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Problems of determination of MultiJet 3D printing distortions using a 3D scanner

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ABSTRACT

Purpose: Analysis and the review of 3D scanning methods, methods of combining 3D scans and tables available on the market (rotary, tilt and turn) as non-destructive testing systems of polymer materials. As the problem of deformation testing of elements produced by 3D printing is relatively novel, so far a small number of publications on this subject have been observed in terms of current solutions in the area of methodology and devices.

Design/methodology/approach: 3D print samples have been prepared using MultiJet Printing (MJP), also called PolyJet Printing. The first sample was left in a UV oven and the second one in a dark cabinet, without access to sunlight (standard conditions 23/50 as described in ISO 554:1976). Non-contact structured blue light 3D metrology grade scanner was used to capture the entire part geometry for inspection. A comparison of subsequent scans after postcuring with reference scans after printing can indicate dimensional changes. The resulting scans are detailed enough to monitor shape and size changes over time.

Findings: Universal 3D printing model beneficial in distortion analysis has been proposed. The method of evaluating 3D print distortions was verified using a metrology class 3D scanner. The results of this study show that deformations are declining through time to near the same values, the only difference is the rate of change of dimensions.

Practical implications: Due to popularity and lower cost of polymer 3D printing, in comparison to metal 3D printing, an initial attempt to analyse the distortion of the locally melted substrate was done using MultiJet 3D printing with photopolymer material. The universal 3D print test part was proposed for verification of 3D printing deformations. Finally, the framework for the determination of 3D printing distortions is presented, taking into account the influence of UV postcuring.

Originality/value: Analysis of a method to measure 3D printing distortions using a metrology grade 3D scanner is presented in the paper. Recently, this matter is becoming more and more important because many prototypes are increasingly produced by 3D printing and 3D printing distortions may cause many difficulties during the manufacturing and assembly process.

Keywords: 3D printing technology, 3D printing distortions, Methods of combining 3D scans, 3D scanners

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

3D printer test print models are used for the performance characterization of additive manufacturing (AM). They are used to benchmark the machines and to compare performance between processes. Usage of test artifacts allows quantifying properties like shrinkage, warpage, overhang angles, achievable tolerances, and accuracy, etc. Despite the wide availability of 3D printer tests, there is a lack of methods that can be used to measure the dimensional stability of 3D prints.

The unpredictable character and the lack of criteria for 3D Printing Distortions increases the importance of developing methods of testing. Standards provide a common reference point to avoid costly and time-consuming problem-solving by trial and error. However, there is a lack of additive manufacturing standards related to in-process monitoring and control, rapid inspection methods for 3D printed parts, machine-to-machine variability and transfer of production parameters. An ongoing need for defining test procedures and quality attributes for 3D printing processes forced international organizations to create groups responsible for developing new standards for additive manufacturing. These committees include ASTM F42, ISO TC261 and CEN/TC 438 [1]. Three standards can be selected from published work and are related to the measurement science for additive manufacturing. ISO/ASTM52902 [2] includes different test artifacts to evaluate performance including accuracy, resolution and surface texture. ISO/ASTM52910 [3] is another standard, which is a helpful guideline for geometric specification and metrology related to design for AM. ISO 17296-3:2014 [4] standard include appropriate test procedures for determining quality characteristics of AM parts. Additionally, numerous companies are not likely to share their technologies and patents freely. They spend their time and funds to develop industrial-grade systems and they don't want to risk their competitive advantage [5].

However, up till now, there are no available standards related to the dimensional stability of 3D printed parts and the determination of 3D printing anti-distortion values.

The precise control of 3D printing distortions is necessary to prevent the warpage and use the correct anti-distortion values. The surface of the printed part should follow the intended shape of the design. Parts produced with UV curable polymer formulations have a risk of not fully curing by its exposure to UV light in the printing process. As a consequence of shrinkage during layer-by-layer curing, residual stress build-up occurs. This results in deformations and distortions of 3D printed parts.

To determine the amount of deformation in the MultiJet 3D printing process, as well as deformation after post curing, a 3D test model is proposed. The model involves scanning the 3D printed samples using a structured-light 3D scanner. Then the mesh model (scan) after printing was compared with the CAD model to obtain colour displacement maps.

1.1. Factors affecting distortion in 3D printed parts

MultiJet printing is a process that uses photopolymer materials to build AM prototypes. Factors that could induce or deteriorate distortion in 3D printed parts, made from photo-curable plastic resin, including the design of the 3D printed part and the curing method [6].

Subsequent layers are cured on top of the first down facing layer, which causes shrinkage force Physical or chemical transformation takes place in the material during curing. For UV cured 3D printing, it is a photochemical crosslinking reaction, for fused deposition modelling changes in the density of the materials. This change involves volumetric shrinkage, which leads to a build-up of internal stress in the part. Built-in internal stresses cause a warpage known as stress creep distortion. The most affected parts include elements, which have:

- flat geometries,
- high aspect ratios (especially when the long axis coincides with the building surface).

