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REPAIR OF HIGH-VALUE PLASTIC COMPONENTS USING FUSED DEPOSITION MODELING

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Abstract: Recent focus on light-weight design and fuel efficiency in several sectors (such as aerospace and automotive), as well as advances in polymer technologies, have made plastic parts more viable for high-value systems. These are often low-production, high-precise parts which require expensive tooling for traditional manufacture, making them difficult to reproduce later; this is especially true when the original tooling is no longer available, and full additive manufacturing (AM) is infeasible. This study explores the application of fused deposition modeling (FDM - extrusion-based AM) in the repair of cracks, chips, and broken features in such plastic parts. A framework for repairing various kinds of plastic parts using FDM is presented, including establishment of repair candidacy, selection of repair material and parameters, post-processing, and repair evaluation. Three case studies, one repairing an optimized truss, one exploring the use of sewing-stitch patch patterns, and one replacing a broken part feature, were developed to demonstrate the presented concepts.

Keywords: *Damage repair, additive manufacturing, fused deposition modeling, plastic materials*

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1. Introduction

The use of polymer-based engineering materials has become widespread in a variety of sectors in recent years. Due to advances in polymer technology, new manufacturing methods, and new mechanical design techniques, these materials are becoming a common choice for essential products. The polymer based materials offer numerous benefits such as low weight, easy manufacturability, recyclability, low cost, good strength-to-weight ratio, and resistance to fatigue and corrosion, and thus, have displaced metals, glass, paper, and other “traditional” materials in numerous applications [1-2]. As a result, they continue to find extensive use in areas such as packaging, construction, automotive, aerospace technologies, and electronics. The global polymer materials industry was expected by Lucintel, Inc. [3] to grow at a rate of 3.9% from 2015-2020 and be worth over the US $650 billion by 2020, as estimated in 2015 by Grand View Research, Inc. [4].

This rapid expansion in application of polymeric materials is providing respite to industries such as automotive and aerospace, where components made from these materials offer reduced weight; the reduced weight can decrease fuel consumption, enabling better performance while also reducing pollution and emissions. As a result, polymer-based engineering materials now constitute 10-15% of the total weight of some cars [5-6]. Standard components such as the bumper structure in BMW, the transverse support beam in some Porsche cars, and a triangle joint used by Audi are now made from polymer-based materials [6]. Similarly, the aerospace industry uses these materials in the production of protective covers, cab interior parts, cockpit components, and other essential items [7-10]. However, there is also growing concern about the expanded use of these materials relative to their environmental impact. Due to the low cost and easy processing of most polymer-based materials, parts made from them are often used just once and then discarded. While most of these materials are recyclable, the recycling culture and infrastructure are not well-established in many places, resulting in disposal of these parts in garbage that finds its way to landfills and ocean beds where it disturbs natural ecosystem. Many of these polymers are not biodegradable. Even the materials that are bio-degradable, require specific conditions to break down (such as temperature range, exposure to ultraviolet light, and specific oxygen content), and the absence of these conditions allows these plastics to remain harmful in the environment [2, 11]. The manufacturing of plastic materials is also a source of greenhouse gasses (GHG) and pollutants in many areas of the world [12-13].

In many cases, these discarded items are genuine trash and should be recycled, but some of them could be considered “high-value” parts that may be worth reusing (if not damaged) or repairing to extend their life. It is not always obvious how repairing such parts could be done efficiently or quickly, as it is often cheaper to discard them to make replacements. Replacement is not always most viable option, as some parts may be very difficult or expensive to duplicate due to legacy/customized design or specialized polymer materials. A strategy for deciding which of these components may be worth repairing and which should be replaced is needed, both to reduce the cost of systems depending on these parts and to prevent waste and environmental damage. While the percentage of plastic components worth repairing using existing methods is admittedly quite small, developing effective and efficient methods for doing this may expand the pool of candidate parts and significantly increase the useful life of parts made from polymer materials. The recent expansion of advanced mechanical design methods such as topology optimization [14] has not only enhancing the performance of standard components but is also increasing their complexity, making them far more difficult to reproduce without access to original models/drawings or tooling.

The use of additive manufacturing (AM) technologies could be a method for accomplishing these repairs, as these manufacturing processes can use a wide variety of materials and are highly automated [15-16]. While additional process development is needed, AM is uniquely suited for repair tasks due to its nature of depositing materials in precise, selective locations without the direct intervention of a human operator. It has already been established that the use of AM in various capacities can result in smoother and efficient strategies for maintenance, repair, and overhaul of systems in the field [17-19]. Apart from being able to salvage broken parts, AM can reduce the time and cost of acquiring spare parts, reduce the need for inventory, and provides freedom to improve design. There are a variety of processes available and a plethora of materials, most of which involve heating or melting the material to shape it, but there are also AM processes which only use local heating or no heating, facilitating repair of heat-sensitive and otherwise easily damaged components.

Most of the work and research so far has been done on investigation of AM-enabled repair for metal components. Several major national projects, such as FANTASIA, TurPro, and the AMOS consortium, have been initiated to investigate the repair and remanufacturing of various components using AM [20]. These projects mainly focus on repair of metal aircraft components, as these are the ones most cost-effective to repair due to their high value and complex nature. The Fraunhofer Institute has successfully certified repair processes for 15 standard components using laser metal deposition (LMD); some of the repair processes developed include those for high-pressure turbine blades, front drums, compressor disk blades, and nozzles for Rolls Royce turbine engines [20-21]. Similarly, the laser engineered net shaping (LENS) process has been used to repair components made from a variety of titanium, stainless steel, tool steel, nickel alloys, and cobalt alloys. At the current stage of development, the cost of repairing the components is reduced by approximately 50% of the cost of replacement, and the required time is reduced from several weeks to a few hours or days [22]. Since LMD and LENS (and similar processes such as laser direct metal deposition (LDMD)) deposit material by spraying or blowing metal powder, deep cracks and internal damage in components can be repaired. This repair process typically involves the machining away of material around the crack or defect and then repairing by filling the groove or slot. Studies by Pinkerton *et al*. [23] and Zhang *et al*. [24] explored this for various parameters and conditions, successfully repairing the metal components when the slot was less than 90 degrees from the stream of powder. In addition to powder-spraying processes used for repair, wire deposition has also been used for repairing metal parts additively. The principles are the same as for the powder-based processes, but, has the advantages of greater material utilization and higher deposition rates [25-26].

In addition to direct spray and wire deposition, other AM processes have also been used successfully for repairing metal parts. Siemens used selective laser melting (SLM) to repair burner tips, requiring only 10% of the standard time for repair and requiring less manufacturing and inspection time [27]. Looking at SLM repair at a more fundamental level, Zghair *et al*. [28] studied the interface between a damaged aluminum component and material deposited to repair it. Their experimental tests suggested that the interface zone was stronger than the base material, showing that the repair was successful. Acharya *et al*. [29-30] discussed the potential application of scanning laser epitaxy (SLE) to repair hot section components in a turbine engine. Scanning laser epitaxy can be used to deposit nickel-based superalloys with equiaxed, directionally-solidified and single-crystal microstructures. The studies demonstrated that the deposed material made a dense, crack-free bond with the repaired surface, as well as showing a higher hardness. Similarly, Basak *et al*. [31] demonstrated deposition of nickel-based superalloy CMSX-4 on investment-cast substrates using SLE as a potential repair method for nickel-based gas turbine blades.

The process for preparing the metal parts for an AM repair has also been studied. The most important consideration when performing these repairs is that they are defect free, so correct preprocessing is essential. Zhang *et al*. [24] discussed machining strategies to prepare the parts, where the area to be repaired is scanned and the optimal toolpath to prepare the surface is generated. They developed a reverse-engineering tool which generated an STL file for the repair, as well as g-code for preparation. Liu *et al*. [32] proposed using stereo vision to detect the defect location and size. Intrinsic and extrinsic parameters can be found using stereo camera calibration. The parameters and spatial information can then be transformed to a hybrid manufacturing system.

Much research is still needed on the AM repair of parts made from polymer-based materials, but the basic principles are straight-forward and similar to those developed for the metal AM repair. This article explores this subject in detail for repairable plastic parts, including the conceptual process for selecting AM-repairable plastic parts, a technique for identifying high-value plastic components, and a discussion of the use of fused deposition modeling (FDM) as the most promising of the standard AM processes for repair of these parts. To further explore the concepts, three specific cases are presented involving the repair of both part geometry damage and restoring broken plastic parts by adding features directly to the surface of the broken component.

2. AM-based Damage Repair: Framework

This section gives a high-level overview of selecting AM-based repair for a damaged part, independent of the material used or the process. More detailed analysis is needed for a selected individual process, which is not covered in depth in this article, except for FDM in later sections. Fundamentally, any potential AM-based repair should go through three levels of assessment to ensure that the repair is feasible, worth the investment of time and materials, and has a reasonable likelihood of success.

1. First, the damaged part should be evaluated in terms of "must replace" versus "candidate for repair," where some simple analysis can be used to find that either the part may be repairable or will certainly require replacement.
2. Next, in the second level, the damage should be further appraised to find the possible methods that are available to repair the part, with the option to reject parts if they are found unsuitable for repair after this further analysis. The outputs of this level are "repairable using AM", "repairable excluding AM", or "reject and replace".
3. Finally, the desired AM process is evaluated to ensure that it can accomplish the repair goals of the user. This stage will be a "go-no-go" decision based on the checklist used.

The first two steps consist of decision analysis problems, where a logical process must be used to evaluate the situation and decide if repair is feasible or desirable. The decision process may exit with a decision of "replace" (i.e., "reject") at any point along the way, so no repair resources are expended until after the process is completed. The final step, evaluating specific processes, should be done using a checklist based on the desired process and material. Several useful checklists for the feasible use of specific processes and process families have been developed and discussed in the AM literature [33-36]. A rough checklist for FDM is developed and discussed in Section 4.3.

