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Reviewed Paper

Investigating the Impact of Decontamination on Recycled ABS Viability in Additive Manufacturing

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Abstract:

Much research in the Additive Manufacturing (AM) has recently focused on sustainability, including Circular Economy (CE), which is increasingly recognised and supported to reduce environmental harm and the impact of climate change. An aspect of this is the effort to recycle polymers and find uses for the recovered materials. However, when these polymers reach the recycling centre, they may not be in a viable state due to contamination from biological, chemical, or pharmaceutical sources. This is highlighted when considering the polymer waste generated by the medical sector, which necessitate decontamination prior to be reformed into a new product. To ensure continuity with the medical sector, the selected procedure follows the same prescribed methodology. Recovered materials are first cleaned in an ultrasonic bath with triple enzyme detergent, then disinfected with a quaternary disinfectant before being sterilised in an autoclave at 121^{o}C for 30 minutes. This procedure is for decontaminating reusable medical devices and is sufficient for ensuring the reclaimed polymer is suitable for use within the AM industry and wider sectors. The work contained in this paper aims to investigate the effects this procedure has on common polymers and their viability for reuse in AM to support a wider circular economy. We believe that common polymers can be recovered, decontaminated and result in viable filament for use in material extrusion-based AM.

Introduction:

Sustainability within additive manufacturing (AM) has become an area of interest in response to criticism over material waste generation, with a focus on the commonest and widely used process of material extrusion (MEX) (1–4). What this means is that for AM to be part of Circular Economy (CE) of manufacturing model (5), the material reclamation needs to be accounted for including what processes are required to ensure that recovered material is safe for subsequent use. Towards this end the material streams from all relevant stakeholders need to be considered and suitable measures taken; one of which is to establish best practices for material cleaning and decontamination, to improve the polymers purity and reduce the likelihood of hazardous contaminants entering the material supply chain. This is imperative to assure the safety of those involved with the material recycling process, the manufacture utilising this new materials stream, and the end user of devices created from this feedstock. With the aim being to retain the value of the recovered material to the AM industry by maintaining its mechanical and thermal properties.

CE and its approach in a sustainable business model has become the subject of much research within the last 5 years (6). CE focuses on continually using, retaining, and reusing product components and or materials to improve the material usage efficiency, reducing, or ultimately eliminating waste. This is a development in contrast to the typical linear life cycle, described as the “cradle to grave” approach, in which manufacturers and designers were

taught to consider how to dispose of the product after its effective life. A key area in the development of the CE is to consider all the stakeholders involved in the supply, manufacturing, use and end-of-life reuse and or eventual disposal of products (7), highlighting key bottlenecks in the process in order to achieve efficient material and energy use and recovery. This needs to be done for long term economic and social benefit (8) and to reduce the demand on critical materials from virgin sources (9). While described as ideally circular, the model depends on how the system is implemented as it can take on many different forms. While this approach is not itself a new concept, the use of modern techniques and research has revealed challenges and critiques facing it (10,11). While the economic viability of this approach will determine the business model or requirement for investment support, this paper focuses on if the material recovered from this process. Comparing it to a control sample to determine what the effects of the decontamination process are on it's mechanical properties, explored through tensile testing.

Research has already been undertaken in this area to explore material use in multiple cycles, but these have largely been conducted under the assumption that the material was clean prior to conversion back into an AM compatible form (12–16). From the literature two notable examples stand out. The first being research conducted by the National Taipei University of Technology, where they used a combination of pristine and recycled zirconia slurry to create dental prostheses via stereolithography (17). Due to the nature of dental prostheses, the potential risk to the patient or end use stakeholder requires the reclaimed material to be shown to be safe. Furthermore, the operational nature of stereolithography does not incorporate environmental factors that would act in a similar method to a decontamination procedure. This means that potential contaminants present in the recycled material, would then be present in the prosthesis and pose a risk to the stakeholder dependent on the source of the material. This would necessitate a rigorous logistical system that can trace material origin, which may not always be possible or economical, as opposed to cleaning and decontaminating the material upon collection. A better example where material cleaning and processing has been considered was done by a UK based company, where recovered fishing nets are reprocessed into usable nylon filament material (18). This has been undertaken to recover as much value from a waste product of another industry, to have a beneficial impact on the local environment.

