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PAPER

Printing orientation defines anisotropic mechanical properties in additive manufacturing of upper limb prosthetics

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Keywords: additive manufacturing, polymer, printing orientation, printing resolution, mechanical testing, scanning electron microscopy

Abstract

Additive manufacturing (AM) technologies are potential future-shaping solutions throughout many special applications in medicine. The mechanical behaviour of the related materials has not yet been fully explored. Here we compared five different industrial quality 3D printing materials produced using various AM processes that can be potentially used in limb-prosthetic development. We focused on the anisotropy of the mechanical and structural properties of these materials by using static and dynamic testing methods and electron microscopy imaging. Both static and dynamic experiments confirmed that amongst the three investigated directions (*X, Y* and *Z*), the *Z* orientation demonstrated, with the exception of polyamide test specimens, the lowest resistance against mechanical forces. Electron microscopy images revealed that greater mechanical stability appeared presumably due to the lengthier cooling time of the individual printed lines. Varying the printing resolution we showed how greater mechanical stability could be achieved, and concluded that special care should be taken when designing the AM processes intended for the fabrication of objects in support of medical applications. Often, the use of poor resolution in respect to quality of printing is desirable and can provide better solutions for actual purposes. These results provide important guidelines in the planning, manufacturing and implementation of higher developed, well-constructed assistive devices.

Introduction

Additive manufacturing (AM) technologies have become future-shaping solutions in many areas including special applications in medicine. 3D printed upper limb-prosthetics offer a significant positive change in lifestyle for thousands of people with a disability worldwide. Several non-profit organizations promote and facilitate the collaboration among engineers, crafters, tinkerers and medical professionals to produce these devices [1–6]. More than 2,000 children possess custom 3D printed upper limb prosthetics [7]. Despite their outstanding potential to improve the social acceptance of the users and the quality of their life [8, 9], there are only limited information available regarding the structural details and mechanical behaviour of 3D printed upper-limb prosthetics. Previous studies have shown that the majority of the devices are not scientifically examined, and most of them were prepared using Fused deposition modelling/Fused filament fabrication (FDM™/FFF) technology. Other 3D printing solutions are also promising [10].

The assistive devices used by upper-limb amputees require both static and dynamic stability [11]. The most common materials - due to desktop FDM/FFF printing - in these applications are Polylactic acid (PLA) and Acrylonitrile butadiene styrene (ABS). Polymers, which are not common in prosthetic manufacturing, such as

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PolyJet™ materials or FDM™ ULTEM™, possess outstanding mechanical properties compared to currently more commonly materials. Polyamide parts, manufactured by selective laser sintering (SLS) technology, may also prove to be excellent solutions in the fabrication of functional parts [10, 12]. J T Kate *et al* also state in a recent review that' material strength is also an important point to consider. No predictions have been made by the developers of the 3D-printed hands with respect to the strength of the parts of the printed prostheses. Further research should be performed on the strength and durability of 3D-printed parts [10].

Material science has only recently caught up with the rapid development of 3D printing machines and has quickly developed into one of the most dynamically evolving areas when considering the corresponding fields of research. Also, innovative solutions in actuating these devices are appeared in the recent years—such as shape-memory alloys (SMAs), shape-memory polymers (SMPs) or artificial muscles [13, 14], where 3D printing can be a game-changer too [15, 16]. However, 3D CAD simulations can help in prosthetics design [17], the materials can be used in the additive manufacturing process are not fully examined yet. According to the principle of personalized medicine, in all cases it is important to establish a framework of criteria for their comprehension including, when and which materials are advisable in the construction. It was previously shown for some of the applied substances that the orientation of 3D printing affects the mechanical properties of the printed objects [5, 18–21]. In these studies, the authors showed that there is strong a correlation between the stiffness of 3D printed object and the printing geometry. Several materials—such as ABS, PLA for desktop printers, different SLS, powder-based composites and photopolymers - were tested with dynamic and static measurements. The experiments showed that the layer thickness, orientation and base-material are key elements in additive manufacturing technologies. However, little information is available regarding the high-grade, industrial 3D printing materials that can be used in prosthetic manufacturing. Previous studies in this field showed that the prosthetic sockets can be manufactured with 3D printers [22–26], but the information regarding other functional parts are limited. Also, it is revealed that not only the mechanical properties of the different polymers and composites are not fully explored yet, but we are not familiar with the degradation process of these 3d printed parts [27]. With the appearance of new materials this problem needs further investigation to include the properties of new materials and to understand the molecular events underlying the appearance of orientation dependent mechanical properties.