Once a damaged plastic component has been identified, it is necessary to establish the desirability and feasibility of repairing it versus replacing it with a new one. Figure 1 below shows a flow diagram for deciding if a damaged plastic part is potentially a repair candidate or is necessary to replace; note that this is a general decision diagram and does not take into consideration any specific repair process.

- The first step is to identify if the part is subject to any standards or certification process that may be affected by repairing it. If not, or if the standard/certification process is unaffected by a repair, then it can be further examined for repair potential. If the standard/certification is affected by modifying the part or repairing it, it is probably best to replace it.
- Next, the component should be inspected to decide if it is salvageable; if not, it can be considered a total loss and no repair is feasible or possible and it must be replaced.
- Next, it should be identified as commercial off-the-shelf (COTS) or not.
    - If it is COTS, it should be checked if a spare is in-hand or if a new part is easily obtainable and can be obtained quickly and cheaply enough to satisfy the stakeholders. If yes, it should be replaced; if it is very hard or expensive to obtain or it is needed before a spare can be obtained, it is potentially feasible for repair.
    - If it is not COTS, it should be classified as a standard part design (i.e., typical, easily reproduced features which can be re-modeled and reproduced easily with standard tools) or a legacy part for which drawings or special tooling existed at some point. If it is a standard design that can be easily reproduced, or a legacy design for which the original tooling or drawings are available, it should be replaced. If not, it should be determined if it

can be digitally scanned and reproduced acceptably using AM. If yes, it should be replaced; if not, it is a candidate for repair.

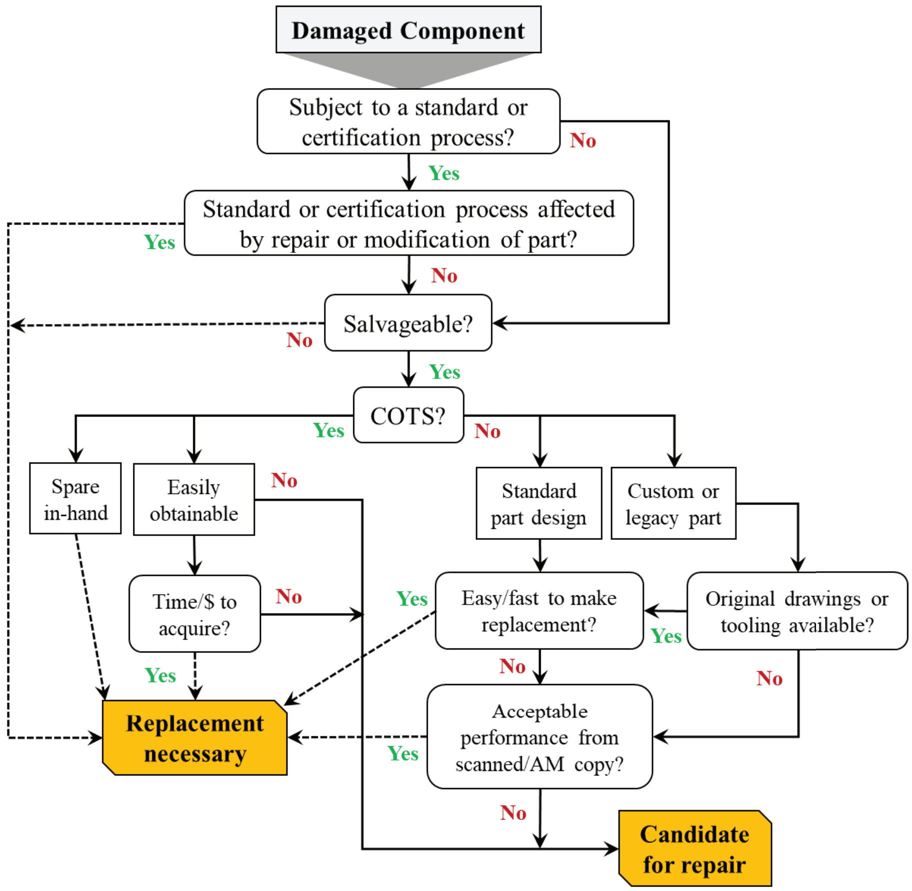

Figure 1. Decision diagram for establishing whether a damaged component must be replaced or if it could be a candidate for repair using some repair method.

Once it has been established that the damaged plastic component is a repair candidate, it should be further examined to see if it is potentially feasible to repair with AM. This process is to establish the candidacy if the component can be repaired using AM in general, where the repair procedure involves adding material either as a patch or to append an existing feature; no specific process nor repair material would yet be selected. Figure 2 shows the decision process for this step; three essential outcomes are possible from this evaluation: (1) repair with AM, (2) repair but not with AM, or (3) reject and replace component. As can be seen in the diagram, there will be cases where either AM or traditional repair methods (e.g. epoxy, soldering) are feasible; in these cases, the stakeholders will need to determine the best choice relative to repair capabilities and performance desired after the repair. In general, a successful repair will require that the repaired component perform at least minimally within its use range of application after the repair.

The first step for determining the feasible repair method will be to inspect and classify the damage carefully. Most damage can be classified into four categories:

1. *Total loss*: The component is not repairable, generally because it is severely deformed or cracked/broken beyond repair. This choice may not be obvious in the process for establishing repair candidacy (Figure 1) but may become apparent during the inspection step.
2. *Small crack or chip*: Minor damage that should be repaired to prevent degradation of performance or a major failure later
3. *Large, deep crack*: Major damage that affects performance but is minor or localized enough to be repairable. In addition to material cracks, this category may also include repairable damage at interfaces in the system (such as joints).
4. *Broken or missing feature*: The part is intact except for a single feature (such as a blade or mounting boss) which has been broken off. In this work, it is assumed that the feature material is lost or destroyed, and it is not possible or desirable to glue or weld it back onto the component.

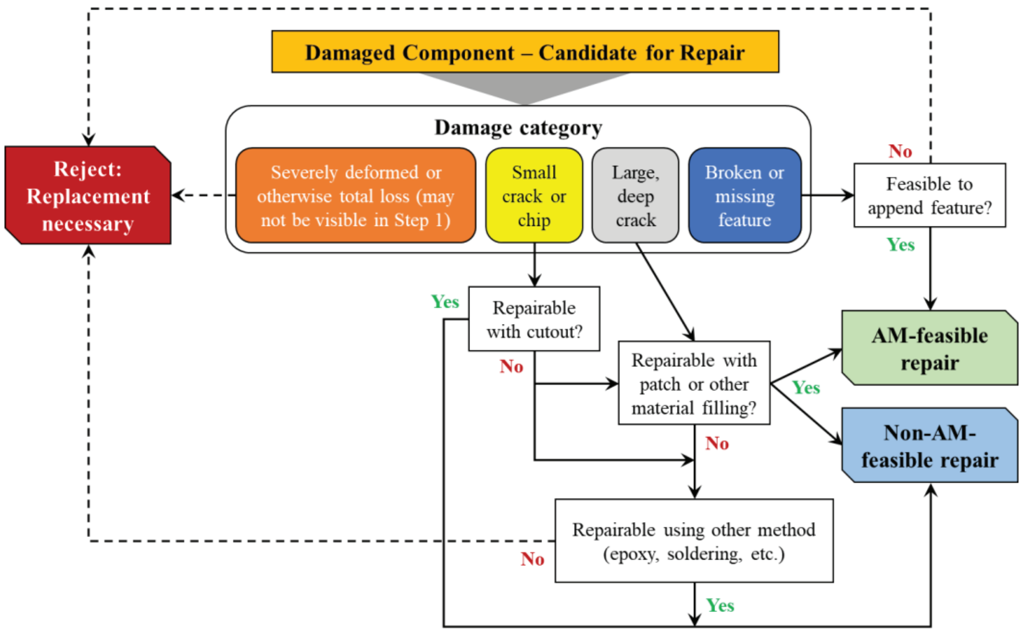

Figure 2. *Decision diagram to determine if candidate part is AM-repairable, non-AM-repairable, or should be replaced*

If the component is discovered to be a total loss, it clearly must be replaced. If minor damage is detected, it should be considered for a simple cutout (such as a rounded groove) to eliminate the crack or local stress concentrations to prevent further damage. If this does not produce desirable results, it should be considered for repair by patching or some other method such as soldering, welding, or epoxy filling. For a large, deep crack or similar major but repairable damage, a cutout will not typically be feasible, and a patch or other material deposition will be needed. If this is feasible, it could be done using either AM or a non-AM method of repair based on the conditions and materials in question. If patching or otherwise adding new material will not satisfactorily repair the damage, other non-AM methods may be considered; if no feasible method is found (even if the damage was judged to be repairable), it should be rejected and replaced. Finally, if a broken feature can be appended on using AM to build up a new feature, this should be considered for AM repair; if not (under the stated assumptions), the part should be rejected and replaced. Note that this decision process does not consider preparation or pre-processing of the material before repair. The pre-processing of the material for the repair process should be done by the stakeholders in a way appropriate for the problem at hand and feasible with the resources available as it may involve cutting or machining the part.

Once it has been established that AM repair is feasible (and desirable), the next step is to select the process to be used and ensure that it is feasible for the specific repair under consideration. Much expert intuition and experience are necessary here, both to select an appropriate process and select the material and parameters for the repair. There is still a possibility that the repair may fail during processing, but careful planning and choice of process and material will minimize this risk and increase the likelihood of success. For this work, the process for evaluating and setting up this third step for the FDM process is developed and discussed in great detail in Section 4. Similar (and possibly more extensive) evaluation on other candidate processes will be a necessary step for the design and repair team if other processes are used or considered.

