Analysis of Bonding Methods for FDM-Manufactured Parts

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Abstract

The fused deposition modeling (FDM) additive manufacturing (AM) technology has been valuable for producing a variety of concept models, functional prototypes, end-use parts and manufacturing tools using a range of durable thermoplastic materials. The largest individual component that can be produced in FDM depends on the dimensions of the build chamber for the specific FDM system being used, with a maximum build chamber size available of 914 x 610 x 914 mm. This limitation is not unique to FDM as all AM systems are constrained by a build chamber. However, by using thermoplastic materials, individual components can be bonded together using different methods to form a single piece. Bonding can be used to help reduce building time and support material use, and also allows for the fabrication and assembly of final products larger than the build chamber. This work investigated different methods for bonding FDM-manufactured parts, including the use of five different adhesives and solvents as well as two different welding techniques (hot air welding and ultrasonic welding). The available FDM materials investigated included acrylonitrile butadiene styrene (ABSi, ABS-M30, ABS-M30i), polycarbonate (PC, PC-ABS, PC-ISO), polyphenylsulfone (PPSF), and ULTEM 9085. Bonding strengths were characterized by comparing ultimate tensile strengths at break and analyzing the mode of failure. Overall, the bonding method of hot air welding produced the strongest bond for all the materials investigated except for ULTEM 9085 for which the strongest bond was achieved with the two-part epoxy adhesive Hysol E-20HP.

1. Introduction

Bonding is an important process used in all fields of industry where the assembly of two substrates (or adherends) is required. There are many plastic assembly methods available for the joining of materials that include the use of fasteners, adhesives, solvents, hot gas welding, ultrasonic welding, friction welding, and induction welding. Please note that this list is not complete, rather limited to notable joining methods all of which have advantages and disadvantages that enhance or limit their applicability (Rotheiser, 1999; Strong, 2006). Often, plastic joining methods are selected based on the materials' characteristics, fabrication method, function, and the desired aesthetics of the assembly. For example, plastics with dissimilar properties (such as melting points) can be bonded with adhesives much easier than with hot air welding (Rotheiser, 1999).

The joining of parts fabricated with traditional manufacturing technologies has been extensively studied (Baldan, 2004; Priyandarshi *et al.* 2007; Kinloch, 1990). As the industry is interested in achieving strong bonds, the choice for the right bonding methods for a given plastic is made after extensive experimentation, especially when bonding with adhesives since the method is very specific to each industry and it is usually difficult to generalize from one application to another (Cognard, 2006). Little work is present that considers the joining of plastics parts fabricated with additive manufacturing (AM), specifically fused deposition modeling (FDM). FDM is a technology that enables users to create functional parts with complex geometries by extruding a semi-molten polymer through a small-diameter nozzle. The polymer is accurately deposited in such a fashion that two dimensional profiles are stacked and fused onto each other.

This study analyzed the bonding of eight commonly used FDM materials by way of solvents, adhesives, ultrasonic spot welding, and hot air welding. Table 1 lists the FDM materials used, along with some of their properties. The following describes briefly the specifics for the bonding methods used.

Table 1. Properties of FDM materials.

Material	Tensile Strength (MPa)	Tensile Modulus (MPa)	Heat Deflection (°C) @ 264 psi	Glass Transition (°C)
ABS-M30	36	2413	82	108
ABS-M30i	36	2413	82	108
ABSi	37	1915	73	116
PC-ABS	41	1917	96	125
PPSF	55	2068	189	230
PC-ISO	57	998	127	161
PC	68	2280	127	161
ULTEM 9085	72	2220	153	186

Solvent joining methods work by applying a solvent to the plastic parts being joined. At the surface, the solvent diffuses in and melts or softens the material and once both interfaces are brought into contact, material from both parts fuse and create a weld when the solvent evaporates (Rotheiser, 1999). On the other hand, adhesive joining uses an adhesive (in one- or two-part components, usually in liquid form, but pastes and solid films are also available) that bonds to the surface of the adherends by going through some chemical or physical change (Strong, 2006). Reactive adhesives (including cyanoacrylates and two-part epoxies and polyurethanes) undergo a chemical change to create a bond. When applied to the surface of the substrate, the adhesive material diffuses into the substrate and then forms a connecting network upon reaction of the components (Strong, 2006; Cognard, 2006). One of the disadvantages of bonding with adhesives is the safety risk associated with their use since most bonding solvents and adhesives are toxic.