Methodology and Discussion:

This research explored the effects of cleaning and decontamination on commonly used polymers such as Acrylonitrile Butadiene Styrene (ABS). To establish a suitable comparison between the effects on recovered and virgin ABS samples were prepared for testing from virgin material and decontaminated material. The material was sourced in 10 mm diameter rods with a length of 100 mm in its natural colour. This was done to ensure no additives would affect the polymer interaction with decontamination and how it was converted into a usable filament. To avoid unknown variables within the test materials, the sourced ABS was in its raw, uncoloured and uncontaminated state. This was done to focus on the effect the decontamination process would have on the polymer.

The material samples were dived into two groups, with half the material for each polymer going through the decontamination process. The process itself consisted of cleaning each sample in an ultrasonic bath with triple enzyme detergent, before being disinfected with quaternary ammonia disinfectant, then sterilised in an autoclave at 121°C for 30 minutes. This is the prescribed method for sterilising medical devices (19), ensuring as much control as possible to reduce the likelihood of unintended contamination of the polymers. ABS had a visible reaction to the decontamination procedure, as exposure to the autoclave caused material warping and discolouration, shown in Figure 1.

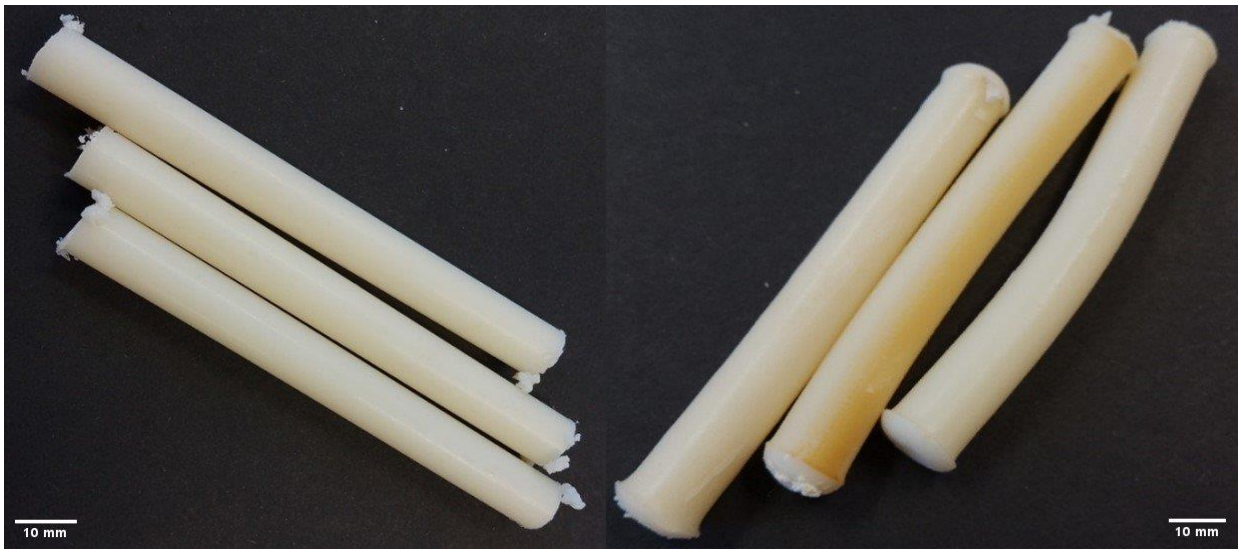

Figure 1: Virgin ABS Samples (Left), Decontaminated ABS Samples (right)

Following the decontamination process, the samples were fed into a granulator. This process involved the polymer samples being impacted by a rotating hammer drum against the metal rim of the granulator, shown in Figure *2*. This happens repeatedly until the polymer rods have been reduced sufficiently to pass through the grading sieve, with 5 mm diameter holes along the section.