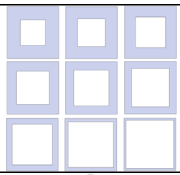
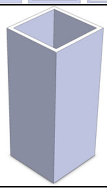
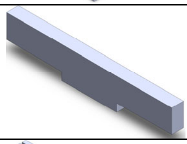
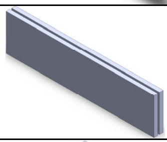
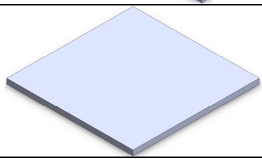
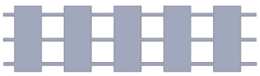
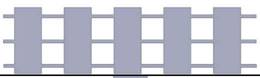
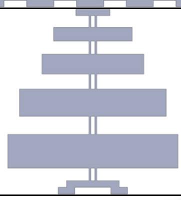
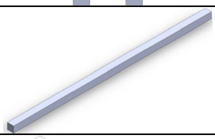
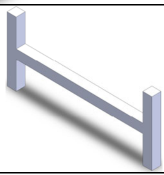
Deformations depend on various factors including UV lamp calibration, shrinkage, the orientation of the printed object, object design, and type of resin. Additionally, process parameters, which influence stress build-up and distortion include layer height in the Z-axis and resolution. The low resolution of the print is caused by longer exposure to UV light, which leads to a greater cure, but at the same time, due to light scattering, the material will be cured around and above the desired volume [7].

Parts after printing can be in a "green" state, which has not been fully post cured. Distortion in this step takes place because of the residual internal stresses of the part. The part can be UV post cured in a UV oven. The additional internal stresses can be introduced by the post curing process and further distort the part. However, this step is necessary to provide dimensional stability, which can be achieved by equally shrinking of all dimensions [6,8].

1.2. Detection of distortion in 3D printed parts

The concept, to use the 3D scanner for distortion measurements of 3D printed parts, is based on the idea of 3D scanning of welding deformations, and in this case, proved to be very effective [9].

Table 1.
Test parts used to characterize the resins and part building methods used in stereolithography [6,8,10]

Determined parameters	**Test part**	**Test part design**
Post cure shrinkage	Nine-Box	
Swelling	Swell-Tower	
Cantilever curl distortion	Twin Cantilever	
Vertical wall post cure distortion	Post cure Walls	
Horizontal slab distortion	Slab 6x6	
Depth penetration, critical resin exposure	Window-pane	
Depth penetration	Reverse Window-pane	
Line width compensation, shrinkage compensation	Christmas Tree	
Dimensional stability	Creep Bar	
Shrinkage, distortion	H-4	

Most of the distortion can be visually inspected, and small differences in shape can be recognized by touch [10].

A standardized test part can be used to verify the quality of material supplied by vendors, and vendors can demonstrate improvements in their product. Used to evaluate the performance of a machine or process, they allow to compare and test limitations (Tab. 1). As shown in Table 1 the test part design is rather simple. It allows specifying the characteristics of the selected distortion type as precise as possible, excluding the impact from other distortion modes.

The ideal test part should:

- be large enough to test near the extremes of the build volume,
- have many features which can be found in real parts (for example holes, ribs, and gussets),
- be built within a reasonable time,
- consume a minimal quantity of material,
- be easily measurable,
- have features with different sizes and shapes [11].

2. 3D scanning methods

3D scanning methods can be divided according to type, basic parameters, and application.

2.1. Contact methods

Contact 3D scanners are usually adapted to work with a fixed measuring table and an articulated arm equipped with a contact probe. The arm can be controlled manually or automatically. The tip of the arm moves over the surface of the object being measured and registers the X, Y, Z coordinates of the probe. Registered points form a point cloud that is used to create a 3D mesh. The disadvantages of contact measurements are low scanning speeds and measuring pressure, which can deform or damage the measured surface [12-14]. Contact methods are often used in industrial metrology [15] and can be used as an independent measurement technique or be used in combination with optical measurement systems and touch probe sensor [16]. A typical example of using the contact method is a coordinate measuring machine equipped with a probe with an electromagnetic or scanning probe [14].

2.2. Coordinate measuring machines

Types of coordinate machines include a portal, bridge, column, and cantilever. Coordinate measuring machines can be manually operated, programmed by teaching method or by means of Direct Digital Control. Coordinate measuring machines can also be equipped with non-contact sensors [13,15]. The advantages of using coordinate measuring machines (CMM) in reverse engineering are:

- high accuracy, usually from a few to several dozen micrometers,
- large measuring range dependent on the dimensions of the coordinate machine,
- number of axes - measuring machines equipped with 3 linear axes and 2 rotary ones for collecting measurement points,
- a wide range of measurement software.

