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Laser Sintering Characteristic of Biomaterial UHMWPE for Additive Manufacturing Process

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ABSTRACT

Background: Additive Manufacturing (AM) is a manufacturing technique to produce part from 3D model data by joining materials in layering. This technique has been used for the production of custom-made designs or individualized small series of medical devices. However the availability of materials for laser sintering techniques is still limited, particularly for medical application. The UHMWPE was chosen as the potential material due to its high performance with others preferable properties such as non-toxic, highly resistant to corrosive chemicals except oxidizing acids, extremely low moisture absorption, low coefficient of friction and is self-lubricating. **Objective:** The aim of this research are; to assess the effects of various laser parameters on the UHMWPE powder material; to evaluate the UHMWPE sample produced by laser sintering technique on the relative density, dimensional accuracy and surface morphology using special devices and to produce laser sintered single layer of UHMWPE material using Nd:YAG laser machine. **Result** : For single track sample, the screening for the sample was made to determine the lower and upper limit of each laser parameters that were tested. This is crucial to observe the effect of laser parameters such as effect of laser power and effect of scanning speed onto the UHMWPE GUR 4120. Therefore, to determine the optimum Power (W) for single track sample and scan speed (mm/min), the variables such as pulse rate and the length of track sample drawn were kept as constant at 100Hz and 17.00mm respectively while the laser power and scan speed were manipulated. The characteristics of the single track sample had been discussed through the relative density analysis, dimensional accuracy analysis and surface morphology analysis. **Conclusion** : Based on the outcomes and observations, the evaluation correspond to effect of laser parameters indicated that lacking of proper heating on powder bed for the warm-up stage has generally caused the post-build single and multiple track to curl and causing a significant change in the relative density and dimensional accuracy and surface morphology

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INTRODUCTION

Ultra High Molecular Weight Polyethylene (UHMWPE), also known as high modulus polyethylene (HMPE) or high performance polyethylene (HPPE), is a thermoplastic with an extremely high molecular weight. It comprises commercial grades range from 3.5 to 6 million g/mol (Olabisi, 1997, Meister, 2000). UHMWPE has proven to have more than 40 years of gold standard since 1960s and successful clinical history of biomaterial for implant used in hip, knee, and for spine implants (Steven, 2004). This material was widely used as plastic spacer in knee joint replacement or knee arthroplasty. Figure 1 illustrates the adaption of UHMWPE as plastic spacer in knee joint replacement. It has been reported that, over 90% of knee joint are using UHMWPE which lasted up to 10 years in the body (Robertsson, 2001, Forster, 2003). This material has a great adaptability in terms of biocompatibility, low cost and effectiveness. In addition, UHMWPE contains excellent mechanical properties of low friction coefficient, high hardness, high tensile strength and high elasticity which make it suitable to be used as artificial joint in human knee. It is also found durable when subjected to high temperature and pressures. This alteration has prompted the materials to obtain very high creep resistance for polymer to resist the deformation under constant stress (Naudie and Rorabeck, 2004).

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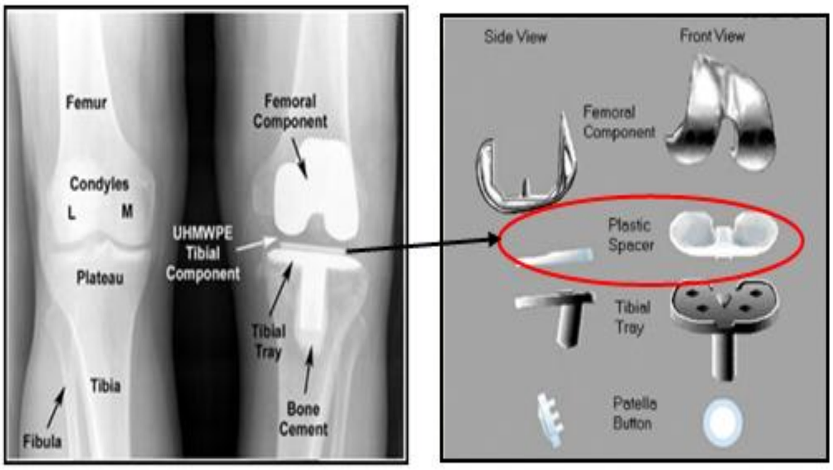