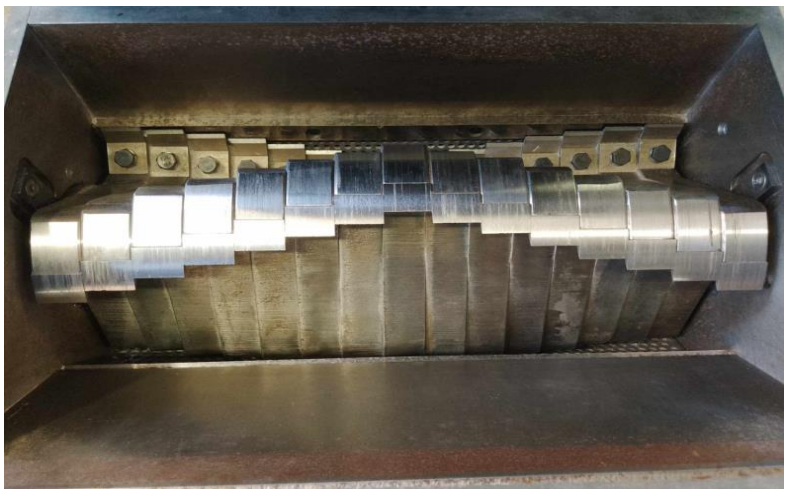
Figure 2: Inside of Granulator

The granulated polymers were reduced in size to be sufficiently to pass through the sieve and fed through the granulating process twice, with the resulting granulations shown in Figure 3. This was to reduce the size of the polymer granules to the size and consistency required for the subsequent extrusion into filament suitable for material extrusion 3D printing.

Figure 3: Granulated Raw Polypropylene Sample

The polymer granules were fed into the Filabot filament extrusion system to turn it into a 3D printable filament. This process included multiple steps starting with feeding the granules into the material hopper to be collected by a heated Archimedes screw, which raises the polymer to a molten state to drive the polymer through a 2 mm extrusion die. This extruded polymer is then passed over cooling fans as it is stretched, then fed onto a spool by an automated winder. The spool winder was also equipped with a dial touch indicator to measure the thickness of the filament, this was done ensure that suitability of the filament for Alternatively, these granules could be used in injection moulding or compression moulding processes.

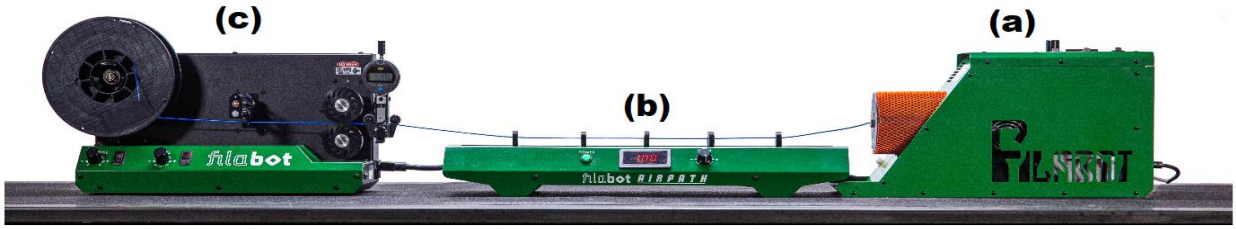

Figure 4:Example of filament making set-up (20); (a) Polymer heater/extruder, (b) Cooling fan Section, (c) Spool winder

To test the recovered filament and determine the effect of decontamination on ABS, test strips were 3D printed. One of these test strips is shown in Figure *5*. For consistency both set of printed samples used the same print parameters and file. These parameters followed standard guidance for printing with ABS, those being a nozzle print temperature of 250°C and a heated bed temperature of 80°C with the print environment being enclosed. The print settings where set to a layer height of 0.2mm, through a standard 0.4mm brass extrusion nozzle. The sample fill density was set at 100% for the tensile test samples.