The limitations of the use of coordinate measuring machines include:

- low speed of measurements, in particular by means of a contact head,
- a low degree of automation when measuring unknown shapes,
- the object of direct measurement is not the length, but the coordinate of the point on the surface, thus the radial correction of the measuring tip is required,
- contact heads are not suitable for measuring flaccid elements,
- high tooling cost [14].

2.3. Non-contact methods

Non-contact 3D scanners study the measured object without physical touch. Instead, they use active and passive surface scanning techniques. Active 3D scanners emit a certain type of radiation, which is detected by the measurement system, while passive ones are based on the detection of reflected ambient light [12]. In non-contact methods, index and reference points are often used [17].

2.4. Hybrid methods

The synergy of two measurement techniques, contact with non-contact, is visible in the optical measurement systems, in which the contact probe makes it possible to control places that are difficult to reach optically. The touch probe is calibrated with a set of markers that are optically tracked and their coordinates are recorded by the 3D scanner. The 3D scanning system additionally registers the full geometry of the part that accurately describes the object [16].

2.5. X-ray methods

Industrial computed tomography (CT) is a tool that allows inspection of the geometry of external and internal structures of the examined object. Systems of industrial computed tomography consist of an X-ray source, an X-ray detector, a rotary table and software for the analysis of measurement data. The advantages and disadvantages of industrial computed tomography are presented in Table 2. Industrial solutions of computed tomography are divided into the following systems:

- Linear Accelerators (LINAC),
- Macro CT,
- Micro CT,
- Nano CT.

The above classification is based on the measuring range, the achieved resolution and the focal size [18].

Table 2.
Advantages and disadvantages of industrial computed tomography [18]

Advantages	Disadvantages
possibility of performing non-destructive testing, detecting defects in the measured object (cracks, pores)	lack of calibration procedures
simultaneous scanning of the external and internal surface of the measured object	large number of factors affecting the measurement result
fast scanning time	non-measurable factors affecting measurement uncertainty

3. Methods of combining 3D scans

When performing a series of scans, they are not oriented to each other. Proper selection of connection technique depends on the options offered by the software and the type of scanner used. In the case of portable 3D scanners, the scans are connected on a regular basis during the movement of the sensor. The division of positioning methods for portable 3D scanners is shown in Table 3.

Table 3.
Positioning methods for portable 3D scanners [19]

Main goal	Positioning	Main limitations
Speed of measurement, simplicity	Method using the shape of a detail	Precision and speed of measurement depends on the object shape
Versatility	Hybrid method (index points + shape of a detail)	A compromise between accuracy and speed of measurement
Reliability, precision	Index point method	Fixing points on the object

4. Advantages and disadvantages of methods of combining 3D scans

The index point method consists of tracking and recognizing the position of 3D markers that are placed on the part or on the surface around the part, e.g. on the revolving table. The advantages and disadvantages of the index point method are shown characterised in Tables 4 and 5. Stickers are offered in various sizes. Their surface can be matte or reflective – in the case of laser scanners, reflective markers are used that diffuse the laser light with greater intensity than the object being scanned [15].

Table 4.
Advantages of methods of combining 3D scans [21]

Index point method
• automatic connection of individual scans, • high connection accuracy, • possibility of scanning symmetrical, cylindrical objects.
Reference points method
• coordinate precision points – the photogrammetric system can be more accurate than the scanner itself, • scans can be performed anywhere in the object, as the coordinates of the points are already known; there's no need to apply scans over one another, • scanning of objects with almost unlimited dimensions.
Method using an automatic rotary or tilt and turn table
• automation of the scanning process, • no need to operate the part – programmed measurement sequence, • shortening the measurement time – during the scan operator can prepare another measured object.
Method using the detail shape
• time-saving – no need for preparing the part for scanning.
Robotic systems
• possibility of scanning around the detail, at different angles in a completely automatic way.
Hybrid methods
• if there is no shape visible for the scanner, it is possible to attach index points.

There is also a possibility to use selection circles, used for marking dates in calendars, maps, and documents. They are easily available in stationery stores in various colours and sizes [20]. In home conditions, tags can be quickly created using paper cutters or embossing machines (e.g. a puncher) and coloured self-adhesive paper or self-adhesive labels. During the measurement, the position of the stickers is recorded by the 3D scanner. Those points are later recognized by 3D scanning software. In order to determine 3D coordinates, in the field of view of the scanner there must always be several index points – 3 as the minimum. Each subsequent scan must cover at least three points from the previous scan. This is the only method that allows portable 3D scanners to achieve high accuracy [19]. The reference points method is somehow an extension of the index points method, which consists of the possibility of reading reference points from an external source, e.g. photogrammetry [21]. Scans can be also positioned by a method using the detail shape. In this method, the system recognizes the geometry and on the basis of it combines scans, without the use of sticky points. A combination of two methods, positioning through the shape of the detail and positioning through index points, are classified as hybrid methods. In a method using an automatic rotary or tilt and turn table the scanned part is rotated around its axis, and combining scans takes place on the basis of the best fit. In this method, reference points can be used to scan the other side of the object. The most advanced variation of this method uses an industrial robot (Fig. 1.) and the measurements are carried out in a completely automatic manner.