Preferred over other methods of bonding, ultrasonic and hot air welding methods are fast, efficient, and are not associated with environmental hazards (Rotheiser, 1999; Zhang *et al,.*

2010). Ultrasonic welding systems use a power supply to convert a typical 50/60 Hz voltage into high frequency (20-40 kHz) electrical energy that is used to create low amplitude mechanical vibrations in the range of 20-30 µm (Rani *et al.*, 2009). This mechanical energy is amplified by a probe or horn and then transmitted by contact to the plastic parts usually using a tip. The high frequency vibrations are transmitted through the plastic until they reach an interface, where frictional energy is developed that melts and fuses the interface of both plastic parts (Rotheiser, 1999; Zhang *et al.*, 2010, Suresh *et al.*, 2007; Rani *et al.*, 2008). Hot air welding uses a welding rod that is driven through a tool while being softened by hot air. The parts to be welded and the rod are locally melted or soften, and the welding rod fills the joints that facilitate the assemblage of the plastic parts. The heated air is produced by a hot gas torch, and the air coming out of the torch (welding temperature) should be controlled and set specifically to the type of material. With hot air welding, it is possible to achieve weld strengths of up to 90% of the parent material strength (Troughton, 2009).

This study analyzed the joining of eight commonly used FDM materials using seven different bonding methods including solvents, adhesives and welding methods. Results from the research provide information that FDM users can utilize as a reference to appropriately select an effective bonding method that properly satisfies their desired outcomes. The following describes the methods and results of this study in more detail.

2. Materials and method

2.1 Materials

Eight thermoplastic materials were used including ABS-M30, ABS-M30i, ABSi, PC, PC-ISO, PC-ABS, PPSF, and ULTEM 9085 (Stratasys, Eden Prairie, MN, USA). Bonding methods included the use of various adhesives and solvents including cyanoacrylate-based instant glue (HST-4 Super T, Satellite City Inc., Newbury Park, CA, USA, referred to as Superglue), solvent adhesive (Proweld Professional Plastic Welder, Ambroid, West Swanzey, NH, USA), and two-part epoxy adhesives Hysol EA 9394 (Henkel, Bay Point, CA, USA), Hysol E-20HP (Loctite, Rocky Hill, CT, USA), and BJB TC-1614 A/B (BJB Enterprises, Inc., Tustin, CA, USA).

2.2 FDM part fabrication

All test specimens were fabricated using a Fortus 400mc system (Stratasys, Inc., Eden Prairie, MN, USA) equipped with T16 tips. Building parameters accommodated a slice height of 0.254 mm (0.010 inch), a solid-normal part interior style with contour width of 0.508 mm (0.020 inch), and a part raster width of 0.508 mm (0.020 inch). Slicing was performed with Insight 6.4.1 and all test specimens were fabricated in a side-edge orientation as shown in Figure 1a. Test specimens were designed so that their dimensions after bonding were equivalent to those of an ASTM D638 Type I specimen (Figure 1b). All test specimens to be bonded were designed with a double-butt lap joint whose dimensions are shown in Figure 1c.