In our study, we compared five different industrial-quality 3D printing materials, intended for use in prosthetic production and development towards the exploration of the most important aspects of the 3D printing process of prosthetic manufacturing. We focused on the anisotropy of the mechanical properties and structural characteristics of these materials fabricated with various AM technologies using static and dynamic tests and electron microscopy imaging.

Materials and methods

3D Printing

In this work we tested several materials; polyamide, Objet™ Vero Grey™, Objet™ Digital ABS, FDM™ M30 ABS and FDM™ ULTEM 9085. In the experiments, standardized shape test specimens were used. According to previous findings, all these polymers are potentially suitable for personalized prosthetic production. The test specimens were produced by PolyJet™ technology in the case of Objet™ Vero Grey™ and Digital ABS™, polyamide by SLS technology, ABS M30 and ULTEM 9085 by FDM™. The printing was carried out using EOS™ Formiga P100™ and in the case of SLS, Stratasys™ Fortus 400mc Large ™ was used in FDM™, and Objet350 Connex3™ was used in PolyJet ™ technology.

ABS test specimens were produced with FDM™ and PolyJet™ technology to investigate the differences between mechanical stability and structure of the objects produced by the two methods. We also examined different layer thickness (Z resolution) to map the effect of resolution on these mechanical properties and determine the correlation between them, including the microscopic structures of the objects. FDM™ ABS specimens were made at 0.178 mm and 0.330 mm resolution. ULTEM specimens were printed at 0.254 mm layer thickness. Polyamide test bars had 0.1 mm layer thickness and Objet ™ materials had 0.03 mm (ABS) and 0.016 mm (Vero Grey™). The droplet size of the PolyJet™ technology was 0.042 mm. The size of polyamide granules varies between 0.04–0.06 mms. The temperature was set to 70 °C in case of PolyJet™ technology, to 250 °C at FDM™ ABS, between 350–400 °C in case of ULTEM printing, and to 186 °C at SLS printings. All test bars were produced with 100% infill density.

In all of the above mentioned, resolutions were applied for objects in their X, Y and Z orientations, i.e. five pieces of each were produced. The layers were determined by the slicing software of the printers according to the placement of the test bars, demonstrated in figure 1. In the case of the X orientation, the bar lies on its 10 mm × 80 mm side, Y orientation on the 80 mm × 4 mm side and Z orientation on the 4 mm × 10 mm side.