3. Identification of High-Value Plastic Components

As plastic components become more sophisticated and widely used, both because of the need for light-weight designs and improvements in polymer technology, a category of "high-value" component naturally emerges. While the majority of (or most, depending on the context) plastic components made from standard materials are easily replaceable using OEM spares or full-AM replacements, this is certainly not always the case. Therefore, a formal definition is needed for high-value plastic components to distinguish them from the standard or easily replaceable plastic components. The primary purpose of this segregation is to distinguish those plastic parts which are feasible and worth the cost to repair and those which are not. In practice, many repair methods can be quite expensive and difficult relative to the amount of material processed [23, 37-40], so it is vital to understand when it is cost-effective to use it instead of simply replacing the part in question.

> **Definition** A *plastic component can be considered to be naturally high-value if it has one or more of four characteristics:*
>
> 1. It is essential to the system operation (with or without a spare on-hand)
> 2. It would be very difficult, expensive, or time-consuming to reproduce
> 3. Specialized tooling or a manufacturing process is required to produce it (and may no longer exist or be available)
> 4. It must be made from a specialized or unavailable material, such as a specially created blend of metal powder or chopped carbon fibers in a polymer matrix

While the designation as high-value does not automatically ensure that it is worth a repair attempt, it does help to screen out the plastic components which are not worth the cost of repair. Note that, according to the definition offered here, which components in the system are high-value is context-dependent and may be different for each system studied. Legacy components (those on old or obsolete systems which are no longer supported) for which original drawings or tooling no longer exists may be considered to be automatically high-value, but they should still be evaluated to ensure that they meet the criteria set by the stakeholders for a worthwhile repair. Also, note that a standard, low-value plastic component may become high-value component temporarily if it fails or is at risk of failing and a replacement is not immediately available.

4. Additive Repair with Fused Deposition Modeling (FDM)

4.1. FDM Process Mechanics

Fused deposition modeling (FDM) is one of the most common additive manufacturing processes [41-43]. It uses a continuous filament of a polymer or polymer-composite material, which is heated inside the extrusion head. The filament material then becomes semi-molten and behaves as a visco-plastic material. Due to its visco-plastic nature the material can flow easily under pressure; in an extruder head, this pressure is applied by a feeding mechanism that pushes the filament downwards, extruding it through the nozzle. When the material exits the nozzle in a semi-molten state, the newly deposited material fuses with the existing material adjacent to it. The extruder head moves along a predetermined path in the X-Y plane to deposit the material at desired location. The basic process and an example FDM system are shown in Figures 3a and 3b, respectively.

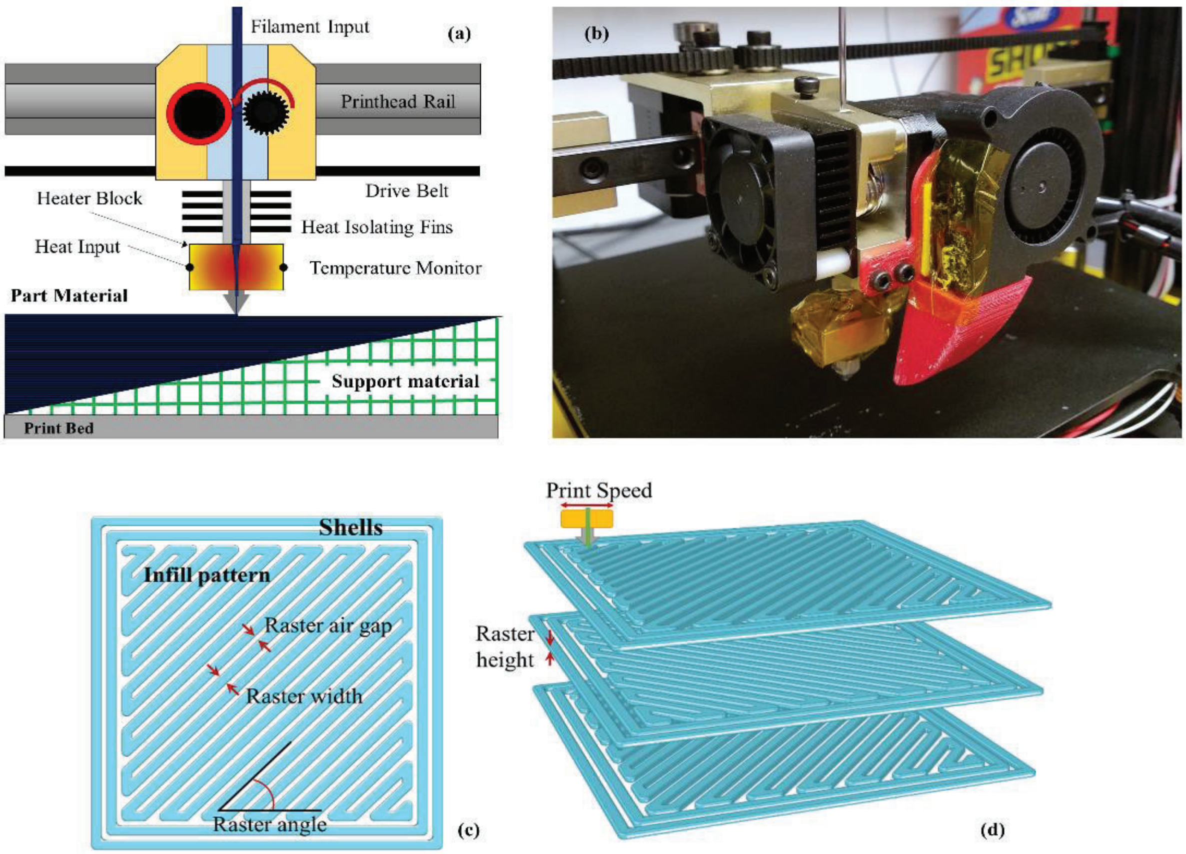

Figure 3. *(a) Process mechanics for FDM, (b) example FDM system, (c) FDM material layer parameters, and (d) view of several layers for a rectilinear deposition pattern.*

The path taken to build the component in layers is determined by a set of g-codes, which is generated directly from CAD software; this is done using an STL file, slicing the model into layers (2-D contours), and then planning a trajectory to complete each layer. Several parameters must be specified (such as those shown in Figures 3c and 3d), as well as the speed of deposition, temperature, and other inputs (discussed further in Section 4.2). After printing one layer either the extruder head moves up along the Z-axis or the printing platform descends along the Z-axis equal to the thickness of the layer and the next layer is printed. As a result, multiple layers are stacked on top of each other to construct the three-dimensional geometry.

4.2. FDM Deposition and Layer Bonding

The final geometry printed by FDM depends on several parameters. Some of the key parameters are road height, road width, raster angle, print speed, print temperature, and orientation of the object. These parameters are shown in Figures 3c and 3d.

1. *Road height* is the height of the material deposited by the nozzle in one pass. It is generally equal to the layer thickness.
2. *Road width* is the width of the material deposited by the nozzle in single pass. It is usually equal to the nozzle size. However, it can be varied somewhat in the software.
3. *Raster angle* is the angle formed by the direction of material deposited with the X-axis and is dependent on the pattern selected. Figure 3 shows the standard rectilinear pattern, but this may vary depending on the needs of the user. Raster angle is a vital printing parameter because the material properties of the final product are anisotropic [42]. As the material is deposited by placing one bead adjacent to another, the material extruded in adjacent bead cools down due to convection. Thus, the bond strength of the material along the deposited bead that is along the raster angle is stronger than the bond strength between two beads.
4. *Print speed* determines the rate at which the material is deposited. Generally, slower speeds produce better quality prints, but this increases processing time (and therefore cost). Thus, a balance needs to be maintained between print speed and the time required to print the geometry.
5. *Print Temperature* is the final temperature at which the material is extruded through the nozzle. The printing temperature should be chosen according to the material of the filament, as different materials behave differently at different temperatures. Some materials are far more sensitive to temperature changes than others, so care should be taken to ensure that the printer is in proper working order and that the temperature sensors are accurate.
6. *Print Orientation* is the orientation in which the part is printed. It is an important parameter to be considered when higher mechanical strength is desired in certain directions as compared to others, due to the anisotropic material properties. Different factors that influence the anisotropic material properties include, the length of the beads of material in the cross-section, and the ratio of shell to infill.

Road height and road width are the primary parameters that control the voids generated between two adjacent passes or two adjacent layers. Several other parameters such as: infill pattern, infill density, and shell thickness, also play a role in determining final material properties of the printed geometry. Additional machine parameters such as motor power, system jerk, belt stiffness, and similar may affect the propertied of the final printed part but, have not been studied in enough detail so far to determine their influence.

4.3. FDM Repair: Practical Considerations

It is not feasible to repair all polymeric parts using FDM. Several things need to be considered to ensure a successful repair of a broken or cracked part with FDM. The following points guide the decision to decide if the damage is repairable using FDM:

1. *Nozzle accessibility*: The area which needs to be repaired should be accessible by the extrusion nozzle. As a result, only surface and shallow repairs are possible via FDM.

2. *Depth of repair*: Since the nozzle of FDM printers, in general, has a short length and wide area, it will not be able to reach the bottom of the crack if it is deep. However, if the crack only needs to be patched at the surface, or if the crack is shallow, it can be repaired using FDM.
3. *Bonding of material*: The material used during the repair should bond well with the exiting material of the component. The stronger is the bond between the two materials, stronger is the repaired part. More on this point will be discussed in the next section.
4. *Printing parameters*: Printing parameters, as discussed earlier, affect the mechanical properties of the 3D printed part. Thus, they should be chosen carefully.
5. *Part geometry:* The part should fit with in the build volume of the FDM machine so that the part can be secured rigidly while it is being repaired.
6. *Residual Stresses generated during FDM*: While printing materials such as, acrylonitrile butadiene styrene (ABS), high residual stresses can be produced due to the thermal cycling effects on the material. High residual stresses can decrease the load carrying capacity and fatigue resistance of the material and should be considered.