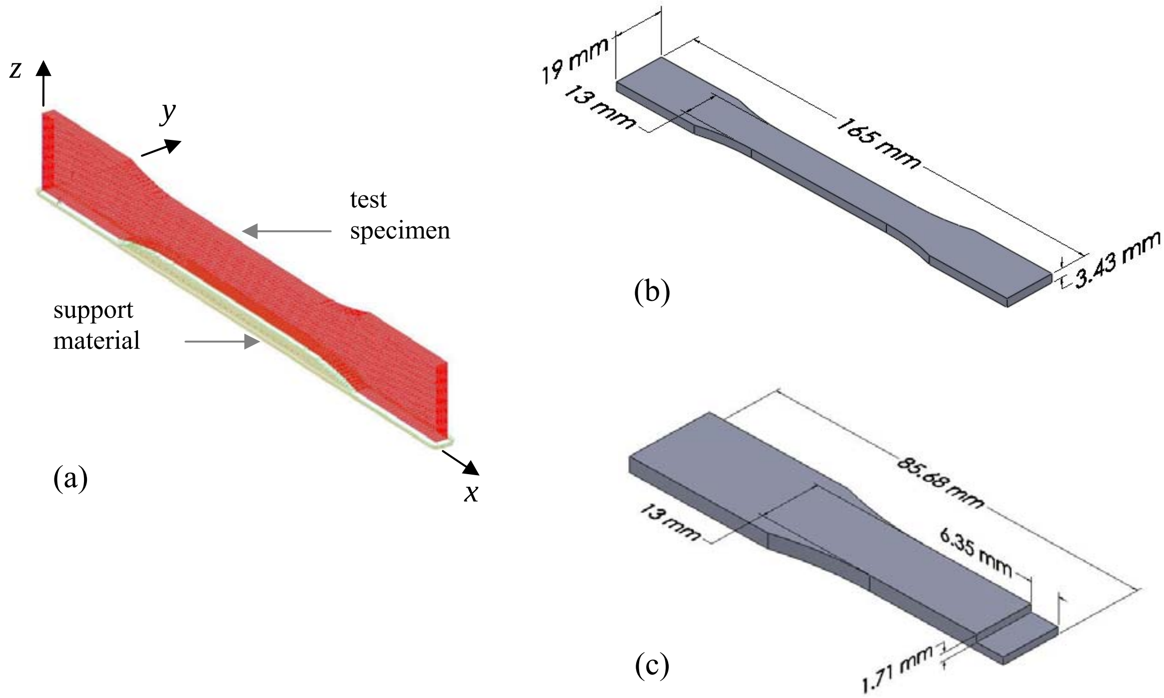

Figure 1. Test specimen designs (a) side-edge orientation used during part fabrication (b) ASTM D638 Type I single-component specimen (c) double-butt lap joint used for all bonding methods.

2.3 Adhesive and solvent joining

Joining with the use of adhesive/solvent was carried out by applying the adhesive/solvent to all areas of the lap joint of both parts to be joined. All two-part epoxies were first mixed following the manufacturer recommendations. Both parts were joined then clipped to a flat surface to ensure that the joints were properly aligned. After all the excess adhesive/solvent was removed, the adhesive/solvent was allowed to cure for at least 24 hours prior to testing.

2.4 Ultrasonic spot welding

A high intensity ultrasonic processor (CPX 500, Cole-Parmer, Vernon Hills, IL, USA) was adapted to create spot welds at the center of the double-butt lap joint location. The ultrasonic processor was equipped with a CV33 converter, A08766HRN horn, and a spot welding tip (Sonics & Materials, Inc., Newton, CT, USA). This combination of equipment produced vibrations with an amplitude of 0.113 mm (0.00443 in.). Prior to joining the test specimens, a penetration study was conducted to determine the amplitude percentage and pulse duration that would create enough energy to fuse the two lap joints. These parameters were found to be specific to each thermoplastic material. Spot welds were created by using amplitude percentages that ranged from 20% to 100% for 1, 2, and 3 second pulse durations. The resulting spot welds were imaged with a stereomicroscope (MZ16, Leica Microsystems, Wetzlar, Germany) and a camera (Retiga 2000-R, QImaging, British Columbia, Canada) to determine the depth of penetration. Desired penetration depths were in the range of 2/3 to 4/5 of the specimen thickness (~1.70 - 2.70 mm). No external forces, other than the weight of the converter, horn, and tip (10.95 N), were applied during the ultrasonic spot welding process.

2.5 *Hot air welding*

A simple fixture, shown in Figure 2, was used to align and clamp the two parts to be joined. The material around the lap joint was melted using a Leister Hot Jet S hot air tool (Leister Technologies LLC, Itasca, IL, USA). The lap joint was then filled by using the hot air tool and a filler rod of the same material being joined.

2.6 *Tensile testing*

All specimens were conditioned at 23 ± 2 ºC and 50 ± 5% relative humidity for at least 40 hours prior to tensile testing. Tensile tests were conducted on an Instron 5866 sytem (Instron®, Norwood, MA, USA) following guidelines provided in ASTM D638. A 10kN load cell was utilized while employing a deformation cross-head speed of 5 mm/min. Each material and bonding method was tested using at least 5 specimens to report an average modulus of elasticity, ultimate strain, and ultimate stress. Data collected during the tensile testing was used to create stress-strain curves. The modulus of elasticity, E, was defined as the slope of the initial linear portion of the stress-strain curve. The ultimate stress, σ_u, was defined as the maximum stress endured by the test specimen and the corresponding strain was defined as the ultimate stress, ε_u.

3. Results and discussion

3.1 *Ultrasonic Spot Welding Parameters*

Table 2 summarizes the specific parameters for each material (amplitude percentage and pulse duration) that successfully fused the two lap joints. Due to the design of the tip, the ultrasonic welding created a rivet that joined the two sections of material together.