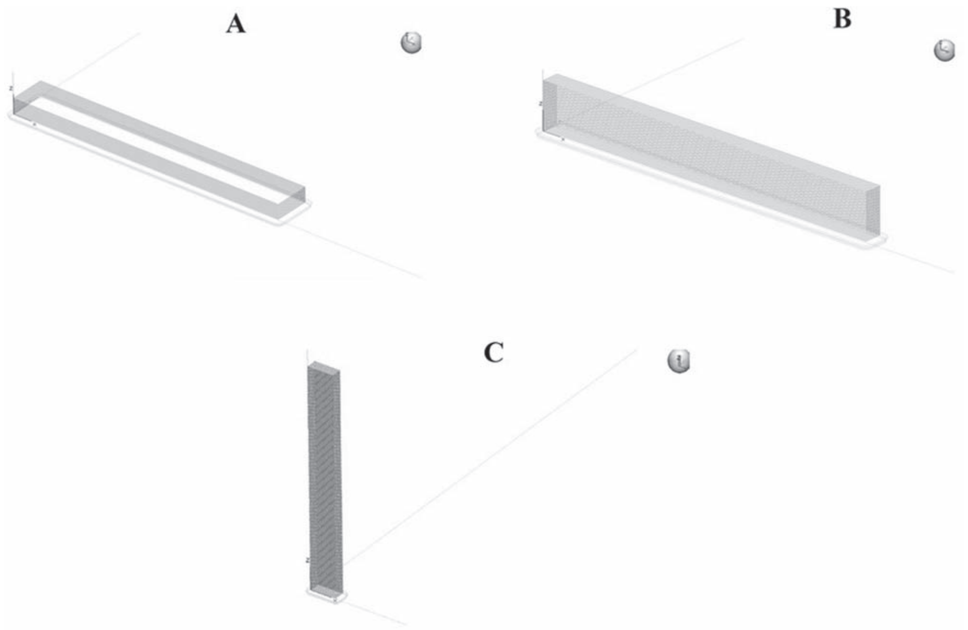

Figure 1. Orientations used during 3D printing. The names –X, Y and Z- correspond to the relative orientation of the main printing direction to the longitudinal axis of the probe objects compared to the printing bed. (A) X orientation; (B) Y orientation; (C) Z orientation.

Mechanical tests

For dynamic mechanical testing we used the Charpy impact test, where specific impact strength was measured. This method is suitable to mimic dynamic forces, such as the falling or bumping of different objects during everyday use. Static measurements were performed using the three-point bending test (speed of bending: 2 mm/min, limit bending stress was measured) and Shore D hardness measurements (duration of measurements: 15 s) which refers to stability in the event when leaning against solid surfaces. ISO 179–1:2010 standard was used (size of test specimens: 10 mm × 80 mm × 4 mm, without a notch). The overall number of test specimens were 180. We performed 5–5 measurements with each material, orientation and layer thickness in case of FDM™.

Electron microscopy imaging

Following the Charpy impact test, the broken surface of the probe specimens were examined with scanning electron microscopy (SEM). This method is a reliable and widely used technique in the screening of surface characteristics. Broken surfaces of the probe specimens were covered with gold and examined with a scanning electron microscope (JSM-6300, Jeol, Japan). The images were made at 15×, 60× or 200× magnification, as indicated in the text.

Results and discussion

In this study we aimed to describe how the mechanical properties of 3D printed objects depend on the nature of the applied material and on the orientation of the 3D printing during fabrication. For the interpretation of the results we established a reference system defined by the geometric properties of the printing (see *Materials and Methods session*). Within this system the three main directions were labelled with *X*, *Y* and *Z*, and they correspond to the relative orientation of the main printing direction to the longitudinal axis of the probe objects. We prepared standardized shape probe objects using several materials and printing methods and first used both static and dynamic tests for their characterisation.

The results from static tests

We tested how the static mechanical properties of printed objects depend on the applied printing technology. In these measurements three-point bending tests were carried out using the probe objects. The data are presented in figure 2. In the case of SLS printing technology we observed that the mean values of the three-point bending tests were not significantly orientation dependent (two-sample t-test, $p = 0.05$ significance level). Using *Z* printing orientation we obtained 40.5 ± 1.5 MPa, similar to the value determined for orientation *X* (45.3 ± 1.23 MPa) and *Y* (40.1 ± 1.9 MPa). In the cases of all other technologies, there was a strong dependence