It is used as a measurement planning software and control station for automated 3D digitalization.

Table 5.
Disadvantages of methods of combining 3D scans [21]

Index point method
• time needed to select places required for points, overlapping the object, removing points after measurement, • points cannot be attached to fragile details such as works of art, • performing scans step by step, • index points partially cover an object – they cannot stick them on measured features.
Reference points method
• investment in the 3D photogrammetric system.
Method using an automatic rotary or tilt and turn table
• limited size of the measured object that can be.
Method using the detail shape
• possibility of incorrect connection of symmetrical, cylindrical shapes.
Robotic systems
• increased measurement error due to low rigidity of the measuring system.
Hybrid methods
• uncertainty concerning acquiring enough index points to achieve accurate results.

a)

b)

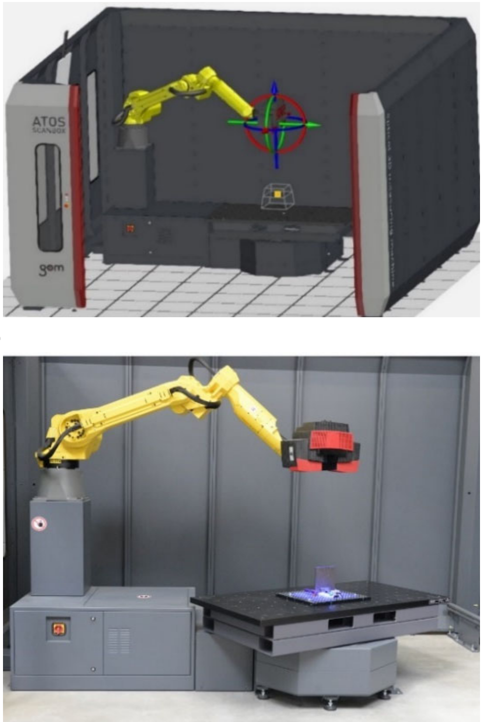


Fig. 1. Virtual Measuring Room (VMR) module included in the software [24] (a) and corresponding robot cell (b)

5. Tables for 3D scanning systems

To automate the scanning process, rotary or swivel tables can be used. Equipping the workplace with such a table allows for:

- time-saving, which is associated with the automation of measurements,
- an automatic combination of scans, without markers or pointing to similar places.

The part can be rotated to scan the base, the operator place reference points on it, so the software can link the scans. Tables can be divided into three basic types (Fig. 2):

- rotary tables controlled manually,
- rotary tables controlled numerically,
- tilt and turn tables [22,23].

These tables will be described in detail later in this chapter.

5.1. Manual rotary tables

The simplest type of table is a manually controlled rotary table. For this purpose, a "Lazy Susan" type table can be used, which is intended for serving food [26]. These tables are relatively inexpensive, but they are difficult to manipulate. The angle of rotation cannot be precisely controlled, which can cause misaligned scans. The simple and time consuming process of turning depends on the manual skills of the operator. With manual rotary tables, there is a risk of taking an insufficient number of scans, which will result in incomplete measurements.

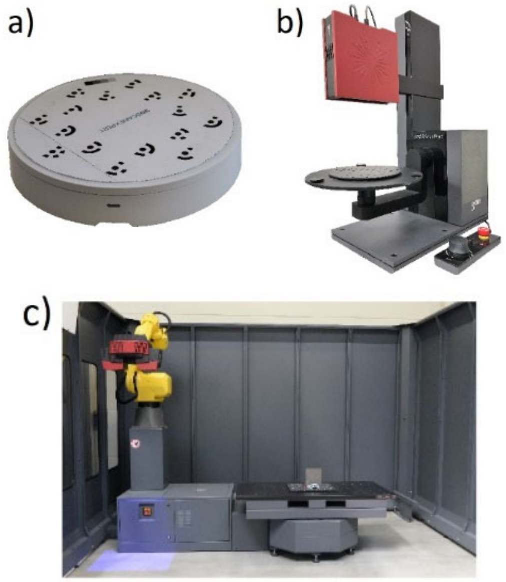


Fig. 2. Selected types of tables: a) rotating platform [24] – on the surface of the table there is a visible glued-on board with 12-bit photogrammetric markers [25], b) 3D scanner with tilt and turn table [16], c) robotic system with numerically controlled rotary table

5.2. Numerically controlled rotary tables

Photographic rotators are devices that use a rotating platform synchronized with a camera. The platform performs a 360-degree rotation, during which the camera records a series of photos. Then based on the pictures taken, the photographer creates so-called interactive packshots, or presenting a product using a moving image in one of the popular formats, such as GIF, SWF, HTML5 or in video format. An alternative solution is to use photographs to make a 3D model using the photogrammetry technique. Parameters of rotating platforms are shown in Table 6.