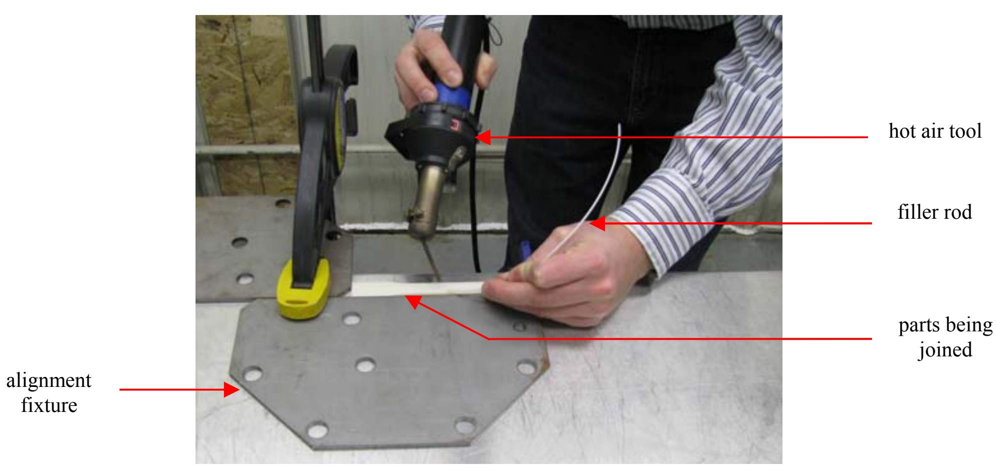

Figure 2. Hot air welding setup.

Table 2. Ultrasonic welding parameters used to produce spot welds in tensile test specimens.

Material	Amplitude (%)	Pulse Duration (s)	Penetration Depth (mm)
ABS-M30	60	2	2.72
ABS-M30i	60	2	2.15
ABSi	70	2	2.63
PC-ABS	70	2	2.50
PPSF	90	3	2.52
PC-ISO	90	2	2.50
PC	90	2	2.43
ULTEM 9085	80	3	2.73

3.2 Tensile Testing

Each of the eight FDM materials were bonded using seven different bonding methods. Sample groups of at least 5 specimens were produced. In addition, one sample group was composed of single-component (non-bonded) specimens for each material that was bonded. The following sections present the results (mean modulus of elasticity, mean ultimate stress, and mean ultimate strain) obtained from the tensile tests.

3.2.1 Tensile Ultimate Stress

The sample groups comprised of the single-component specimens were used as benchmarks for all bonded sample groups. Materials were grouped and graphed according to the mean ultimate stress associated with the single-component groups. Figure 3 contains Group A which is comprised of the materials ABS-M30, ABS-M30i, ABSi, PC-ABS, and PPSF whose single-component specimens exhibited a mean ultimate stress between 30 and 45 MPa. Group B consists of the remaining materials, PC-ISO, PC, and ULTEM 9085, that exhibited a mean ultimate stress in the range of 65-75 MPa as shown in Figure 4. The data shown in the graphs represents average ± one standard deviation.

Table 3 presents the performance percentage of each bonding method when used on each material. A rating is assigned based on the normalized mean ultimate stress that was determined by employing the following equation:

$$Performance\ \% = \left(\frac{mean\ ultimate\ stress\ of\ bond}{mean\ ultimate\ stress\ of\ single\ component}\right) X\ 100$$

In addition, the failure mode is described by the shading of each cell where a shaded cell represents a failure at the adhesive as shown in Figure 5a and a non-shaded cell represents a failure within the test specimen material as shown in Figure 5b.

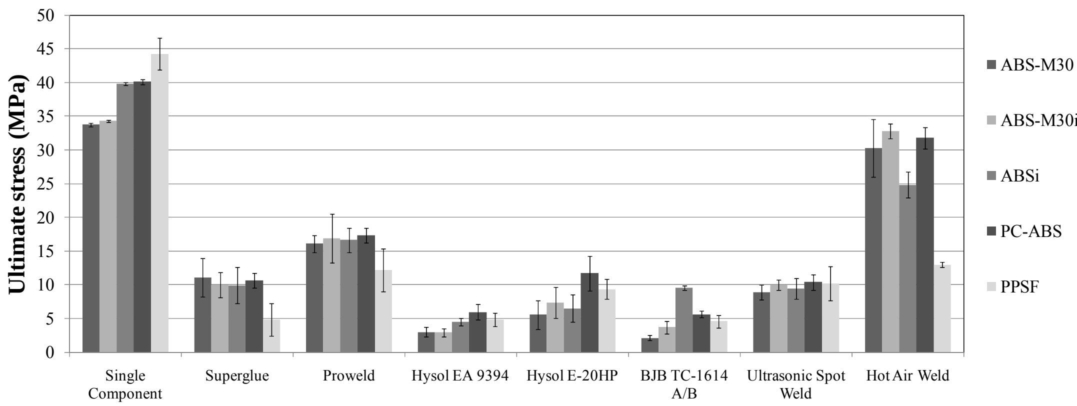

Figure 3. Ultimate stress results for FDM materials in Group A. All data represents average ± one standard deviation.