The purpose of the test strips was firstly to ascertain the 3D printing performance of the filament and secondly to demonstrate that these filaments can be used to create new 3D printed products. To compare the mechanical properties tensile testing was done according to ASTM D638 Type IV (21).

Figure 5: Printed ASTM D636 Type IV Test Strip Sample.

Results and Discussion

Due to time and material constraints 5 test strips were printed using the decontaminated ABS Filament, and 4 test strips were printed from the virgin ABS filament. These samples were each individually placed into a Instron 3369 to conduct a tensile test. The experimental set up is shown in Figure *6*, and repeated to maintain consistency in test procedure.

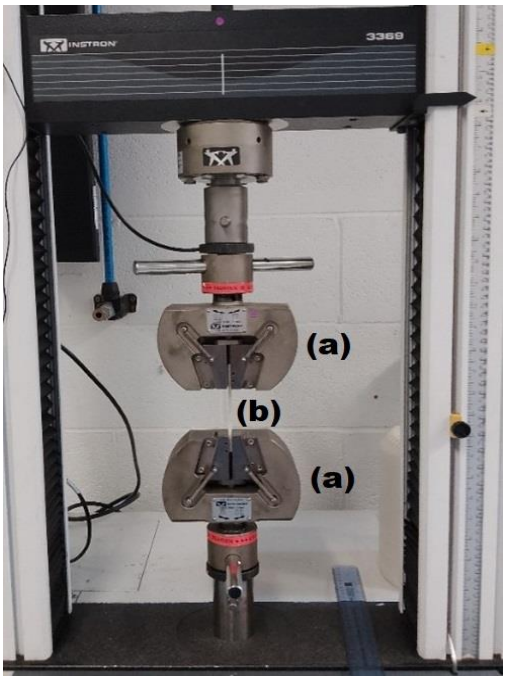

Figure 6: Tensile Test Set-up; (a) Instron tensile specimen grips, (b) Tensile test sample

The averages of the tensile test results are shown in Figure *7*, with a polynomial line of best fit plotted to better understand the trend of the data. The average data points are derived from the average force for the test samples at the point of tensile displacement, with the average being adjusted for samples failing before other samples. The results for each sample tested are shown in appendix A. Both sample sets behaved similarly until a displacement of approximately 1 mm, where the resistive force of the decontaminated samples starts to decline comparatively. Using the line of best fit, the average peak for the resistive force is 0.65kN for the decontaminated and 0.71kN for the virgin material. This equates to a reduction in mechanical behaviour of the printed sample of approximately 8.5%.

The implication of the results in Figure *7* and the visual distinction between samples seen in Figure *1* prior to granulation, would indicate that the polymer chains and interlocking weave has been degraded. This is most likely to have occurred during the autoclave step of the decontamination, where the prolonged heat exposure resulted in discoloration and material expansion. However, even though this has occurred the material was still capable of being processed and successfully utilised in material extrusion AM.

