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Dimensional stability of parts manufactured by additive technologies

Diplomová práce

Studijní program: N2301 – Mechanical Engineering
Studijní obor: 2301T049 – Manufacturing Systems and Processes

Autor práce: **Rakeshkumar Durgashankar Soni**
Vedoucí práce: Ing. Radomír Mendřický, Ph.D.

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Faculty of Mechanical Engineering

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Master thesis

Study programme: N2301 – Mechanical Engineering
Study branch: 2301T049 – Manufacturing Systems and Processes

Author: **Rakeshkumar Durgashankar Soni**
Supervisor: Ing. Radomír Mendřický, Ph.D.

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DIPLOMA THESIS ASSIGNMENT

(PROJECT, ART WORK, ART PERFORMANCE)

First name and surname:	**Rakeshkumar Durgashankar Soni**
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Topic name:	**Dimensional stability of parts manufactured by additive technologies**
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Rules for elaboration:

The aim of thesis is to analyse the long-term geometric stability of parts produced by additive technologies (using 3D printing). The contactless measurement methods will be used to assess the dimensional and shape accuracy of the models.
Recommended methods elaboration:

1. Become familiar with the laboratory equipment needed to implement the practical part of the work (3D printers, 3D contactless scanner Atos II 400, Inspection SW GOM Inspect and with principles of 3D printing and optical digitization.
2. Analyse information about stability of the material used for 3D printing and make search of published research papers related to that topic.
3. Digitize samples (made on different 3D printers - such as FDM, PolyJet, SLS, SLA) using a contactless 3D optical scanner. Expose the models to UV radiation (or other external influences) and re-digitized.
4. Compare actual models obtained by digitizing with the nominal CAD model and analyze the dimensional and shape stability of additive manufacturing from the point of view of ageing in time. In the analysis take into account the effect of the technology used, the 3D printer used, the effect of UV radiation or other effects.
5. Assessment of the results and conclusion.
6. Prepare paper on this topic for publication in a technical journal or conference.

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[1]GEBHARDT A. Understanding Additive Manufacturing. Munich: Verlag, 2011. ISBN 978-3-446-42552-1.
[2]TEMPELMAN E., H. SHERCLIFF and B. N. VAN EYBEN. Manufacturing and Design: Understanding the Principles of How Things Are Made. Oxford: Elsevier, 2014. ISBN 978-0-08-099922-7.
[3]CHUA CH. K., K. F. LEONG and CH. S. LIM. 3D Printing and Additive Manufacturing: Principles and Applications. World Scientific, 2014. ISBN 78-981-4571-40-1.
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[6]GOM MbH. Inspection: V8 Manual Basic. Braunschweig (Germany): GOM MbH, 2014.

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Abstract

This thesis mainly focuses on an analysis of the long-term dimensional stability of parts produced by additive technology (using 3D printing). Firstly, the study about the 3D printing technology was done like how it works, which principle is used and which materials could be used for printing. Furthermore, the detailed study about the material properties and which parameters will affect for long-term dimensional stability. A year ago, models were already manufactured by different additive technologies such as FDM, Polyjet, SLS, and SLA. These models were scanned by using 3D contactless scanner ATOS II 400 and inspected by GOM Inspect Professional. An inspection was done with duration of time like 3 months, after a year and after a year with standard test-1 is called humidity and temperature and standard test-2 is called UV radiation. Then this analysis of measurement was compared with CAD and first day of models printing. Based on this analysis and from point of view of ageing with respect of time, which technology and material will have good dimensional and shape stability is discussed. Furthermore, some of parameters were taken into account such as an effect of the technology used, the 3D printer used and the effect of test-1 and test-2.

Key words: Additive technology, Fused deposition modeling (FDM), Polyjet, Selective Laser Sintering (SLS), Stereolithography (SLA), 3D optical scanner, 3D digitization.

Anotace

Tato práce se zaměřuje především na analýzu dlouhodobé rozměrové a tvarové stability dílů vyráběných aditivní technologií (pomocí 3D tisku). Dále je pozornost věnována technologiím 3D tisku, principům použití, vlastnostem materiálů používaných pro 3D tisk a parametrům, které ovlivňují dlouhodobou rozměrovou stabilitu. Modely pro testování byly vyrobeny různými technologiemi 3D tisku, jako jsou FDM, PolyJet, SLS a SLA. Vzorky byly skenovány pomocí bezdotykového skeneru ATOS II 400 a vyhodnocovány v SW GOM Inspect Professional V8. Digitalizovaná data byla porovnávána jak s nominálním CAD modelem, tak především s naskenovanými daty, které byly pořízeny ihned po vytištění vzorků. Tímto způsobem byla provedena inspekce modelů 3 měsíce po vytištění, po roce od vytištění a po roce a testu 1 (cyklické zatížení vlhkostí a teplotou) a testu 2 (vystavení vzorků UV záření). Výsledky byly analyzovány jak s ohledem na stárnutí v čase, použité technologii a materiálu, tak z pohledu účinků testu 1 a 2.

Klíčová Slova: Aditivní technologie, FDM, PolyJet, Selective Laser Sintering (SLS), Stereolitografie (SLA), 3D optický skener, 3D digitalizace.

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Glossary of Terms and Abbreviations

AM – Additive Manufacturing

CAD – Computer Aided Design

3DP – Three-Dimensional Printing

RP – Rapid Prototyping

SLA – Stereolithography

FDM – Fused Deposition Modeling

SLS – Selective Laser Sintering

SLM – Selective Laser Melting

UV – Ultraviolet

RE – Reverse Engineering

CMM – Coordinate Measuring Machines

CCD – Charge-coupled device

ABS – Acrylonitrile Butadiene Styrene

1. Introduction

Additive Manufacturing (AM) has been developed for industrial applications due to its remarkable capabilities, such as building complex parts that are otherwise difficult to manufacture by the conventional methods. AM is a layer by layer automated fabrication process for making scaled 3-dimesional physical objects directly from 3D CAD data without utilizing part-depending implements. It was basically called "3D printing". This is a pleasing to all good quality among AM processes by virtue of its quicker producing time; easily useable and affectability. As first started Additive Manufacturing processes were sent for making models and prototypes parts quickly; as an outcome the rapid prototyping (RP) is often applied for characterizing these processes. AM is subdivided into different techniques such as Stereolithography (SLA), Selective laser sintering (SLS), Fused deposition modeling (FDM) , Selective Laser Melting (SLM), Laminated Object Manufacturing (LOM) many more processes such as three–dimensional printing (3D printing) and Polyjet, accessed the market. Today AM has a trend in all major industries like automotive, aerospace to medical implants, fashion and other fields (e.g., advanced craftsmanship and structural plan). Furthermore, AM is applicable in engineering, non-engineering and domestic utilization as well. In engineering applications, AM is primarily used for prototype manufacturing, tool manufacturing and end-use part manufacturing. The most powerful change that industries need to talk is the approval of Additive Manufacturing (AM) in our design and manufacturing engineering processes [1, 2, 3]. The advantages and disadvantages of each Rapid Prototyping (RP) processes have dependency on the type of material and building styles utilized for the fabrication of components. The material utilized in these processes include Acrylonitrile-Butadiene-Styrene (ABS), Polycarbonate (PC), photo-curable resin, polyamide, wax, metal/polymer/ceramic powders, adhesive coated sheets etc. [2,4]. The quality of RP materials is adequate for limited scale application, but does not always fulfill the quality and accuracy precondition for vast application for industrial purposes [2, 4, and 5].

In this thesis mainly the focus is on an analysis of the long-term geometric stability of parts produced by additive technologies such as Fused Deposition Modeling (FDM), Polyjet, Selective laser sintering (SLS) and Stereolithography (SLA). First study about the additive technology how it's work, which principle used for printing the part and which material used for printing. The models were already printed a year ago and would be scanned by 3D contactless scanner

ATOS II 400 and inspected by GOM Inspect Professional V8 with principle of 3D printing and optical digitization. In addition, these all models were scanned and inspected during some time intervals like as after 3 months, after a year and after one year with standard test-1 (i.e. temperature and humidity) and test-2 (i.e. Ultraviolet lighting). These measurements were compared with CAD model and first day of printing. Then concerning the evaluation of the data obtained analysis of each individual parameter with duration of time. Based on these analyses the dimensional and shape stability in each measureable parameters of additive manufacturing from point of view of ageing in time must be checked. Finally, for result the individual measurement was considered as average and with color map to better visualization. Furthermore, some of parameters were taken into account such as effect of the used technology used, used 3D printer and an effect of test-1 and test-2.

2. Research Approach

I reviewed one research paper about Dimensional accuracy of parts produced by 3DP [3]. In this research paper they investigated the dimensional accuracy and repeatability of parts produced by 3D printing. For experiment, they designed and manufactured a simple U-shaped test part with a hole. Based on this part they measured the length dimensions and hole diameter. In this experiment they used the material of high performance composite powder Z150 with clear binder solution zb63 and measured by Discovery Model D-8 coordinate measuring machine (CMM). Based on this experiment finally they concluded, the variation of linear dimension for considered XY plane i.e. external length, internal length and width are undersized. On the other side, the dimensions in the Z direction i.e. height was oversized. For hole was same as linear dimensions.

I studied a project about measuring accuracy of 3D printed parts of Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) especially for FDM technology [6]. In this project they printed small rectangular prism and sphere by Rapid prototyping machine Creator Pro Dual Extension built by Flashforge. They observed in earlier research project Part accuracy is one of the important aspects in the manufacturing industry. Today one of the main challenges in the RP industry is the part accuracy that must be improved upon. They observed previous research project that parts were warp and shrink after printed based on 3D CAD model with original dimension. Generally, earlier material used to manufacturer had low yield strength. With advancement in material science the photopolymers and thermoplastics used now have much higher yield strength and durability.

For this they studied about factor affecting accuracy and it mentioned below:

There are a number of factors, which impact in an unexpected way the achievable accuracy. At to begin with these are the essential parameters such as scaling factor and saturation value. Those factors are recommended by the system manufacturer with peculiar values on the accuracy of these factors as well as of the component area within the build stage, have been examined and “optimal” values suggested. The scaling factor, however, reflects too the specific environment conditions and hence cannot be announced as ideal in general. Experience and research results show that a few other factors have much higher effect on the accuracy. These are:

- Material Used (MU);
- Build Orientation (BO);

- Post treatment procedures (PT);
- Nominal dimensions, small, medium, large (ND);
- Infiltrating agent (IA);
- Geometric features and their topology e.g. open or closed contours (GF);
- Wall thickness shell, rafts, solid (WT).

Furthermore, especially for SLS process parameter is more important and varies such as powder size, scan speed, powder density, pulse frequency, fill laser power, scan size, scan spacing, part-bed temperature, layer thickness, pulse size, laser power, laser energy, spot size, powder size distribution, ration of the powders of the mixture [7, 8].

One of the research papers examined about the effect of humidity changes on dimensional stability of 3D printed parts by SLS [8]. First of all they studied about the SLS process parameters, I already mentioned in above. It's depending on the thermal properties of powder material such as melting and recrystallization temperature. For identify the thermal properties of polyamide 12 (PA12) powder, they used differential scanning calorimeter. Many researchers have also reported the deformation of 3D printed parts, and the loss of mechanical strength due to moisture absorption. According to ASTM-D6207, the highest and lowest humidity levels were 95 ± 5 % RH and 15±5% RH, respectively. In this experiment they used ESPEC ARS-0390; the ramp up and down time was determined to be one hour considering the control limit of environment chamber. Furthermore, the highest and lowest strain values were reported to be 0.08% and -0.13% respectively. Therefore, the test condition based on experiment they determined the humidity 20 % and 90 % RH, yielded a total %-strain change of 0.2%.A survey on RH history revealed that the minimum and maximum RH in a year was reported 20.9% and 93.6%, respectively.

Based on surveyed one of the research paper mainly consideration on the issue of accuracy and uncertainty of parts made with additive manufacturing processes [9].They divided two method (test) for experiment. In that there were mentioned first test that to characterize the performance of a machine or process is through production and measurement of a test. The primary assumption of the AM system accessed by building and measuring the AM test artifact is via geometry accuracy and surface roughness of the test artifact. For this test they used stainless steel on an EOS M270 powder bed Fusion AM system using default machine parameter settings for that material. The second test artifact was made to represent the type of metrology challenges encountered in display AM parts. The part is a 3x3x3 lattice composed of 4.5 mm octet truss unit cells. The octet lattice truss is a microstructural architecture, which combines low density with high structural stiffness. For this test they used Computer Tomography (CT) metrology system at Zeiss and LLNL. In the measurement, some complicated of the parts will want multiple evaluations with optical, tactile and X-ray sensors. The main goal will be defining the geometric accuracy of produced component, surface flaws, accuracy of internal features, porosity and material stress effects on dimensional stability. Presently, metrological CT system can perform strong measurement with sub-micrometer interpolated resolution of edge detection, as well as accuracy of measurement better than 2µm.In experiment they used CMM equipped with vast XXT scanning sensor with measurement accuracy declared by manufacturer as 1.8 µm ± L/300 (L-length in mm) & resolution of 0.2 µm. Based on this experiment they discussed the CMM measurement also determine the issue of when to measure the parts to best identify the machine. When the part removed from the build platform, the shape is significantly changed. In spite of that we cannot say these errors are fully depended on the machine performance, especially if there is a heat treatment before removal of parts. On other hand CT metrology work reveals that the Lattice truss structure can be frequently manufactured. It also aids in analyzing several errors trends which can be used for further part developments, including location and general form of part variation as well as error. This expertise can be used to both adjust the design and the manufacturing process to improve the lattice truss strength and reliability.

3. Additive Manufacturing Processes and Materials used

Additive Manufacturing (AM) processes are divided based on material like liquid, solid and powder. The processes discussed in this chapter are recognized to be most important and promising with respect to the general future of this rapidly emerging technology for a wide range of materials. AM processes are briefly described below [10]:

3.1 Types of AM processes are briefly discussed in this section are:

i. Stereolithography (SLA)
ii. Fused Deposition Modeling (FDM)
iii. Selective Laser Sintering (SLS)
iv. Polyjet

3.1.1 Stereolithography (SLA)

Stereolithography, at first created by 3D Systems, Inc. (Rock Hill, SC), was the first and most widely enforced rapid prototyping process. The basic principle of this process is produces only plastic parts specifically from 3D CAD model; by solidifying surface of a liquid photopolymer layer by layer with the use of a laser beam (UV light).The ultraviolet light acts as a catalyst for the responses; the process is also known as ultraviolet curing. It has too been found to be relevant for powders of a ceramic suspended in a liquid. It is one of the broadly utilized RP methods. The material used in this process is liquid photo-curable resin, acrylate. The key components or parts of a Stereolithography (SLA) machine are shown in Figure 1.

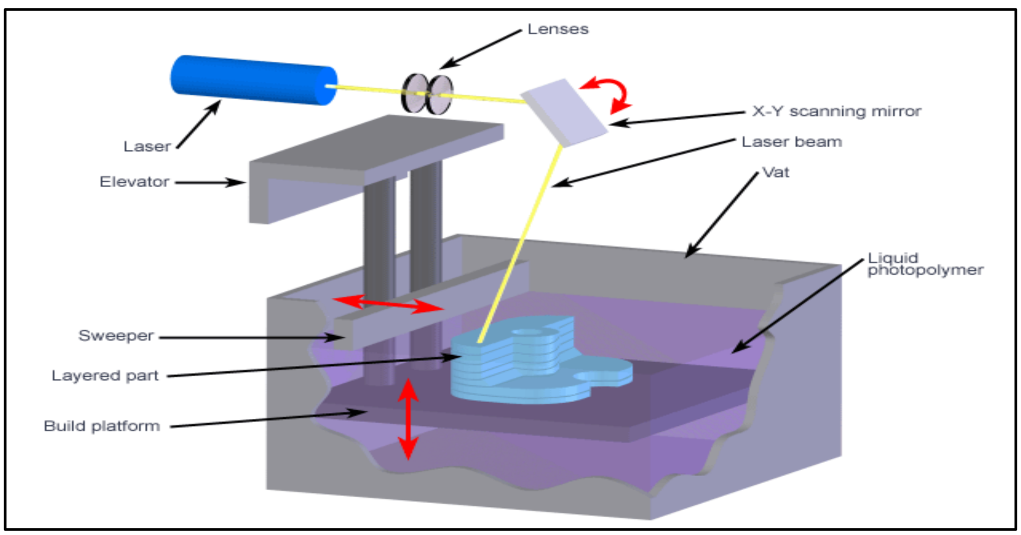


Figure 1 The schematic diagram of Stereolithography (SLA) process [11]

Stereolithography is usually used for prototyping parts. For generally low price, Stereolithography can be creating accurate prototypes, even of irregular shapes [5, 12].

- The advantages of SLA are followings:
  - High accuracy up to 0.1mm,
  - High surface quality,
  - Higher resolution,
  - Complex parts can be creating.
- The disadvantages of SLA are followings:
  - Higher investment
  - As time pass out, the resin can absorb the moisture in the air, resulting in the soft thin section bending and curly
  - Requires support structures.

3.1.2 Fused Deposition Modeling (FDM)

FDM is the most typical extrusion based additive manufacturing technology, created and developed by Stratasys because of ease of operation, low cost of apparatus of portion made by the process, durability of product and easy material changeability. FDM operation a heating chamber where the raw material is provided and it gets liquefied. It is commonly known as extruder where the material is provided in and a liquefied thermoplastic is extruded. Parts made utilizing FDM are among the toughest for any polymer –based additive manufacturing process. The working schematics diagram shown in fig.2 [7].

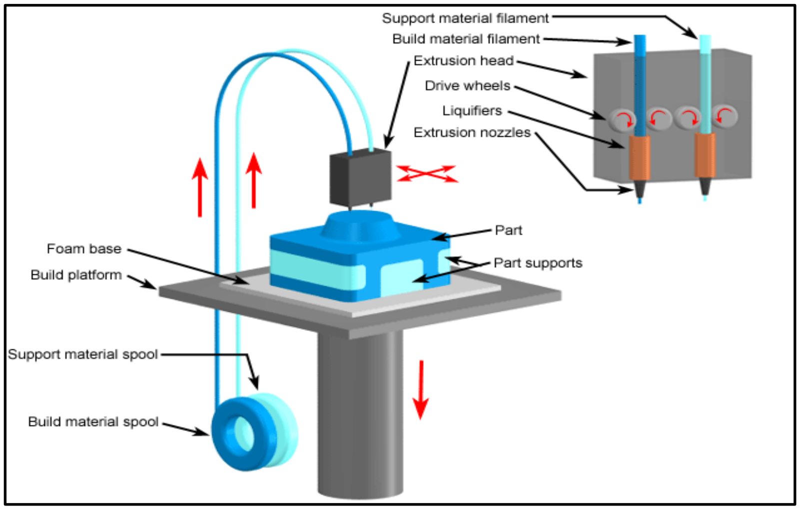


Figure 2 The Schematic diagram of FDM process [7]

FDM builds up a physical model layer by layer, fusing higher layers of material to the layers of below them to create new object. The most common materials utilized for FDM are Acrylonitrile Butadiene Styrene (ABS) and polylactide (PLA), with their characteristics of getting to be a liquid substance with unsurprising flow properties in reaction to heat, while shaping a solid strong once cooled. This process of heating and cooling plastic, in inclined to arbitrary variety, with undesirable results depending on the estimate part being modeled. Contrasts in material properties across manufacturers and alike among various material from the same manufacturer can result in very different printing results, requiring user interference to refine several printer parameters until usable prints are accomplished. These include extrusion rate, nozzle temperature, bed temperature and the properties of the design, itself. In FDM technology accuracy which is ability to meet exact physical dimensions, consistent shapes, and unsurprising surface finish is important in case of engineered mechanical devices [6, 13, 14].

- The advantages of FDM are followings[12]:
  - Easy to use
  - No need for special tooling
  - High accuracy
  - High speed
  - Automatic scaling
  - Complex parts can be produces
  - Low cost
- The disadvantages of FDM are followings:
  - Raw material limitations.
  - Higher investment
  - Limited size of product

3.1.3 Selective Laser Sintering (SLS)

Selective laser sintering (SLS) is a creative manufacturing process based on the utilize of powder-coated metal additives, a process typically utilized for rapid prototyping and instrumentation. The term “Sintering” specify to a process by which objects are made from powders utilizing the mechanism of atomic diffusion. In spite of the fact that atomic diffusion happens in any quicker at higher temperatures which is why sintering includes heating a powder. Sintering is distinctive from melting in that the materials never reach a liquid state during the sintering process. Selective laser sintering is a layer manufacturing process which allows user to generate complex 3D structures by solidifying progressive layer of powder material on top of each other. Consolidation is achieved by processing the chosen areas utilizing the thermal energy provided by a focused laser beam [16, 17]. The working schematics diagram shown in fig.3 [7].