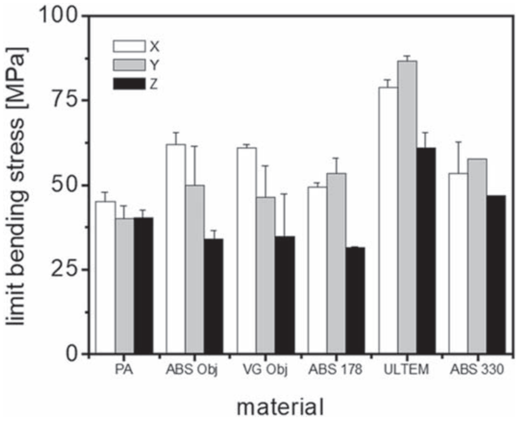

Figure 2. The summary of the results obtained in three-point bending tests. Mean values of limit bending stress are presented from experiments performed with 3-point bending test. The materials and printing technologies are indicated as the following: *PA:* polyamide, SLS printing technology, *ABS Obj*: Objet™ Digital ABS, PolyJet™ printing technology *VG Obj*: Objet™ Vero Grey™, PolyJet™ printing technology, *ABS 178*: M30 ABS with 0.178 mm resolution, FDM™ printing technology, *ULTEM*: ULTEM™ 9085, FDM™ printing technology, *ABS 330*: M30 ABS with 0.330 mm resolution, FDM™ printing technology.

of the mechanical properties on the printing orientation. In the cases of FDM™ and PolyJet™ technologies, the results were significantly lower for the *Z* printing orientation than for either X or Y orientations. These observations become important when one designs the fabrication method for a given part of prosthetics with special mechanical requirements. The data clearly demonstrated, if and when a specific direction required the best mechanical stability, the orientation of the printing of this direction should not be parallel with the *Z* orientation. Thereby, simple consideration in designing can substantially enhance the applicability and durability of the objects created.

Next, we investigated the effect of the applied material on the mechanical anisotropy of the printed objects. In comparing the materials printed with PolyJet™ technology, we did not find significant differences (two-sample t-test, $p = 0.05$ significance level) between the results obtained for Vero Grey ™ and Objet ™ Digital ABS (figure 2). In all of FDM™ printed cases, the *Y* orientation reached the highest mean values, 53.6 ± 2.2 MPa in the case of ABS with 0.178 mm printing resolution, 57.6 ± 1.9 MPa with 0.330 mm resolution and 86.6 ± 0.75 MPa with using ULTEM™ test specimens. We observed that the Shore D hardness -a static parameter-, did not show a significant difference amongst the different printing orientations in any materials. The largest mean value belonged to the *X* orientation of Objet™ Digital ABS with 76.6 ± 0.4, and the lowest was for FDM™ ABS with 65.3 ± 0.33. In using FDM™ Objet™ technology the results showed a broader distribution and variability in the cases of the different orientations, than that was observed for the SLS technology. Also, it was revealed how the two Objet™ materials possess the same characteristics in all three directions. The least variation of the obtained values appeared with polyamide test bars (figure 2). These results showed that no uniform scheme was valid for describing the various technologies and materials as the different printing methods applied here had various modification effects upon the orientation dependence of the mechanical properties. One has to be aware of these observations and consider the special properties of the available printing materials when planning and developing printing applications intended for professional use.

The determined static parameters also showed that, even using the same technology, the chosen resolution of printing introduced differences to the mechanical properties of the printed objects (figure 2). The larger the resolution is, the stronger the material is once it is printed. The explanation for this observation is provided later based on the electron microscopy studies.

The results from dynamic tests

While static tests provide important information regarding the mechanical properties of the printed objects, a more detailed description often requires the application of additional methods. Therefore, we also carried out dynamic tests to understand the nature and behaviour of these materials and the effects of printing technologies on the mechanical properties. The applied Charpy impact test revealed differences between stiffness values resulted from the chosen printing orientations and resolutions. We found the *Z* orientation was the weakest in the cases of all applied materials and technologies. The ULTEM™ had outstanding strength against dynamic powers in the case of *X* orientation where 36.69 ± 0.49 kJ m^{-2} was measured (figure 3). The polyamide objects obtained with SLS technology proved to be much more durable and mechanically more resistant than those objects printed with the Objet ™ 3D printing materials (figure 2). The lowest values were measured with Vero Grey™, in which we obtained 2.28 ± 0.09 kJ m^{-2} and 2.16 ± 0.17 kJ m^{-2} for the *X* and *Y* orientations,