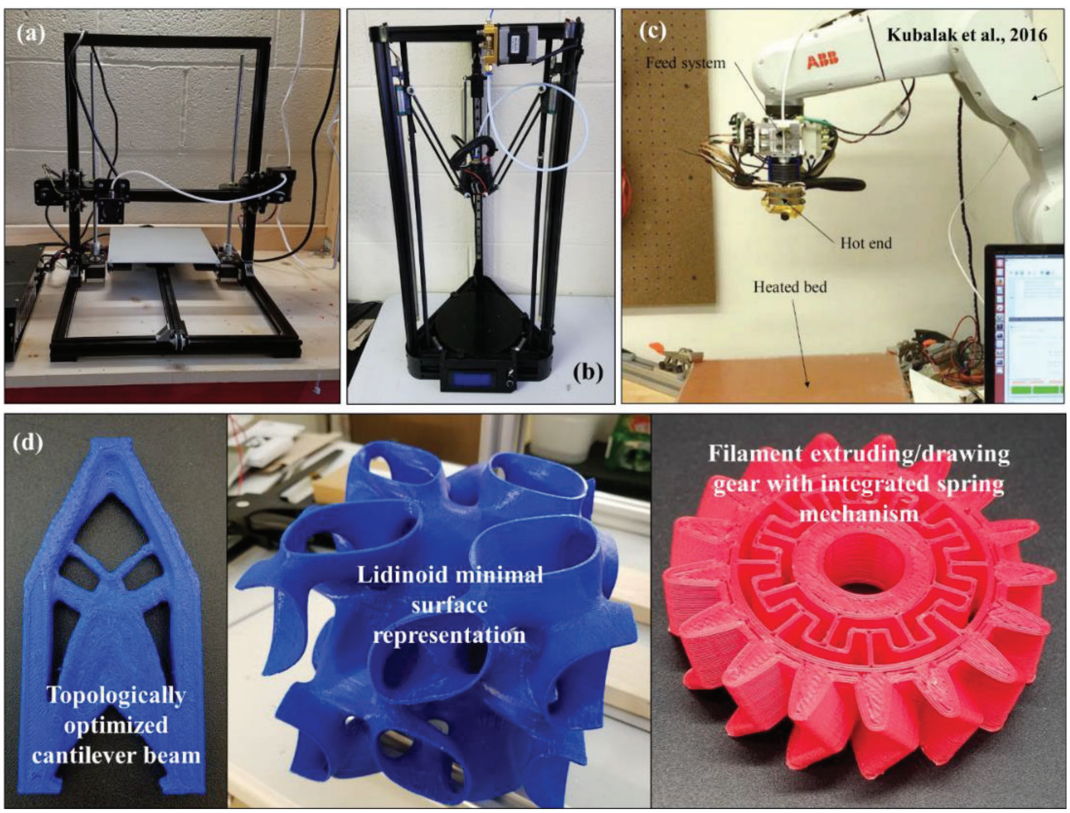

Figure 4. *Examples of (a) cartesian axis, (b) delta, and (c) robotic arm-based FDM machines [73], along with examples of complex plastic components made using FDM*

4.4. FDM Repair: Advantages and Challenges

Once the applicability of FDM for the needed plastic component repair has been established, its use can offer several major advantages, in particular:

1. *Machine architectures*: There are several different FDM architectures available for use in repair, most notably the cartesian axis design (Figure 4a), the delta system (Figure 4b), and the multi-axis robotic arm (Figure 4c). With the available machine designs, the material can be deposited on nearly any reachable surface to accomplish the needed repair.

2. *Material flexibility*: Great flexibility exists to choose the material used to accomplish the repair, as any polymer or polymer-composite material that can make a polymer bond with the part material and is extrudable through the FDM nozzle can be used. No special form of the material is needed, as this repair method will use standard FDM filamented materials that are readily available.

3. *Material placement control*: FDM allows precise control of the deposition pattern, repair density and the thickness of the deposited layer or layers. The resolution can be as precise as a few dozen micrometers [44-46] in some cases, far more precise than most other plastic repair processes (soldering, epoxy patches, friction repair, and others). FDM can easily create and thus, repair very detailed features in complex geometries, including textures (Figure 4d) and even stitch-like patterns (Figure 4e) if needed.

4. *Repair strength*: Following major studies [47-53], the FDM deposition bond on a properly prepared substrate or previous layer seems to be strong for most materials and combinations studied; it is comparable to epoxy or soldering [54-59] in some cases.

5. *Preparation and surface treatment*: In general, minimal surface treatment and preparation is needed, mainly consisting of cleaning off any dust, grease, and loose material fragments so that the hot deposited material can make a good surface bond. The part may be easily pre-heated if needed, as this may aid in deposited material bonding for some materials, especially if the deposited material temperature is below the glass transition temperature of the part being repaired.

6. *Heat field*: The heat field produced by FDM penetrates the substrate material, ensuring that the surface is locally warm and can make a bond with the deposited material. This field has been observed to affect the surface interfaces for several layers [60-64], helping to form a stronger and more complete polymer bond [49, 65-67]. The depth of the heat field can also be controlled easily by controlling the deposition temperature, print speed, and the distance of the nozzle from the surface.

7. *Post-processing and inspection*: The repairs made by FDM can be easily inspected and post-processed, as needed. Several standard methods have developed for the inspection of plastic AM materials [68-72], but any traditional non-destructive evaluation method could be used for inspection. Post-processing may include machining, cutting, or chemical treatment, but may not be necessary if FDM alone can produce the desired geometry and coverage.

8. *Automation*: With the proper equipment setup and in combination with a scanner, this FDM repair process can be semi-automated to produce repairs using a pre-defined catalog of repair types, materials, and geometries.

Some challenges associated with the repair using FDM, however, remain. These challenges should be considered carefully before choosing to build or use an FDM-based plastic part repair system. These challenges consist both of fundamental FDM limitations and the practical considerations of repairing polymer-based materials.

1. *Cost*: With the resources required, AM-based repair may be much more expensive than some other repair methods (such as epoxy or plastic welding), so it is only economical when used for high-value plastic parts.

2. *Repair depth*: The depth of the repair is limited to the depth at which material can be extruded into the damaged area. Therefore, the repair is typically limited to surface repairs and patching, but deeper areas can be repaired if a groove or cut is made before repair (such as is common with the repair of small cracks).
3. *Reachability*: Repair surface must be reachable by the deposition head. The complexity of the repair is limited by the type of FDM system used. For most cartesian and delta systems, the repair surface must be mostly flat, but this is not true for arm-based systems which can move in more than three axes.
4. *Repair material glass transition temperature*: Generally, patch material needs to have a higher melting or glass transition temperature (which depends on the materials in question) than the material being repaired [52, 54-55] for the surface to be melted enough to initiate a new polymer bond with the patch material.
5. *Repaired component material*: Choice of patching material is dependent on knowing the material composition of the repaired part without further damaging it and on the ability of the user to be able to clean it properly in preparation of polymer bonding during the repair.
6. *Jig or fixture required*: Unlike with fresh FDM, some tooling is required during repair
7. *Part damage level*: Severely plastically deformed parts may not be repairable using FDM
8. *Part damage*: Assuming that the part being repaired is not a total loss, a failed repair may cause additional damage to it
9. *Repair area*: The size of the repairable area is limited by the reach of the printer.
10. *Shape of repair*: May not be able to make very small features without a series of straight lines to allow efficient extrusion.

5. Evaluation and Post-Processing

While not discussed in-depth in this work, the need for evaluation and post-processing of repairs is included here for completeness. Various inspection techniques are available, both destructive (e.g., fracture and tensile tests) and non-destructive (e.g., performance analysis or inspection) to evaluate the quality of the repair. Post-processing may include such actions as removing support material, surface finishing, sintering, and other actions. The case studies described in the next section present both destructive and non-destructive tests to assess the value of the repairs. Further work and development are needed in this area, but it is beyond the scope of this work.

6. FDM Repair Case Studies

To further explore the concepts presented, a case study was completed for each of the basic repair tasks feasible with FDM (simple patching, textured patching, and feature appendage), as presented in this section. The three cases used broken parts, which are high-value according to the definition given in Section 4. All repairs were performed using a Prusa i4 FDM machine (Figure 5a) and several materials with a 0.4 *mm* tool steel extruder; the printing parameters and assumptions are given within each of the cases. All pre-processing was done using Ultimaker® Cura© as the authors are experienced using it and it allowed easy direct control of the printer during the repairs. Per typical ASTM standards for testing polymer-based materials, all components were conditioned at 24°*C* and 40% relative humidity for at least 40 hours between each major operation. Also, washing of the parts before the repair was performed using a Formlabs® isopropyl alcohol (IPA) bath (Figure 5b), as it was determined to be important for the surfaces to be as clean and free of dust/grease as possible. All parts were handled with gloves after washing to avoid contamination of the cleaned surfaces. The nozzle was offset to 0 *mm* for all printing, so the nozzle was just touching the surface (Figure 5c) of the repair region to ensure that the maximum possible contact was made between the repaired parts and the deposited material. The proximity of nozzle also helps in keeping the surface warm, promoting the bonding.