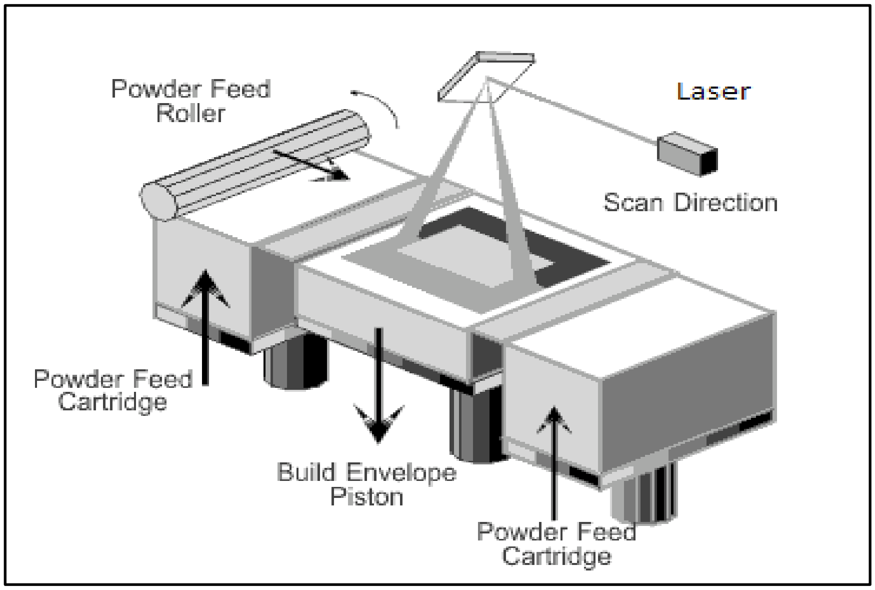


Figure 3The Schematic diagram of SLS process [7]

- The advantages of SLS are followings:
  - Fabricated prototypes are porous (typically 60% of the density of molded parts), thus impairing their strength and surface finish.
  - Fast build times
  - Limited use of support structures
  - Variety of materials (plastics, ceramics, sands, and some metals)
- The disadvantages of SLS are followings:
  - Rough surface finish
  - Less accuracy
  - Material changeover difficult compared to FDM & SLA.
  - Some post – processing/ finishing required.

3.1.4 PolyJet

PolyJet is a 3D printing technology and its works by jetting state of the art photopolymer materials in ultra-thin layers (16µ) onto a build tray layer by layer until the component is completed. Each photopolymer layer is cured by UV light instantly after it is jetted, creating completely cured models that can be taken care and used instantly, without post-curing. The gel-like support material, which is extraordinarily planned to support complicated geometries, is freely removed by hand and water jetting. The working schematics diagram are shown in fig.4 [18].

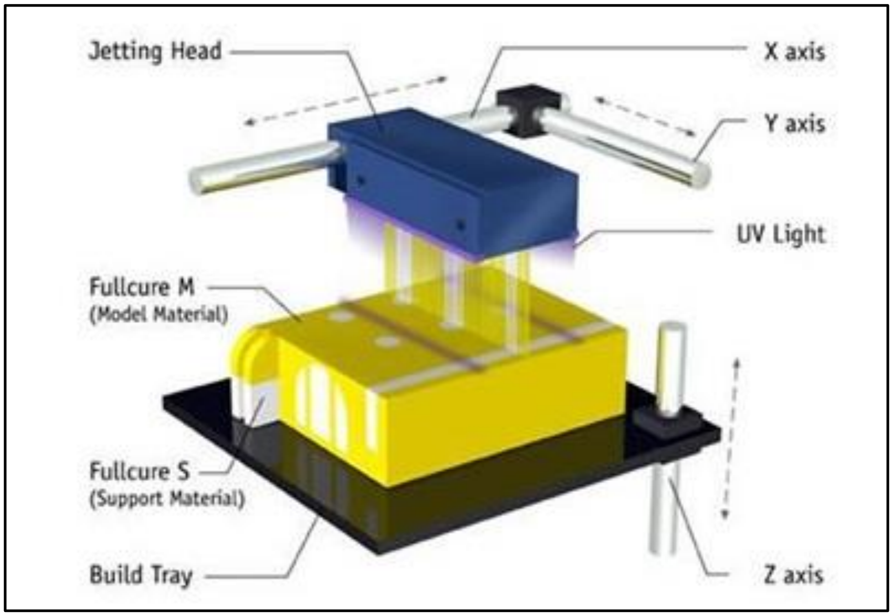


Figure 4 The Schematic diagram of PolyJet 3D printing [18]

The PolyJet rapid prototyping process uses high-resolution ink-jet technology to produce parts rapidly and cost-effectively. This technology makes a difference us in printing inflexible parts, Transparent Parts, Rubber like/Flexible parts required for prototyping applications. This is the only technology which can print multimaterials and multi-color in a single build [18, 19].

- The advantages of PolyJet printing are followings:
  - Rapid build times
  - Good tensile strength
  - High-resolution parts with detailed features that simulate final-product aesthetics.
- The disadvantages of PolyJet printing are followings:
  - Water jet is prescribed means of removing support
  - Where support material is needed, varnish finish is not accomplished until post processing
  - Requires manual support removal

3.2 Classified Material based on AM processes and its properties

The filaments are the materials utilized in 3D printers as the raw materials utilized for making models. There are a few varieties of filaments accessible for the commercial employments of the 3D printer's most commonly utilized filament types are as follow [21].

3.2.1 Acrylonitrile Butadiene Styrene (ABS)

ABS is the most familiar material used in 3D printing. ABS as a polymer can take various shapes and can be altered to have numerous properties. It is solid plastic with a few adaptability. It has fabulous affect quality at low temperatures. ABS is soluble in Acetone, which permits welding of parts together with a few drops, and make high gloss by brushing or dipping full pieces in Acetone. Its quality, machinability, flexibility, and higher temperature resistance makes it most favored plastic in 3D industry. Mechanical characterization has been performed to recognize both this variety of additive manufacturing and the ABS polymer [16].

Table 1 ABS Properties

Properties of ABS
Extrude at 225^0 C
Requires heated bed
Works reasonably well without cooling
Adheres best to polyimide tape
Filament tolerances are usually
Prone to cracking, delamination, and warping
Flexible with Flexural strength of 11000 psi
Can be bonded using adhesives or solvents (Acetone or MEK)
Petroleum Based
High toughness with tensile strength of 6500 psi
Excellent Impact Resistance
Good resistance to ultraviolet light
Heat Resistance to 105^0 C
Resistant to Aqueous Acids
Density is 1.03 to 1.38g/cm^3

The particular properties of ABS are shown in Table 1 [16]. ABS is broadly utilized on the entry –level FDM 3D printers in filament form. It is an especially solid plastic and comes in wide range of colors. ABS can be bought in filament form from a number of nonproprietary sources. This made the filament very fashionable in the market [22].

3.2.2 Polylactic Acid (PLA)

Polylactic Acids are commonly utilized filaments because it is simple to utilize and effortlessly accessible. It is too a bio-gradable substance and produced from crops such as corn, potatoes or sugar-beets. So it is an eco-friendly material. It is thermoplastic aliphatic polyester which is defined from the renewable resources like plant based structures. It travels rapidly from liquid to solid; it follows itself so it can be used for high speed printing [19]. PLAs are not perfect for high temperature environments, like utilizing it for long period in outside. One obstacle of using this material is its lower melting temperature which makes it unsuitable for many applications. Accuracy of parts is much less in PLA when compared to ABS. PLA undergoes a phase-change when heated and gets to be much more liquid. In the event that effectively cooled, much sharper details can be seen on printed corners without the chance of breaking or distorting. The increased flow can too lead to stronger binding between layers, improving the strength of the printed part. Some general properties of PLA are shown in table 2 [16].

Table 2 PLA Properties

Properties of PLA
Extruded at 180-200^0 C
Benefits from heated bed
Benefits greatly from cooling while printing
Adheres well to print bed
Prone to curling of corners and overhangs
Flexural Strength of 8020 psi
Tensile Strength of 8.383 psi
Plant Based
Can be bonded using Adhesive

3.2.3 Vero Gray

Utilizing the PolyJet process, Vero Gray has the leading by and large properties of the inflexible materials. With an extremely high resolution layer slice (0.015 mm), models have smooth from surfaces and the appearance of generation parts, with exceptionally small post-processing. Rigid PolyJet parts are awesome for creating accurate, high resolution small and medium prototypes that require the finest highlights and detail. Some general properties of Vero Gray are shown in table 3 [23].

Table 3 Vero Gray Properties

Properties of Vero Gray
Opaque medium grey appearance
High resolution
High rigidity
Glass transition temperature at 48.7^{0}C
Elongation at break up to 10-15%
Quickly and economically produces parts

3.2.4 PA 2200

The white powder PA 2200 on the basis of polyamide 12 serves a wide variety of application. Typical applications of the material are fully functional parts with high end finish right from the process, which easily withstand high mechanical and thermal load. Some general properties of PA 2200 are shown in table 4 [24].

Table 4 PA 2200 Properties

Properties of PA 2200
High strength and stiffness
Good chemical resistance
High selectivity and detail resolution
Balanced property profile
Various finishing possibilities like metallization, vibratory grinding, bonding, powder coating

4. Reverse Engineering and 3D scanning

4.1 Introduction of RE

Reverse Engineering is represents as the process of receiving a geometry CAD model from 3D points captured by scanning/digitizing existing parts/product. As per researchers defined RE based on specific task, the process of digitally capturing the physical bodies of a component. Yau et al. (1993) define RE, as the "process of retrieving new geometry from a manufactured part by digitizing and modifying and existing CAD model" [25]. RE is a referred as the conversion of physical–to–digital process shown in figure 5.

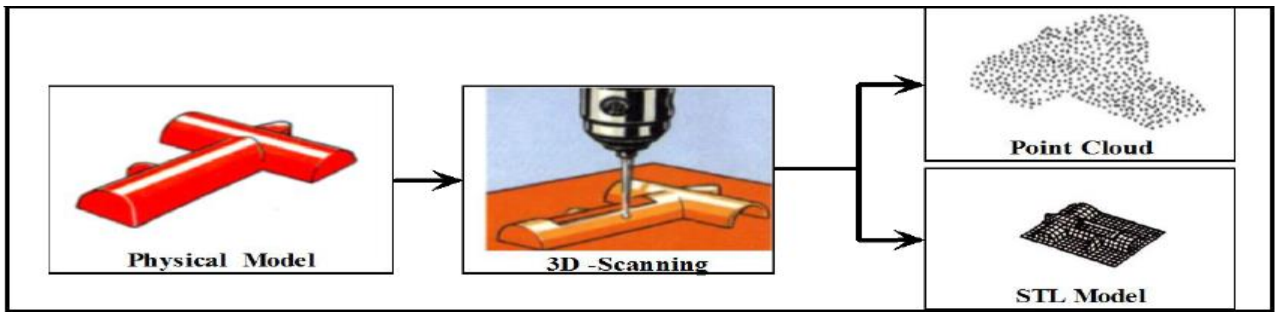


Figure 5 Physical–to–digital process [26]

Presently, RE is more and more used in various applications such as manufacturing, industrial design, medical, Software engineering, and jewellery design and reproduction. For example, when a new car is launched on the market, competing manufacturers may buy one and disassemble it to learn how it was built and how it works [25]. Reverse Engineering has been described as "a four-stage process in the development of technical data to support the efficient use of capital resources and to increase productivity". The following four stages are below as well as shown in fig.6 [27]:

- Data Evaluation:- Visual inspection, dimensional inspection, quality evaluation, possible failure analysis
- Data generation: - Engineering drawings, CAD models.
- Design verification:- Prototyping, model testing, model failure analysis, quality assurance
- Design implementation:- Prototype delivery, project summaries, economic analysis, final implementation

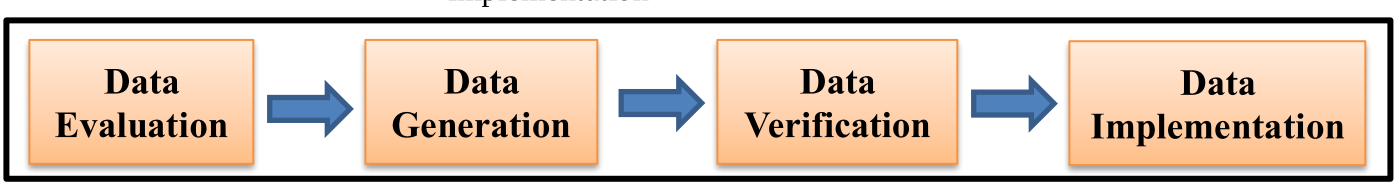


Figure 6 Stages of Reverse Engineering

4.2 3D Scanning and Measuring

4.2.1 Introduction of 3D Scanning

3D scanning is specially for increasing the productivity, while at the same time securing quality in product development. Currently 3D scanners are available to digitize objects from microscopic to large structure in size. 3D scanners are very similar to cameras. 3D scanners have a conical visual field and can collect information on noticeable surface. The difference between them: cameras gather the surface information and color within its boundary of view (creating images) while the 3D scanner uses the image captured to extract 3D data (collecting information on the distance and the surface within its boundary of the view) [28, 29, 30].

4.2.2 Different method of 3D Scanning

There are two types of 3D scanners such as contact and non-contact. The following description of the two methods:

A. Contact Scanner

The contact means that the measuring probe touches the recovery surface of part or object during the scanning. As the probe contacts the object's surface the scanner reports the X, Y, Z position of the probe by taking positional measurement of the armature. Currently in the marketplace, contact probe scanning devices are based on CMM (Coordinate Measuring Machines) technologies. It is controlled by manually or computer. CMM is shown in fig.7. It is mostly used in industry for dimensional inspection of manufactured parts and can be very precise [31].

Figure 7 Coordinate Measuring Machines (CMM) [32]

The advantages and disadvantages of contact methods compared to non-contact methods are as follows [25]:

- **Advantages:**
  - High accuracy
  - Low costs
  - Ability to measure deep slots and pockets ,and
  - Insensitivity to color or transparency.
- **Disadvantages:**
  - Slow data collocation
  - Distortion of soft objects by the probe.

B. Non-Contact Scanner

In non-contact scanner, there are no physical part contacts. Non-contact devices use lasers, optics and charge coupled devices (CCD) sensors to capture point data. Latest ATOS triple scan non-contact scanner is shown in fig.8.

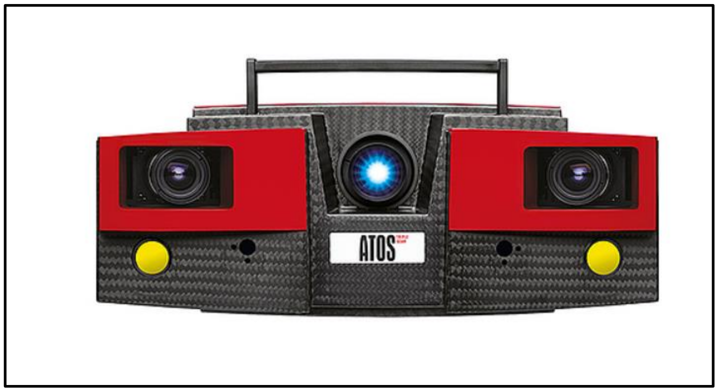


Figure 8 ATOS triple scan non-contact scanner [33]

The advantages and disadvantages of non-contact methods compared to contact method are as follows [25]:

- **Advantages:**
  - No physical contact
  - Fast digitizing of substantial volumes
  - Good accuracy and resolution for common applications
  - Ability to detect colors
  - Ability to scan highly detailed objects, when mechanical touch probes may be too large to accomplish the task.

- **Disadvantages:**
  - Possible limitations for colored, transparent, or reflective surfaces and
  - Lower accuracy

4.2.3 Basic Principle of optical scanner (Camera)

A common method for extracting such depth information from each other by a known distance. Basic Principle of optical scanner (camera) is shown in the figure 1.The simplest model is two identical cameras separated only in the **X** direction by a baseline distance **b.** The image planes are coplanar in this model. A feature in the scene is viewed by the two cameras at different positions in the image plane. The distance between the locations of the two features in the image plane is called the disparity. In fig.9 the scene point P is observed at points P_l and P_r in the left & right image planes, respectively. Furthermore, M and N are left camera axis and right camera axis, respectively [34].

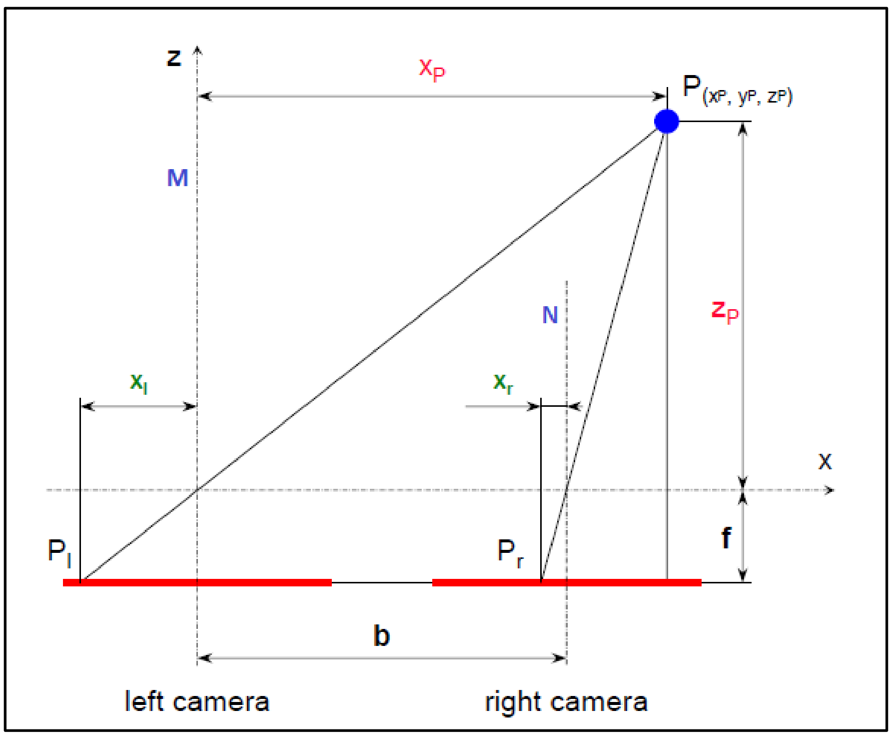


Figure 9 Basic Principle of Optical scanner (Camera) [35]

Without loss of generality, Let us assume that the origin of the coordinate system coincides with the left lens center.

- Based on geometry of the left camera we get,

$$\frac{X}{Z} = \frac{X_l}{f} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

- Based on geometry of the right camera we get,

$$\frac{X-b}{Z} = \frac{X_r}{f} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2)$$

- Combining these two equations, we get

$$Z = \frac{bf}{(X_l - X_r)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3)$$

Thus, the depth at various scene points may be recovered by knowing the disparities of corresponding image points.

4.2.4 Contactless Optical 3D Scanner Measurement

Currently, Optical 3D measuring technology and full-filed surface measurement systems has become a standard tool within virtually all industries worldwide. In this thesis we are using Optical Contactless 3D scanner manufactured by GOM-ATOS II 400 as shown in figure 10. Technical parameters of this scanner are shown in table 5. ATOS 3D scanner is 3D coordinate measuring machine with flexible. The fast, non-contact, optical 3D scanners deliver a high resolution point cloud which precisely describes free-form surfaces, finishes, and geometries. The sensor forms the basis for a diverse range of measuring tasks – from simple 3D scanning to fully automated measurement and inspection processes. The ATOS Essential line with the GOM Scan software is designed for simple scanning tasks. Its focus is on 3D scans of high data quality for applications such as reverse engineering or rapid prototyping [36].

Table 5 Technical Parameters of ATOS II 400 optical scanner

ATOS II 400 optical scanner	
Weight	5.2 kg
Dimensions	490 x 260 x 170 mm
Time of 1 scan	1 second
Measured Volume	700 x 560 x 560 mm 250 x 200 x 200 mm 55 x 40 x 33 mm
Number of points in one scan	Up to 1,400,000 **or** 1392 X 1040 pixels
Point density	0.04 -0.18 -0.5 mm
Measurement accuracy	**Approx...30 µm**

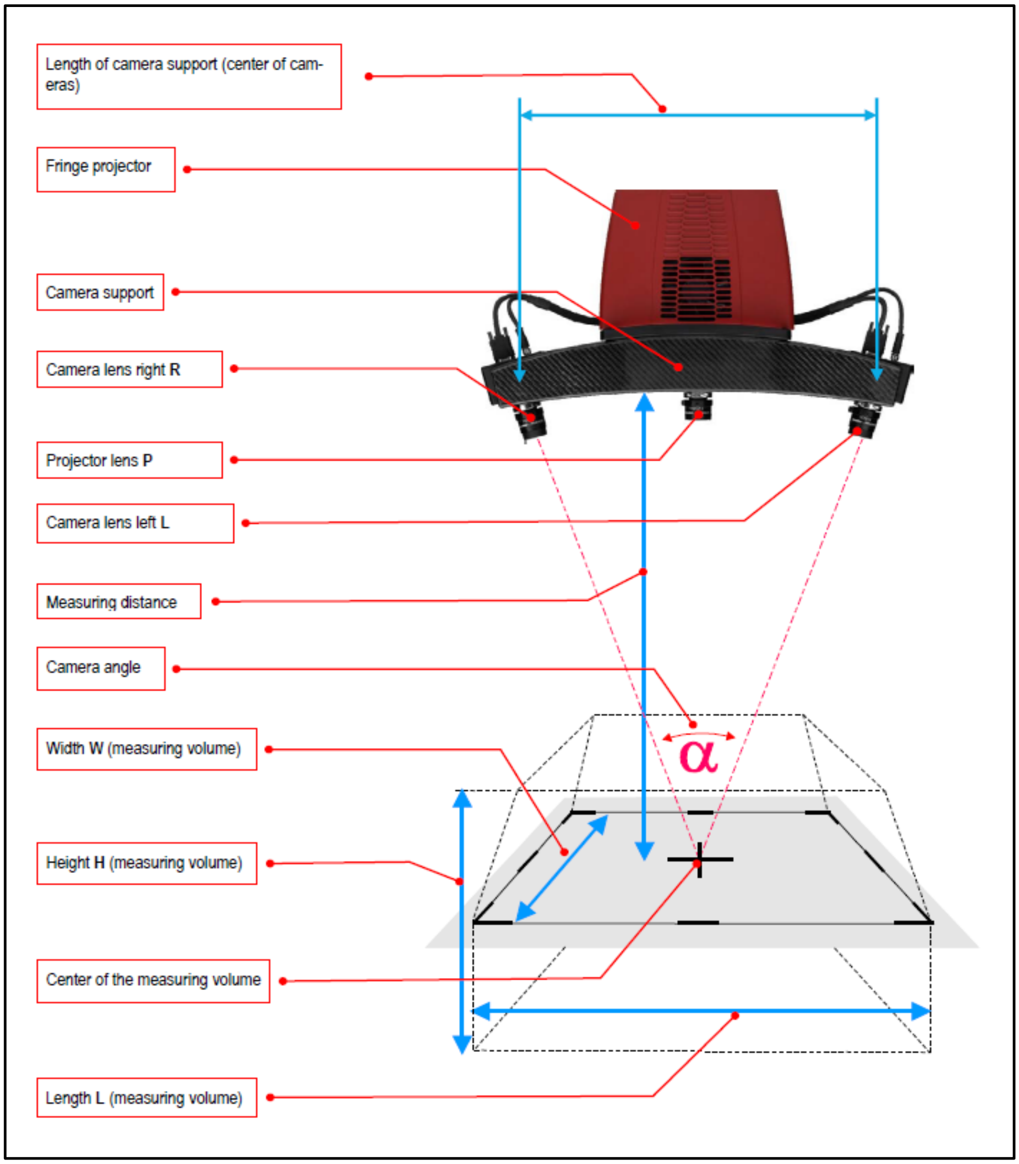


Figure 10 ATOS optical scanner with definition of terms referring to the sensor unit [36]

Furthermore, ATOS provides three-dimensional measurement data and analysis for industrial component such as sheet metal parts, tools and dies, turbine blades, proto-types, injection molded parts, casting, and more. It's fitted with lens and measurement of volume 250x200x200 mm. This scanner is recommended min. reference point size in diameter of 3 mm and measuring point distance is given by up to 0.18 mm .All lenses are marked with L (Left) or R (Right) or P (Projector). Left and right are defined from the sensor view in normal operating position. ATOS sensor combines high data quality in short measurement time with flexibility and stability for industrial environments. ATOS systems are used to reduce development times, optimize production processes and at the same time, improve process security [36].