For all materials, the BJB TC-1614 A/B adhesive exhibited a low performance % when compared to the single-component samples of the same material. The Hysol EA 9394 two-part epoxy adhesive exhibited similar results. All sample groups bonded with the two-part adhesive Hysol E-20HP yielded a performance % range of 0-39% with the exception of ULTEM 9085 whose performance % range was 40-59%. All ABS blend materials joined with the solvent adhesive Proweld demonstrated a performance % range of 40-59%. All other materials bonded with Proweld achieved a performance % range of 20-39%. Similarly, all ABS blend materials bonded with Superglue (cyanoacrylate-based adhesive) yielded a performance % range of 20-39% and all other materials ranged between 0-20%.

All materials joined with ultrasonic spot welding exhibited a performance % of 20-39% with the exception of PC-ISO and ULTEM 9085 (performance % of 19 and 15%, respectively). The bond method that performed the best was hot air welding with a performance % of 40-100% on most materials. Materials whose glass transition temperatures were relatively lower (108-161ºC) performed best: ABS-M30, ABS-M30i, ABSi, PC-ABS, PC-ISO, and PC. In contrast, materials with elevated glass transition temperatures (180-230ºC) such as PPSF and ULTEM 9085 only yielded a performance % of 20-39% when bonded with hot air welding.

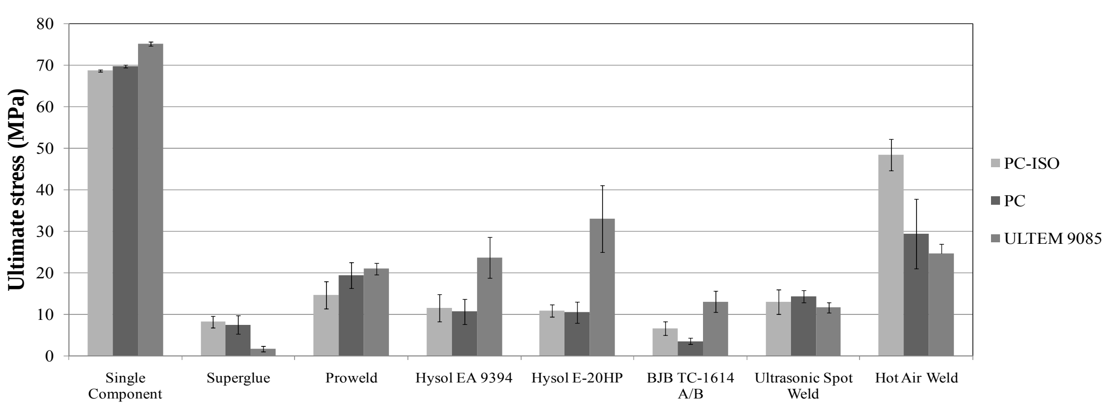

Figure 4. Ultimate stress results for FDM materials in Group B. All data represents average ± one standard deviation.

Table 3. Performance of each bonding method when used on the different FDM materials.

	Superglue	Proweld	Hysol EA 9394	Hysol E-20HP	BJB TC-1614	Ultrasonic Spot Weld	Hot Air Weld
ABS-M30	O	√	X	X	X	O	√√√
ABS-M30i	O	√	X	O	X	O	√√√
ABSi	O	√	X	X	O	O	√√
PC-ABS	O	√	X	O	X	O	√√√
PPSF	X	O	X	O	X	O	O
PC-ISO	X	O	X	X	X	X	√√
PC	X	O	X	X	X	O	√
ULTEM 9085	X	O	O	√	X	X	O

Performance Percentage

X	0-20%
O	20-39%
√	40-59%
√√	60-79%
√√√	80-100%.

$$Performance\ \% = \left(\frac{mean\ ultimate\ stress\ of\ bond}{mean\ ultimate\ stress\ of\ single\ component}\right) X\ 100$$