Fig. 1: Adaptation of UHMWPE as plastic spacer in Knee Joint Replacement

The increase in demand for medical application has encouraged researchers and manufacturer to explore different processing techniques to produce customized component. However, both the materials and workmanship of the devices have to meet high quality standards especially when dealing with health and medical application. Products must also be quickly available, and preferably at an economical price. Conventional thermoplastic processing method is not suitable to fabricate UHMWPE due to its extremely high molecular weight. Nevertheless, this material must be consolidated using controlled pressure, temperature and time. The available techniques that currently being utilized are ram extrusion and compression mould in a form of cylindrical bar and plate respectively. The materials are then machined into the required design and specification. Besides, direct compression mould (DCM) is the alternative technique to produce small scale of the orthopaedic implant directly from the mould and therefore, reducing the machining process required as conventionally produced. Figure 2 shows some of the sample parts which have been produced by ram extrusion, compression mould, machining and direct compression mould techniques.

The design for the corresponding component is generally customized suites for each patient particularly for medical purposes. Since the UHMWPE material is highly viscous, even with numerous up to date techniques available, not many of them are capable enough to undergo the fabrication process for this type of material. However, the advantages of some advance techniques seem enough to cope with this limitation. One of the techniques involved is rapid prototyping (RP) or also known as additive manufacturing (AM). In this research, a mode of the fabrication type under the umbrella of the rapid prototyping technique is employed and known as selective laser sintering (SLS). This kind of technique offers several advantages among others including a wide range of process-able material (Deekard, 1989) to fabricate precise intricate parts with mass production.

Therefore, the aims of the present research are; to assess the effects of various laser parameters on the UHMWPE powder material; to evaluate the UHMWPE sample produced by laser sintering technique on the relative density, dimensional accuracy and surface morphology using special devices and to produce laser sintered single layer of UHMWPE material using Nd:YAG laser machine. The SLS technique basically starts with the programming stage where the parameters involved is set on the desired cross-sectional area of the part. Before the laser beam is switched on to sinter the parts in the favoured cross-sectional area, the target of the laser beam is scanned over on top the layer of the powder; scanning each of the boundaries of the cross-section. The powder feeders then apply the powder on top of the previous part and with this repetitive process, subsequently each layer being sintered until a completed part is created. This research focuses on one of the medical application known as knee arthroplasty, which is defined as an application by using the artificial body parts (prosthetics) to cure damaged or worn out articular cartilage of the knee; causing bones crushing together rather than normal behaviour which is sliding over each other at minimum friction. It is done through the implantation of artificial prosthesis which consists of an orthopaedic metal and plastic component or plastic spacer as shown in Figure 2. It is formed and designed similar to a joint structure to enable knee to move properly (Nordqvist, 2012).

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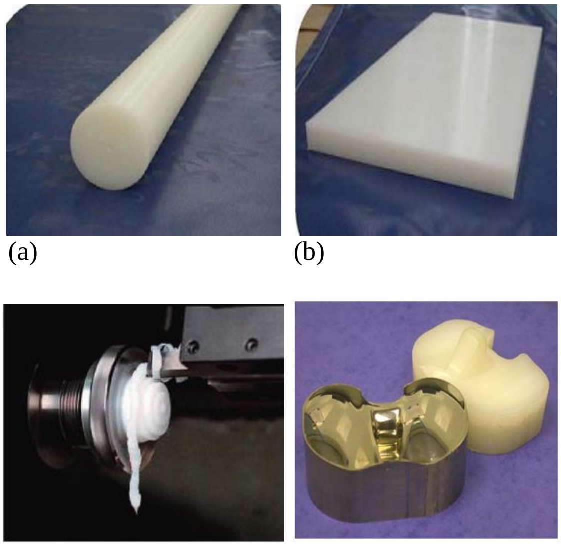
(a) (b) (c) (d)

Fig. 2: Sample parts produced by (a) ram extrusion, (b) compression mould, (c) machining and (d) direct compression mould

Methodology:

The UHMWPE grade which has been used in this research is GUR 4120. It is a linear polyolefin resin with a molecular weight more than 10 times of high molecular weight high density polyethylene (HMW-HDPE) resins. UHMWPE GUR 4120 is in white powder form. The important characteristics of the material for this research are the density value of approximately 930 kg/m^3 based on the ISO 1183 and the average particle size of 140 ± 20 µm. The product details and properties are shown in Table 1, data based on the Material Safety Data Sheet (MSDS), and Figure 3.