5. Standard Test

5.1 Testing of Resistance to Environmental cycle test

5.1.1 Description

This Test specification describes an environmental cycle test (elevated temperature/low temperature cycle) for testing units, e.g. vehicle parts in the engine compartment [37].

The behavior of the units and/or parts during environmental cycle stressing by means of cycling temperature and moisture shall be assessed here (e.g. susceptibility to cracks, deformation, separation on the composite material, etc.).

The purpose of the test specification (e.g. temperature -40^{0}C) is to uncover component weakness in a short-term test with accelerated time effect, not to define general component requirement for continuous operation.

5.1.2 Procedure

The temperature shall be regulated with a tolerance of ± 2^{0}C and the relative air humidity (rel. humidity in the following) with a tolerance of ± 5%.

The climatic chamber shall be set to room temperature (23^{0}C) and 30% rel. humidity before the test specimen is inserted.

The holding times must always be maintained. The heating and cooling phases can be varied according to the performance capability of the climatic chambers used. Deviations shall be specified in the test report.

One cycle (see Figure 11) lasts for 720 min (12 h) and comprises the following temperature and humidity profiles:

-60 min	heating phase	to +80 °C and 80% rel. humidity,
-240 min	holding time	at +80 °C and 80% rel. humidity,
-120 min	cooling phase	to -40 °C, when freezing point is reached: approx. 30% rel. humidity, the air humidity remains unregulated as of T < 0 °C (depending on the system, humidity regulation can also be suspended as of T < 10 °C),
-240 min	holding time	at -40 °C, air humidity remains uncontrolled,
-60 min	heating phase	to +23 °C, rel. humidity is regulated to 30% as of T = 0°C

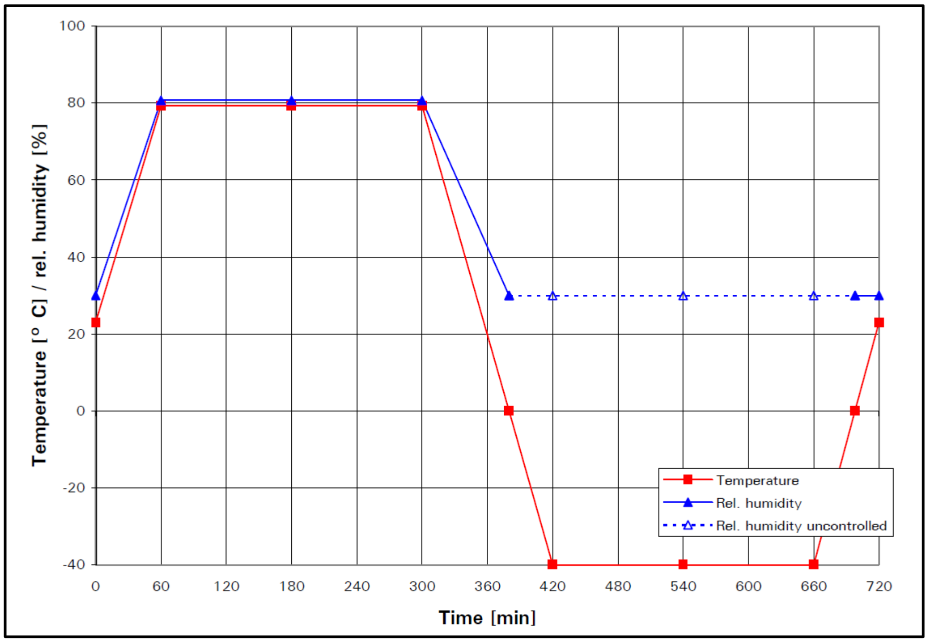


Figure 11 Test cycle for PV 1200 [37]

5.2 Ageing of components in Solar Simulation Units

We are using simulation units DIN 75 220 for this thesis. The description about this unit is as follow [38]:

5.2.1 Field of application and scope

This unit is specially determining for the behaviour of polymer automobile parts in their original installed positions and mountings. It is relevant to complex assemblies or whole vehicles and so, particularly suitable for reporting interaction between different materials within one component or between several components.

Furthermore, In DN 75 220 in that changes of all properties significant to use, such as shape, color, gloss, feel to touch, strength and the consequences of different degrees of thermal expansion resulting from exposure to artificial global radiation, heat/cold and moisture are evaluated.

5.2.2 Terms

Artificial global radiation

Artificial global radiation is radiation similar to global radiation which is used for test purposes.

Test chamber

The test chamber is a device in which the outdoor condition on the external surfaces of a component are simulated: *outdoor conditions*

Test box

The Test box is a device in which the climatic conditions found in an enclosed component interior are simulated: *indoor conditions*

Reference plane

The reference plane is an imaginary plane in the test chamber or test box in which the specified climatic parameters, such as radiation intensity, temperature, etc. are measured.

Brief description of the procedure

External components are placed suitably in test chambers. Internal components are assembled as for installation and placed in test boxes. Radiation emitters, which generate an artificial global radiation, irradiate the specimens with pre-specified radiation intensity at additional climatic parameters specified in table 7. When the test is finished, the component in question is evaluated.

Radiation unit

The radiation unit is used to generate artificial global radiation. The main components are radiation sources, reflector systems and, if necessary, filter systems. The radiation unit shall conform to the requirements in table 7 and the following requirements.

The tolerance for the radiation intensity shall ± 5 % in the reference plane.

In the usable test area, the radiation intensity shall be within ± 10 % of the desired value (according to table 7) on each element of surface which is parallel to the reference plane. The spectral radiation distribution shall conform to table 6.

Table 6 Spectral radiation distribution of artificial global radiation

Wave length range (nm)	**Proportion of total radiation intensity (%)**
230 to 280	0.5 ± 0.2
320 to 360	2.4 ± 0.6
360 to 400	$3.2^{+1.2}_{-0.8}$
400 to 520	17.9 ± 1.8
520 to 640	16.6 ± 1.7
640 to 800	$17.3^{+1.7}_{-4.5}$
800 to 3000	42.1 ± 8.4

Test chamber

Depending on the test specification, for testing components, the test chamber shall provide the following options for controlling the ambient temperature:

During operation of the radiation unit in the range: 35 to 45 ^{0}C

During the dark phase in the range: -10 to +10 ^{0}C

The temperatures set shall be maintained to within ± 3 K. The heating-up rate from low to high temperatures shall be approximately 0.5 K/min. The cooling down rate from high to low temperatures shall be 0.25 K/min. Care shall be taken to ensure that the values for relative air humidity given in table 2 are set.

Test box

The test box temperature settings shall range from -10 to 90^{0}C. The temperatures set shall be maintained to within ±3 K within the useable test area. The heating up rate shall be 1K/min. The cooling down rate shall be 0.5 K/min.

Conditioning

Before the test, all specimens shall be stored for 24 hours in a constant standard atmosphere.

Cycle test (Z)

A cycle test consists of 15 dry climate cycle performed in accordance with dry climate cycle (an approximate simulation of a dry-hot Arizona climate) and 10 humid climate cycles performed in accordance humid climate cycle (an approximate simulation of a hot and humid Florida climate in the day and a cold Alpine climate at night). A cycle test may be performed in outdoor conditions in accordance with table 7. According to this standard we are using outdoor cycle test (Z-OUT).

Table 7 Test climates for Outdoor - daytime

Climate parameter	Unit	Dry climate	Humid Climate
Black standard temperature	^{0}C	(measured value)	(measured value)
Test chamber temperature	^{0}C	42 ± 3	42 ± 3
Rel. atmospheric humidity	%	< 30	> 60
Radiation intensity	W/m^2	1000 ± 100	1000 ± 100

6. Evaluation software for 3D measuring data

GOM Inspect Professional and GOM Inspect are software package for the analysis of 3D measuring data for quality control, product development and production [39]. The GOM software is used to evaluate 3D measuring data derived from GOM systems, 3D scanners, laser scanners, CTs, CMMs and other sources.

6.1 *The following steps or command used in GOM Inspect software:-*

A). Polygon Mesh:

3D meshes for parts and components are calculated from 3D point clouds for visualization, simulation, reverse engineering and CAD comparison. The precise polygon meshes can be exported to a number of standard formats such as STL, G3D, JT Open, ASCII and PLY.

B). 3D Mesh Processing

Polygon meshes can be smoothed, thinned and refined. In addition, holes in the mesh can be filled and curvatures can be extracted. The mesh is processed using curvature-based algorithms and tolerances. Software provides the user with a live preview of each processing step. Furthermore, a golden mesh can be determined by finding the best mesh or calculating an average mesh.

C). CAD Import

CATIA V4, CATIA V5, PRO/E, Unigraphics, IGES, STEP, JT-Open, Parasolid, PLY, etc.

D). Measurement Plan Import: ASCII, CSV, FTV, etc.

E). Parametric Inspection

Creation path within the software structure. All actions and evaluation steps are fully traceable and interlinked. Individual elements can be modified and adjusted at any time, and a one-button solution updates all dependent elements automatically after changes have been made.

F). Alignment

Automatic pre-alignment, RPS, 3-2-1, plane-line-point, best-fit, hierarchical, alignments based on local coordinate system.

G). CAD comparison

Surfaces, primitives such as lines, planes, circles or cylinders, cones.

H). GD & T Analysis: Based on ISO 1101 and ASME Y14.5 standards.

I). Point-Based Inspection

All evaluation function can also be used on point clouds. Construction functions can then be applied to create geometry elements based on several points. This all allows GD&T analysis on the generated elements, including flatness, cylindricity or positional accuracy.

J). Import of Volume Data

Directly used for visualizing and evaluating scanned volume models. Also import of various different materials from the scanned object as separate surface meshes.

K). Surface Defect Map

It enhances the surface inspection. Detects small defects based on meshes and display them in the color plot. Theoretical surface for more realistic results.

L). Reporting

Create reports containing snapshots, images, tables, diagram, text and graphics, as well as exported to a PDF document, free definable report templates.

- The following procedure for the inspecting the scanned models are below:

  The GOM software has many interfaces for importing measuring data from different sources like laser scanners, white light scanner, CMMs and CTs. Common an neutral as well as native formats .stl file are available for importing CAD data. First import the CAD data by designed in CATIA V5, PRO/E and then import the Polygonal mesh from point clouds of ATOS scanner. Based on CAD and polygonal mesh consider the automatic pre-alignment. After the pre-alignment could be start the measurement for that first construct basic geometrical elements (spheres, line, cylinders, Planes). It was calculated by interlacing the fitting elements with Gauss Best-fit 3σ. For measurement of parameters have done by GD &T analysis. From GD &T analysis it can automatic calculate the diameter of spheres, diameter of cylinders, distance between two spheres, cylindricity, flatness and horizontal and vertical dimensions with comparison of CAD. It will directly represent the deviation between them. Furthermore, there could be comparison of polygonal mesh with CAD or different polygonal mesh as consider as CAD model so that it depicts the color map deviation for better visualization of inspection.

7. Experimental Part

7.1 Model descriptions

In this chapter, I would like to describe about the model description and which technology we used for manufactured of parts. The model already designed in CAD software a year ago is shown in fig.12.

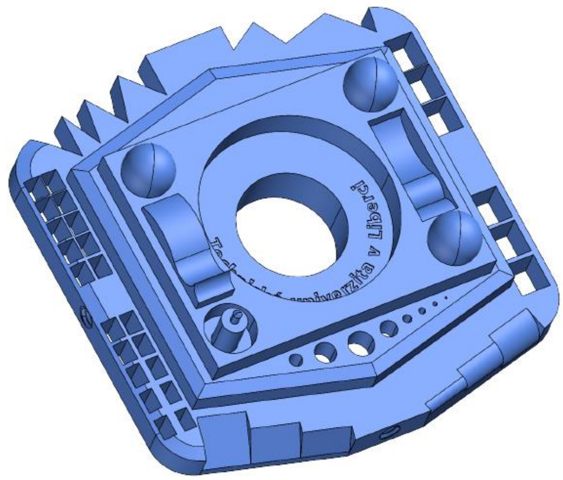


Figure 12 Designed 3D CAD model

Based on the designed 3D CAD model, further describe about the dimensions and measureable parameters by scanning are called inspection with help of GOM Inspect Professional V8 software. Measureable parameters are like diameters of sphere 1, sphere 2, sphere 3 and Spacing between spheres and diameters of Inner cylinder 1, cylinder 2, cylinder 3 and outer cylinder 4. Furthermore, about flatness and dimensions of horizontal and vertical. These all things are representing in 2D drawing of the CAD model with inspection labels in fig.13. In addition, the manufacturer's properties of model print are described in table 1.We have 10 different types of model printed. A year ago, Models were printed by different technology like FDM, Polyjet, SLS and SLA with different structures and materials. In this thesis we have to measure and check about dimensional stability with duration of time like after printed is called Golden Mesh (i.e. Part was scanned the day after printed - the result was scan = Mesh. The second scan was done after 14 days of printing. In order to increase accuracy, the average mesh called Golden Mesh, was made from these two meshes. This mesh was used as a default for comparison), after 3 months, after a year and after a year with standard test. Here we used two types of standard test like test 1 is called humidity and temperature and test 2 is called UV lighting. These test already described in chapter 5.

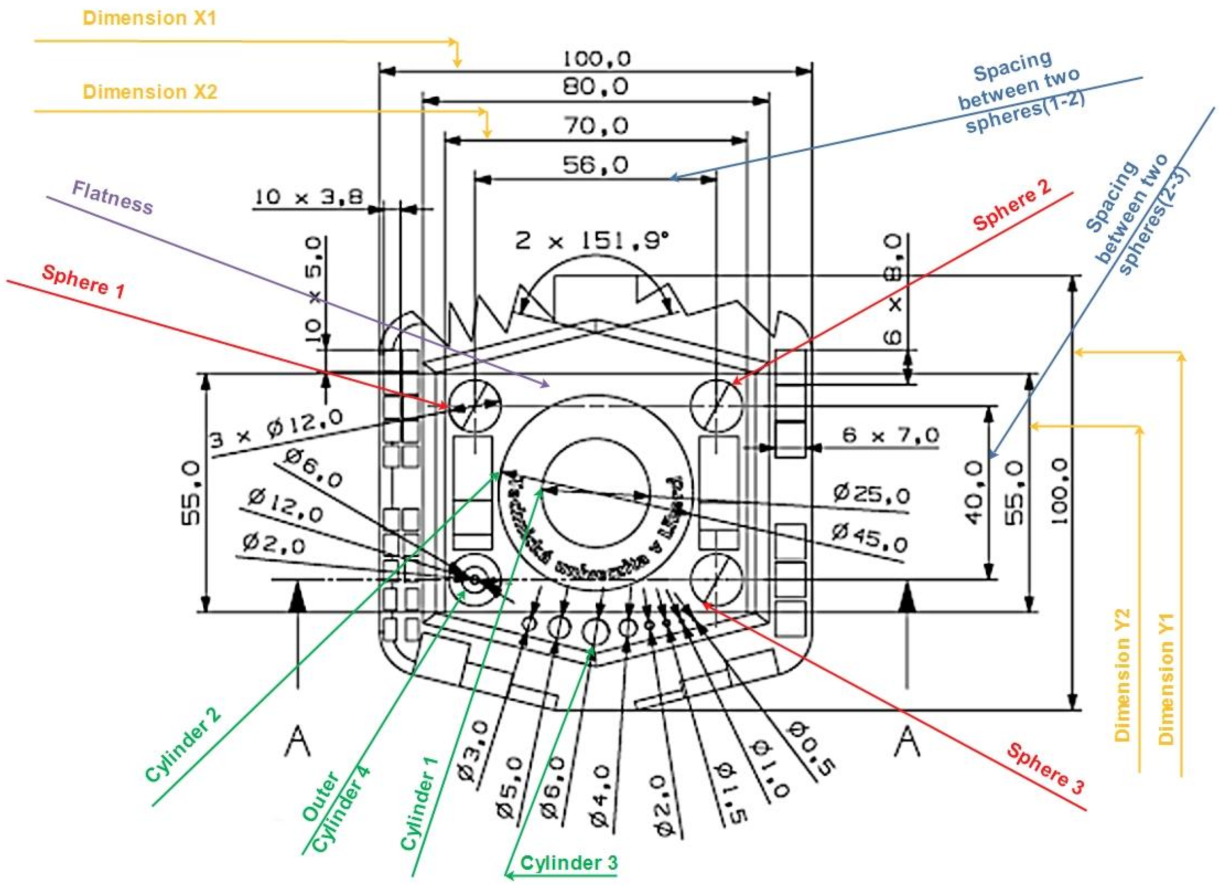


Figure 13 2D drawing of the CAD model with inspection labels

The below table 8 is representing about description of model manufacturer's and standard test with different structures and materials, with different layer of thickness.

Table 8 Description of model manufacturer and standard test

Sr. No.	Printer	Material	Layer thickness mm	Model	Standard Test
1	FDM Dimension	ABS-P400	0.25 mm	Full Solid	2
2	FDM Dimension	ABS-P400	0.25 mm	Sparse light	1
3	FDM Fortus	ABS-M30	0.25 mm	Full Solid	1
4	FDM Fortus	ABS-M30	0.25 mm	Sparse light	2
5	Polyjet Object 500	Vero Gray	0.016 mm	Matt	2
6	Polyjet Object 500	Vero Gray	0.016 mm	Glossy	1
7	SLS EOSint P395	PA 2200	0.1 mm	Vertically printed	2
8	SLS EOSint P395	PA 2200	0.1 mm	Horizontally printed	1
9	SLA Form 2	White Resin	0.05 mm	Full model TUL	2
10	SLA Ultra 3SP	ABS 3SP Tough	0.05 mm	Full model Out side	1

7.2 Scanning

7.2.1 Adjustment and calibration of the device

It is necessary to perform adjustment and calibration of the device prior to performing measurement. Some steps are required before each measurement, others after changing lenses or transporting of the device. All settings and control of scanning processes are performed directly in GOM ATOS Professional software. In this software, we have to fit cameras and projector with suitable lenses and selecting optics (measurement volume). Setting the recommended measurement distance from calibration etalon. In addition, setting the camera angle by the help of center cross projected on the pad intersect is shown in fig.14. Furthermore, the adjusting laser pointers via laser beams are contact at the same spot on the pad. It's representing in fig.15. [36]

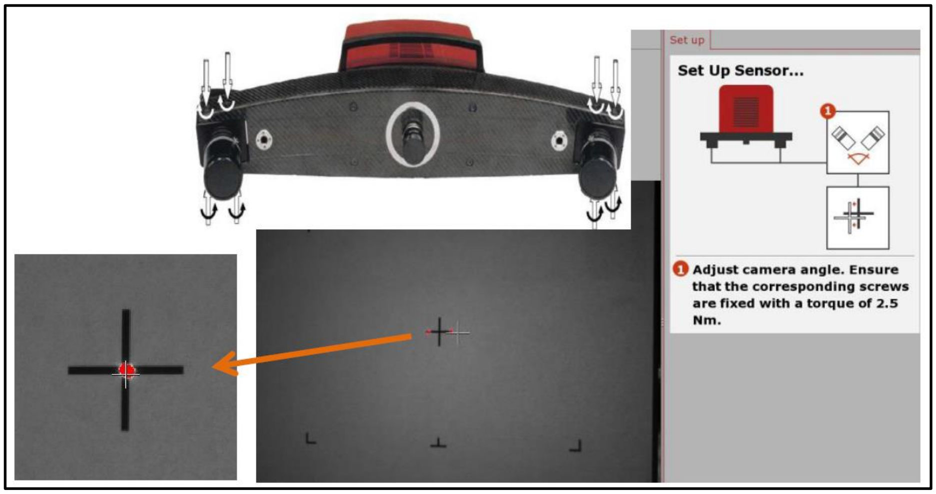


Figure 14 Adjustment the cameras angle in GOM ATOS Professional software [36]

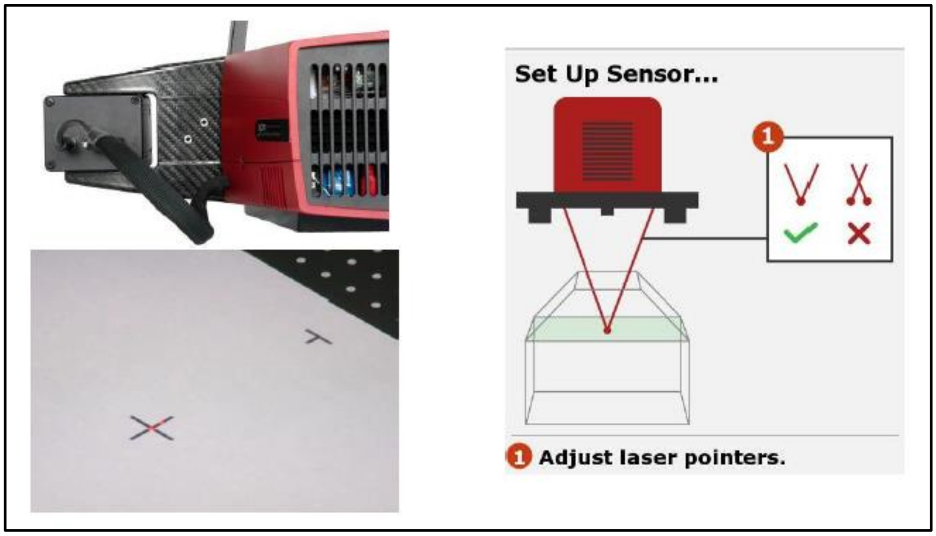


Figure 15 Adjustment the laser pointers in GOM ATOS Professional software [36]

7.2.2 Preparing parts for measurements (Scanning)

- Placing reference points.