The simplest solutions available on the market include swivel platforms. The basic parameter is the diameter of the platform and its carrying capacity. The smallest platforms can have a diameter of 90 mm and a load capacity of 300 g.

Table 6.
Parameters of rotating platforms

Parameters of the rotating platform	Additional features
dimensions (diameter and height), weight	possibility of replacing the rotary table.
bearing capacity	possibility of hanging to the ceiling.
rotational speed (basic models rotate at a constant speed)	speed control using one or a combination of the following methods: • the knob on the platform housing, • IR remote control, • USB using a computer, • wirelessly using a smartphone, • triggering the camera shutter with the remote control cable or IR diode.
the direction of rotation (basic models rotate in one direction)	adjusting the direction of rotation using one or a combination of the following methods: • the knob on the platform housing, • IR remote control, • USB using a computer, • wirelessly using a smartphone.
power supply	• AC adapter, • built-in battery, • replaceable alkaline batteries, • power supply via solar cells.
additional features	• gradual angular graduation, • automatic tilting of the platform.

Small platforms are most often powered by solar cells. Larger models with a diameter of 20 cm and a load capacity of 1.5 kg can be powered by a mains power supply or alkaline batteries, thanks to which the power cord is invisible in the pictures and the platform itself is more mobile.

The rotation speed and rotation angle can be realized by means of:

- the knob on the casing,
- IR remote control,
- the computer connected via a USB interface,
- smartphone or through controlling a camera shutter by means of a cable switch.

The most advanced solutions, in addition to the rotating platform, include a shadow less tent and movable arm of the camera, which allows any manipulation of the angle and the position of the lens relative to the photographed object. Some of them are equipped with an integrated LED strip [27] placed at the back of the platform. Using it with the shadow less tent, allows to lightly radiate the image on the border between the rotating platform fragment, and the background of the tent. With the aid of such a designed lighting system, a bright, uniform background is obtained when photographing the product placed on the turntable. Interchangeable tables offer the operator to increase the diameter of the turntable by replacing the rotary table with a larger one. Turntables can be also suspended to the ceiling, which allows taking pictures of hanging products, but the load capacity is limited for hanging objects. The largest swivel platforms can allow a car to be turned. Such platforms have a capacity of 2.5 tonnes and a diameter of 5 m.

Revolving platforms designed for mobile photography, can be controlled using a smartphone. A noteworthy factor of mobile platforms is the function of triggering the shutter of the camera using an infrared diode, which is built into the base of the platform. The process of taking pictures is then almost automatic, the rotational movement of the platform is synchronized with the successively recorded photographs. Mobile rotating platforms can also have a built-in battery.

Mobile rotary tables can be also designed to use them with PCs. An interesting feature is the possibility of automatic tilting of the platform. The rotary table automatically tilts by 15 degrees, which allows to comprehensively register the geometry of the object [28].

5.3. Tilt and turn tables

Tilt and turn tables enable 360° rotation and the ability to tilt the table. The 3D scanner attached to an adjustable column has the option of adjusting the scanning height in the vertical plane. The swivel tables should be equipped with a sudden stop button, as there is a risk of collision with the scanner, surroundings and/or detail. Their basic advantage is the lower price compared to the robot. Tilt and turn tables are also lighter and mobile, and do not require complex training in service [29].

6. Experimental verification

6.1. Design of 3D printed part

Verification of a method to measure 3D printing distortions using a metrology grade 3D scanner was done. The 3D printed part (Fig. 3) was designed to use a minimum quantity of material and reduce waste (in the form of support). It is based on the idea of "Creep Bar" [8], where the internal build stresses serve as the distortion mechanism. Creep distortion may not be constant through time. It becomes worse for parts with flat geometries and high aspect ratios, especially in the case when the long axis coincides with the building surface [8].

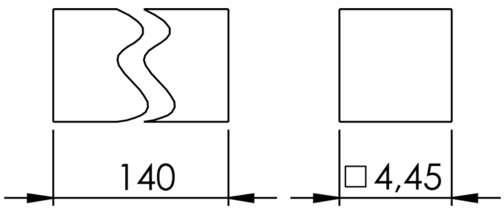


Fig. 3. Dimensions of the bar sample with a rectangular section

For the given length of the part h, and width b, we can define the aspect ratio (1), for the part presented in Figure 3, as follows:

$$Aspect\ ratio = \frac{h}{b} = \frac{140}{4.45} = 31.46 \tag{1}$$

6.2. Materials and printer used for 3D printing

Test samples were 3D printed (Figs. 4, 5 and 6) using MultiJet 3D printer (Objet30 Prime manufactured by Stratasys). High dimensional stability 3D printing material (RGD720) and soluble support material (SUP706) were used. Settings chosen in 3D printing software (Objet Studio) were glossy surface and high quality (HQ) mode. The estimated time of printing of one bar is 1:22*h*, but the printing of two bars is only a little bit longer – 01:26*h*. The estimated consumption of support and building material is respectively 2 g and 6 g per sample.