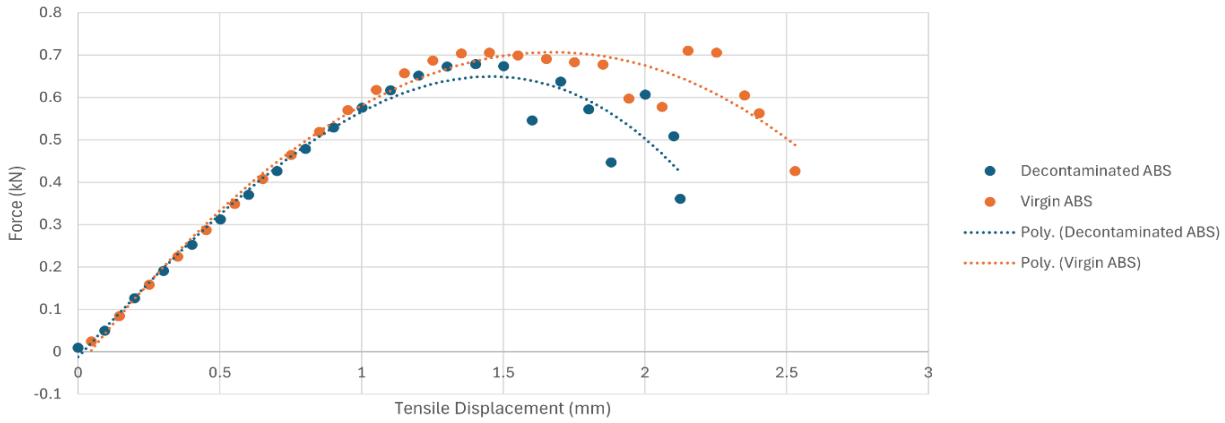

Figure 7: Average Results of Tensile Displacement Test

Conclusion

In conclusion, as more devices are used and disposed of a greater expectation needs to be placed on their planned end of life management. This is particularly important for devices in hazardous industry sectors like medical devices, which may become contaminated through their operational life. These devices still retain some value, even if it is in their material composition. This study has emphasized that it is possible to subject polymers to the accepted decontamination procedure prior to the material being recycled back into a feedstock form. While it may lose some of its mechanical capabilities it is still a viable material for many applications that may not require such stringent criteria. AM is a viable route for materials such as these to be reclaimed and remanufactured into new devices, either retained within the medical sector or used for a new purpose.

Further research is required to validate this recycling route for different materials, meta-materials and expanding the potential applications of them. Furthermore, this research

should be undertaken with the goal to establish an industrial standard for the recovery, reprocessing and recycling of material arriving from hazardous industries. This will enable better resilience in a more circular economy, as material value is retained, ideally reducing the need to extract further materials from finite sources and or that will be lost via disposal via incineration (leading to CO2 emissions) or land fill leading to environmental pollution.