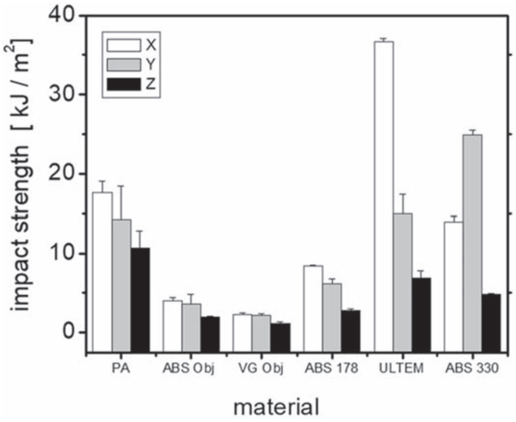

Figure 3. The summary of the results obtained in Charpy impact tests. Mean values of specific impact strengths are presented from experiments performed with Charpy impact test. The materials and printing technologies are indicated as the following: *PA:* polyamide, SLS printing technology; *ABS Obj*: Objet™ Digital ABS, PolyJet™ printing technology; *VG Obj*: Objet™ Vero Grey™, PolyJet™ printing technology; *ABS 178*: M30 ABS at 0.178 mm resolution, FDM™ printing technology; *ULTEM*: ULTEM™ 9085, FDM™ printing technology; *ABS 330*: M30 ABS with 0.330 mm resolution, FDM™ printing.

respectively. In the Z direction, the value was smaller (1.16 ± 0.14 kJ m^{-2}) than those for the X and Y directions. These dynamic test results were in correlation to the tendencies we observed using static tests and corroborated our conclusion in which special attention should be given when objects and fabrication methods are designed for given purposes including characteristic mechanical needs.

In the case of prosthetic development, it is important to provide reproducibility and uniform mechanical properties while manufacturing the different parts of a planned instrument. For these cases, a simple solution can be the application of SLS technology using polyamide. The focus should be on the consistent melting temperature, printing velocity and laser effectivity. It is also important in which increased rigidity is required in several key parts of the printed system of objects. When considering our static test results, we also investigated how the resolution of printing affects the mechanical parameters. In the case of FDM™ ABS the three-point bending test showed greater values in all orientations at the 0.330 mm resolution. FDM™ ABS printed with 0.330 mm resolution also featured significantly higher results in dynamic testing, compared to printed test specimens at 0.178 mm resolution. Additionally, the highest *Y* value in the Charpy impact tests was observed at the at 0.330 mm resolution with FDM™ ABS (24.88 ± 0.73 kJ m^{-2}). This was the only case of the Charpy impact tests in which the *Y* value was higher than the *X* results. Based on these observations, and those we made with the static tests, we concluded in which, in some cases, when the needed refinement of the shape allows, a diminished resolution might offer higher mechanical values.

Scanning electron microscopy images

The static and dynamic tests gave information regarding the dependence of the mechanical properties of various materials on the printed technology and orientation. These data provide an excellent framework for the investigation of the underlying molecular processes and events. In every *Y* orientated 3D print run, we noted higher results in dynamic and static material testing when compared with the *Z* orientation. To understand the reasons in support of these observations we imaged the fine structure of the printed materials. The probes were broken and the surfaces opening up were visualized by using high resolution imaging methods. Scanning electron microscopy with 15 x magnification revealed the rough inner structure of FDM™ ABS printed test specimens.

At the *Y* orientation, we observed smaller gaps (0.3–0.4 mm) between the individual printed lines and a smoother layer with a relatively large connecting surface. The *Z* orientation featured a rough, platelet-like surface, with 0.65–0.85 mm gaps. This tendency applies to all of the FDM™ materials (figures 4(A) and (B)).

