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Surface evaluation of recycled nylon for FDM 3D printing for the purpose of dental prosthesis construction

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Abstract. Fused deposition modeling (FDM) is 3D printing technology that is used in many fields in today's world. In dentistry, FDM is mainly used to produce dental models and appliances by using polymers in filament form. This study aimed to evaluate the usage of recycled nylon filament in terms of surface hardness, surface roughness and build-up thickness. In this study, the recycling process was conducted by polymer compounding extrusion machine at a temperature of 250°C. Two groups of Nylon samples were used, control nylon and recycled nylon. Each group consisted of 10 specimens. The specimens were printed by Creality Ender 3 Neo FDM printer with printed standards followed for Nylon filament. The study samples were submitted to Shore D surface hardness test and surface roughness measurement, while the sample thickness values were recorded by digital caliper. The study results showed that the mean surface hardness was not significantly different after recycling, while surface roughness was significantly decreased for the recycled group. However, there was a significant increase in the specimens' thickness mean values. In conclusion, dental prosthetic work requires a high level of surface properties and accuracy. This study showed that recycled nylon filament would significantly improve surface roughness despite the increase in the printing layers' build-up thickness which can be managed digitally by proper setup of the printing parameters.

Keywords: FDM; Nylon; recycled filament; 3D printing

1. Introduction

3D printing is an advanced automatic additive manufacturing technology that has been introduced to several fields including medical and dental sectors (Tian *et al.* 2021, Tack *et al.* 2016). 3D printing technology has been involved in dentistry since the late 1990s to develop models for various oral structures for the purpose of education. Later one this technology has evolved to be used for treatment of patients. Nowadays, 3D printing offers various innovative solutions for dental problems and rehabilitation modalities in several aspects such as dental implant, orthodontics, dental prosthetics, as well as dental tissue engineering. There are several methods for 3D printing mainly are Sterolithography SLA, Digital Light Projection DLP, Selective Laser Sintering SLS, and Fused Deposition Modeling FDM (Shahrubudin *et al.* 2019). FDM is used in dentistry for models construction and designing of dental prosthesis (Németh *et al.* 2023, Kamio and Onda 2022, Kamio

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Table 1 3D printing Specifications

Specification	Details
Printing speed	100% (50 mm/s)
Nozzle temperature	250°C
Bed temperature	90°C
Infill %	100%
Nozzle diameter	0.4 mm
Layer thickness	0.2 mm

Fig. 1 Polymer compounding extruder

et al. 2018). FDM uses polymeric materials in filament form which are then melted and liquefied to be added as layers according to predesigned CAD models (Kristiawan *et al.* 2021). This technology is considered to be safe and affordable compared to other types of 3D printing technologies since no chemical reaction is involved in the procedure, besides the availability of various types of thermoplastic polymers to be used as filaments for this technology (Gao *et al.* 2021, Dey and Yodo 2019, Al Khawaja *et al.* 2020).

One of the key elements for securing economic growth is to minimize the waste of industrial products and efficiently use it through recycling process to produce other products with minimized cost yet with similar expected quality (Maziero *et al*. 2023, Atikah Kamaruddin *et al.* 2024). Recently, there has been a great demand for using recycled filaments from waste 3D printed materials in FDM technology including several polymers such as high density polyethylene HDPE, polyethylene terephthalate PET, polylactic acid PLA, acrylonitrile butadiene styrene ABS, and polypropylene PP (Mishra *et al.* 2023, Mikula *et al.* 2021). Nylon (polyamide) is one of the strongest filament materials used for dental models construction (Moraru *et al.* 2018). Dental models are essential parts to design dental prosthesis and restorations. These models require high accuracy of reproducing oral tissues for successful designing of the restorations (Metlerski *et al.* 2020, Jin *et al.* 2018). It is important when introducing a new approach or modification for model construction is to make sure that the results meet the required standards. Therefore, this study aimed to evaluate some physical and morphological properties of 3D printed models made from recycled Nylon filament. The observation criteria were surface hardness, surface roughness and printed sample thickness.