  The following rules are placing the reference point marks on the parts:

  → Place the point marks to flat or slightly curve surfaces.

  → Do not place the point marks too close to edges- trouble of gap filling.

  → The reference point marks must be appropriately distributed throughout the whole length, width and height of the measurement volume.

  → Use as many reference point marks as necessary for the sensor to reliably identify at least three reference point marks from the previous scan.

  → Do not place the point marks into straight line.

  → If we want to scan or measure part from both the sides, we have to place the point marks at least 3 around the whole part to connect partial measurement series.

  → When scanning flat surfaces, we cannot place the point marks on the same place of opposite surfaces (risk of point interchanging = transformation error).

- Anti-reflection coating means modification of surface by the help of spray painting because the part we chose which is transparent and shiny as shown in fig.16.
- After coating we must clean the reference point of marks.
- Mounting the part to a measurement table.

Figure 16 Spray painting on the models

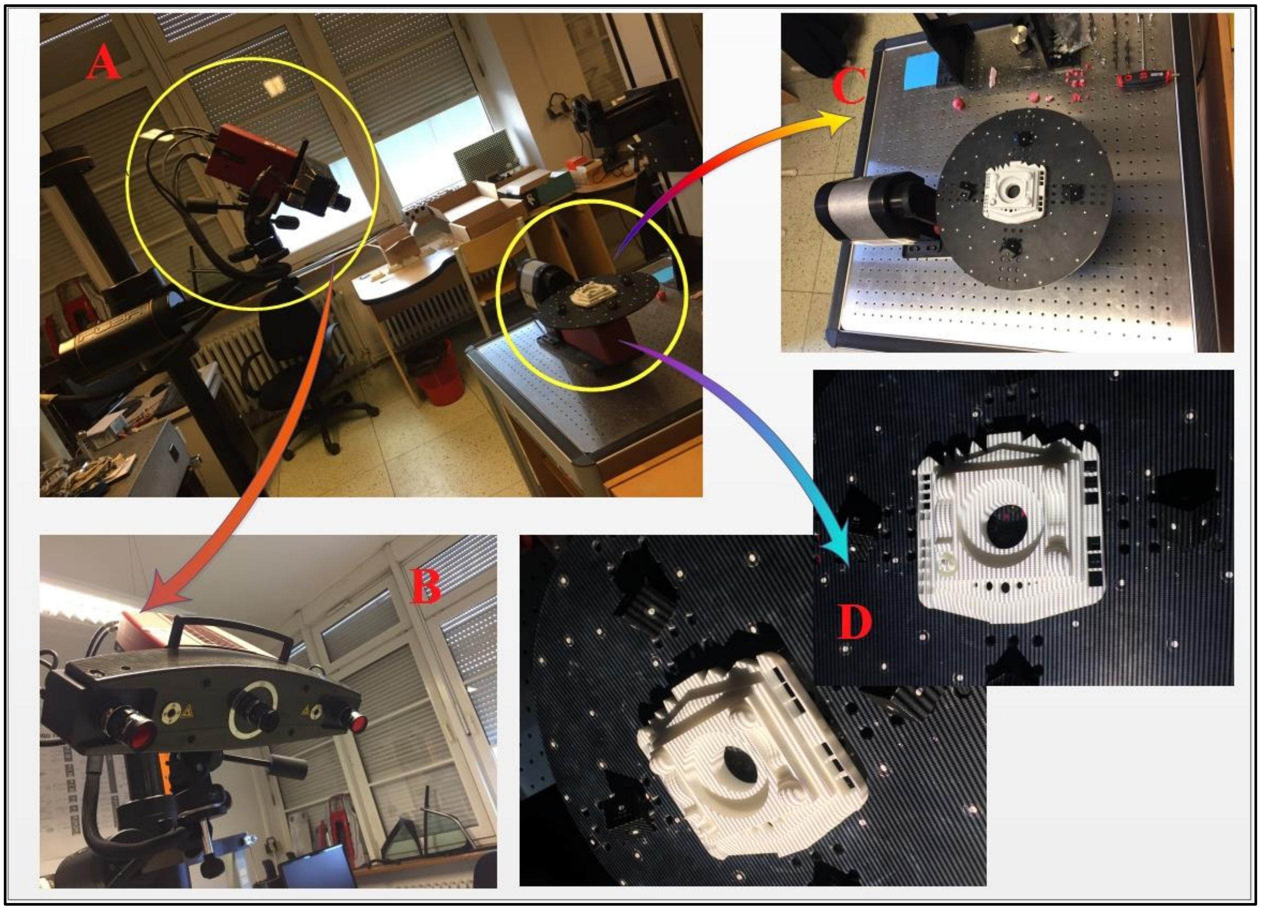


Figure 17 Preparation for measurement (Scanning) of models

In above fig.17 is showing the preparation for measurement (scanning) of models by the help of ATOS II 400 optical scanner. The following description about fig.17 is as:

- In fig.A is representing full scanning arrangement.
- In fig.B is representing about scanner. It has two cameras with projector lens. We set scanner at 45^0 angles for scanning the models.
- In fig.C is representing the rotating measuring table with marked the reference point.
- In fig.D is representing scanning or measuring the models by rotating table from all side and scanning light strip on parts.

7.2.3 Part digitization and data processing

The ATOS system is based on the triangulation principle: The sensor unit projects different fringe patterns on the object to be measured and observes them by two cameras, shown in fig.18. Based on the optical transformation equations, the computer automatically calculates the 3D coordinates for each camera pixel with high precision. [40] The scanner is connected with software of ATOS professional V7.

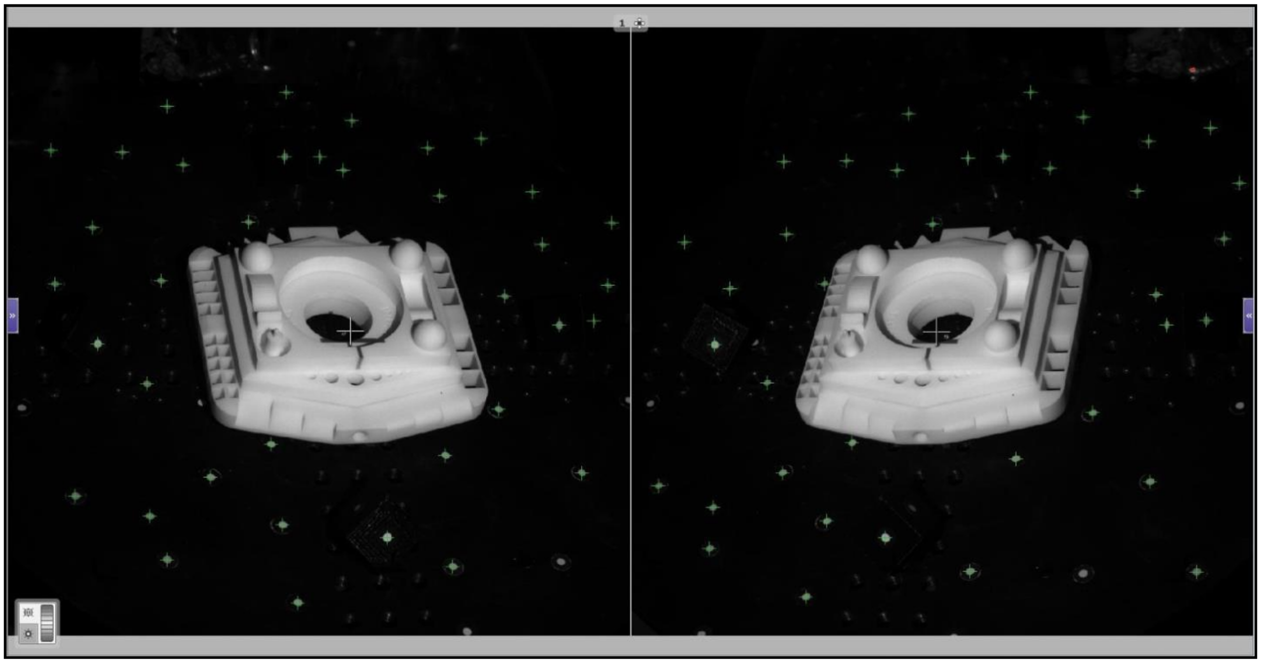
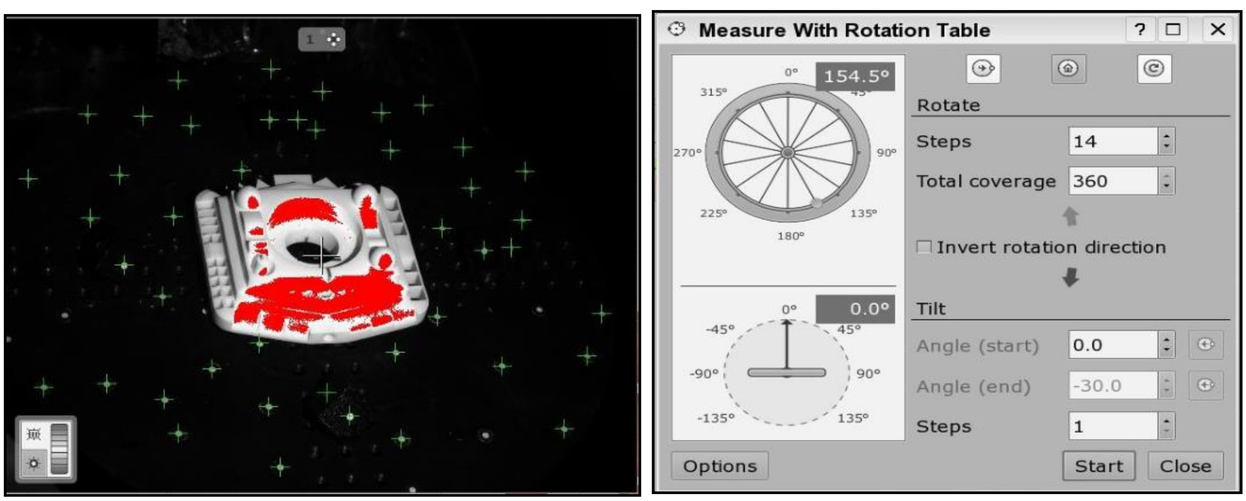


Figure 18 Both the cameras on part



(a) (b)

Figure 19 (a) For setting the exposure time of display; (b) For selecting the table rotation

In above fig.19 (a) is representing about setting an optimal exposure time for measurement. It is giving better quality of scanning. We can change by mouse rolling button. In fig.19 (b) is representing setting about the rotating table. We set the 14 no. of steps to capture images within 360^0 rotating table. In this case scanner is fixed on angular position at 45^0 and part is rotating by the rotating table. Furthermore, part is scanning step by step we set the steps and rotating table rotations shown in fig.20.

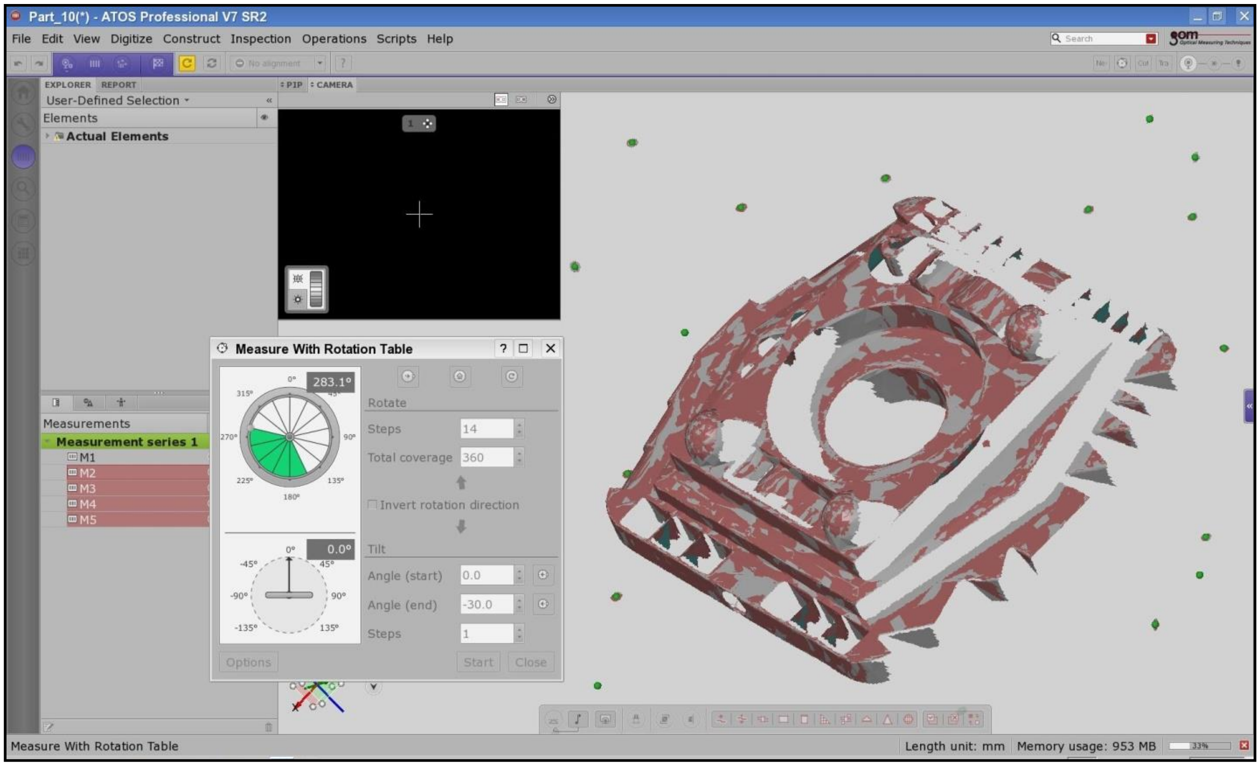


Figure 20 Procedure of measuring (scanning)

During the scanning or measuring the object, we have to set the special volume for better visibility. After scanning we can see better visualization of scanned part within volume as shown in fig.21. Depending on the camera resolution, a point cloud of up to 4 million surface points' results for each individual measurement. First of all, the partial images automatically assembled together by the help of software as shown in fig.22.Then, we have to remove unnecessary parts of scan. In case of bilateral scanning, the individual measurement series are to be transformed using common reference point to a transformation within the coordinate system as shown in fig.23.