Table 1: UHMWPE GUR 4120 physical mechanical and thermal properties (MSDS 3E Company 2008)

Properties	Value	Test Standard
Density	930 kg/m^3	ISO 1183
Intrinsic Viscosity	2100 ml/g	ISO 1628-3
Tensile stress at yield (50mm/min)	17 MPa	ISO 527-2/1A
Tensile strain at yield (50mm/min)	20 %	ISO 527-2/1A
Specific heat at 23°C	1.84 kJ/(kg.°K)	Internal
Melting Point	138°C	-

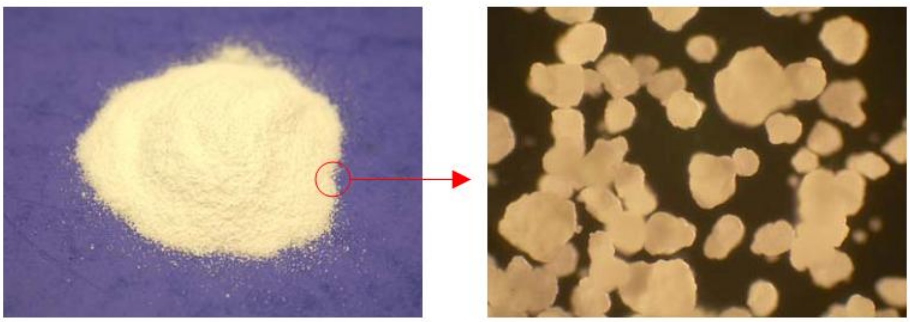

Fig. 3: Photographic images of UHMWPE powder

The process started with the preparation of base plate for the powder to be hold during the laser sintering process. The base plate for the powder was made from mild steel. Mild steel was chosen as the material of the tray or the base plate due to its relatively high melting point as compared to the UHMWPE GUR 4120 powder to avoid the stickiness and to withstand high melting point during laser sintering process. The dimension of mild steel base plate would be 17 cm by 15 cm. The depth of each specimen insert would be 0.25 cm. The depth of the frame of the plate to the surface of the specimen would be 0.3 cm.

The sample was then processed by using a laser machine of JK300HPS high power pulsed Nd:YAG. This research ought to meet the challenge by utilizing a non-actual laser sintering machine to sinter the powder which supposedly be done by the actual laser sintering machine for laser sintering purposes. Laser screening was done to develop a processing window of single layer of UHMWPE GUR 4120. By using this machine, a screening process was conducted to determine the lower and the upper limit for the laser sintering process. The lower and upper limit of each parameter setup was identified through several trials of sintering onto the powder. In this case, the set or range of the laser power and scan speed was identified on single track sample along with overlap spacing for multiple track sample. This had led to the optimum laser parameters to be found through different analysis. Additionally, MasterCam software was used to draw the required dimension of the single and multiple track samples and then was transferred to the laser machine for laser sintering process.

The samples produced was then analysed through different analysis. First, the dimensional accuracy analysis had been done by taking the dimension of the samples produced using the vertical profile projector Mitutoyo device. The dimensions such as length, width and thickness of the samples are able to be identified using this device. For the surface morphology analysis, tool maker measuring microscope had been used. This analysis is important to determine the texture and surface morphology of the samples produced. Sintered sample images had been taken for each specimen from the laser machine. For relative density analysis, the mass of the sample is being taken using electronic weight balance device. Finally, the dimension of height, width and length of the samples were taken using vertical profile projector Mitutoyo. The effect of laser parameter on the polymer powder was observed and the results were discussed.

RESULT AND DISCUSSION

For single track sample, the screening for the sample was made to determine the lower and upper limit of each laser parameters that were tested. This is crucial to observe the effect of laser parameters such as effect of laser power and effect of scanning speed onto the UHMWPE GUR 4120. Therefore, to determine the optimum Power (W) for single track sample and scan speed (mm/min), the variables such as pulse rate and the length of track sample drawn were kept as constant at 100Hz and 17.00mm respectively while the laser power and scan speed were manipulated. The characteristics of the single track sample had been discussed through the relative density analysis, dimensional accuracy analysis and surface morphology analysis.