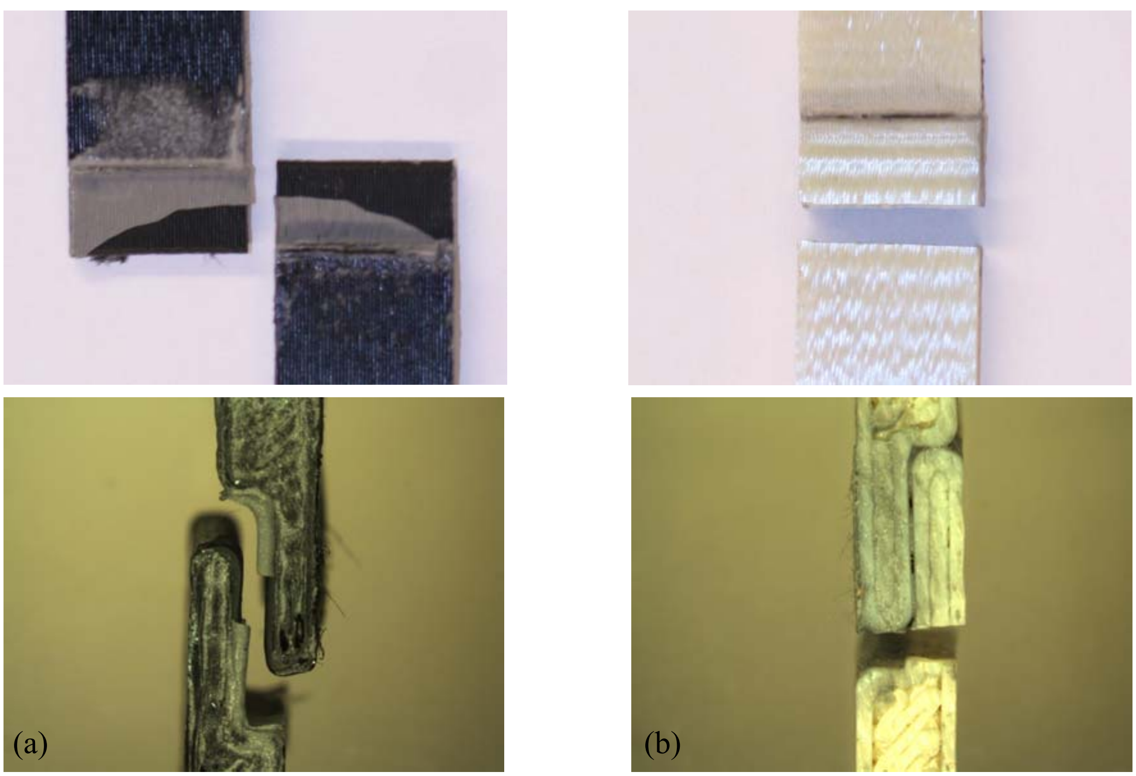

Figure 5. Two types of failure modes (a) Failure of the adhesive as demonstrated in a PC-ABS test specimen bonded using the two-part epoxy Hysol EA 9394. Note that the two sections forming the specimen were separated without damage to the material, and the adhesive peeled off remaining evenly distributed in the lap joint of each section. (b) Failure of the material as demonstrated in a ULTEM 9085 test specimen bonded with Hysol EA 9394. Note that the fracture occurred within the material breaking completely the lap joint of the bottom section.

3.2.2 Tensile Ultimate Strain

Figure 6 illustrates the results obtained for the mean ultimate strain (ε_u) for each material of Group A. Mean ultimate strain for each material of Group B can be found in Figure 7. In general, the hot air welded sample groups closely matched the single-component samples. All other joining methods differed considerably from the single-component samples.

3.2.3 Modulus of Elasticity

For all materials, the stiffness (Figure 8 and 9) associated with the hot air welding method closely approximated that of a single-component. In general, bonding with adhesive, solvent, and ultrasonic welding resulted in a decrease of stiffness. Other than with hot air welding, few notable equivalents in stiffness were observed. These combinations included PC-ABS, PC, and ULTEM 9085 when joined with Hysol EA 9394; PC and ULTEM 9085 when joined with Hysol E-20HP; and ULTEM 9085 when joined with BJB TC-1614 A/B.