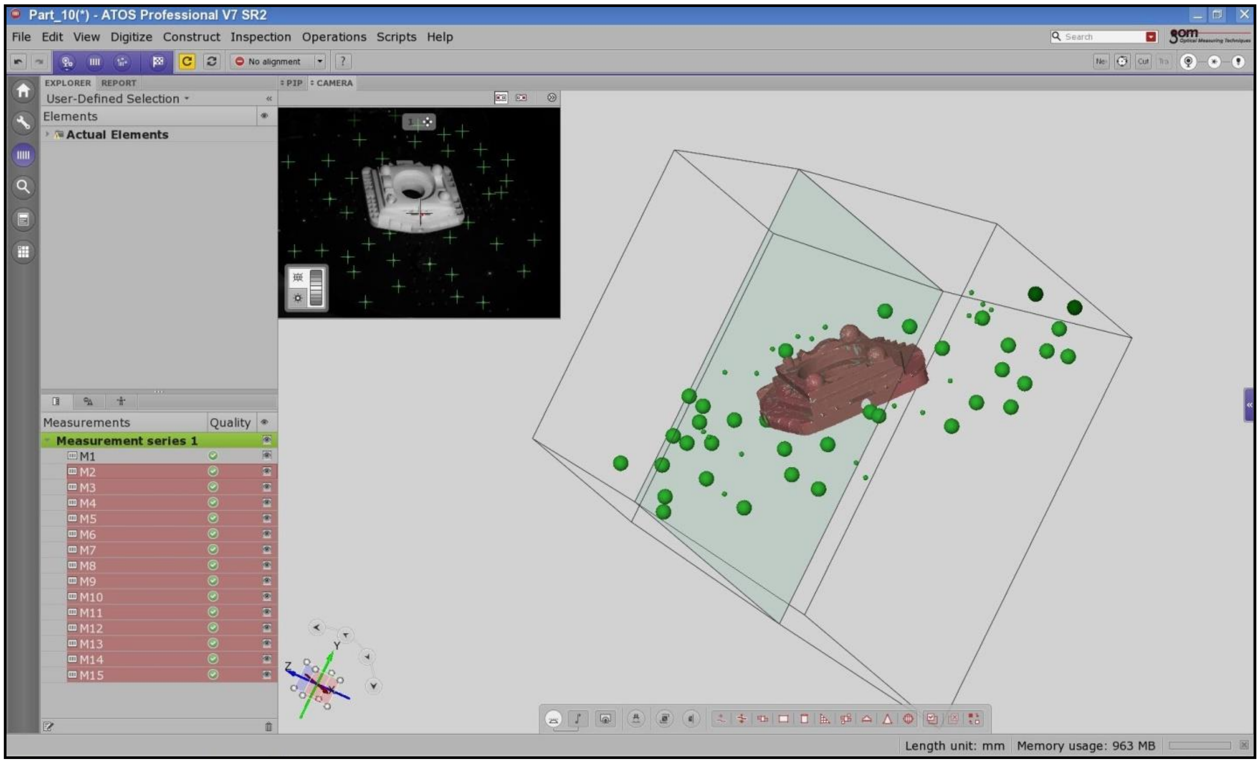


Figure 21 Visibility of part measuring in special volume

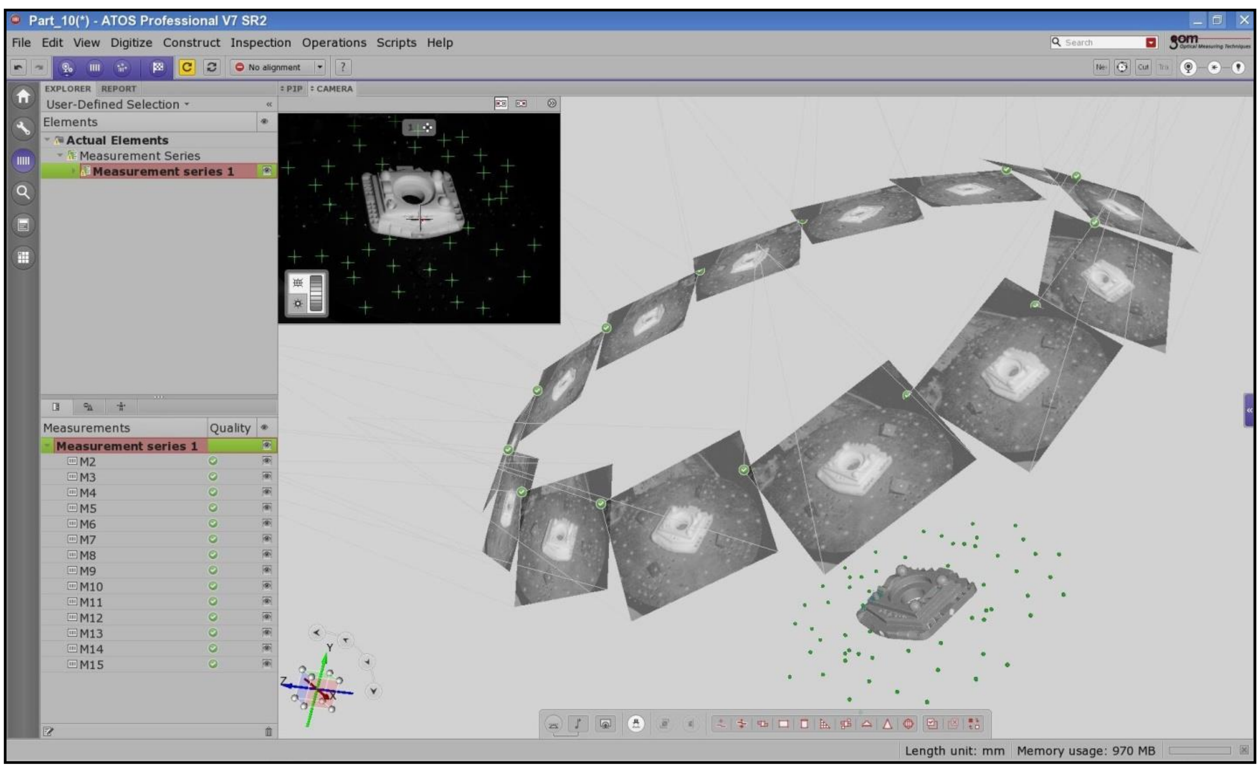


Figure 22 Rotate 3D camera on/off the entire plane in one picture

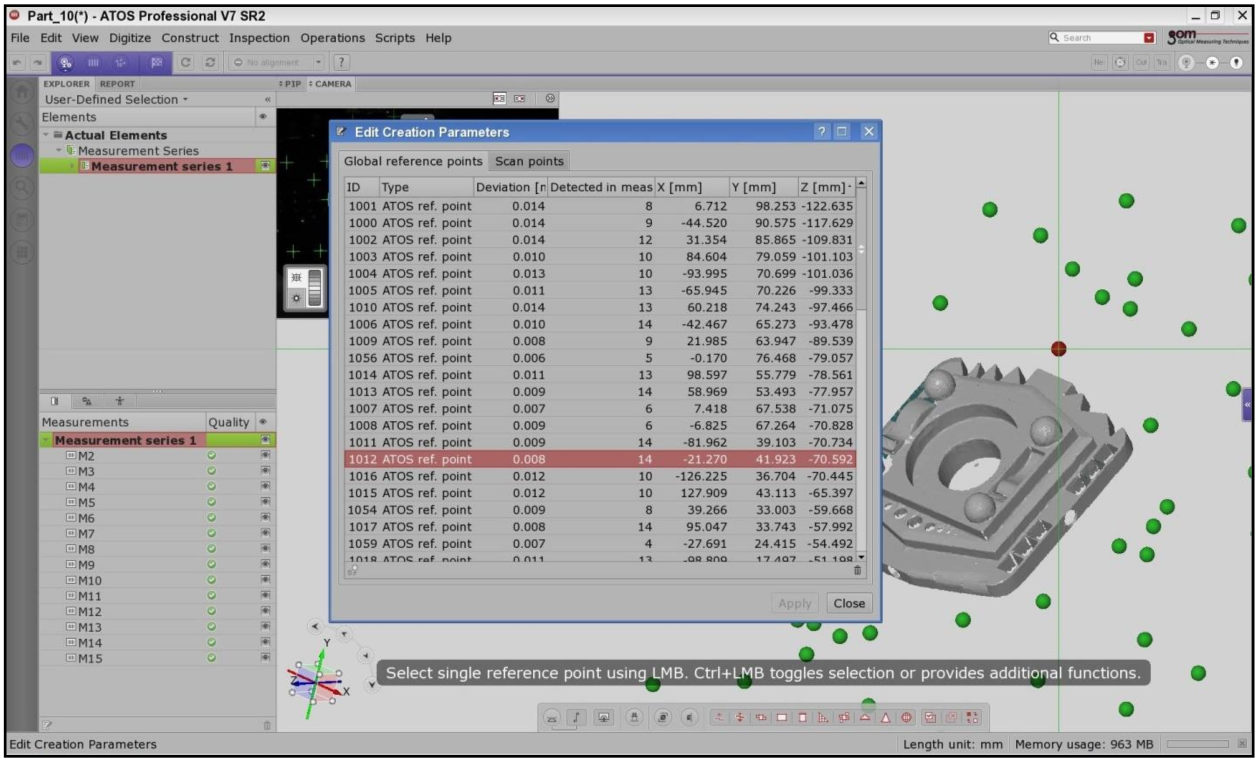
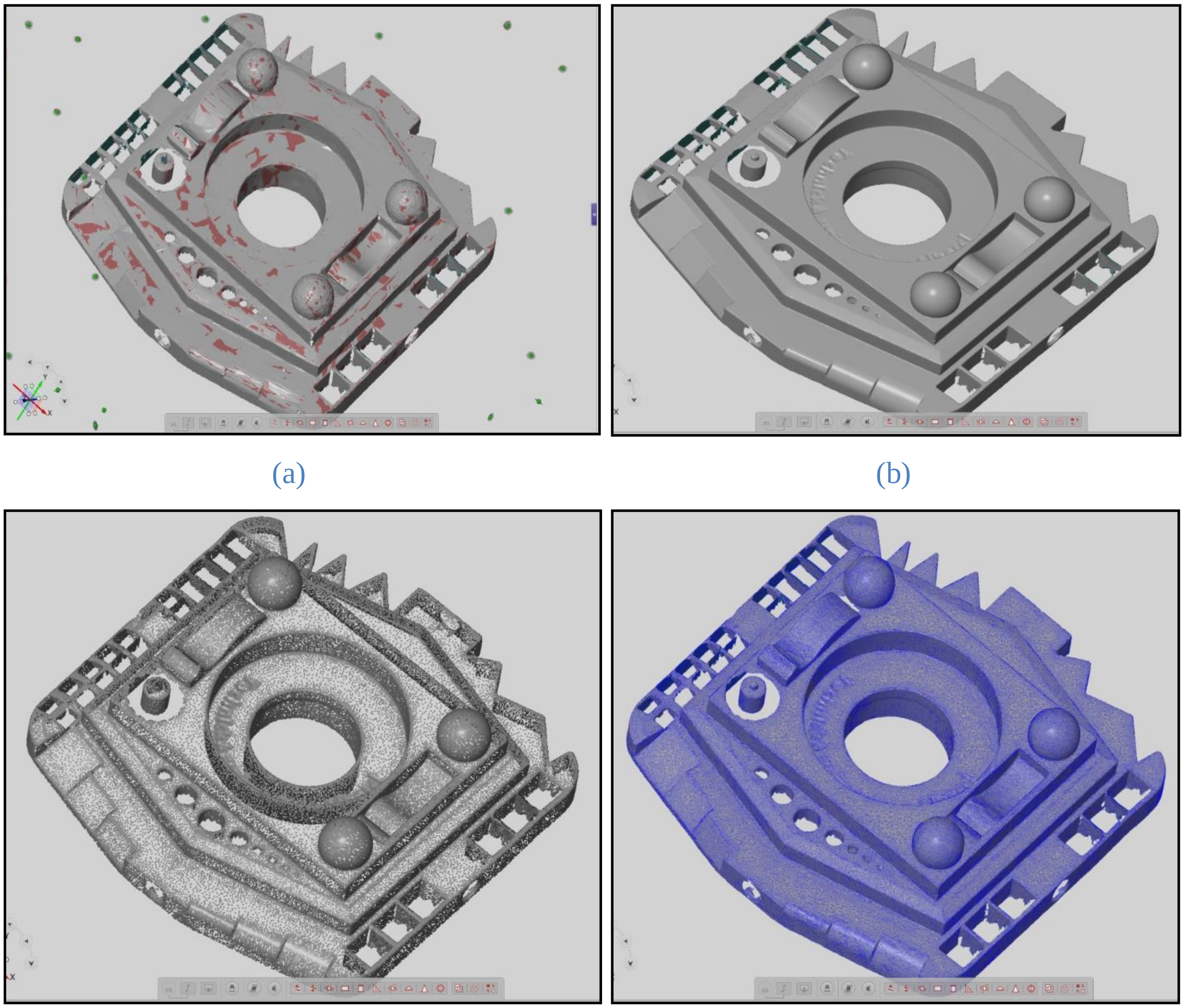


Figure 23 Accuracy of transformation from reference point

On the side of completely digitize an object; many individual measurements from various views are required. Transformation into a global coordinate system is done automatically by means of the reference points. Each individual measurement completes the building-up of the 3D model of the object to be scanned as shown in fig.24 (a). After remove the unnecessary part from scanned then we converted into .stl file. It gave better quality visualization. I can be used for following modification and quality inspection. It is called mesh structure as illustrated in fig.24 (b). In addition, point cloud structure is revealing in fig.24 (c).It is representing about the all the scan one by one point then make all plane in triangular. Finally, at the end of the digitizing process, a high-resolution polygonal mesh of the surface completely describes the object as shown in fig.24 (d).



(a) (b)

(c) (d)

(a).Visualization of part by scanning (b).Mesh structure with good quality surface

(c). Point cloud structure (d). Polygonal mesh structure

Figure 24 Scanning result with different structures.

7.3 Inspection

After the scanning models and converted file into .stl. We were measured the dimension with the help of GOM Inspect Professional V8. I already describe about software in chapter 6. Basic geometrical elements (cylinders, spheres, planes, etc.) were calculated by interlacing the fitting elements with Gauss Best-fit for 3σ. Here we measured the spheres diameter, spacing between two spheres and inner cylinders, outer cylinder with cylindricity as shown in fig.25 & 26.It is illustrating that nominal means CAD data and actual dimension means scanned data with deviation. It is scanned and measured the dimension after a year and after a year with standard test 1 and 2.

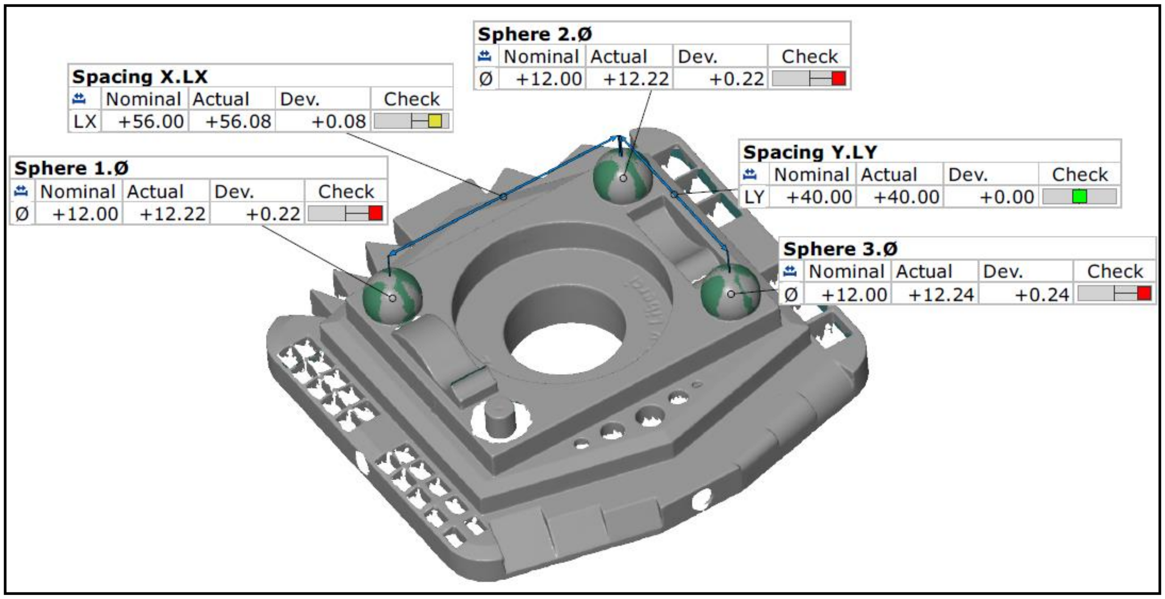


Figure 25 Inspection of spheres diameter and spacing between them.

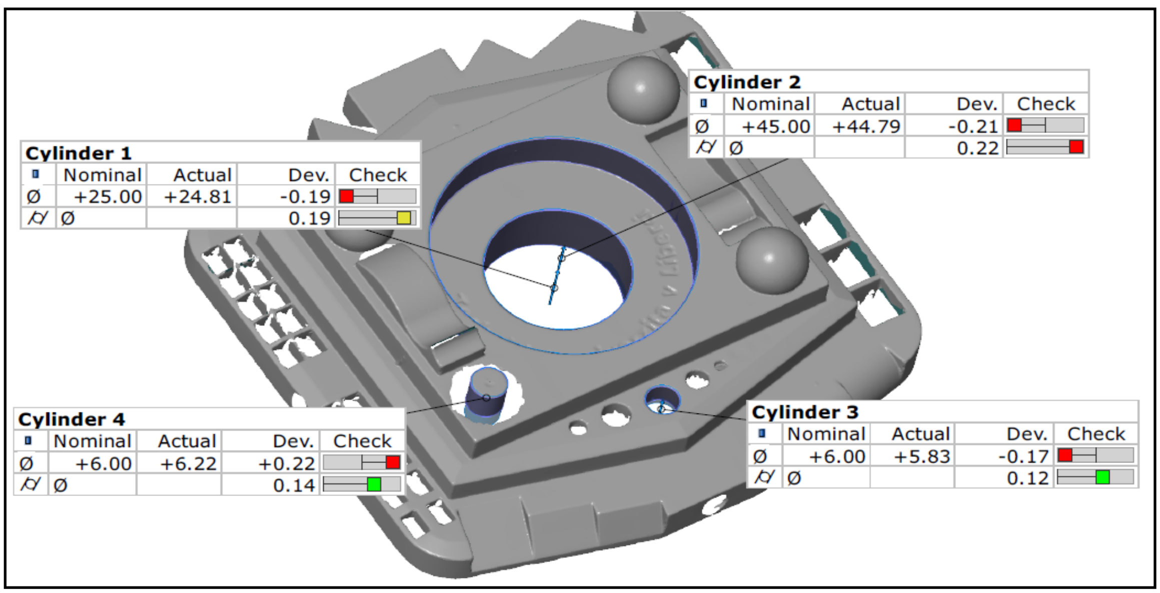


Figure 26 Inspection of inner cylinders diameter and outer cylinder diameter.

In fig.27 is representing about the surface flatness with different colors deviation labels. It measured with CAD data. In deviation “positive” values about the dimensions is increasing and “negative” values about the dimensions is decreasing.

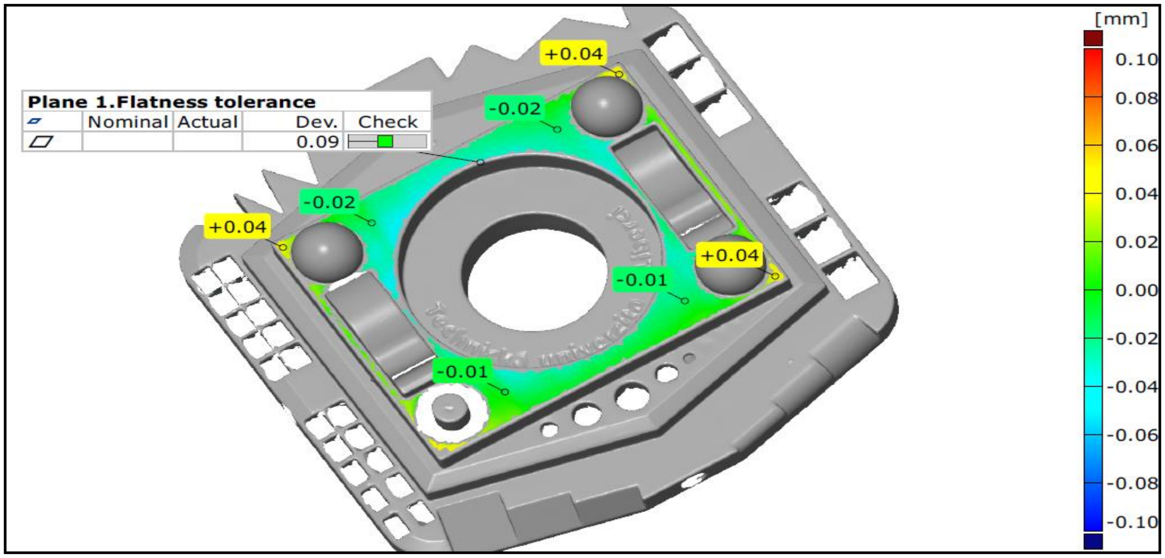


Figure 27 Inspection of surface flatness tolerance with deviations label.

In fig.28 is presenting about the horizontal and vertical dimensions. It measured with CAD data. It is showing that nominal CAD dimension and actual scanned dimension. Based on this we can analysis about the dimension stability with some period of time.

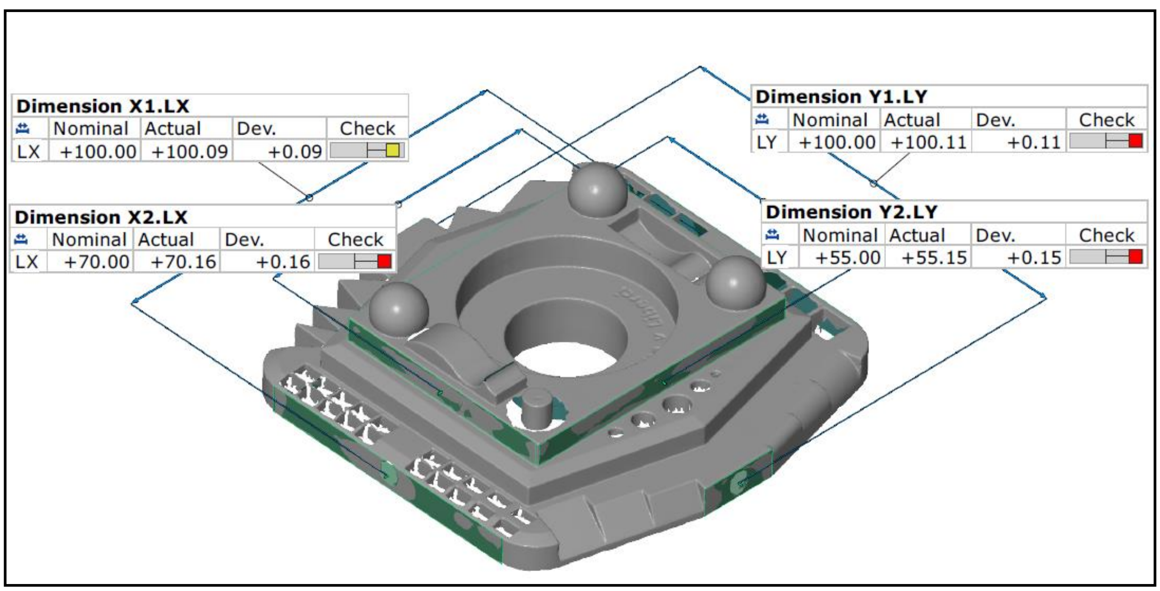


Figure 28 Inspection of horizontal and vertical dimensions

8. Analysis

First of all, we had the scanned and inspected dimensions data such as nominal CAD, first day of printing and after 3 months of printing. Then we scanned and inspected dimensions after a year and after a year with test. Based on this, an analyses divided into two groups are like that test 1 is called the humidity and temperature; test 2 is called the UV lighting. Here we measured and inspected parameters like that diameters of spheres, spacing between two spheres, diameters of cylinders and cylindricity, surface flatness tolerances and horizontal and vertical dimensions of the models. Here we used 10 types of models manufactured by different technology equally FDM, Polyjet, SLS and SLA. Furthermore, we compared the measured dimension with CAD and first day of printing. We considered deviation between them. All analysis and results are placed accompanying in Appendix and CD.

8.1 Analysis of Spheres

In fig.29 and fig.30 reveal that deviations in mm and duration of time with different technology and specifications like FDM Dimension, FDM Fortus, Polyjet, SLS and SLA. In addition, fig.29 represents based on test-1 and fig.30 represents based on test-2 sphere diameters analysis. We have sphere-1, sphere-2 and sphere-3 with diameter of 8 mm as shown in fig.13. Here we scanned and measured spheres diameters after a year and after a year with test-1 as shown in fig.29. Based on the fig.29, we compared this measured diameters with first day of printing then we can say that Polyjet-6, SLS-8 and SLA-10 up to after a year there were no changes in the spheres diameters but after a year with test-1 significantly changed up to 0.07 mm deviations. On the other side, there were no more changes up to 0.05 mm deviations in FDM Dimension-2 and FDM Fortus-3 throughout the duration of time. It means we can consider as measurement errors.

As the fig.30 shows that the after a year and after a year with test-2. Based on the fig.30, we can say that there were no changes above 0.05 mm in FDM Dimension-1, FDM Fortus-4, Polyjet-5, SLS-7 and SLA-9.

Finally, I can say that from fig.29 & 30 there were no major changes above than 0.05 mm in FDM dimension-1 & 2, FDM Fortus-3 & 4, Polyjet-5, SLS-7 and SLA-9 during the all-time.