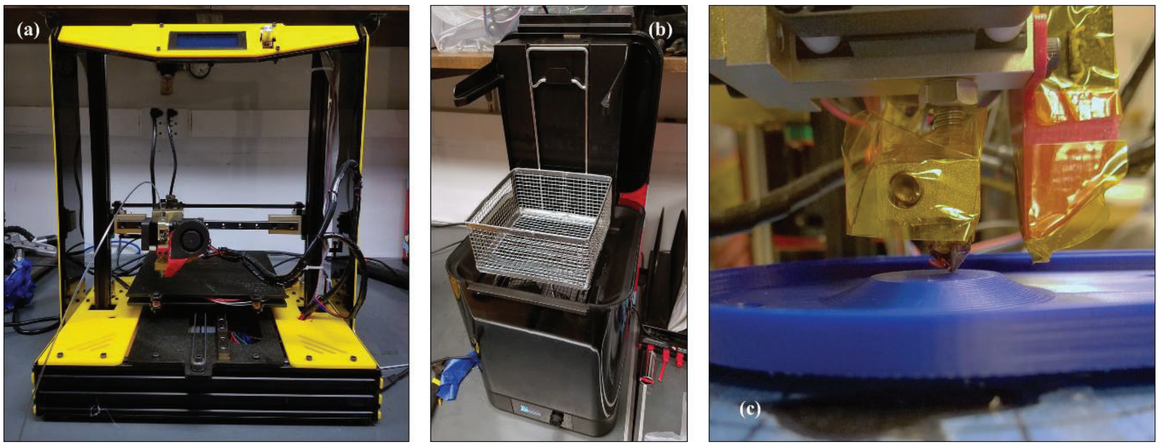

Figure 5. *(a) Prusa i4 printer used for the three presented case studies, (b) IPA bath used to clean and prepare components before repair, and (c) nozzle starting position relative to repair surface*

6.1. Copper PLA Truss with ABS Repair

A generatively-designed copper PLA (5% copper powder in a polylactic acid (PLA) matrix) truss (Figure 6a) was identified as being damaged and in need of repair or replacement. The truss was designed to be loaded at four locations, as shown in Figure 6b, and to support a load of 100 *N* while remaining as stiff as possible. It was identified as high-value and potentially feasible for repair since (1) it was essential to the system operation, (2) would be very difficult to reproduce without the original design files, and (3) was made from a non-standard material. Manufacturing of the original part was not considered to be difficult from the original design, as it could be made using injection molding or one of several additive manufacturing processes; therefore, it met three of the criteria for a high-value plastic part.

For this case study, the simulated broken component was manufactured using FDM with Gizmo Dorks 5% copper PLA, printed full density at a temperature of 220°C and print speed of 70 *mm/s* on a heated 60°*C* glass plate. The truss design was completed using the generative design toolbox in the Siemens® SolidEdge© 2019 3-D modeling software. The simulated break (Figure 6c) was made using a thin saw blade, where the material was carefully cut to ensure no local material property disturbances. Once this was completed, the part was considered to be in "as-found" condition to best simulate the realistic conditions of such a repair. No post-processing or surface treatment was done besides removal of the support material.

Repair candidacy evaluation was first done to ensure that it was feasible for repair. It was not subjected to any standard or certification process and was not considered to be damaged beyond repair (Figure 6c) upon inspection. The component was certainly not COTS nor did it have a standard design (since it was optimized using the generative design tool). The original files and tooling were considered to be unavailable, and the stakeholders determined that a rough scanned copy was not sufficient for the need of the system; therefore, it was shown to be a reasonable candidate for repair. It was also determined to be feasible for AM repair in general and FDM repair specifically following the process developed in Sections 2 and 4. With this information, the repair process was initiated. The stakeholders decided that a simple patch on the surface around the break would be sufficient. Upon further evaluation, it was determined that a large surface patch on the face of the part (Figure 6c) would interfere with its operation, so side patches (Figure 7a and 7b) were generated based on the size of the part. The largest patch thickness determined to allow the truss to still function as designed was 1.5 *mm* thick and covering the entire width of the sides around the break (Figure 7a and 7b). The selected patch material was ABS since it has a higher melting temperature than the base material and was more resistant to fatigue and further breaking after the repair. The patches were printed from Makerbot® ABS filament at a speed of 30 *mm/s*, a layer height of 0.2 *mm*, and extrusion temperature of 240°*C*; the final results are shown in Figure 7b.

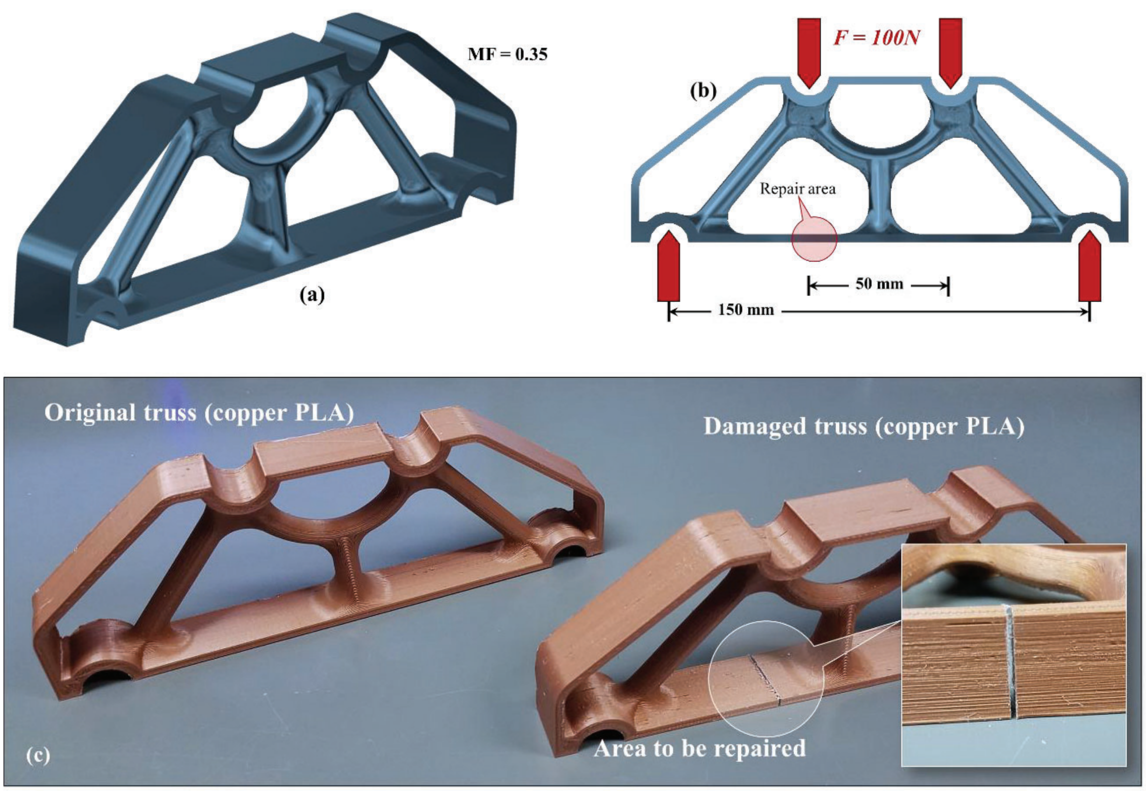

Figure 6. *(a) Generated truss design (SolidEdge® 2019 generative design toolbox, mass fraction (MF) of 0.35), (b) load case and damage location, and (c) manufactured intact and broken truss with damaged area highlighted*

However, it was also noted that the two materials have not yet been conclusively established in the AM literature as compatible in all cases, primarily since they are produced from very different sources and the base material contained particulates; therefore, some uncertainly may remain in the quality of the repair. Surface smoothing may help with this, but no literature was available which showed the effect, so two cases were completed, one with the raw surface (washed in the IPA bath) and the other with the surface smoothed using a file. The mean surface roughness of the raw component was measured to be

113.5 μm (n = 25, standard deviation = 35.2 μm) and for the surface treated one was measured as 74 μm (n = 25, standard deviation = 24.9 μm). Surface roughness measurement was done using a DeFelsko® Positector® surface profile gauge with 1 μm resolution.

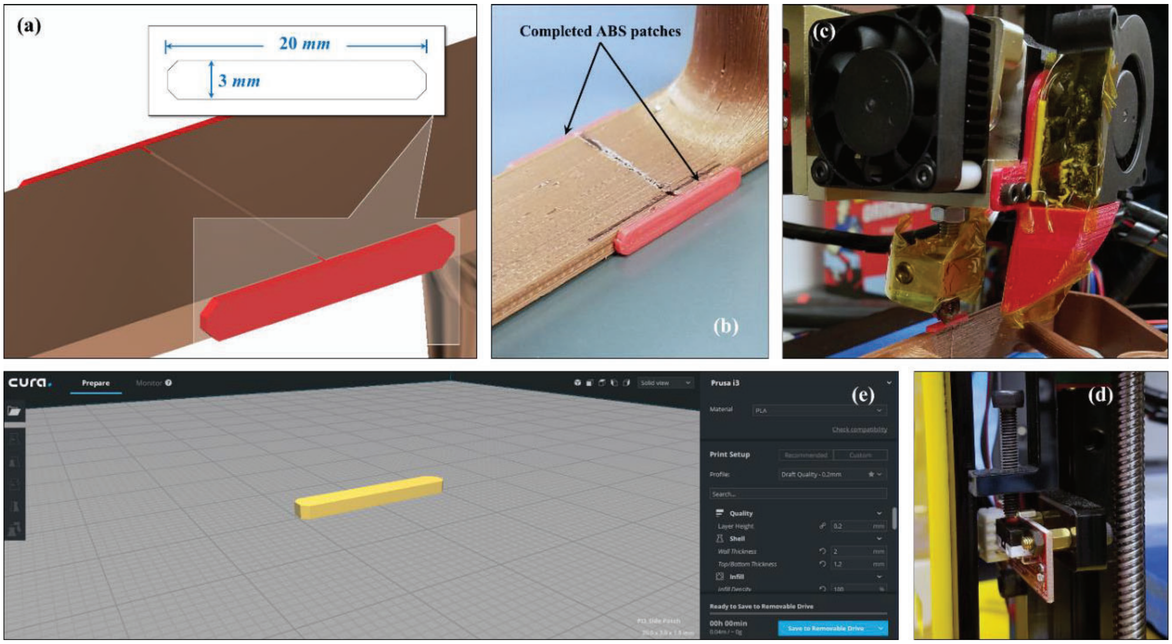

Figure 7. *(a) CAD model of ABS patch, (b) completed repair, (c) repair in-process, (d) machine height adjustment, and (e) pre-processing setup for the patch*

Patching was performed by generating an STL file of the repair material to be deposited, pre-processing it (Figure 7e), and directly printing the material onto the part. The component was fixed to the build plate of the material using double-sided carpet tape (Duck® DT-75), which was strong enough to hold the part securely for repair while allowing easy removal. The precise positioning of the part on the build plate was facilitated by using a grid pattern on the bed which was aligned with the software driving the printer, allowing precise positioning. The printer had an easy height adjustment setup (Figure 7d), so the offset to accommodate the component was quick and straightforward to complete. For more complex repairs, the broken part could be scanned, and the repair position determined automatically; it was not necessary for this case study. The repair time took approximately 90 seconds per patch once setup, positioning, and heating were completed. Patching was observed to add about just a few milligrams of mass to the 46 *g* components.