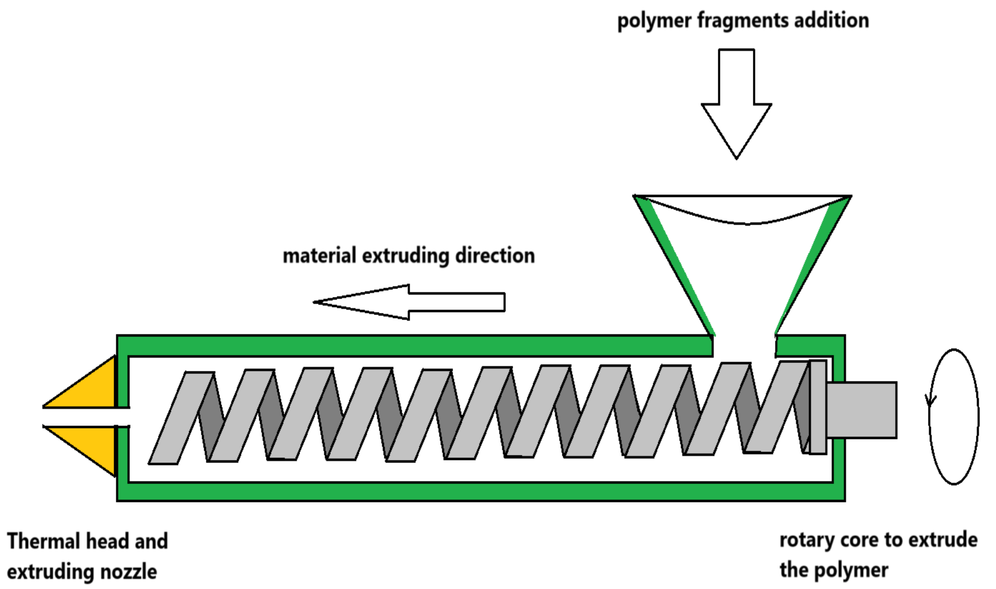

Fig. 2 Recycling polymer process by the thermal extruding machine for filament production

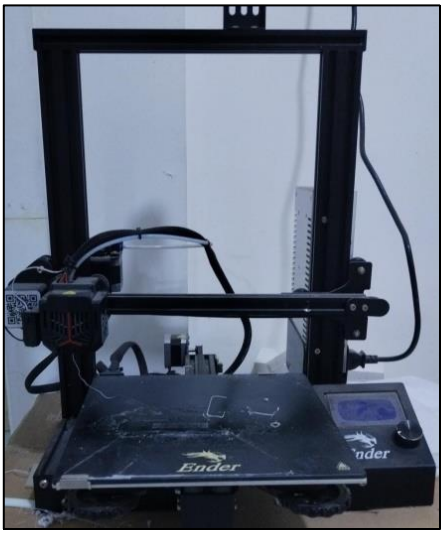

Fig. 3 Creality Ender 3 Neo FDM printer

2. Methods

Nylon filament (polyamide) Torewell™, China, was used for printing the control specimens. Fragments from the printout materials from the same filament was crushed and recycled by polymer compounding extrusion machine as shown in Figs. 1 and 2 into filament form for printing the recycled group specimens. The recycling temperature was set to 250 °C. The printer type used in this study was Creality Ender 3 Neo China, as shown in Fig. 3, and the printing specifications were set to the standards required for nylon filament printing as illustrated in Table 1.

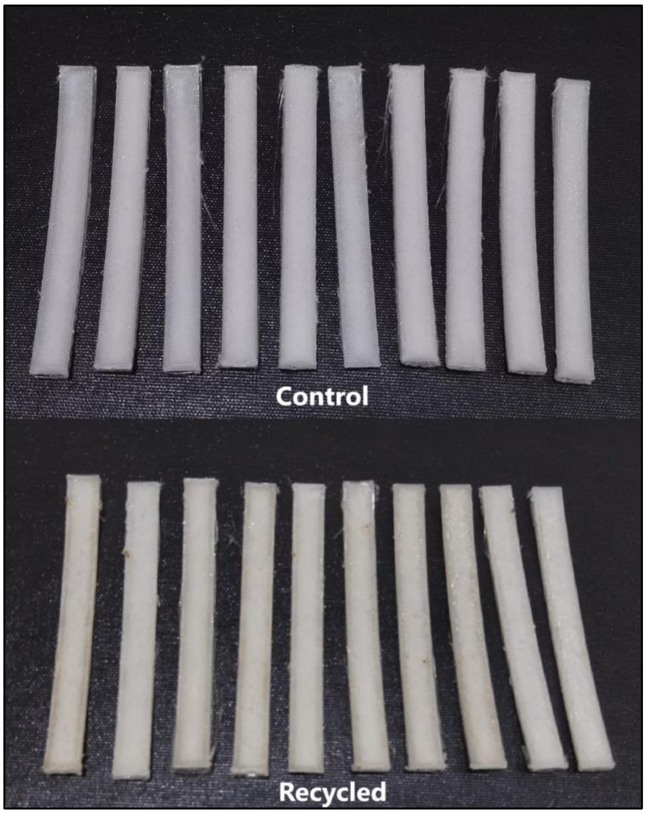

Fig. 4 Study groups' specimens (control and recycled nylon samples)