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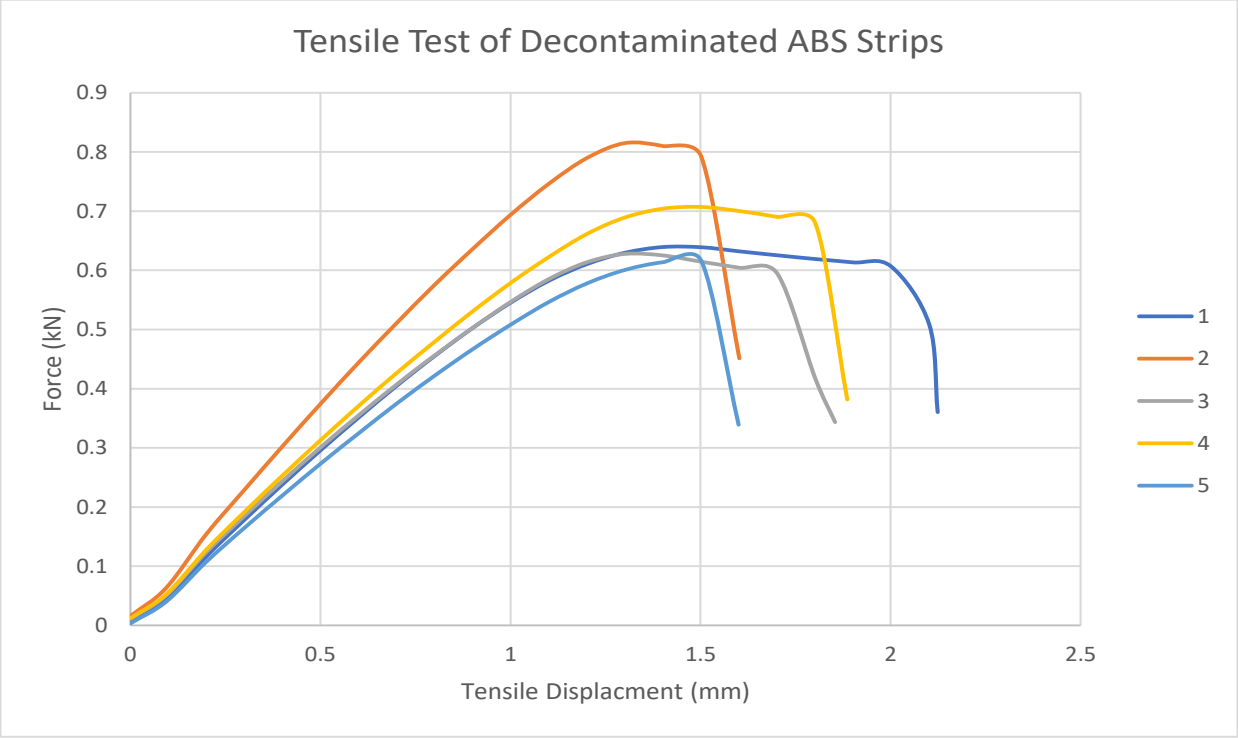
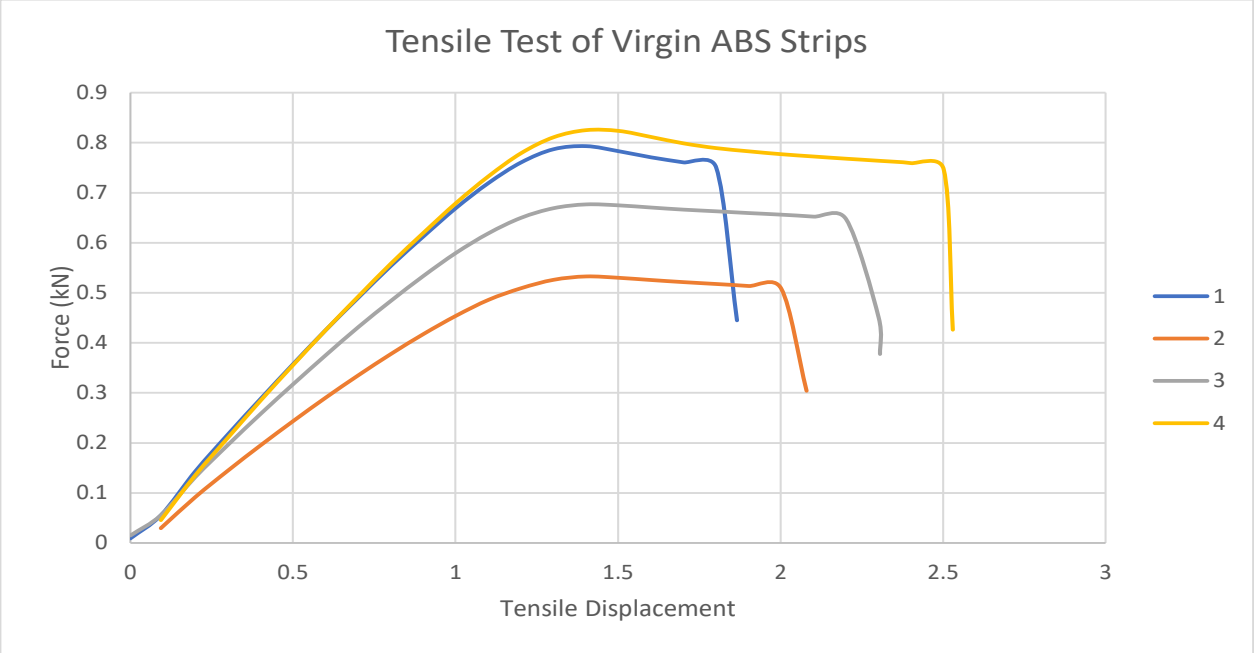
Appendix A




Tensile Test of Virgin ABS Strips
Force (kN)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
Tensile Displacement
1
2
3
4