Overall, the relative density analysis can be concluded that the laser parameters of single track sample ranged at 80 W to 90 W of laser power, 100 mm/min to 150 mm/min of scan speed and 100 Hz of pulse rate. The sample produced showed a significant change in relative densities throughout the change of laser power and scan speeds as shown in Figure 4, which gave the range of 64.84% and 75.81% difference with the value of maximum density of UHMWPE GUR 4120. As reported by previous studies, the powder experienced different gradient of temperature as the UHMWPE GUR 4210 melted at 138^{o}C whereas the temperature surrounding (room temperature) is 30^{o}C which contributed to the shrinkage of the sample and thus affected the relative density of the single track sample produced. The results showed that these parameters are considerably optimum parameters for single track sample which had been carried out for multiple track sample testing.

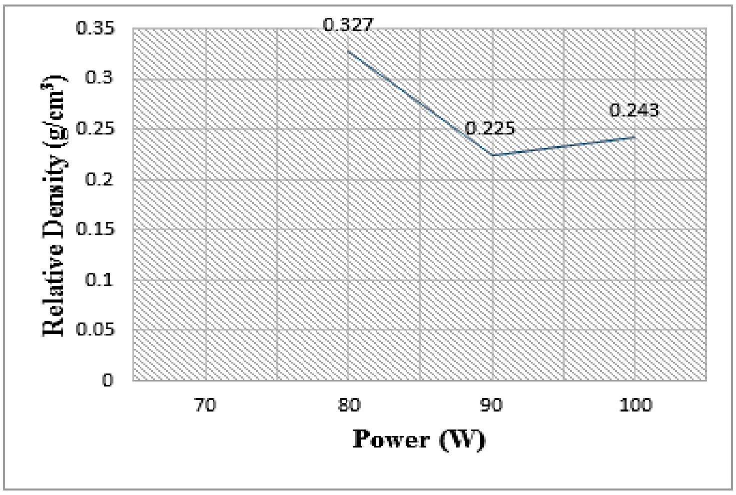

Fig. 4: Change of relative density (g/cm^3) for scan speed 150 mm/min of single track sample.

For the dimensional accuracy analysis, it can be seen that the increase in scan speed and power gave lesser dimensional error. This can be concluded that the samples shrink even more as the scan speed and power increases. Therefore, in order to obtain good dimensional accuracy, the scan speed must be at the range of 100 mm/min to 150 mm/min which resulting in the drop of dimensional error from 8.94% to 8.58% and on the other hand, resulted in the drop of dimensional from 4.52% to 3.92% as compared to the initial length and also 80 W to 90 W of laser power. However, the scan speed and laser power are not the reasons why the dimensional error occurs. Previous studies reported that these difficulties occurred because of the relatively fast re-crystallization of UHMWPE (Goodridge, 2009). For laser sintering, the rate at which a semi-crystalline polymer crystallizes was indicated to significantly influence its proneness to curl and the possibility of obtaining good dimensional accuracy. In order to achieve optimum results, it is important that the material should re-crystallize at a slow rate (Kruth et al., 2007). Therefore, higher scan speed and laser power ranging from 80 W to 100 W determined an important role in binding of the UHMWPE GUR 4120 powder by giving lower dimensional percentage error.

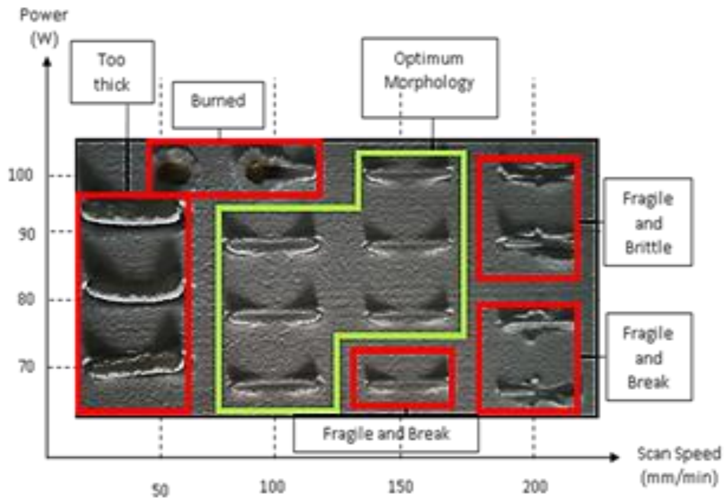

Fig. 5: Effect of laser parameters on the surface morphology of single track sample.