After the repairs were completed, they were evaluated non-destructively by comparing the performance of the original non-broken components against the repaired ones. The experimental setup is shown in Figure 8a; a 4-point bending tool was used with an MTS universal testing machine with a 2 *KN* load cell and a testing speed of 2 *mm/min*. The force-deflection curves for these tests are shown in Figure 8b, where the patched cases are compared with both intact and broken (and not repaired) specimens up to the working load of 100 *N*. Note that the patched cases are both stiffer than the original, unbroken case; this may be due to the ABS absorbing more energy than the PLA or other factors and deserve further investigation in future research. Finally, to test the maximum performance of the small patches printed (Figure 7b), the specimens were loaded until the patches failed, as shown in Figure 8c. In both cases the patches fractured and did not delaminate from the PLA part, indicating that the bond was very strong. Overall the repairs were considered successful, with the patches providing excellent stiffness and strength about six times what was needed for minimum performance.

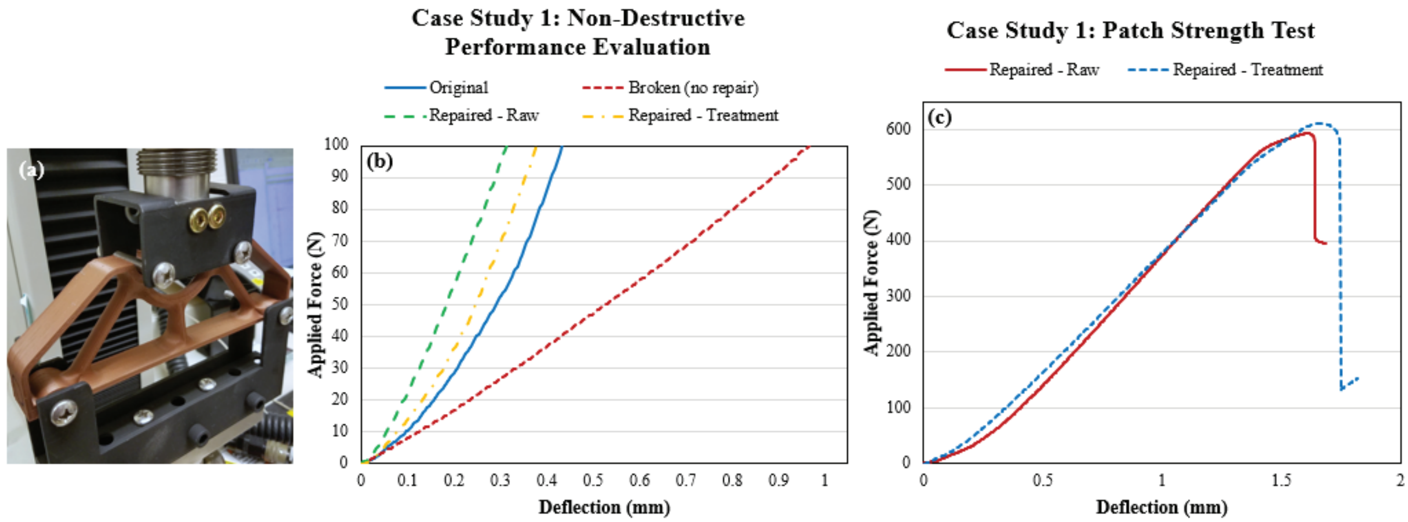

Figure 8. *(a) Experimental setup for Case Study 1, (b) results of the non-destructive evaluation tests, and (c) patch strength testing results*

6.2. ABS/PETG Stitch-Repair of Notched Molded ABS Block

Simple patching was demonstrated to work in the previous case study, but it is not always desirable to use a solid or heavy patch, or the patch may need a tailored shape to cope with specific conditions. In such a case, a customized or localized repair is needed, which adds the smallest possible amount of material or arranges it in a specific way. The second case study for this article explores this by producing and testing several sewing stitch-shaped patches used to repair a notched molded ABS block subjected to a 3-point bend loading. Sewing stitch patterns as patches is an interesting concept, as it facilitated the creation of complex and strong structures which are easy to calculate and reproduce. They allow mostly straight lines during printing (allowing more efficient extrusion and less need for filament retraction) and offer familiarity and intuition for the design and repair team. The three cases selected were the slanted single-line stitch (Figure 9a), the honeycomb stitch (Figure 9b), and the zig-zag pattern stitch (Figure 9c); the patterns and names for the stitches came from standard sewing terms, and the patterns/dimensions are shown. Since this case study is a continuation of the concept presented in Case Study 1, the feasibility and desirability of completing the repairs are assumed to be in place, so they do not need to be presented again.

Since the objective of this case study was to continue the theme of Case Study 1, but from the perspective of a complex patch, the repaired surface was a simple ABS bar which had been notched using a 45° router bit with a 0.1 *mm* tip using a milling machine at a cutting speed of 2000 *RPM* and a notch depth of 3 *mm*; the notch geometry is shown in Figure 10a and the loading case in Figure 10b. A total of 6 cases were completed, one of each stitch with a patch made from ABS and one each with another useful FDM material, polyethylene terephthalate glycol (PETG). These can all be seen in Figure 9. The observed mean surface roughness of the molded base material was measured to be 52.9 μm (n = 25, standard deviation = 23.8 μm); measurement was performed in the same manner as described in Case Study 1. All the printing parameters for these patches were identical to those used in Case Study 1, except that the PETG was extruded at a temperature of 245°C. No surface treatment of the samples was done other than an IPA bath before printing. All patches were 2 *mm* (10 layers at 0.2 *mm* each) thick and covered the full width (25.4 *mm*) of the ABS beam.

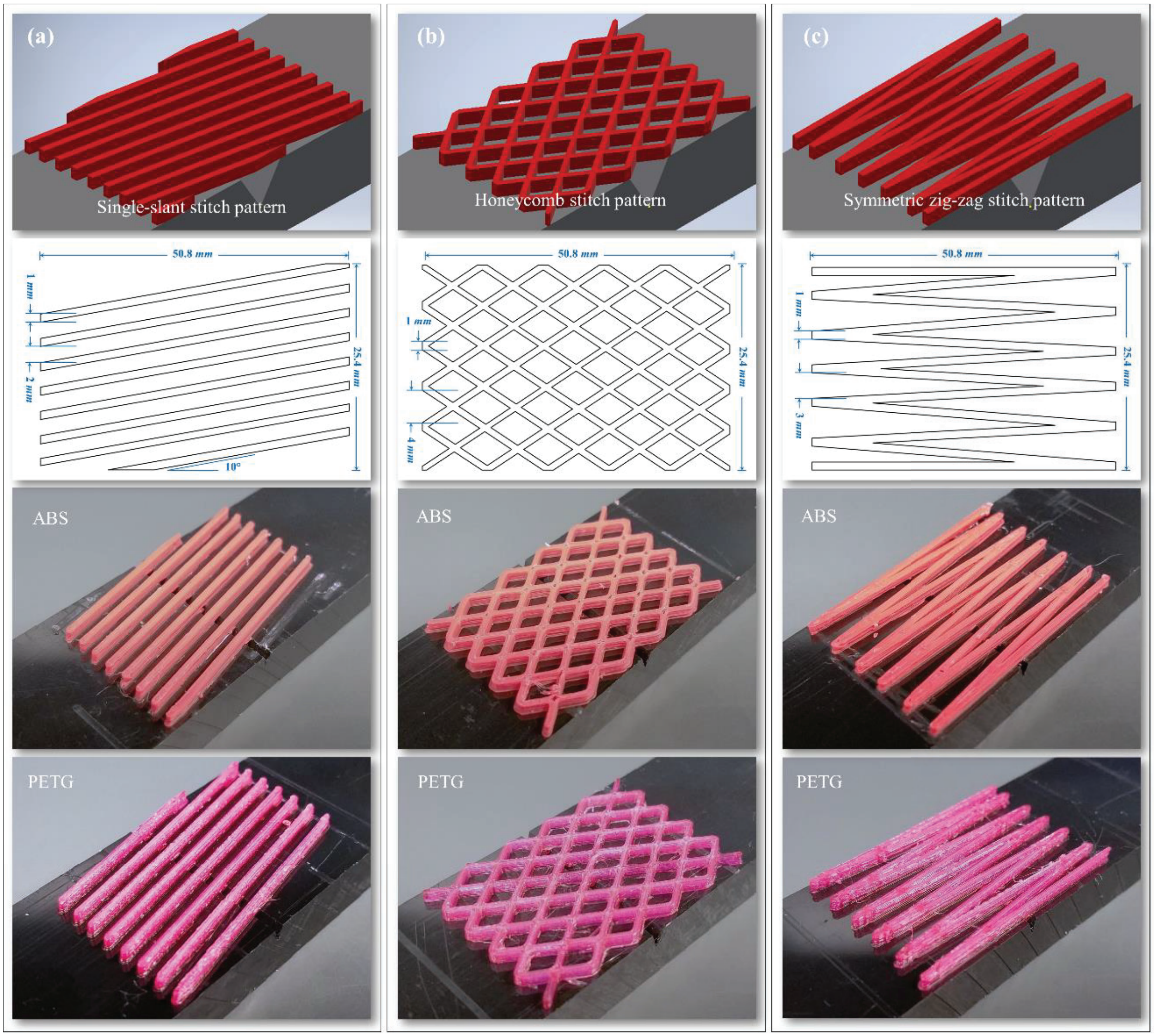

Figure 9. *Stitch repair patterns, dimensions, and application with ABS and PETG for (a) slanted stitch pattern, (b) the honeycomb stitch pattern, and (c) the zig-zag stitch pattern*