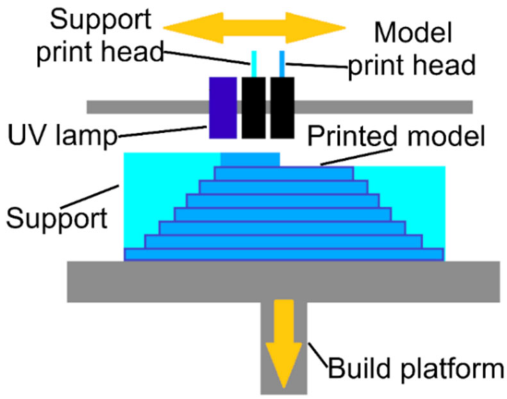


Fig. 4. MultiJet 3D printing process [30]

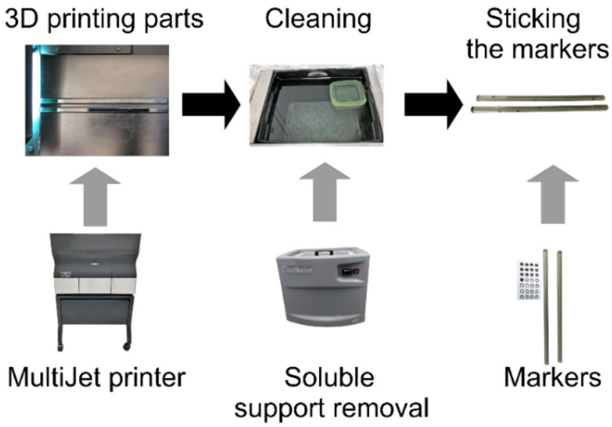


Fig. 5. Sample preparation process

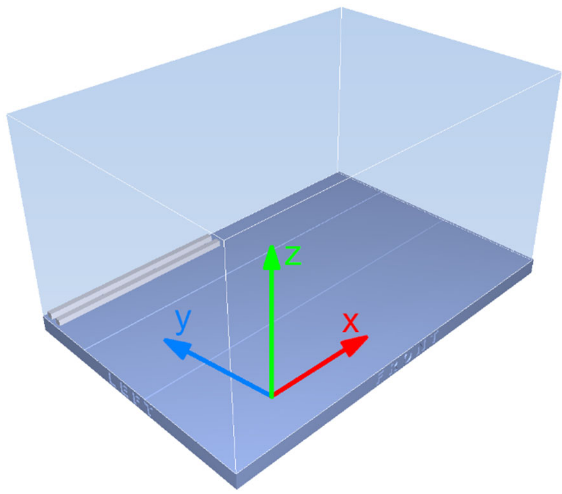


Fig. 6. The orientation of 3D printed samples on the printer build platform. Two samples were printed per print, in total 12 samples were manufactured.

Releasing 3D printed parts from the bed can deform them if reasonable force was not applied. Removing 3D prints was done carefully using a flat and sharp object.

Removing support material was done using a soluble support removal system (CleanStation DT3). Washing time was set for 1 h and the temperature was 22°C.

6.3. Preparation of the surface before scanning

The 3D printed test parts are made of transparent material and had a glossy surface, and it was necessary to cover them with white paint [31] – thin TiO_2 coating prior to scanning. TiO_2 paint was prepared using 5 teaspoons (approx. 5 ml) of TiO_2 powder and 250 ml of denatured alcohol. It was gently mixed by hand and the paint cup of the airbrush was filled with it.

The parts were degreased with methanol and washed with water from any impurities. Every step was performed using nitrile gloves when handling specimens to avoid contamination of scanned surfaces. After cleaning, parts were carefully sprayed with one even layer of paint. The TiO_2 and denatured alcohol solution allow restoring specimen to the previous condition, without the use of cleaning solvents or mechanical cleaning that can damage the surface of the object.

This step was performed to reduce the future post-processing of the scans, which is done manually. If the samples weren't painted with white paint, there will be a risk of errors in the form of the holes in the mesh [32].

Then, the samples were covered with index points with a diameter of 0.8 mm. The points were gently grasped with the tweezers by the black boxes so as not to damage their geometry and then glued to the sample. The points are made in high tolerance class and any damage would affect the measurement result.