Photopolymer based additive manufacturing techniques offered increased rigidity in the test specimens. In the use of electron microscopy, calibrated to 60 ×, the image of PolyJet™ Vero Grey™ featured a smooth broken surface with a filled structure. The FDM™ ABS had a regular articulated structure created by the printed columns, rotated to 90° at each level. We also observed weaker connections between the layers there, than in the case of printing at 0.330 mm resolution (figure 5(A) and (B)).

Better resolution structural analysis utilizing a 200 x magnification produced enhanced details regarding the nature of objects manifested with different technologies. In the case of FDM™, platelet-like patterns appeared at each column. We also identified the deformation of the cross section. It was not round as the nozzle (the component responsible for the extrusion that is heated to a desired temperature for the thermoplastic to melt),

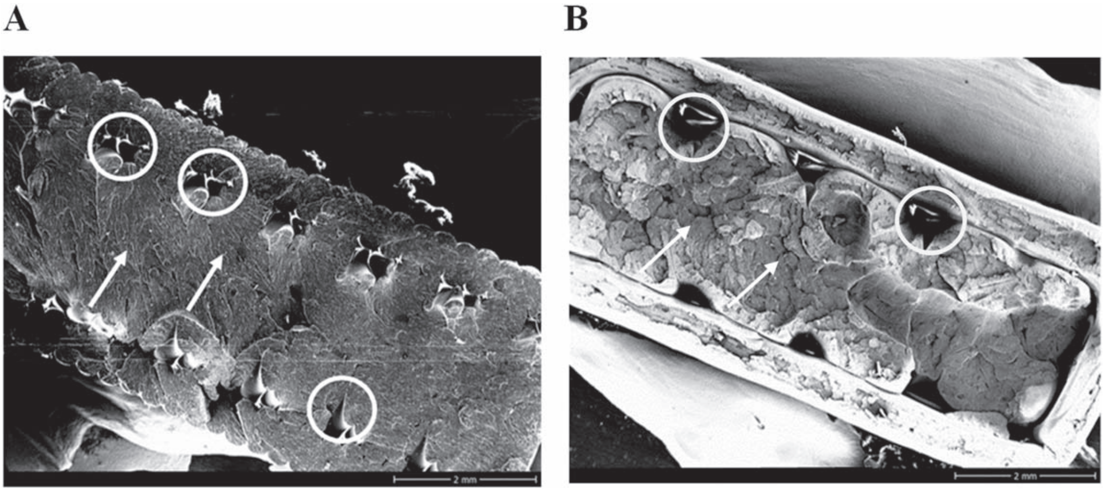

Figure 4. Scanning electron microscopy image of FDM™ ABS test specimen's (0.178 mm) broken surface at 15 x magnification. (A) *Y* orientation; (B); Z orientation. The circles indicate the gaps between the printing columns; the arrow shows the characteristic platelet-like structures. In *Z* orientation the connections between the sheets are less developed, the upper layer removed in one piece. The interconnecting gaps are significantly larger.