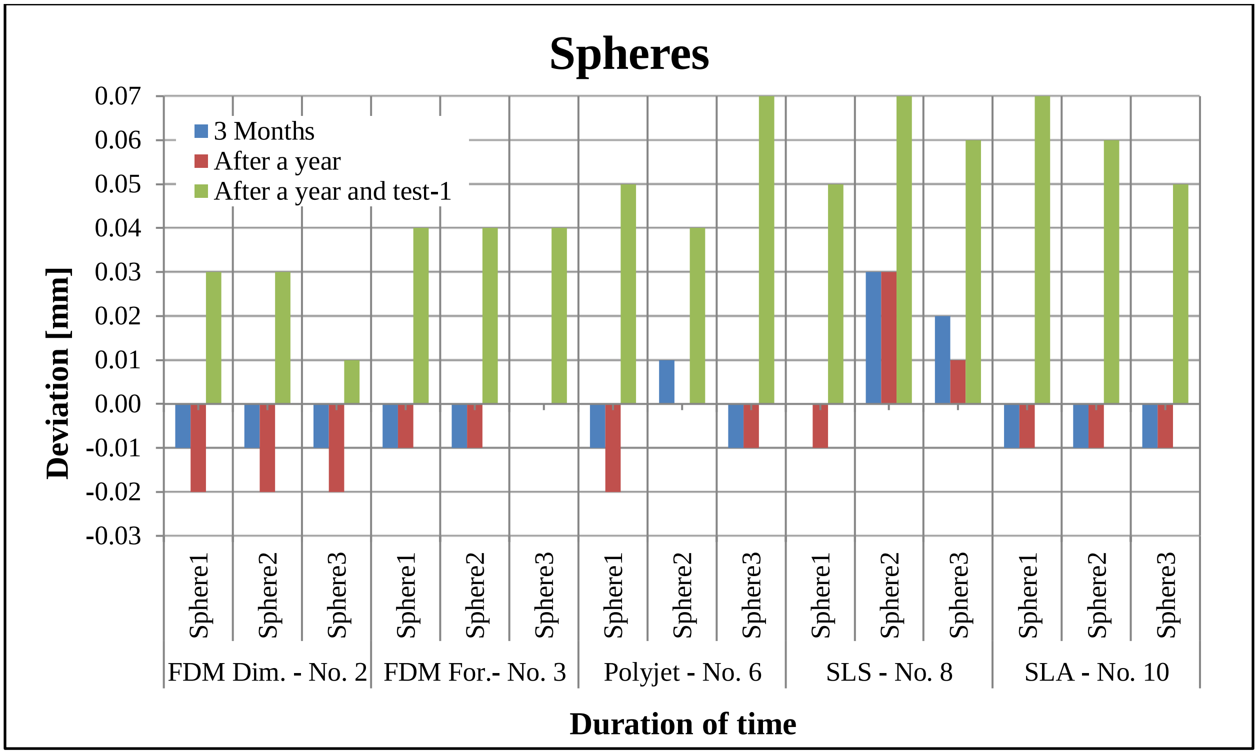


Figure 29 Deviations of diameter of the spheres with duration of time (test-1)

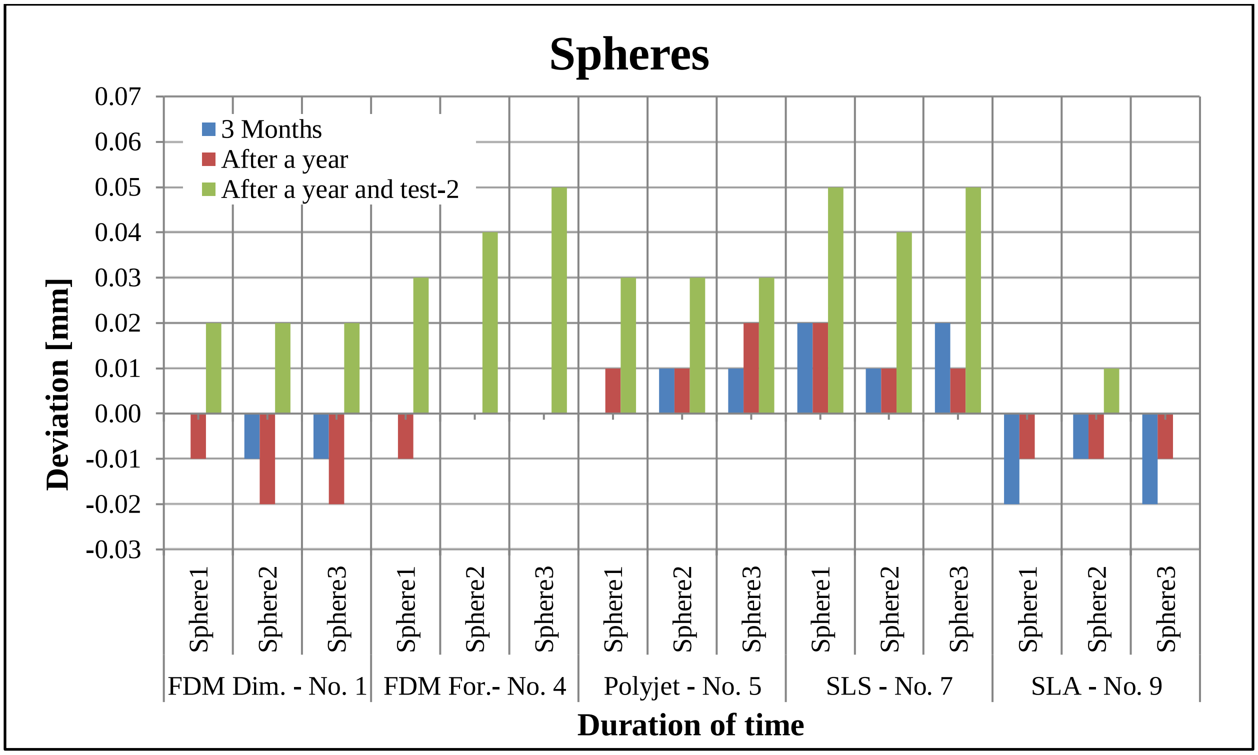


Figure 30 Deviations of diameter of the spheres with duration of time (test-2)

8.2 Analysis of Spacing between two spheres

From fig.31 and fig.32 represent about an analysis of spacing between two spheres in the deviation in mm and duration of time with different technology such as FDM Dimension and Fortus, Polyjet, SLS, SLA. In above mentioned an analysis of spheres diameter based on that we measured and analysis of spacing between them. Spacing X and Y are designated in fig.13.First of all, we have data of CAD and first day of printing scanned and measured dimensions based on that we scanned and measured again after a year and after a year with test-1 and test-2. Test-1 and test-2 are showing in fig.31 and fig.32 respectively. Then we compared the dimensions with first day of printing.

The fig.31 indicates the day by day increasing the spacing between two spheres in Polyjet-6 up to 0.15 mm and day by day decreasing the spacing between two spheres in SLA-10 up to -0.15 mm. Furthermore, as Polyjet -6 technology suddenly went up between after a year and after a year with test-1; as SLA-10 technology quickly went down in spacing Y between after a year and after a year with test-1.However, there were no more changes above 0.05 mm in other technology such as FDM Dimension-2, FDM Fortus-3 and SLS-8 from first day of printing to after a year with test-1. It could be considered as measurement errors.

The fig.32 indicates rapidly decreased in SLA-9 the spacing between two spheres within after a year and after a year with test-2 from 0.04 to -0.15 mm in spacing X and 0.01 to -0.13 mm in spacing Y. In polyjet-5 spacing X increased up to 0.06 mm deviation at after a year there were no changes during the 3 month and after a year with test-2. In FDM Fortus-4 there were remained stable during the all-time. Although there were no changing more than 0.05 mm during the all-time in technology such as FDM Dimension-1 and SLS-7.

Finally, I can say that from fig.31 & 32 there were no major changes above than 0.05 mm in FDM Dimension -1 & 2, FDM Fortus-3 & 4 and SLS-7 & 8 during all-time.

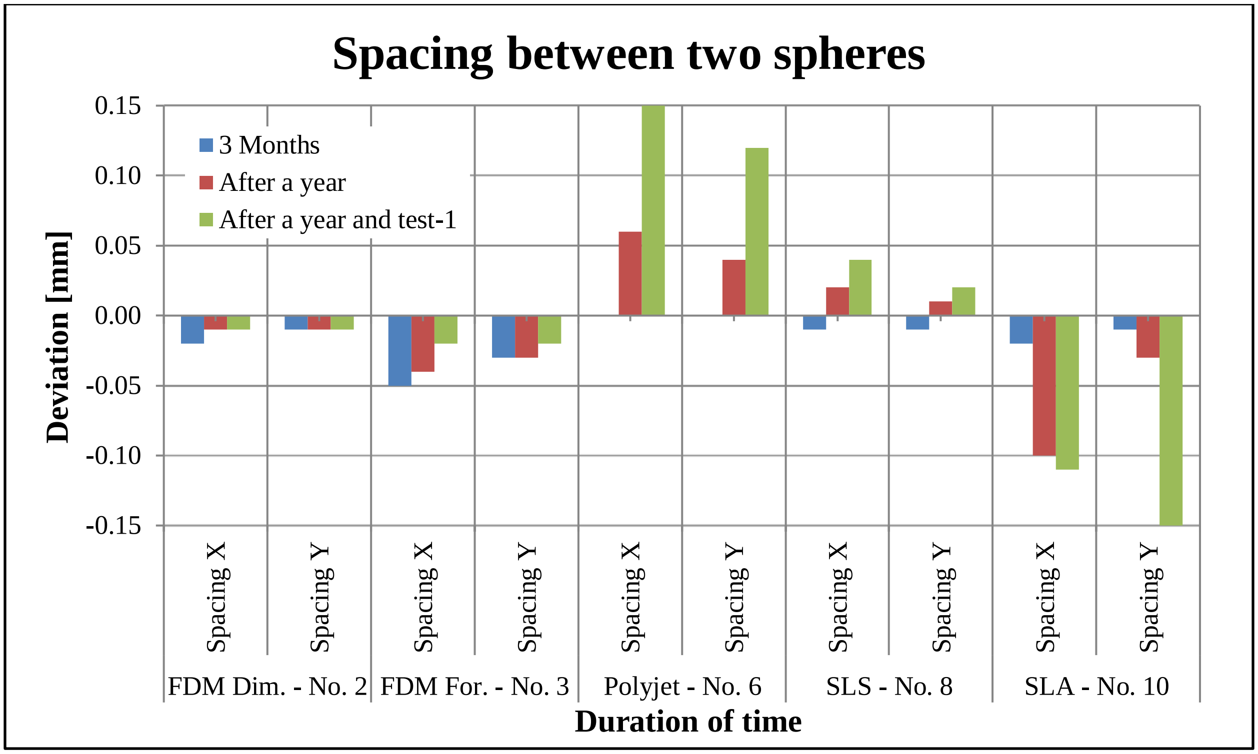


Figure 31 Deviations of spacing between two spheres with duration of time (test-1)

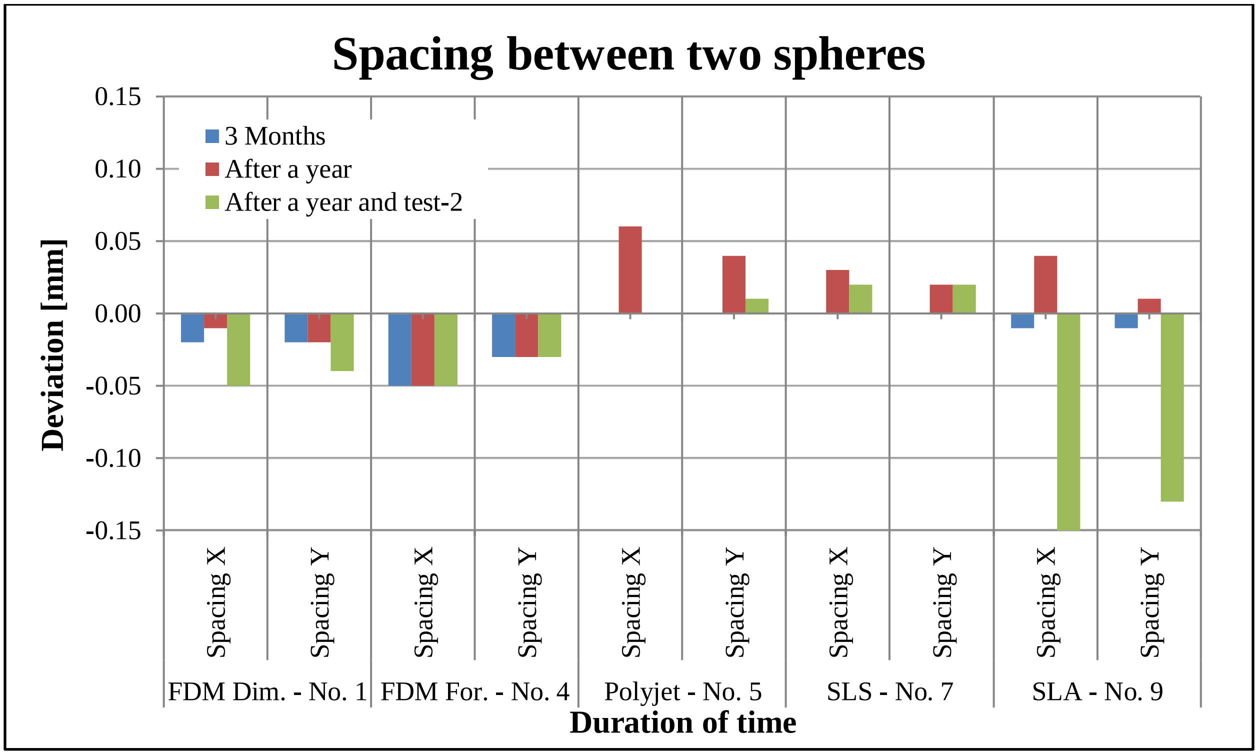


Figure 32 Deviations of spacing between two spheres with duration of time (test-2)

8.3 Analysis of inner and outer cylinders

As the fig.33 and fig.34 show about an analysis of inner cylinders diameters like inner cylinder-1, cylinder-2 and cylinder-3.These cylinders marked in fig.13. Deviations in mm with duration of time are showing in fig.33 and fig.34. In fig.33 and fig.34 illustrate an analysis of inner cylinders after a year with performed by test-1 and test-2 respectively.

The model Polyjet-6 is increasing cylinders diameter day by day but there was no any changes in cylinder-3 as shown in fig.33. Moreover, the model SLA-10 suddenly changed in cylinder-1 during the time but in cylinder-2, cylinder-3 steadily decreased deviation during the time. Also there were suddenly decreased after a year from 3 months. There were uneven decreased the cylinders diameters in FDM Dimension-2 and FDM Fortus-3 but after a year with test-1 minimum changes -0.04 and -0.03 mm deviations in cylinder-3.Additionally, During the all-time minimum changed up to ± 0.02 mm in SLS-8.

It is clear from fig.34 that SLA-9 inner cylinder diameters quickly increased between the 3 months and after a year of time but there were suddenly went down from 0.07 to -0.08 mm deviation in cylinder-1, 0.08 to -0.14 mm deviation in cylinder-2 and 0.03 to -0.05 mm deviation in cylinder-3. Furthermore, in FDM Dimension-1 cylinder-2 and FDM Fortus cylinder-1 & cylinder-2 were major decreased the diameter deviation in after a year with test-2 but remaining cylinder there were no any changes above than 0.05 mm deviation.

Finally, I can say that from fig.33 & 34 in SLS-8 and SLS-7 were no major changes during all-time.

As can be seen from fig.35 and 36 that an analysis of the outer cylinder-4 diameters. It designated in fig.13. There were no major changes above than 0.05 mm during all-time. Here we considered measurement errors up to 0.05 mm deviations. Based on these, we can say that Outer cylinder-4 diameter no any more changes above than 0.05 mm deviation in FDM Dimension-1 &2, FDM Fortus-3 & 4, polyjet-5 & 6, SLS-7 & 8 and SLA-9 & 10 during all time with test-1 and test-2.

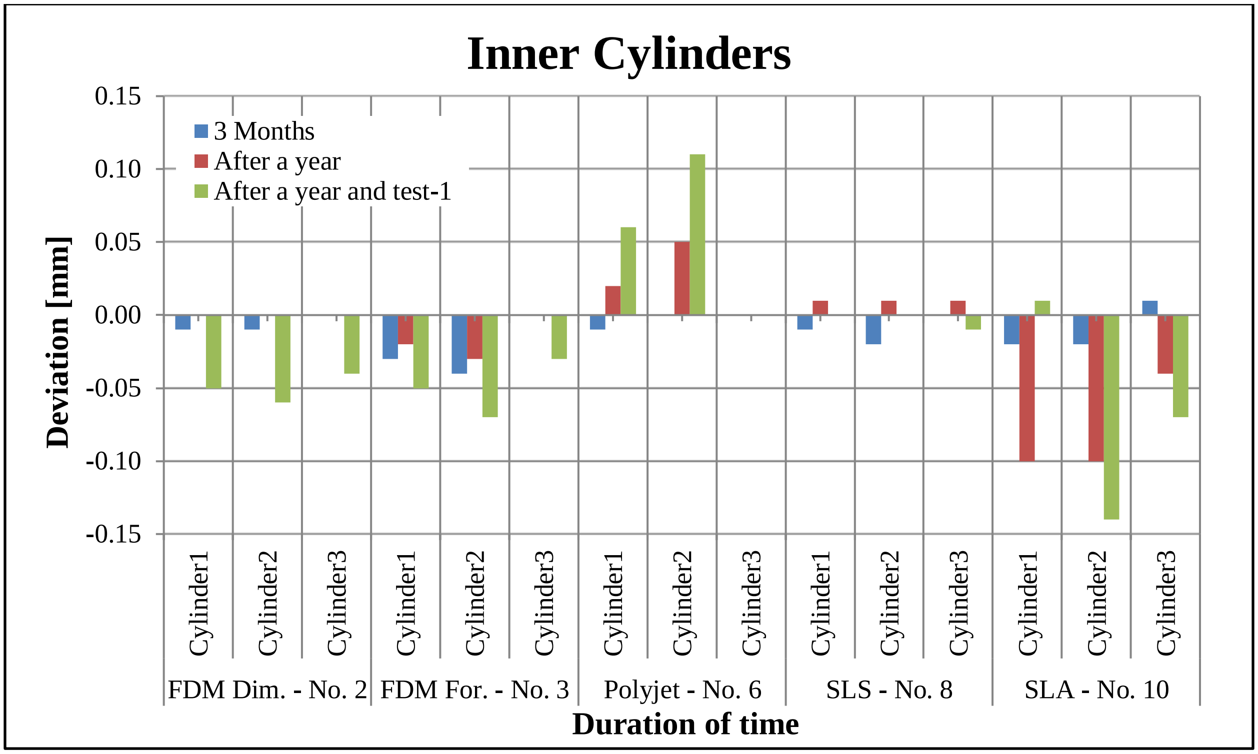


Figure 33 Deviations of diameter of the inner cylinders with duration of time (test-1)

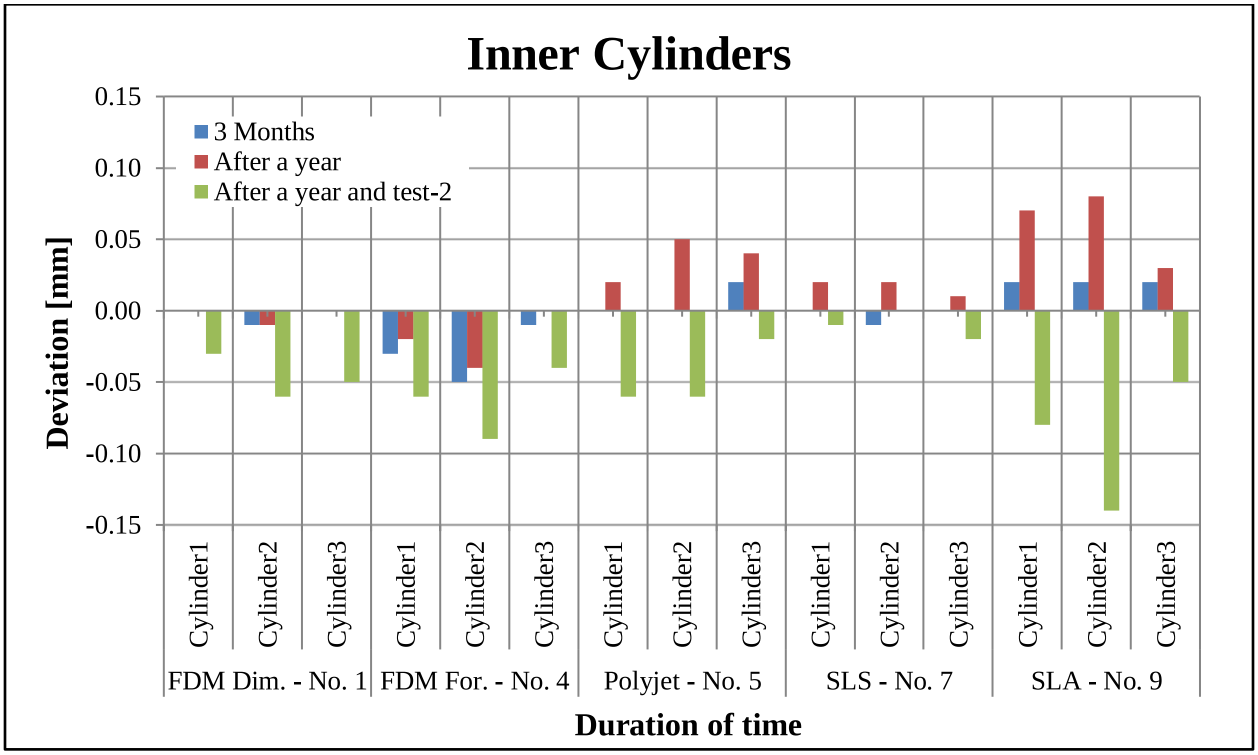


Figure 34 Deviations of diameter of the inner cylinders with duration of time (test-2)