Once the repairs were completed and the samples conditioned (40 hours in the same ambient environment as the samples for Case Study 1), they were tested for performance using a 3-point bending test and were broken to find the force-deflection curves for each case. The experimental set up is described by Figure 10b and the results of the tests (compared with the non-patched baseline case) in Figure 11a for the ABS patches and Figure 11b for the PETG patches. It was obvious from the experimental results that there was a significant difference in performance between the materials and patching patterns, with the ABS honeycomb providing the most benefit (41 *N* increase in strength). The ABS honeycomb and zig-zag patches were observed to be the only two of the six cases were the patch itself broke under stress, the rest failing by delamination of the patch. This suggests that surface treatment is needed and more flexible materials (PETG is far stiffer than ABS) should be expected to perform better.

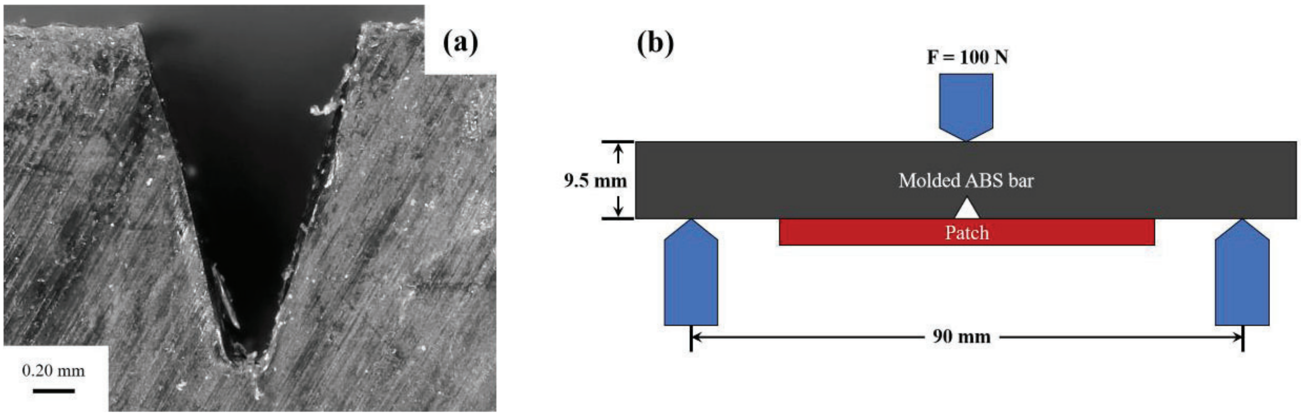

Figure 10. *(a) Example machined notch in ABS beam and (b) loading case for repair tests*

It was also noted that using the stitching patch actually decreased the strength of the joint for the slant patch for both materials. It was observed during the tests that the slant patches completely separated from the surface of the ABS bar during the tests, but not without carrying some of the load early in the test; it appears that the breaking of the patch introduced a shock to the base material, suddenly increasing the load around the notch. This behavior was captured in the experimental data and can be seen in Figure 11a. Overall, four of the six cases were successful in adding strength to the base material while adding only a minuscule amount of extra material to the part. The benefits, however, were not significant in two of the cases. The different patch geometry showed significantly different performance, thus, this is a promising method of repair once the behavior is more well-known. Further study is needed in this area for different kind of patch materials, surface treatments, and boundary conditions.

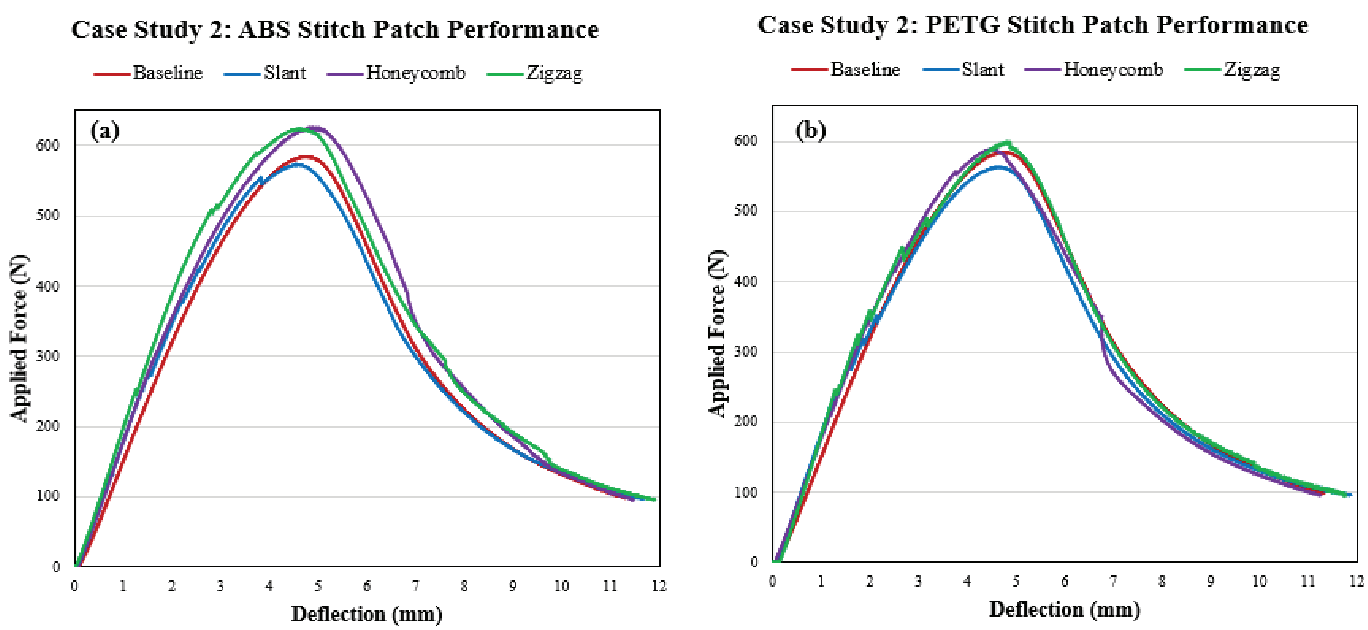

Figure 11. *(a) performance for ABS patches, and (b) performance for PETG patches*

6.3. Addition of Missing Feature to Broken ABS Part

In the final case study, FDM was used to repair a broken high-value plastic part by printing a replacement for a feature that had broken off. The feature in question was a mounting boss that was used to help contain a pulley running a soft rubber belt in a power transfer system (and therefore subjected to a load of 50 *N*); Figure 12 shows the setup before the break and the location of the repair. The part to be repaired is the lower housing, made from ABS and was originally made (for the purposes of this case study) using FDM from Hatchbox® ABS (print speed of 60 mm/s, extrusion temperature of 220°C, layer thickness of 0.2 mm, and printbed temperature of 90°C). Using the same technique used in the previous two case studies, the mean surface roughness for the area to be printed on was observed to be 76.6 μm (n = 25, standard deviation = 24.2 μm). Similar to Case Study 1, the part was determined by the stakeholders to be repairable, as the part met two of the four criteria for a high-value plastic part (essential to the system and much more expensive to replace than repair) and was determined to be easy to repair since the printing surface was flat and easily reachable.

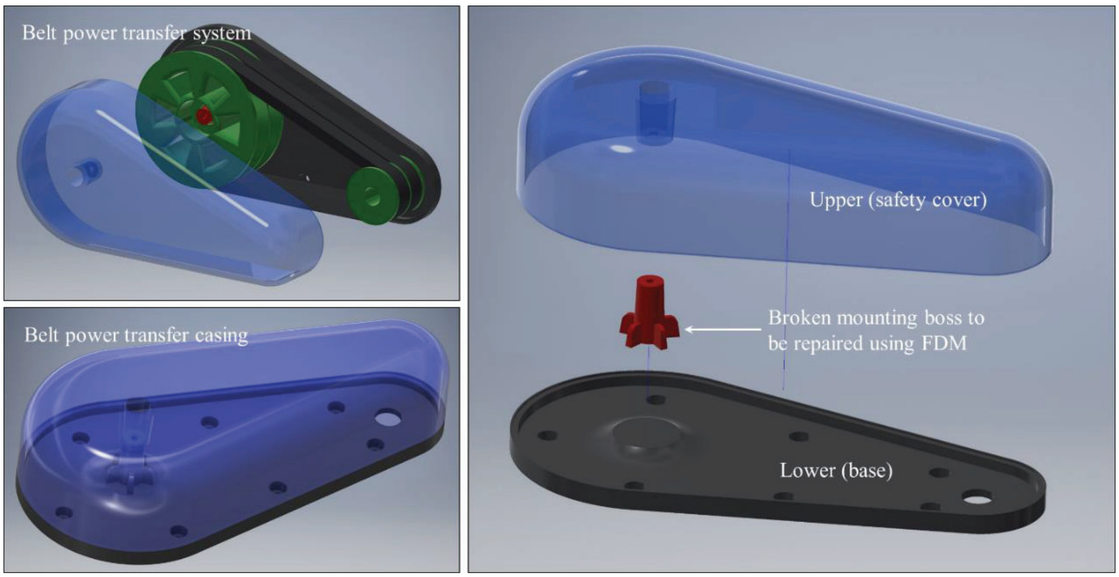

Figure 12. *Power transfer system with broken feature to be repaired using FDM*

The mounting boss was a standard design (attached to a customized part), allowing quick and easy modeling and generation of a repair plan for adding it to the part. Overall, it was determined to be easily repairable, but the repair material to be used was a source of contention among the stakeholders. Since the compatibility of different FDM materials has not been conclusively established, it was decided that four different materials should be tried and the one with the best performance (under the loading conditions shown in Figure 13a) would be selected to repair the component (Figure 13b). The four cases were to:-

1. Print a new feature immediately on the ABS base using the same brand of ABS filament and settings as the original part (Figure 13c). This process was used as the baseline case to compare the performance of the other three cases.
2. Print the new feature using a higher-temperature ABS (Makerbot ABS, extrusion temperature of 240°C) with a print speed of 30 mm/s (Figure 13d).
3. Complete the repair using PETG, with an extrusion temperature of 245°C and a print speed of 30 mm/s (Figure 13e).
4. Finally, repair the component using a new feature made from polycarbonate (PC) printed at 245°C and 30 mm/s (Figure 13f).