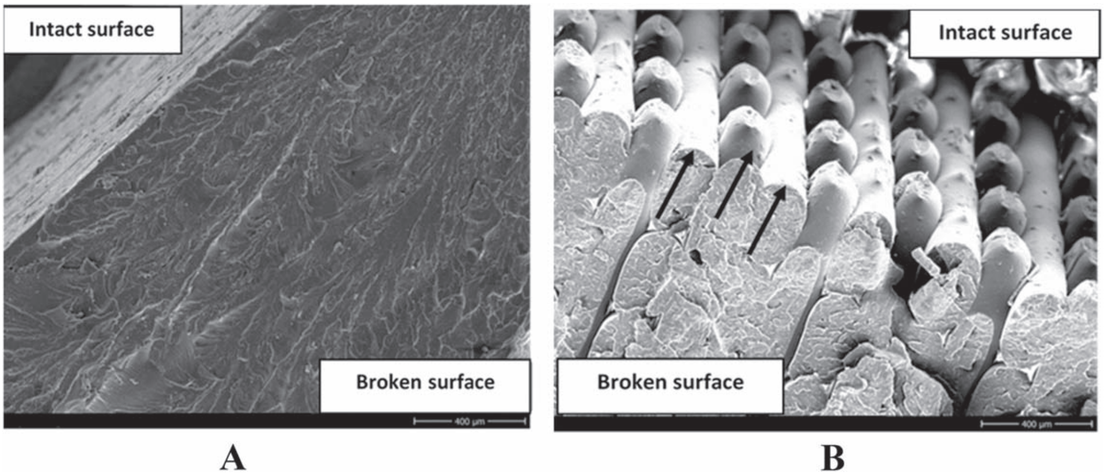

Figure 5. Scanning electron microscopy image of Polyjet™ Vero Grey™ and FDM™ ABS (0.178 mm) broken surface of the test specimens at 60 x magnification. (A) the Polyjet™ Vero Grey™ material, showing smoother and more comprehensive structure. (B) The FDM™ ABS material, showing column-like structure. The arrows indicate the layers rotated with 90 degrees relative to one another.

but had different levels of widening, in parallel to the plate of the 3D printer. The magnitude of the deformation is dependent upon the layer thickness and on the nature of the applied material. In consideration of Polyjet™ technology, we found a more continuous, solid surface. In the case of a polyamide test, we could not detect any differences using different printing properties (figures 6(A) and (B)).

These images provided excellent bases for the understanding of the results from static and dynamic tests, also we got information about layer adhesion. The structure of the materials during the printing process is formed by individual columns of melted thermoplastic, placed upon one another in a well-designed geometric pattern. The columns are at high temperature when placed into their intended location and begin cooling immediately after exiting the nozzle. The rate of cooling is dependent upon the ambient temperature and also upon the size of the printed columns. The latter effect is due to the different heat capacity of objects with different sizes, i.e., those with different masses. There should be an optimal cooling time, which allows the melting of the columns together while provides the conditions in which the designed shape of the object is not yet distorted during the cooling process. These findings are essential in prosthetic manufacturing, because they strongly affect the quality of the end-product. While optimal settings may differ amongst materials and printing technologies, printing times also vary depending on the applied parameters and should also be taken into consideration to assure the proper application. When the rigidity or stiffness of the object is diminished in the *Z* direction printing, an