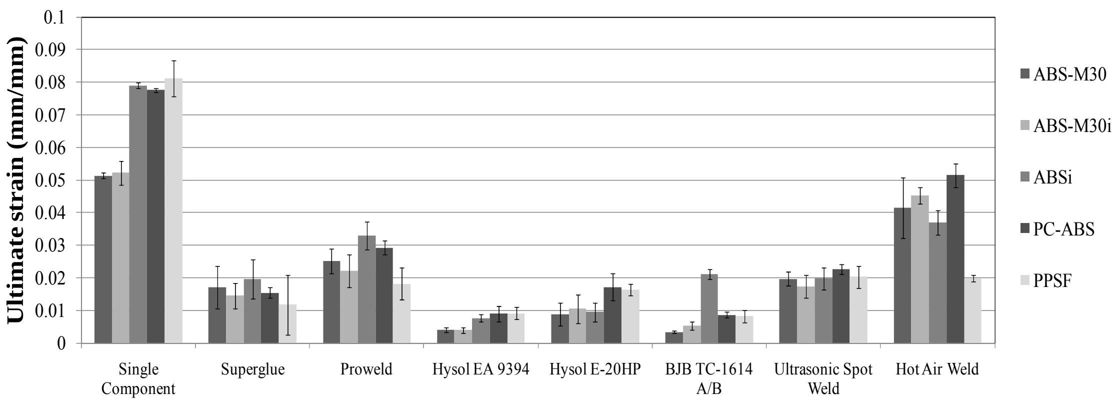

Figure 6. Ultimate strain results for FDM materials of Group A. All data represents average ± one standard deviation.

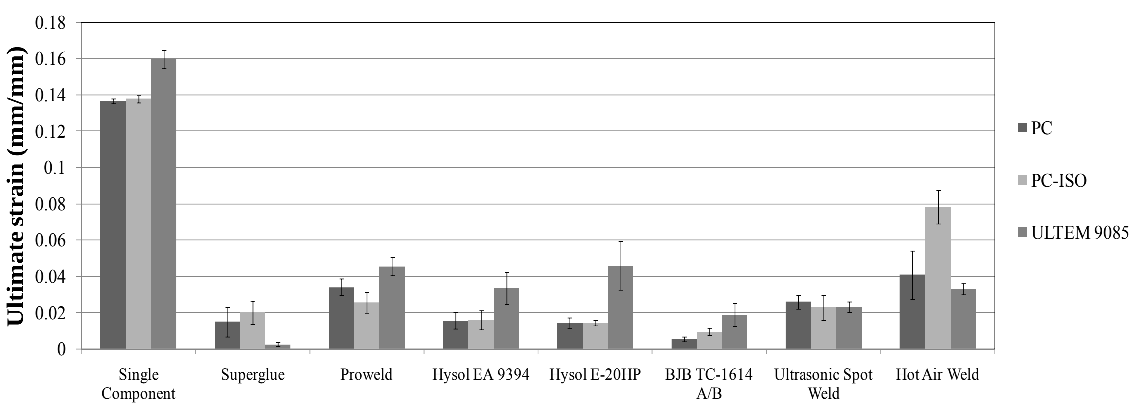

Figure 7. Ultimate strain results for FDM materials of Group B. All data represents average ± one standard deviation.

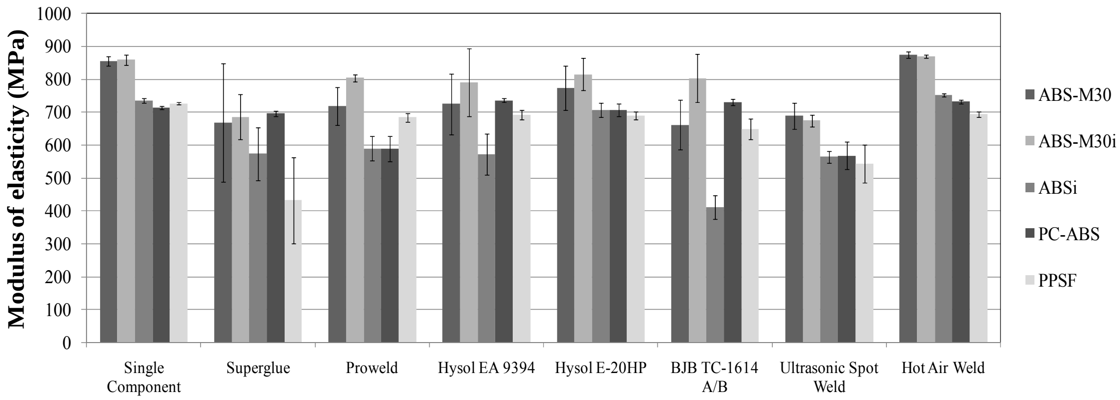

Figure 8. Modulus of elasticity for FDM materials of Group A. All data represents average ± one standard deviation.