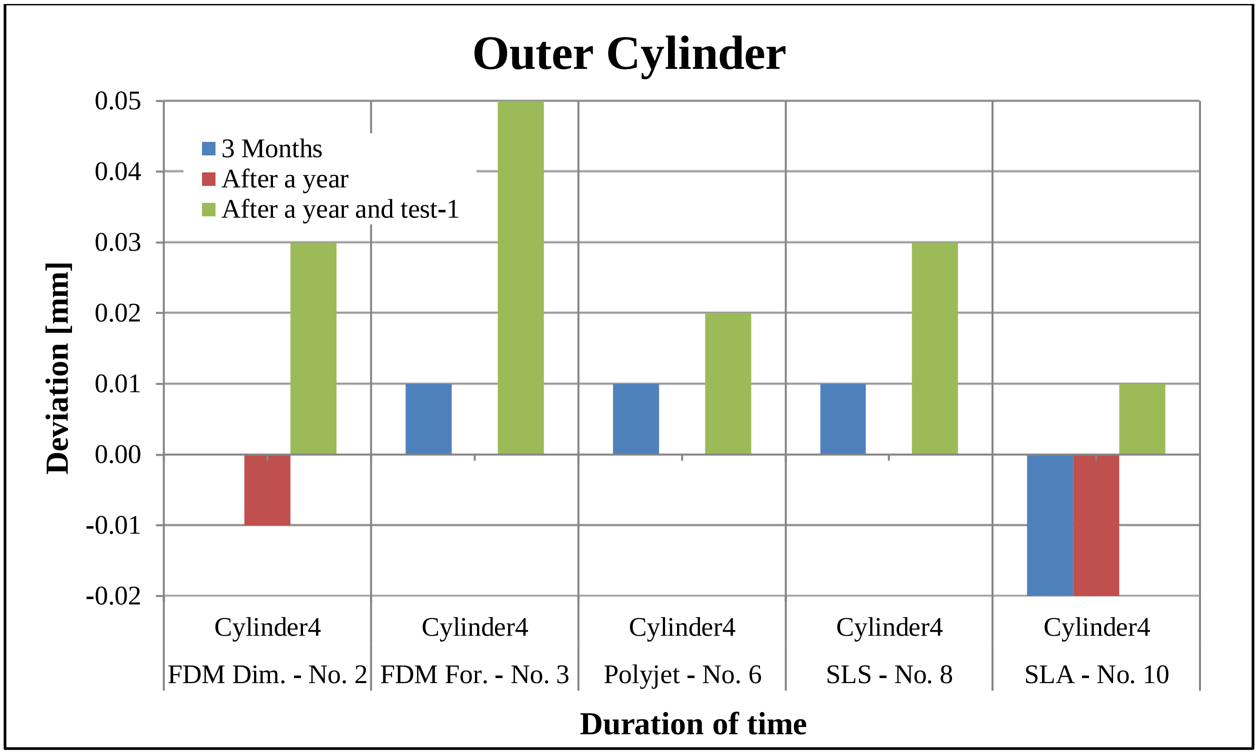


Figure 35 Deviations of diameter of the outer cylinders with duration of time (test-1)

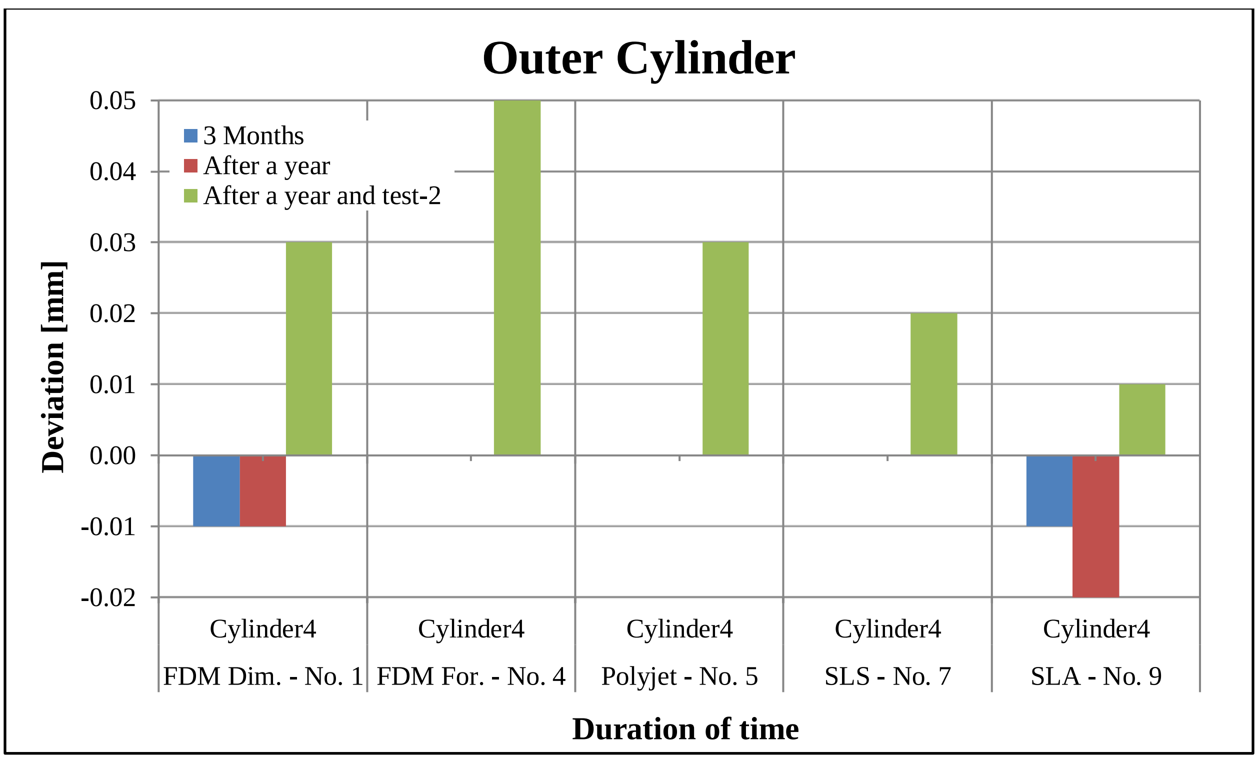


Figure 36 Deviations of diameter of the outer cylinders with duration of time (test-2)

8.4 Analysis of Flatness

From fig.37 is showing about inspected the models after a year with test-1 & 2 of surface flatness by GOM Inspect Professional software. In FDM Dimension-1 were no more changed greater than 0.05 mm deviation but in SLA-10 were more changed like +0.18 and -0.10 as shown in fig.37.

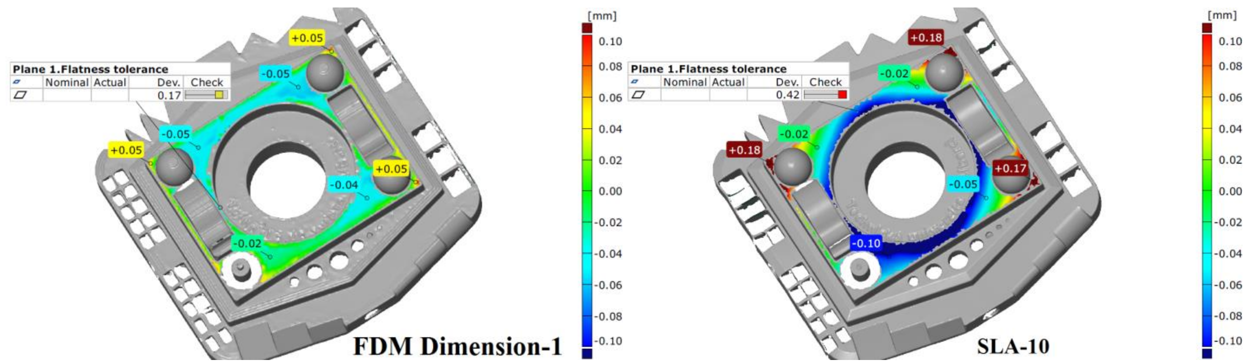


Figure 37 Inspection of surface flatness after a year with test-1 & 2

In the fig.38 and fig.39 indicate about an analysis of surface flatness of models manufactured by different technology with duration of time and performed test-1 & 2.

It is clear from fig.38 that big change of surface flatness in SLA-10 after a year with test-1.In addition, the peak deviation of surface flatness is 0.29 after a year with test-1 as shown in fig.38.In polyjet-6 there were no changed from 3 months to after a year but suddenly increased the surface flatness after a year with test-1 up to deviation of 0.06 mm. On the other side, the models FDM Dimension-2 FDM Fortus-3 and SLS-8 there were no changed more than 0.05 mm during all time as illustrated in fig.38.

In contrast fig.39 is representing about the surface flatness during 3 months, after a year and after a year with test-2. Based on this, in SLA-9 surface flatness is increasing day by day from 0.02 to 0.10 mm deviation during all-time and remaining technology such as FDM Dimension-1, FDM Fortus-4, Polyjet-5 and SLS-7 there were no changed above than 0.05 mm deviation and sometimes remained constant during all-time.

Finally, I can say that from fig.38 & 39 there were major changeable surface flatness in SLA-9 & 10 and Polyjet-6 on other side remaining all technology there were no changed more than 0.05 mm during all time.

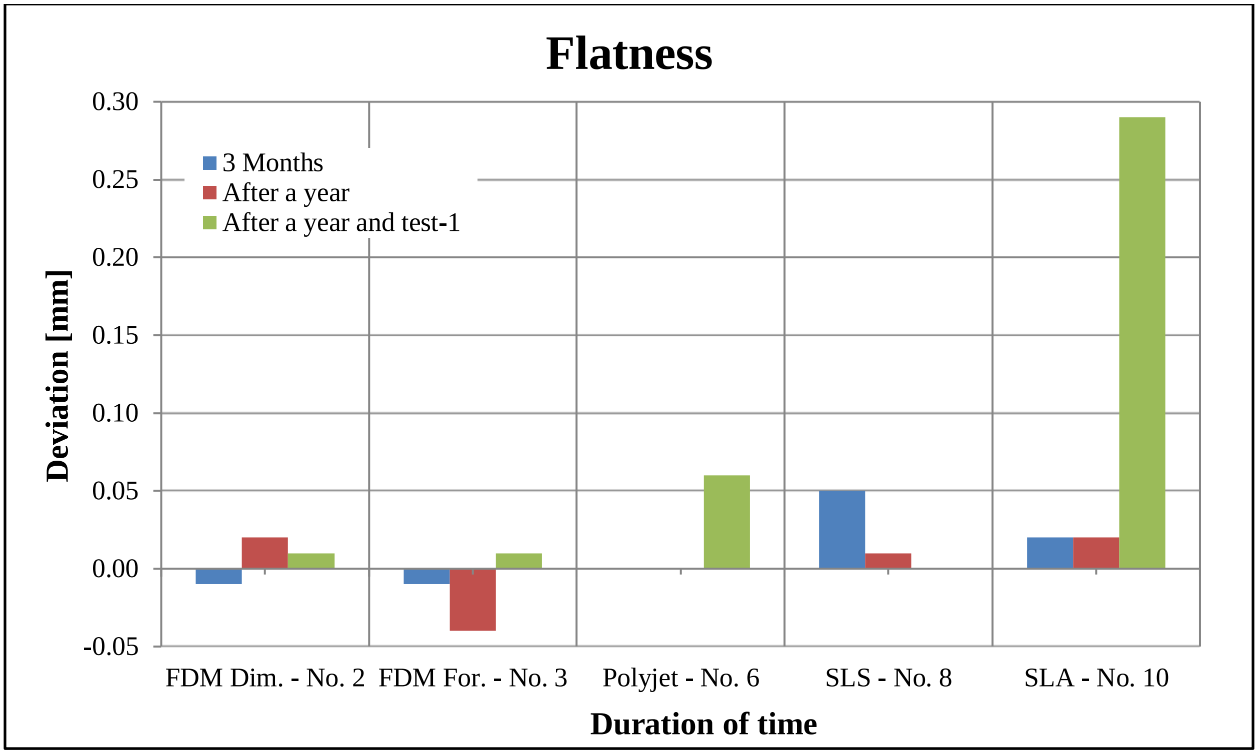


Figure 38 Deviations of Flatness with duration of time (test-1)

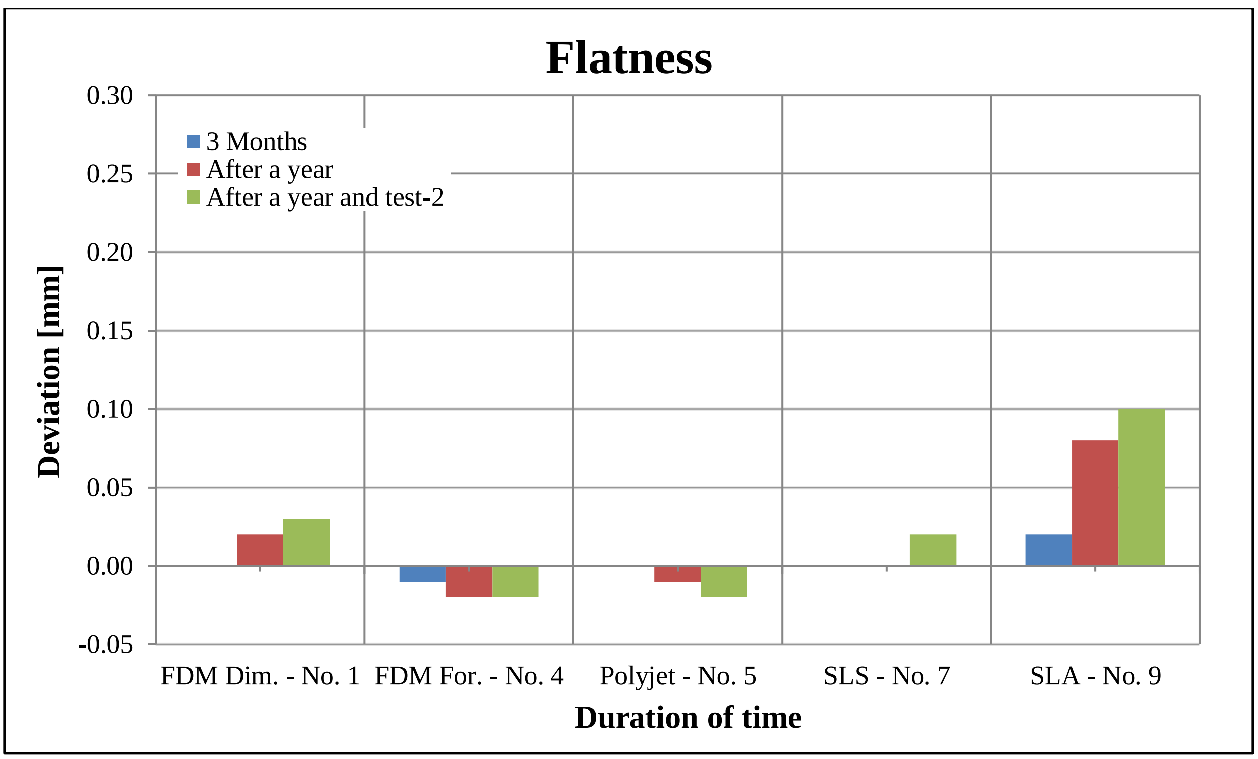


Figure 39 Deviations of Flatness with duration of time (test-2)

8.5 Analysis of Dimensions

From fig.40 & 41 are showing the deviation analysis of horizontal and vertical dimension of models manufactured by different technology with duration of time. Horizontal dimension X1 & X2 and vertical dimension Y1 & Y2 designated in fig.13.The fig.40 shows about analysis of dimensions were performed by test-1 and fig.41 were performed by test-2.

It is clearly seen that from fig.40 the major deviation was observed in Polyjet-6 during all time. It means the deviations of dimensions are increasing day by day throughout all time. It is noticeable peak value of deviation 0.24 mm in Polyjet-6 Dimension Y-1 after a year with test-1.Also in SLS-8 dimensions are increasing every day during all time. Moreover, in SLA-10 dimensions are major fluctuating during all time. The highest deviation from -0.09 to -0.23 mm decreased in SLA-10 dimension X1 between 3 months and after a year then after a year with test-1 returned to original dimension of deviation -0.02 mm. In addition, the major remarkable changes from -0.17 to 0.14 mm deviation in SLA-10 dimension Y1 then dimension X1, X2 and Y2 returned back to maximum deviation less than 0.05 mm in after a year with test-1.In FDM Fortus-3 dimensions are reducing over a time. It means there were more significant decreased deviations after 3 months of printing and increased after a year and after a year with test-1.Furtheremore, there were no major changes above than 0.05 mm in FDM dimension-2 during all time.

As is illustrated by the fig.41 in SLA-9 the major dimensions were increased up to after a year but suddenly after a year with test-2 dimensions were decreased in dimension X1 & X2 and Y1 & Y2 such as from 0.06,0.07,0.15 and 0.04 to -0.15, -0.10,-0.19 and -0.10 respectively. Furthermore, In Polyjet-5 dimensions are considerable increasing from 3 months to after a year then it comes in minor deviations dimension like less than 0.06 mm after a year with test-2.In SLS-7 dimensions are increasing day by day from 3 months to after a year with test-2. In FDM Fortus-4 were remained fairly steadily during 3 moths to after a year but after a year with test-2 the deviation comes in zero so that it means there were no dimension changed after a year with test-2. In the end FDM Dimension-1 were no more changed above than 0.05 mm and sometimes it remains constant during all-time.

Finally, I can say that from fig.40 & 41 were major changed in Polyjet-6, SLS-8, SLA-9 and SLA-10 and minor changed in FDM dimension 1 & 2 throughout all time.

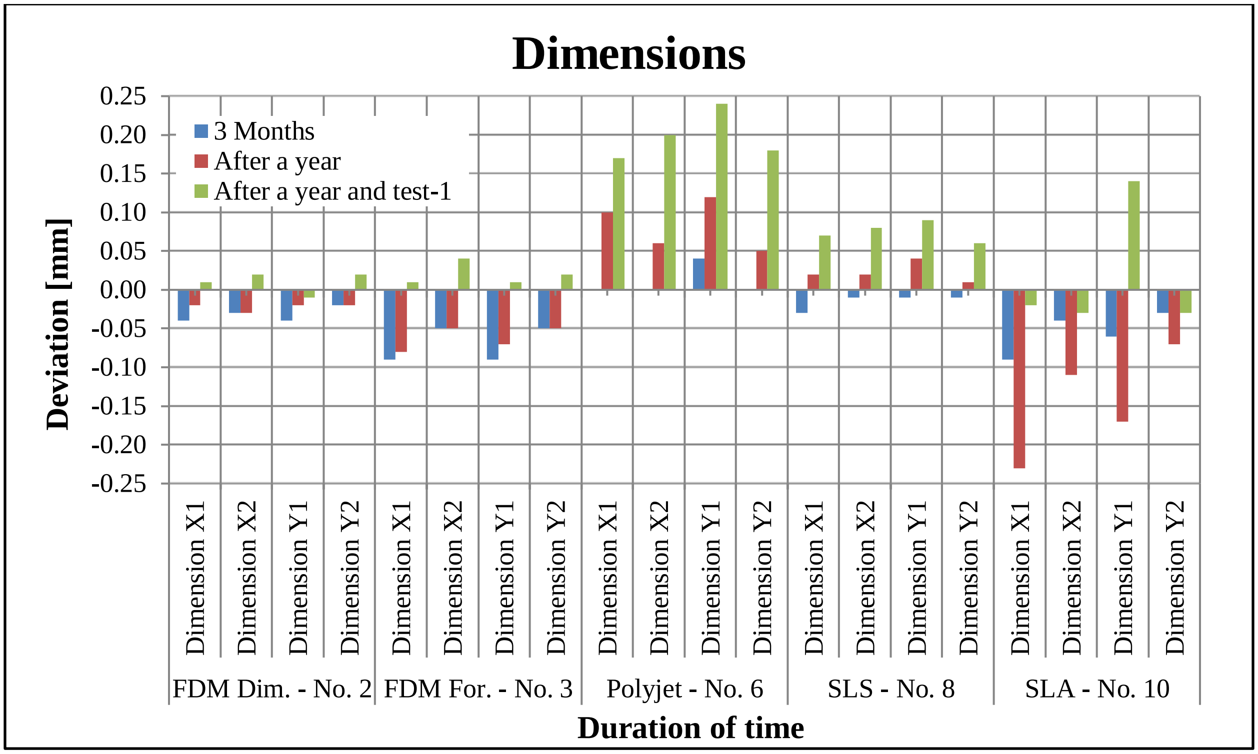


Figure 40 Deviations of dimensions with duration of time (test-1)

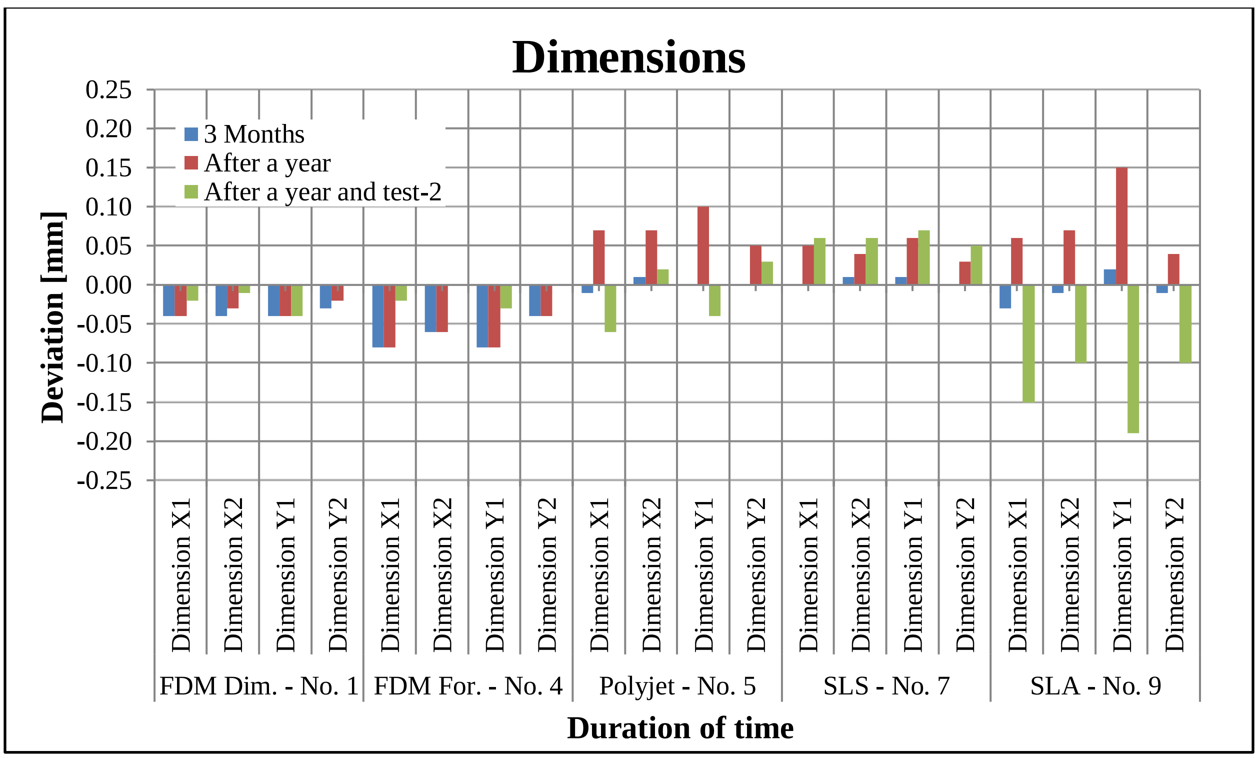


Figure 41 Deviations of dimensions with duration of time (test-2)