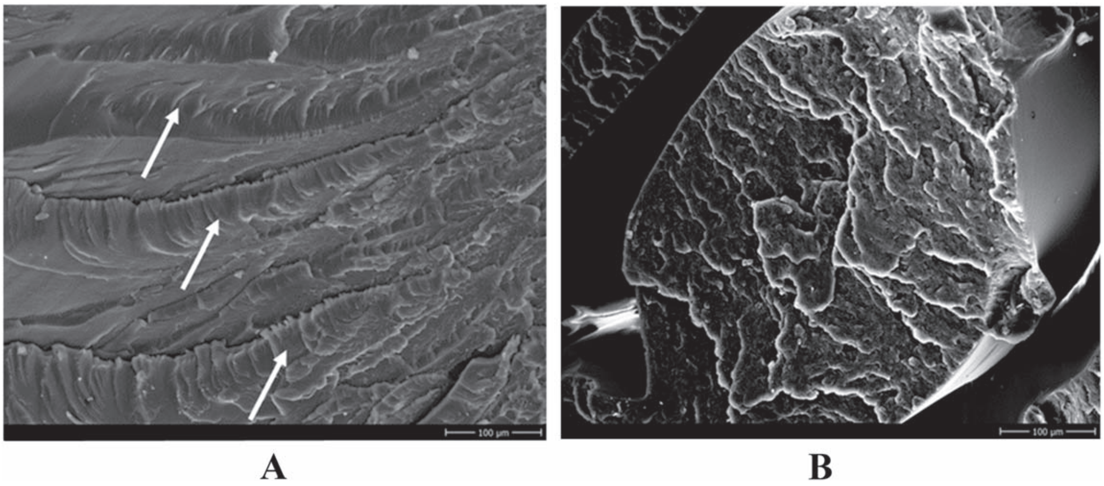

Figure 6. Scanning electron microscopy image of Polyjet™ Vero Grey™ and FDM™ ABS (0.330 mm) test specimen's broken surface. A): Polyjet™ Vero Grey™, showing smooth, solid and continuous structure with a wave-like pattern (indicated with white arrows). (B): FDM™ ABS, showing plain, platelet-like surface with a layered structure (indicated with white arrows).

obvious solution is to increase the size of the printed material columns, i.e., to increase the time of cooling. In this way, one can allow longer time for the subsequent columns to fuse together and thereby assure an improved rigid connection between the layers of printed substances. Note however, that in these cases setting should avoid lengthy melting times in which the shape of the object deforms easily. Based on our observations, we concluded that the stronger and more rigid object is required for a specific purpose, and the less refined surface properties of the object do not pose any major limitation to the applications, or we have the possibility to post-process (e.g: polishing) it, the choice of a diminished resolution is desirable. Distinctively, an additional advantage of the application of diminished resolutions also appears when considering how, in these cases, a shorter time is required for the actual printing, which is an important element of clinical related applications.

Conclusions

Additive manufacturing is a promising technology in upper limb prosthetic development, however we need to take special care in rehabilitational engineering [28], since both the design process, both the 3D printing parameters strongly influences the end-product's quality [29]. Also, at the moment time-consuming productivity rate and the lack of technical experience can be a barrier in clinical application. Recently, several excellent materials have been developed for various related applications. We demonstrated here that special care should be taken in designing the printing processes, because the mechanical properties of the manufactured objects are significantly influenced by the actual orientation of the printing. Both static and dynamic experiments confirmed that amongst the three investigated directions (X, Y and Z), the Z orientation showed the lowest resistance against mechanical forces in most cases. We also showed that less refined Z resolution could provide greater mechanical stability for the printed objects. Those parts, for which mechanical strength is required, but detailed manufacturing is not essential, FDM™ with diminished, more rough resolution provides better solutions. In these cases, the shorter printing time and often the better cost-benefit ratio also appear as advantages. For constant stability in all directions, such as in the case of flexion modules, sockets or connecting parts of the wrist, SLS technology is a suitable choice. We concluded that apart from their use in rapid prototyping some of the examined materials could also be applied for creating productions in the prosthetic industry. In correlation with previous studies in the field, we can presume that the SLS technology is ideal for socket and functional part fabrication. This statement is true for the FDM™ ULTEM™ material too. Other FDM™/FFF technologies and materials could be a great tool for rapid prototyping [30, 31] of these devices, or can be used in aesthetic prosthetic manufacturing, where mechanical stability is less important. For precise parts —for example sockets for electrical and actuating components - PolyJet™ technology can be an ideal solution [32].

Based on the electron microscopic images of the printed objects we propose that the greater mechanical stability at declining resolutions appeared due to the longer cooling time of the individual printed material lines, i.e., due to the longer time available for the subsequent lines to establish their mechanical coupling. Liquid photopolymer based printing materials demonstrate consistently similar results. Our data also revealed that polyamide test specimens offered distinctly similar bending results when printed in the three different orientations. This observation was likely attributed to the constant melting processes due to the application of lasers (30 W, CO_2) during the printing process. The SEM images showed that the layer adhesion—mainly in FDM/FFF technology - should be improved. For this problem, gamma-irradiation can be an effective solution, according to previous study [33], since it is revealed that the adhesion and orientation [34] between layers are key points in AM technologies.. The results revealed that further investigations are necessary in this area, and will provide important guidelines for the planning and manufacturing of well-constructed assistive devices[10].

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