6.4. Measurement system and its configuration

Sample scanning was performed on the metrology grade 3D scanner (GOM ATOS ScanPort). ATOS ScanPort consists of, among others:

- industrial structured blue light 3D scanner ATOS Core 135 (measurement area 135x100 mm, point spacing 0.05 mm),
- tilt and turn table (Fig. 7).

The 3D scanning system is based mainly on the principle of triangulation. Each 3D measuring point is registered using two different methods by means of a quasi-triangular measurement. During the measurement, the 3D scanner projects the measured pattern consisting of bands, which is recorded by both cameras. For the full digitization of the item, several separate measurements from different directions are usually required. Using 3D scanning software and reference points (round markers), the operator can transform individual measurements into a common global coordinate system. Round markers can be placed directly on the measured object or in its surroundings (on brackets, rotary tables, frames) [16].

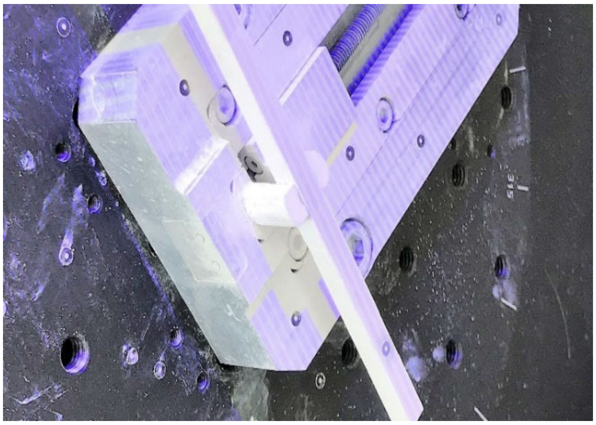


Fig. 7. Tilt and turn table with the sample mounted in a vice. The sample is covered with TiO_2 coating

6.5. Comparison with CAD data

After completion of measurements, a resulting 3D model was polygonised to obtain mesh data. Around 210 000 triangles were saved in the STL file for each sample. The comparison of dimensions of scanned parts with CAD nominal model was performed. The dimensional comparison was performed in the inspection module included in ATOS Professional analytical data processing software. It has been ensured that the shape of both specimens is near identical.

6.6. UV curing

Alpina BIO130-A2 biological Safety Cabinet class 2 was used to post cure specimens with UV light. The procedure was as follows:

- placing object for UV radiation for 20, 40 and 60 minutes,
- take out from UV oven and 3D scanning the part every 20 minutes.

The other sample was left in the room (dark cabinet) and taken out to measure every 24h (24, 48, 72 hours).

6.7. Preparation for measurement and measuring

The preparation for the measurement consisted of the camera settings, the rotary table settings, the fixing of the measuring object and the generation of data in the STL format.

The software used during scanning is ATOS Professional 2017. After setting the correct camera exposure, the scanning parameters were selected: high quality and a quick scan. In the "high quality" mode, which is recommended by GOM, it is possible to achieve the best data quality possible, because points with a too high error are not accepted. Due to small dimensions of the sample, the standard resolution mode was used to keep a higher number of recorded points (as opposed to “fast scan” mode, which utilizes only half resolution and shortens the measurement time by limiting the number of recorded points). The effect of the applied settings was the high quality 3D scan output.

6.8. Fixture of the specimen during measurement

The main aim of measurements was to make a qualitative comparison. Samples were mounted in the custom vice. In case to allow the use of effective anti-distortion values the support method should be carefully selected. To properly support a bar at the point of minimum deflection, special points should be used like Airy, Bessel or minimum deflection due to gravity.

7. Results and discussion

Directly after 3D printing and cleaning deviation from the first specimen scan (subjected to UV post curing) to the second specimen scan surface was similar, and the difference did not exceed 1.75%.

Compared to 20 minutes UV post curing, the value of deformation was reduced by 34.7% after 40 minutes of UV post curing and 32.35% after 60 minutes UV post curing. Insignificant growth by 3,6% between 40 and 60 minutes UV post curing can be caused by deformation of the bar during handling. In comparison with 24 hours sample without UV post curing, the deformations were reduced by 20.25% after 48 hours and 58.65% after 72 hours (Figs. 8, 9). 20 minutes of UV post curing results in 28.27% smaller deformations than 24 hours sample without post curing. In the second case, 40 minutes of UV post curing and 42 hours without post curing, the difference observed is greater and is 41.27%. Only in the third case, the specimen after 72 hours without post curing had 17.34% smaller deformations than 60 minutes UV post curing. The deformations were smallest after 72 hours without post curing.

The main advantage of non-contact measurement methods is a reduction of unnecessary mechanical forces, which can distort the sample [8].