Fig. 5 Shore D surface hardness test

Fig. 6 Surface roughness tester

Table 2 Descriptive statistics for the study groups

Grouping		N	Mean	Std. Deviation	Std. Error Mean	Sig (p-value)
Hardness	Control	10	57.9	2.13177	0.67412	>0.05
	Recycled	10	55.5	4.03457	1.27584	
Roughness	Control	10	0.377	0.032281	0.010208	<0.05
	Recycled	10	0.341	0.025216	0.007974	
Thickness	Control	10	3.12	0.02000	0.00632	<0.05
	Recycled	10	3.31	0.02404	0.00760	

The specimens' dimensions were 100mm length, 10mm width, and 3mm thickness as shown in Fig. 4, which was digitally designed by Designspark Mechanical 6.0.3 software to generate the Standard Tessellation Language file (STL). The STL file was then sliced by PrusaSlicer 2.6.1 software to be converted to G-code file than can be processed by the 3D printer.

The study samples were submitted to Shore D surface hardness, surface roughness, as well as the thickness measurements as illustrated in Figs. 5 and 6. The study data was analyzed statistically by IBM SPSS software (version 20) for significant difference. The Independent Sample T test along with descriptive statistics was conducted for data analysis with minimum confidence level of 95%.

3. Results

Surface hardness test results showed no significant variation between the control and recycled mean values between the study groups. These results were confirmed by the independent sample T test which showed no significant difference between the two groups (p-value > 0.05). In terms of surface roughness, the mean value for the recycled group was lower than the control group which

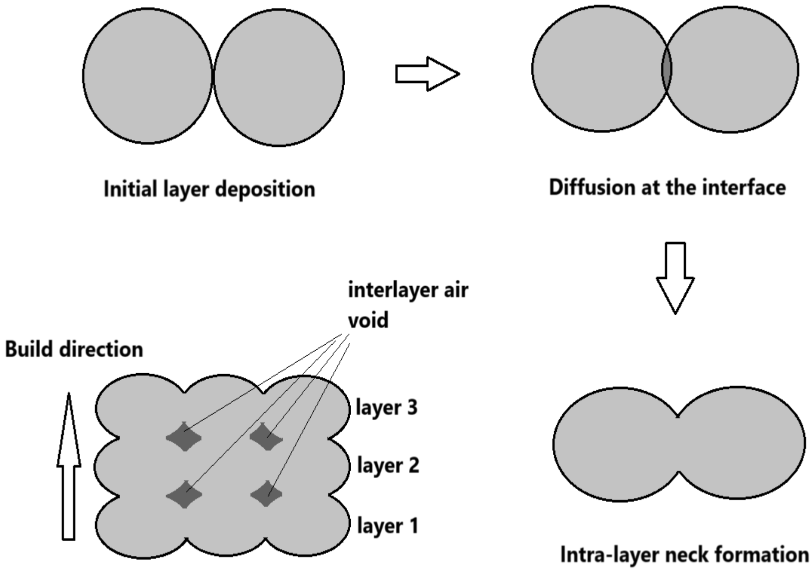

Fig. 7 Inter-layer bonding for FDM printing

was confirmed by the independent sample T test for significant difference (p-value <0.05). Specimens' thickness measurements also showed a clear difference between the study groups. The mean thickness value was higher for the control group than the recycled group. The same confirmation was obtained by the independent sample T test which showed statistically significant difference between the two groups (p-value < 0.05) as illustrated in Table 2.

4. Discussion

Despite the fact that additive manufacturing technology has been implemented in dental prosthesis construction, the demand for evaluating their accuracy and precision is increasing gradually (Mostafavi *et al.* 2021). Moreover, FDM printed models lack some suitable physical properties due to their principle of printing which involves layer by layer addition (Park *et al.* 2021, Freitas *et al.* 2023). Since the filament materials used for this technology are thermoplastic, there have been several attempts to reuse the waste of the printed product and reform it as new filament for other appliances printing. According to the literature, thermal and mechanical properties of modified recycled nylon filament showed improved properties and printability (Farina *et al.* 2019). However, limited information was available on surface properties assessment for the recycled nylon. Therefore, this study was conducted to evaluate the quality of the recycled printed models in terms of surface hardness, surface roughness, and layering buildup thickness.