Additionally, it can be concluded for surface morphology analysis, that the laser power and scan speed are below the range of optimum surface morphology region (labelled as in the green area) and at the range of 70 W to 100 W at 50 mm/min, as well as 100 W at 50 mm/min (labelled as “Too thick” and “Burned”) as shown in Figure 5. This causing the lased polymer powder to shrink significantly from the surrounding bed which experienced by Rimell and Marquis (2000) in their effort to process UHMWPE using an experimental laser sintering system was the high point of shrinkage that occurred as the powder particle fused (Rimell and Marquis, 2000). This was worsened by highly porous nature of UHMWPE powder and poor packing of the particles in the powder bed. As a result, the sintered sample curled, thickens and some were burned. Laser power and scan speed above the range of the optimum surface morphology was not adequate enough to provide structural integrity for the sample to be handled (labelled as “Fragile and Brittle” and “Fragile and Break”). Therefore, for consistency, the laser power of 80 W to 90 W and the scan speed of 100 mm/min to 150 mm/min upon with 100 Hz of pulse rate as in magnified view of single track sample in Figure 6 is the range of laser parameters which would be the optimum laser parameters. This had been contributed in the experiment for multiple track samples for overlap spacing analysis.

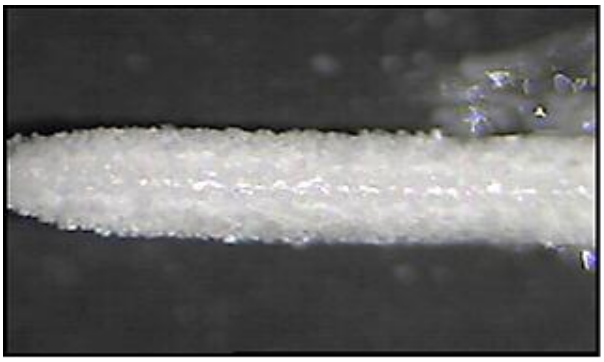

Fig. 6: Surface morphology for 150 mm/min scan and 80W laser power of single track sample.

For multiple track samples, the effect of the laser parameter on overlapping spacing was observed and discussed. The laser parameters are set as 80 W of laser power, 100 Hz of pulse rate, 10% of path height respectively. Single scan counted which was employed at single track samples previously changed continuous. On the other hand, the average width (diameter) of the single track sample was set to 3.1099 mm while manipulating other variables such as 130 mm/min and 150 mm/min, 40% (1.24 mm) overlapping, 50% (1.55 mm) overlapping and 60% (1.87 mm) overlapping between scan regions with the number of overlap occurrence per sample is 5 times.

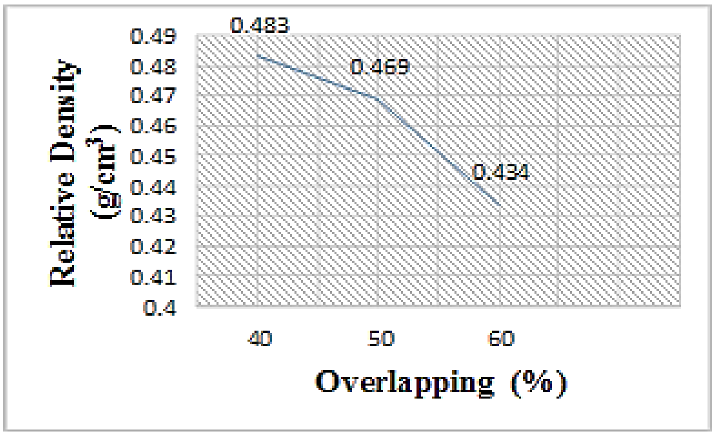

Fig. 7: Change of relative density for scan speed of 150mm/min and overlap spacing of multiple track samples.