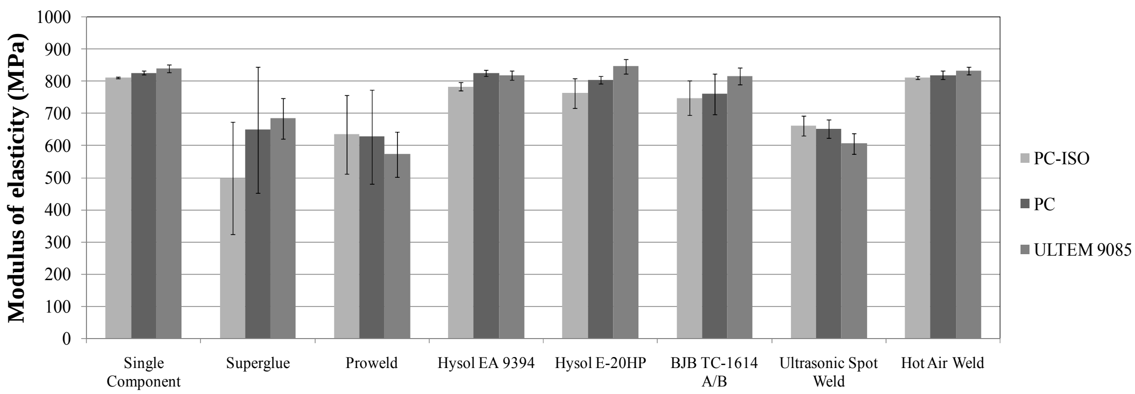

Figure 9. Modulus of elasticity for FDM materials of Group B. All data represents average ± one standard deviation.

4. Conclusions

Bonding methods play a crucial role in the joining of parts whether manufactured with traditional or non-traditional methods. Parts fabricated with FDM often are limited in size since FDM systems have building chamber limitations. Consequently, over-sized parts must be fabricated in smaller components and assembled as a post process. The joining method is dependent on the characteristics of the FDM-manufactured parts. Results from this study showed that certain materials have a better compatibility with specific bonding methods. For example, materials containing ABS and joined with superglue or Proweld bonded better than materials that were not an ABS blend. Additionally, hot air welding generally performed better than all the bonding methods analyzed in this study.

This study provides information (Table 3) that FDM users can utilize as a reference to appropriately select an effective bonding method that properly satisfies their requirements. Adhesive and solvent bonding methods are suggested when one values aesthetic results and is not concerned with mechanical property performance. Please note that using adhesives and solvents can become time consuming as curing times must be taken into consideration. If one desires to avoid curing times, then ultrasonic welding or hot air welding is recommended. While ultrasonic welding is fast, economical, and relatively easy, the results of this study showed that the assemblies created with ultrasonic welding did not exhibit high mechanical property performance. Conversely, hot air welding provided the advantages of ultrasonic welding while maintaining high mechanical property performance. The use of bonding methods in AM can help reduce building time and support material use, and also allows for the fabrication and assembling of final products larger than the build chamber.

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References

Baldan, Adhesively-bonded Joints in Metallic Alloys, Polymers and Composite Materials: Mechanical and Environmental Durability Performance 2004

Kinloch, A. J. Adhesion and Adhesives, Science and Technology. Cambridge, UK Cambridge University Press. 1990

Rani, M. R., K. Prakasan, and R. Rudramoorthy. "Study of Different Joints for Ultrasonic Welding of Semicrystalline Polymers." *Experimental Techniques*, 2009: 36-42.

Rani, M. R., K. Prakasan, and R. Rudramoorthy. "Studies on High Density Polyethylene in the Far-field Region in Ultrasonic Welding of Plastics." *Polymer-Plastics Technology and Engineering*, 2008: 762-770.

Rotheiser, Jordan. *Joining of Plastics: Handbook for Designers and Engineers.* Cincinnati: Hanser Gardner Publications, Inc., 1999.

Strong, A. Brent. *Platics: Materials and Processing.* Columbus, Ohio: Pearson Prentice Hall, 2006.

Suresh, K.S., M. Roopa Rani, K. Prakasan, and R. Rudramoorthy. "Modeling of Temperature Distribution in Ultrasonic Welding of Thermoplastics for Various Joint Designs." *Journal of Materials Processing Technology*, 2007: 138-146.

Troughton, M. Handbook of Plastics Joining. A Practical Guide. Burlington, MA, Elsevier, 2009.

Zhang, Zongbo, Xiaodong Wang, Yi Luo, Shengqiang He, and Liding Wang. "Thermal Assisted Ultrasonic Bonding Method for Poly(methyl methacrylate) (PMMA) Microfluidic Devices." *Talanta*, 2010: 1331-1338.