Surface hardness is a critical property for dental models, as it plays a key role in maintaining the model's accuracy over time. This property is particularly important because dental models are extensively handled by practitioners during various stages of the dental treatment process. The hardness of the model's surface ensures that it resists deformation and maintains its surface details, which is essential for achieving the desired fit and function of prostheses. Additionally, a high surface hardness contributes to the model's overall durability, allowing it to withstand the physical stresses and wear that occur during the construction of the prosthesis. In this study, surface hardness results showed no observable difference in its mean values for both control and recycled groups as recycling process did not affect the hardness property of the polymer. These results disagree with a study conducted by Plaza and his associates who found that reheating nylon would significantly minimize its hardness value. They also found that fillers incorporation would improve nylon surface hardness after reheating (Plaza *et al.* 2024). Therefore, considering fillers reinforcement for the recycled polymer would be a viable suggestion.

Surface roughness is considered to be a critical aspect since it affects the prosthesis hygiene and esthetics at the same time. Smooth prosthesis surface would minimize biofilm formation as it facilitates the cleanliness of the restoration. According to this study, the recycled nylon filament produced a more uniform printed surface compared to the control filament as the roughness measurement was significantly lower in the recycled group than the control group. It is suggested that filament recycling process reduces polymers crystallinity and improves thermal mixing behavior of the crystalline polymers as well as slightly lowering their melting temperature (Wieser *et al.* 2021). This would be beneficial especially when it comes to reducing the cost of prosthesis production with slightly optimized properties at some level.

Dimensional accuracy is also an important property for dental models because it ensures the optimum fit and proper occlusion of the final dental prosthesis. FDM printing experience some limitations regarding dimensional accuracy in comparison with other 3D printing technologies. FDM level of accuracy is acceptable for preliminary dental models as well as educational models construction. According the study results, the layering buildup thickness mean values showed significant increase for the recycled group specimens. From practical prospective, this issue can be resolved by modifying the layer buildup measurement digitally through the slicer software. FDM printed model strength is quite dependent on the inter-layer bonding as illustrated in Fig. 7. When the filament is extruded and deposited on top of the previous layer, rapid cooling makes it difficult to the new layer to blend and bond firmly with the previous layer. This will generate voids that weakens the printed structure and might affect its dimensional accuracy (Ismail et al., 2022). Printing speed is also an important factor that affect the mechanical strength of the FDM printed material. According to Feng and his associates, nylon (polyamide 12) filament recycled from SLS printed waste can be used for FDM printing at printing speed of 40 mm/s which demonstrated sufficient mechanical strength (Feng *et al.* 2019).

Overall, this study highlights the potential for using recycled nylon in the production of dental models and prostheses through 3D printing utilizing FDM technology. The findings suggest that recycled nylon could be a possible material option in the dental field, offering an environmentally friendly and cost effective alternative to traditional nylon material. However, the study also emphasizes the need for further experimentation to evaluate additional physical properties and performance characteristics of recycled nylon. Future studies should focus on a more comprehensive assessment of its strength, durability, biocompatibility, and other relevant factors to fully understand its suitability and potential for general application in dental 3D printing.

5. Conclusions

Polymer recycling highlights economic and environmental significance. Thermoplastic polymers play major roles in several industrial, medical, and dental applications. FDM 3D printing is a technology used for constructing dental models and prostheses from thermoplastic polymers such as nylon. This study was conducted in an attempt to evaluate three parameters of the recycled nylon filament usage for FDM 3D printing which were surface hardness, surface roughness, and sample thickness. The study results revealed that the recycled printed material showed a decreased surface roughness, with a mean value of 0.341 ± 0.025 μm, compared with the as-received material (control), which had a mean value of 0.377 ± 0.032 μm. This difference was statistically significant ($p < 0.05$). Additionally, the surface hardness of the recycled group showed minimal change ($p > 0.05$). Despite this, a higher layering thickness was observed in the recycled printed material, with a mean value of 3.31 ± 0.024 mm, compared to the as-received material, which had a mean value of 3.12 ± 0.02 mm. This issue can be technically managed by modifying the printing parameters in the slicing software before printing. It is recommended to use recycled nylon filament for FDM 3D printing applications if surface finish of the prosthesis is of significant concern.

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