).
- Material A (PMMA) consistently contributes to welds with mediocre weld factors.
- Lens material D (PMMA) and housing materials 2 (PC+ABS) and 6 (ASA+PC) consistently create welds with low weld factors, displaying general incompatibility.

FUTURE RECOMMENDATIONS

There are plans for continuation of this research: strength testing of additional thermoplastics to build a weld strength database (amorphous and semi-crystalline thermoplastics, including unreleased materials from suppliers that plan to be adopted by automotive manufacturers in the future), different vehicle areas of focus (interior lighting and underhood), different welding methods (IR welding and laser welding), microscopic analysis of the weld interface, and environmental stress cracking evaluation (including effects of annealing).

IR welding and subsequent strength testing has already begun for the materials in this study. After the full study on IR welding is complete, it will be repeated for laser welding. Both of these welding methods create more aesthetically appealing welds than LVW.

Further strength testing is already planned for thermoplastics used in different areas of the vehicle: the interior and underhood. The materials to be tested are both amorphous and semi-crystalline thermoplastics. The same testing methodology and experimental procedures will be used. The adoption of advanced unreleased materials for automotive applications are also being discussed with suppliers. These will be integrated into future studies to ensure their adoption into the vehicle design is beneficial.

From an application standpoint, manufacturers may need to weld 2 materials together that have a low weldability due to their individual benefits, such as impact or heat resistance. In this case, it is advised that alternative material grades should be tested to attempt to find an increase in weldability. Research efforts should be focused on continuing to build a weld-strength database of thermoplastic materials which have automotive applications.

A microscopic study would explore the impact of the welding parameters on the morphology of the weld materials at the weld interface. This will be helpful in explaining some of the combinations' phenomenon that do not follow the general trends. A microscopic insight will give great insight on explaining some of the results that seem random and volatile with no current explanation. Hopefully, a physical explanation can be determined.

Lastly, the end sections of the 5 in weld samples from this study are to be utilized for an ESC project. One end will be annealed while the other is not. The two end piece samples will then be tested. Each material combination will come in contact with a mixture that accelerates ESC. Different combinations will be introduced to different mixtures that target the specific materials in use. The samples will be compared visually and subjectively, as well as studied under microscope. This study will be used to determine how effective the annealing process is for each material combination. If the annealed sample pieces display great benefit, then this annealing process for the dissimilar welds should be adopted by automotive engineers.

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