As with the other case studies, strong carpet tape was used to secure the parts to the printbed. The base parts used were conditioned for 40 hours, as previously described, before printing of the features. The only exception was the original ABS (Figure 13c), which was printed as soon as the base part was cool.

This exception was done to distinguish it from the later repair, using the higher temperature ABS and to provide a baseline for comparison.

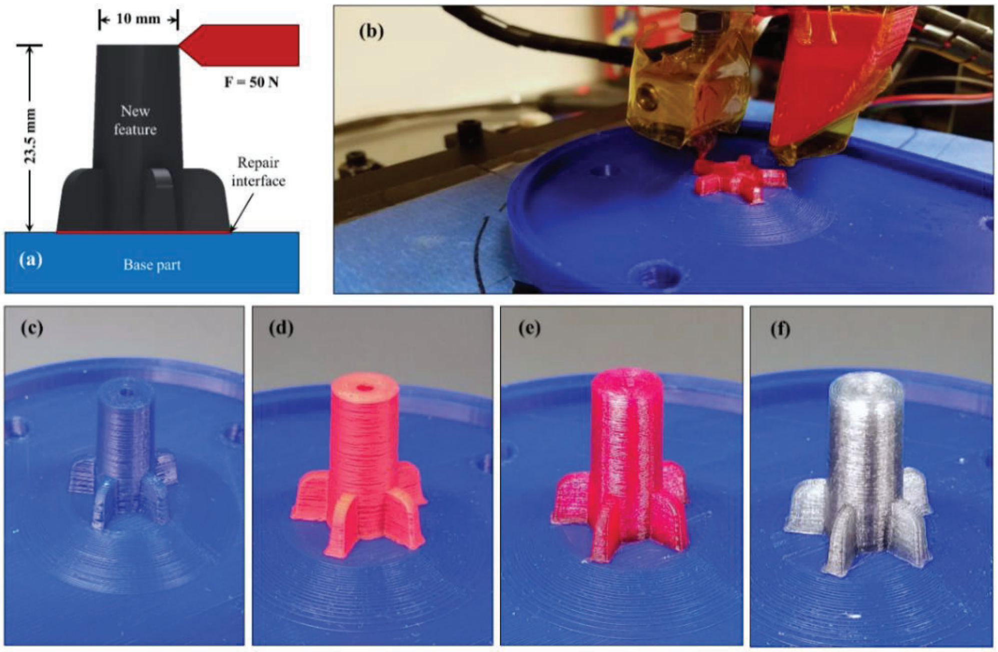

Figure 13. *(a) Loading condition and interface for broken feature, (b) repair processing, (c) baseline feature, (d) ABS repair, (e) PETG repair, and (f) PC repair*

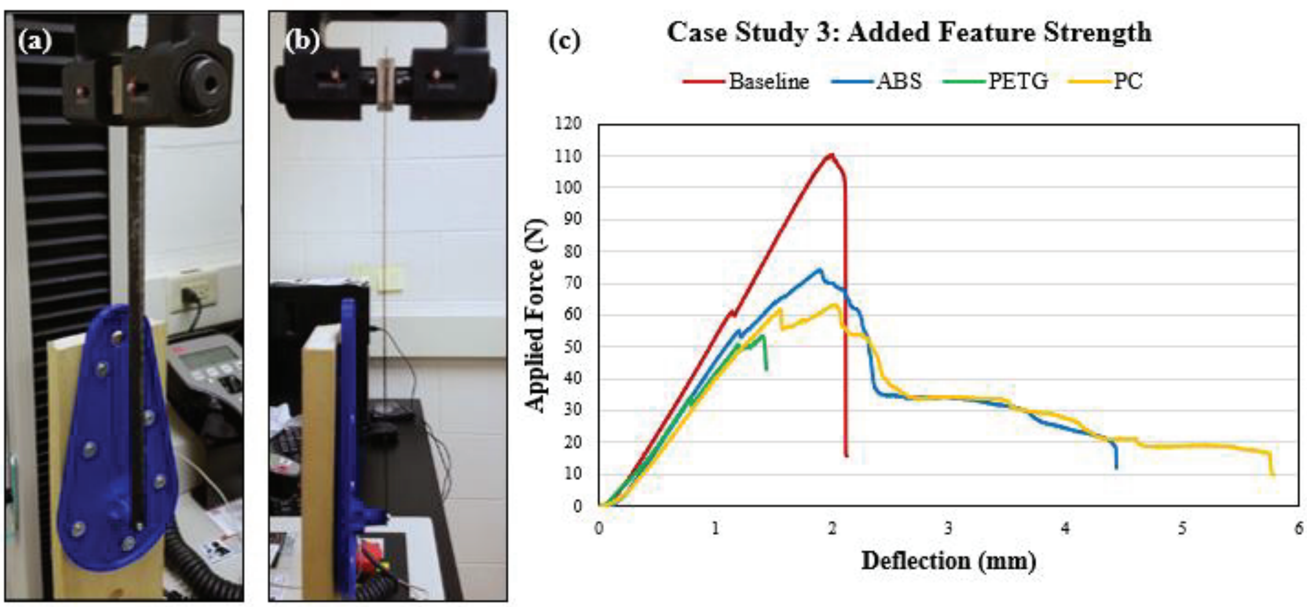

Figure 14. *(a) Experimental setup view 1 and (b) view 2 and (c) the experimental results for repair cases*

To test the realistic performance of the appended feature for the four cases, a custom destructive testing apparatus was built, as shown in Figures 14a and 14b. In this experiment, the repaired component was secured to a piece of wood with screws, which was attached to the lower part of the MTS universal testing machine used in the previous two case studies. A tensile testing grip was used on the top end to hold a steel strip which was attached to the boss to apply the load shown in Figure 14a. The results of the four tests are shown in Figure 14c. The baseline case performed the best, but all four were able to tolerate the 50 N load necessary for the component to be used. The baseline case, as shown in Figure 14c, broke in the boss itself and left the interface intact. The other three cases were observed to fail by delamination (specifically, separation at the joint interface in Figure 13a), the PETG failing suddenly and the other two slowly separating from the main component. Of the three repair cases completed after conditioning, the 240$°C$ ABS performed the best with PC coming in a close second. This order was not a surprise, but it was surprising that the conditioning of the base part and the difference in temperature were so impactful on the bonding conditions. After the performance of the PETG patches in Case Study 2, the results observed for this material were expected. Overall, all the repairs were successful under the use conditions, but with a wide variance of performance and behavior for the various cases.

7. Summary and Conclusions

This study focused on exploring the use of fused deposition modeling (FDM) as a method for repairing high-value plastic components. First, the benefits of repairing plastic components were discussed in depth, as well as important previous works on additive repair methods were enumerated, both to motivate the research presented in this article and to better understand the limitations of the current knowledge in the area. Next, a framework for logically determining the feasibility of repairing high-value plastic parts was proposed, consisting of three fundamental levels: (1) determination of the feasibility of repairing the part, (2) determination if an AM process would be appropriate for the job, and (3) determination of the value of a particular AM process for this. The first two were presented as decision analysis problems, with the third simply being a checklist to ensure feasibility and that a good repair outcome was likely. A detailed definition of what a high-value plastic part was then given, where four criteria determine the designation; any one or combination of these criteria could make a given part "high-value". After this definition was given, the FDM process itself was analyzed in great depth so that the benefits and challenges are clear before using it as a repair process. A brief discussion of post-processing and repair evaluation was presented, but it was not covered in depth as it was not within the scope of this study; the method for post-processing and evaluation for the case studies were presented in depth, but a general discussion was not undertaken. This is a topic of further research. Finally, three large case studies were done to further explore the concepts and derive conclusions about the value of FDM as a repair process for various tasks involving high-value plastic parts; the two fundamental AM repair tasks (patching and feature addition) were explored, with two of the case studies examining different aspects of the patching task. Major conclusions from this study were:

- FDM was a good repair process for some of the cases presented, but not for all.
- More ductile materials, such as ABS, performed much better as repair agents than stronger but more brittle materials such as PC and PETG.
- Some potential repair materials are far more compatible with each other (such as ABS on PLA) than others (such as PETG on ABS).
- Surface preparation, as observed in all three case studies, is vital for a successful repair.
- Conditioning of the surfaces after preparation and before repair had a very high impact.
- The highly anisotropic nature of FDM materials was very apparent in the results of the case studies, providing a wide range of performance relative to small changes in the design and orientation of the repairs.
- In conclusion, FDM appears to be a feasible process for repair of plastic parts, as long as the conditions of the repair are taken into consideration, and careful preparation is performed.

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