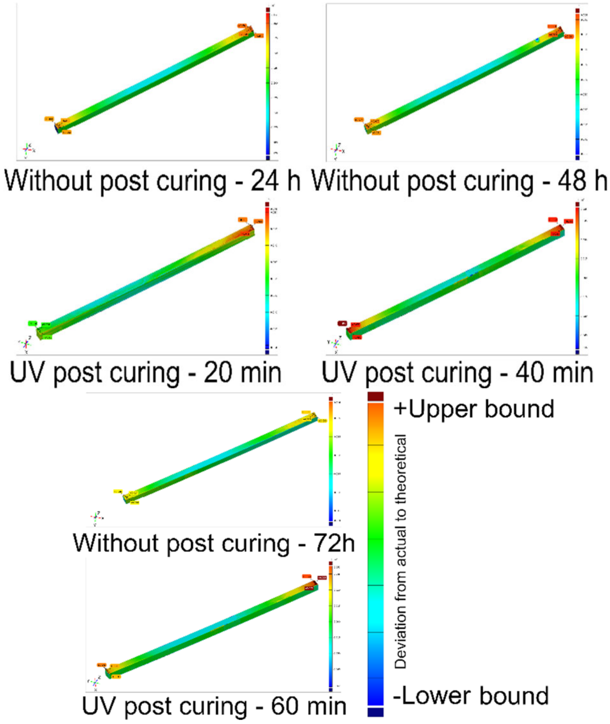


Fig. 8. Examples of colour deviation maps of 3D printed parts. The orange and red regions are visible at the end of the bars, indicating curl distortion

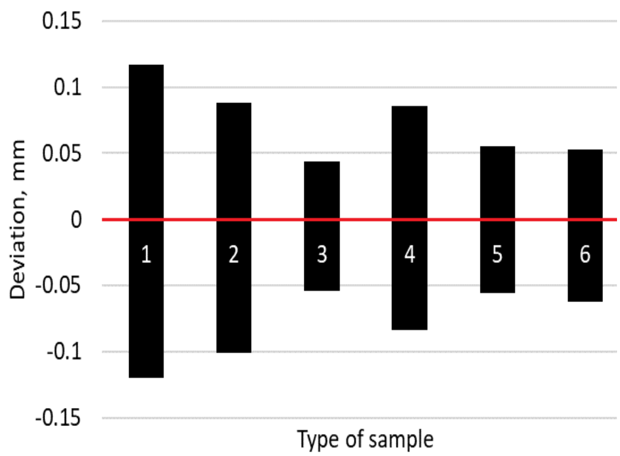


Fig. 9. Maximum and minimum deviation from the scan to the CAD nominal surface. 1, 2, 3 – samples without UV post curing (24, 48, 72 hours), 4, 5, 6 – samples with UV post curing (20, 40, 60 minutes), red line – nominal value

The simple bar shape can be measured with less time-consuming methods than 3D scanning. Digital single-lens reflex cameras can be used to take photos of the bending curvatures of the samples, which can be later measured using ImageJ software as a function of illumination time [33].

Another method is based on the IR photodiode light source. Displacement of the bar causes variations in total optical power received by the photodetector, influencing voltage readings. These results can be converted into distortion data [8].

However, 3D scanning methods offer an automated workflow for 3D distortion measurements, with the ability to register multi-directional deformation of complex parts. The usage of 3D scanning technology for distortion measurements in polymer 3D printing is a promising application, which can be further extended for other 3D printing processes such as metal 3D printing. The data from the 3D scanning system can be used to support and verify numerical approaches of prediction of distortion. The ability of automated measurements is a promising application in obtaining large datasets needed for deep learning models, which can be used for distortion prediction [34].

8. Conclusions

In the article, the method of measuring deformations using the 3D scanner was proposed.

To build highly accurate parts it is necessary to determine dimensional stability. 3D scanning can help decide which post curing solution is best for the selected 3D printing method depending on the effect we want to achieve, as well as the case.

The proposed approach will allow building parts with high dimensional accuracy, taking into consideration the specific material, required accuracy and fit tolerance. It can determine post curing uniformity, even with complex-shaped parts, which are difficult to measure with traditional measuring equipment. The accuracy of the 3D scanner is enough to capture small dimensional changes of the 3D printed parts, which undergo curl distortion.

During measurements, it was found that factors that can influence 3D printed parts distortion include operations of removing the parts from printer bed and mounting the part during measurements.

The results of this study show that the sample which was left in a dark cabinet achieved almost the same deformation values as the sample with UV post curing, but after a longer period of time.

Deformations are declining through time for both UV post cured sample and sample without post curing.

Both methods of activating remaining photo initiators are similar in final deformation results. The main difference is the time needed to achieve a dimensionally stable part, which is very important in the assembling process of multiple 3D printed parts. Allowing parts to post cure can help build assemblies with the correct fit. Depending on the production volume and our requirements, it is possible to speed up post curing process from 3 days to 40 minutes.

Future research should focus not only on the dimensional stability of the material but also on the build process. The 3D scanners should be incorporated into the 3D printing process, to enhance the quality of 3D printed parts and provide anti-distortion values for designers.

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