For relative density analysis, based on Table 1, UHMWPE GUR 4120 have the highest density value of 0.93 g/cm^3 as compared to the highest relative density for both scan speed 130 and 150 mm/min of 0.483 g/cm^3, which it is 48.06% difference as shown in Figure 7 from the highest density of the polymer. Previous studies reported that the powders are highly porous which will have a knock on effect to the structures formed by laser sintering and the shrinkage that occurs upon processing by laser sintering will be even more obvious if the powder particles themselves are porous (Goodridge, 2009). Therefore, this resulting in large difference of the relative density of the multiple track samples compared to the maximum density.

For dimensional analysis, it can be stated that the width of multiple track at 130 mm/min scan speed decreased significantly from 9.064 mm to 7.251 mm as the overlapping percentage increased from 40% to 60%. This occurs similar to the overlapping percentages for the scan speed 150 mm/min from 9.250 mm to 6.675 mm. This is because as more powder particle was being sintered by the laser beam; more part is built for every occurrence of overlap spacing. In addition, it can be stated that at 150 mm/min of scan speed at overlapping percentage of 60% the width produced is much significantly smaller than the width produced at 130 mm/min of scan speed. This is because lower scan speed will results in more powder particles to be sintered upon laser sintering and this resulting in more powder particle to become closely packed and melted thus creating higher dimension in width which also implies to the length of each multiple track sample produced. In conclusion, the highly porous of the polymer particles contributed in the shrinkage factor hence resulted in the significant change of dimensions as the scan speeds and the overlapping percentages increased.

Fig. 8: Effect of 130mm/min scan speed and 60% overlapping percentage on surface morphology.

For surface morphology analysis, it can be concluded that the scan speed and overlapping percentages affected significantly the observations on the surface morphology of the multiple track sample produced. Slower scan speed and higher percentage of overlapping gave better surface morphology of the multiple track samples as shown in Figure 8. However, for the relative density analysis, results showed that higher scan speed gives higher relative density. This indicated that slower scan speed resulting in better surface morphology. Therefore, it is important to understand the behaviour of the UHMWPE GUR 4120 that if the powder particles themselves are porous, the shrinkage that occurs upon processing by laser sintering will be even more prominent.

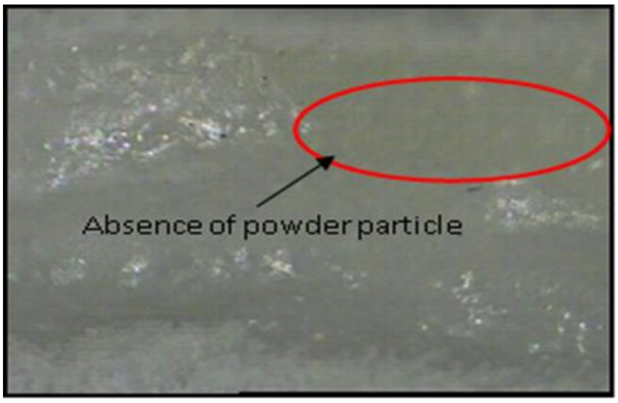

Fig. 9: Magnified view of the effect of 130 mm/min scan speed and 60% overlapping percentage on surface morphology showing no presence of unsintered powder particle.

Conclusion:

Assessing the effects of laser parameters such as scan speed and laser power upon single track sample and multiple track samples indicated that it is possible to fabricate the single layer of UHMWPE (both single and multiple track samples). Based on the outcomes and observations, the evaluation correspond to effect of laser parameters indicated that lacking of proper heating on powder bed for the warm-up stage has generally caused the post-build single and multiple track to curl and causing a significant change in the relative density and dimensional accuracy and surface morphology. However as a breakthrough of this research, it showed that there is possible to produce a single layer (single and multiple track) sample with a non-commercial laser sintering machine. As for the recommendation, to overcome the large thermal gradient occurrence, pre-heating the powder to a temperature just below its melting temperature is crucial to aid the laser in order to easily tip the material over into its molten state and ultimately allowing it to remain at that temperature for sufficient time after binding. In addition, an automatic roller sequence as in a printer should be introduced in future studies for automated powder feeding tool as a substitute to the current feeding tool which will then contribute in reducing time consumption and increase the efficiency of the research.

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