8.6 Analysis of Color maps

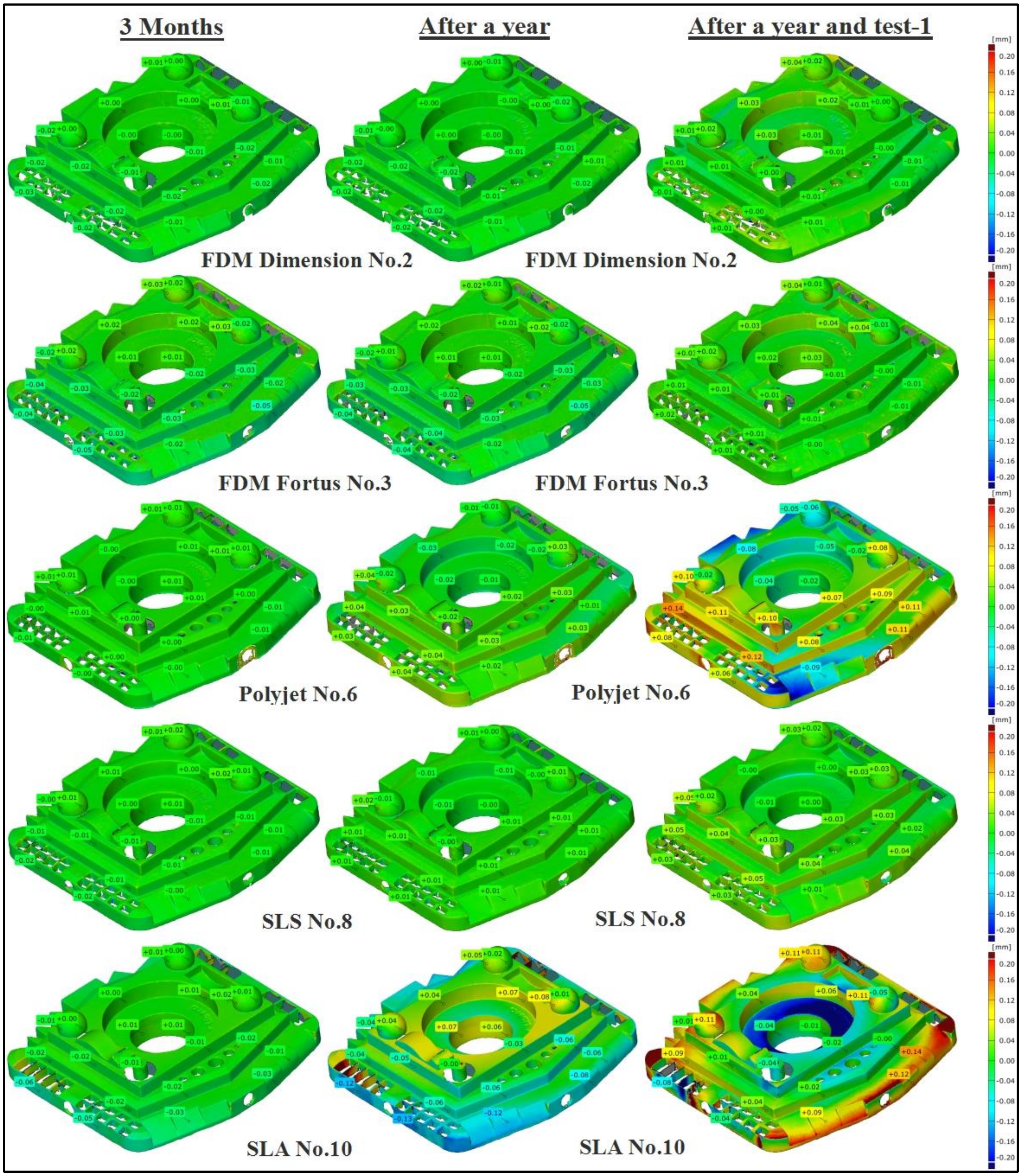


Figure 42 Color maps deviations comparison with first day of printing differentiate by test-1

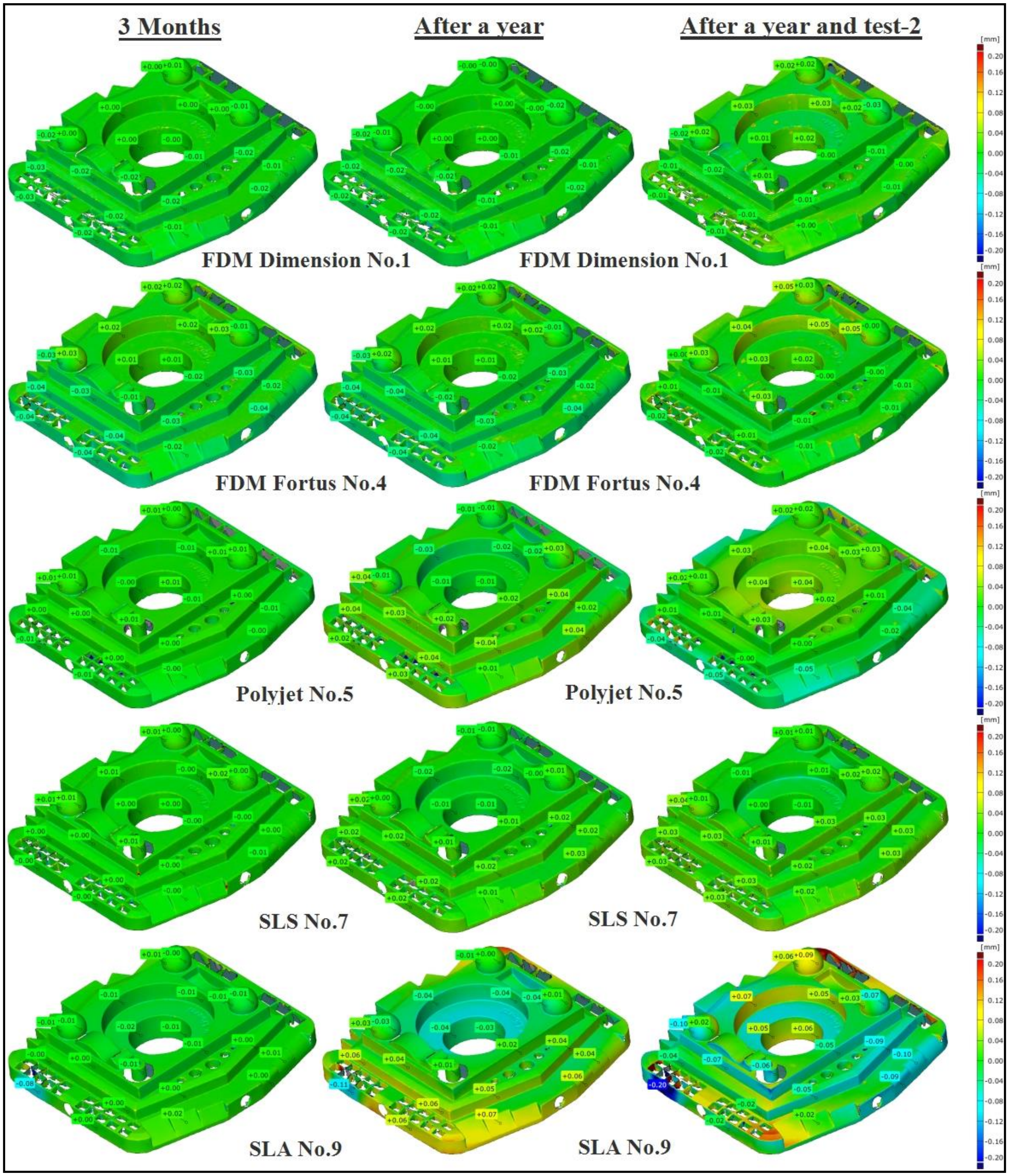


Figure 43 Color maps deviations comparison with first day of printing differentiate by test-2

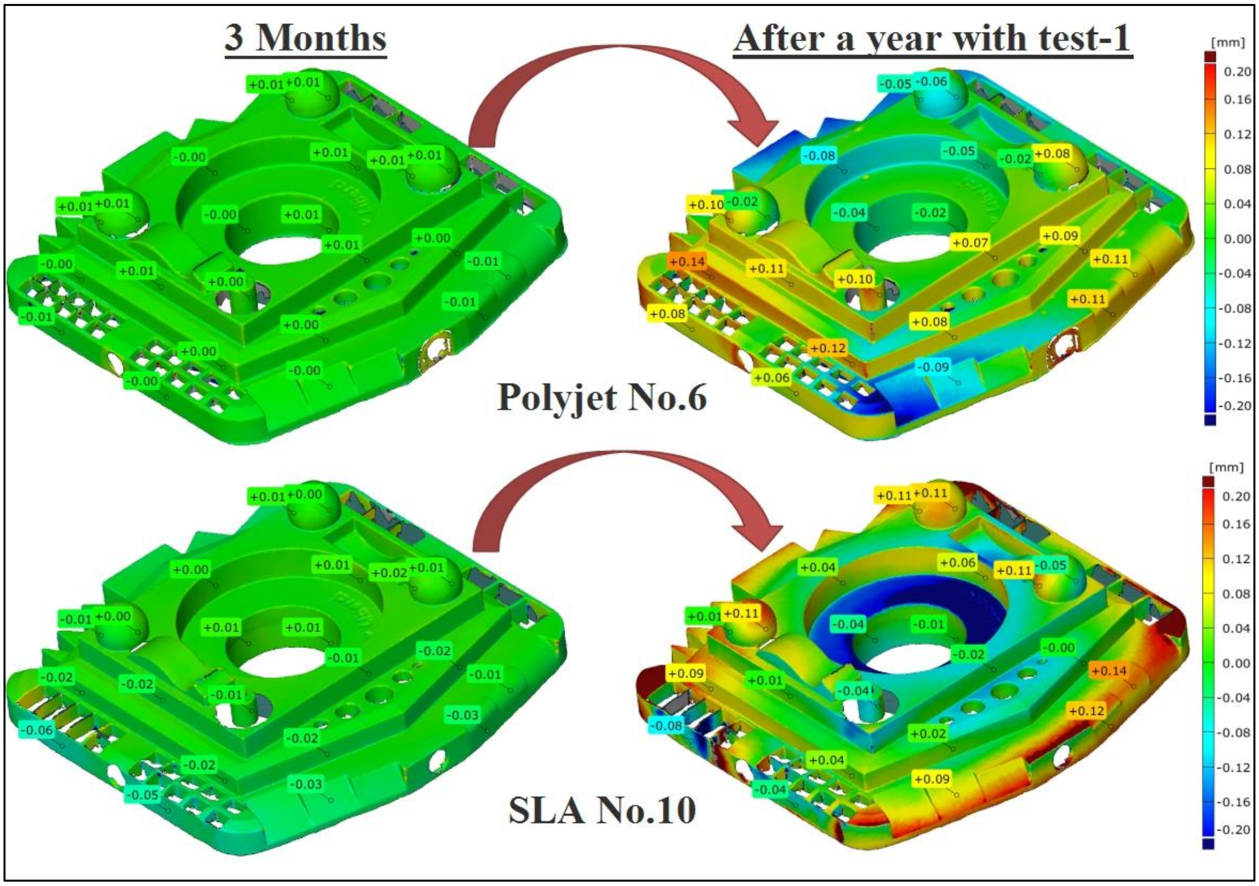


Figure 44 Comparison of color maps between 3 months and after a year with test-1 with first day of printing

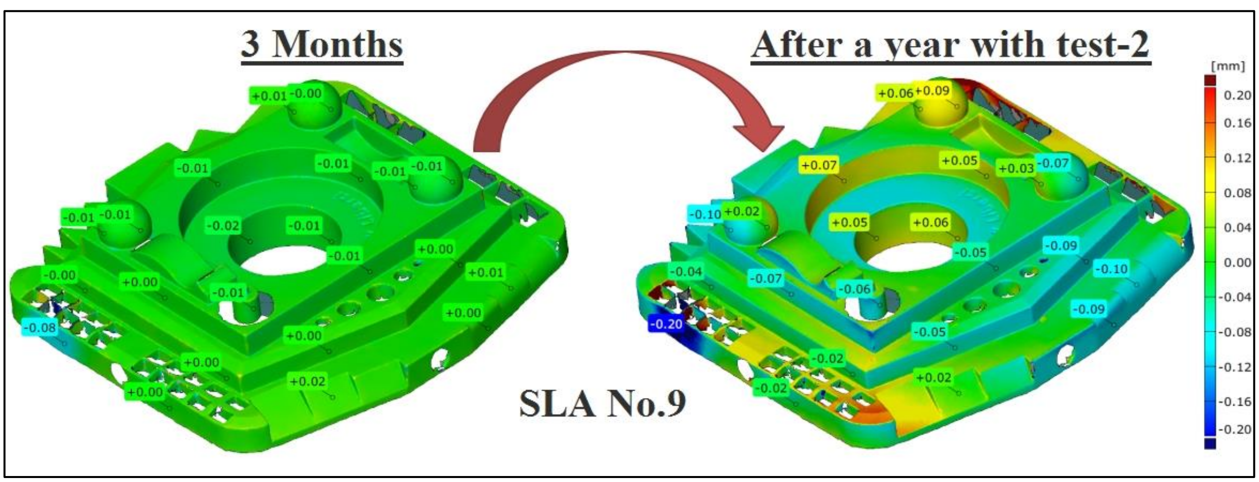


Figure 45 Comparison of color maps between 3 months and after a year with test-2 with first day of printing

From fig.42 and fig.43 represent about the color maps deviation with duration of time such as 3 months, after a year and after a year with test-1 & 2. In addition, fig.44 and fig.45 indicates about the comparison of color maps between 3 months and after a year with test-1 & 2 respectively. These color maps were comparison with first day of printing (see appendix).

It is clear from fig.42 and fig.44 that in Polyjet-6 and SLA-10 were changed the models dimension after a year with test-1 but in SLA-10 were changing the model dimension from 3 moths to after a year and after a year to after a year with test-1.In addition, there are showing the maximum deviation values -0.09 to +0.14 mm, it means models dimension are increasing on the outer surface side in Polyjet-6. In SLS-10 were illustrating the deviation values -0.13 to +0.08 mm in the period between 3 months and after a year but after a year with test-1 were suddenly changed the dimension and deviation values it shows -0.08 to +0.14 mm. It means dimensions decreased to increase on outer surface between after a year and after a year with test-1.On the other side, there were no changing of models dimension throughout the duration of time in remaining models such as FDM Dimension-2, FDM Fortus-3 and SLS-8.

As can be seen from the fig.43 and fig.45 that in SLA-9 were changed the model dimension from 3 months to after a year and after a year to after a year with test-2. Furthermore, In SLA-9 are showing the maximum deviation values from -0.11 and +0.07 mm in the period between 3 months to after a year but after a year with test-2 were rapidly changed the dimension and deviation values it shows -0.20 to +0.09 mm. It means first dimensions were decreasing in inner cylinders and increasing on outer surface over the period 3 months to after a year whereas the dimensions were increasing in inner cylinders and decreasing on outer surface in the period from after a year to after a year with test-2. Moreover, the remaining models such as FDM Dimension-1, FDM Fortus-4, Polyjet-5 and SLS-7 were no changed above than ±0.05 deviations during all-time.

Finally, I can say that from fig.42 & 43 and fig.44 & 45 were major dimension changed in Polyjet-6, SLA-9 and SLA-10 throughout the duration of time but remaining models likewise FDM Dimension-1 & 2, FDM Fortus-3 & 4, Polyjet-5 and SLS-7 & 8 there were no more changed above than ±0.05 deviation throughout the duration of time.

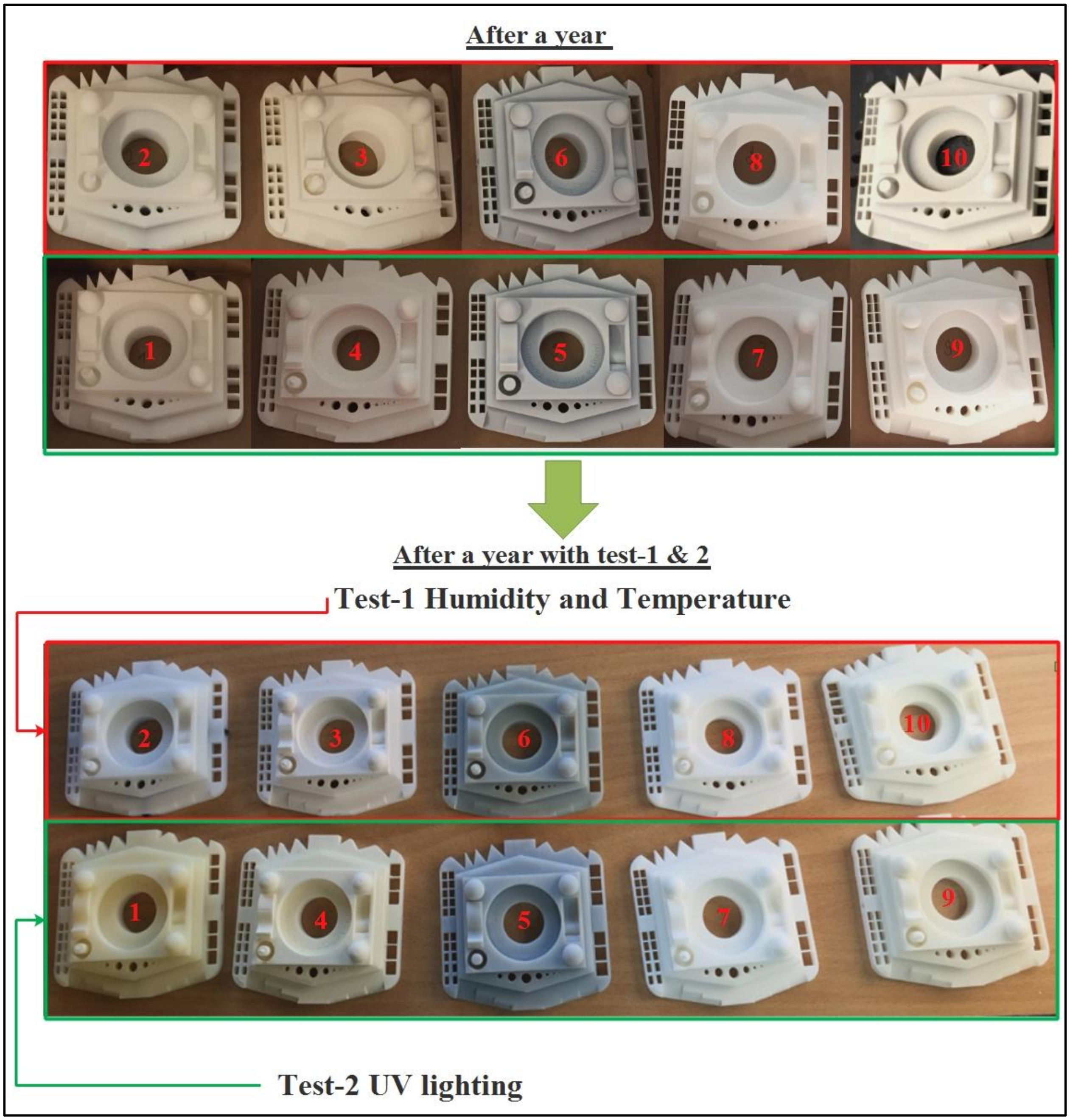


Figure 46 Visualization of surface color differences between after a year and after a year with test-1 & 2

Above fig.46 shows about the visualization of surface color difference between after a year and after a year with test-1 & 2. There were 10 models for experiment. These all models manufacture's and materials description are representing in table 8. It is clear from fig.35 after a year with test-2 were surface color changed due to UV lighting.

9. Result and discussion

In the previous chapter-8 there was discussed about the each deviations analysis of the Spheres diameter, Spacing between two spheres, Inner & outer cylinder diameters, Surface flatness and horizontal & vertical dimensions. The deviations of dimensions during the time like 3 months, after a year and after a year with test-1 & 2 compared with the first day of printing. Here we calculated the average deviations of value and divided into two groups of deviations value which one is less than 0.05 mm it considered as measurement errors and another more than 0.05 mm it considered as models errors and no good dimensional stability during the time.

From fig.47 reveals that average deviations of sphere diameters with duration of time after the manufacturing such as 3 months, after a year and after a year with test-1 & 2. It is clear from fig.47 that in Polyjet-6, SLS-8 and SLA-10 there were good dimensional stability less than 0.05 mm deviation up to after a year but suddenly used the standard test-1 there were increased the deviations above than 0.05 mm and no longer dimensional stability after a year with test-1 & 2. On the other side, the remaining models such as FDM Dimension-1 & 2, FDM Fortus-3 & 4, Polyjet-5, SLS-7 and SLA-9 there were good dimensional stability less than 0.05 mm deviations throughout all time as shown in fig.47.

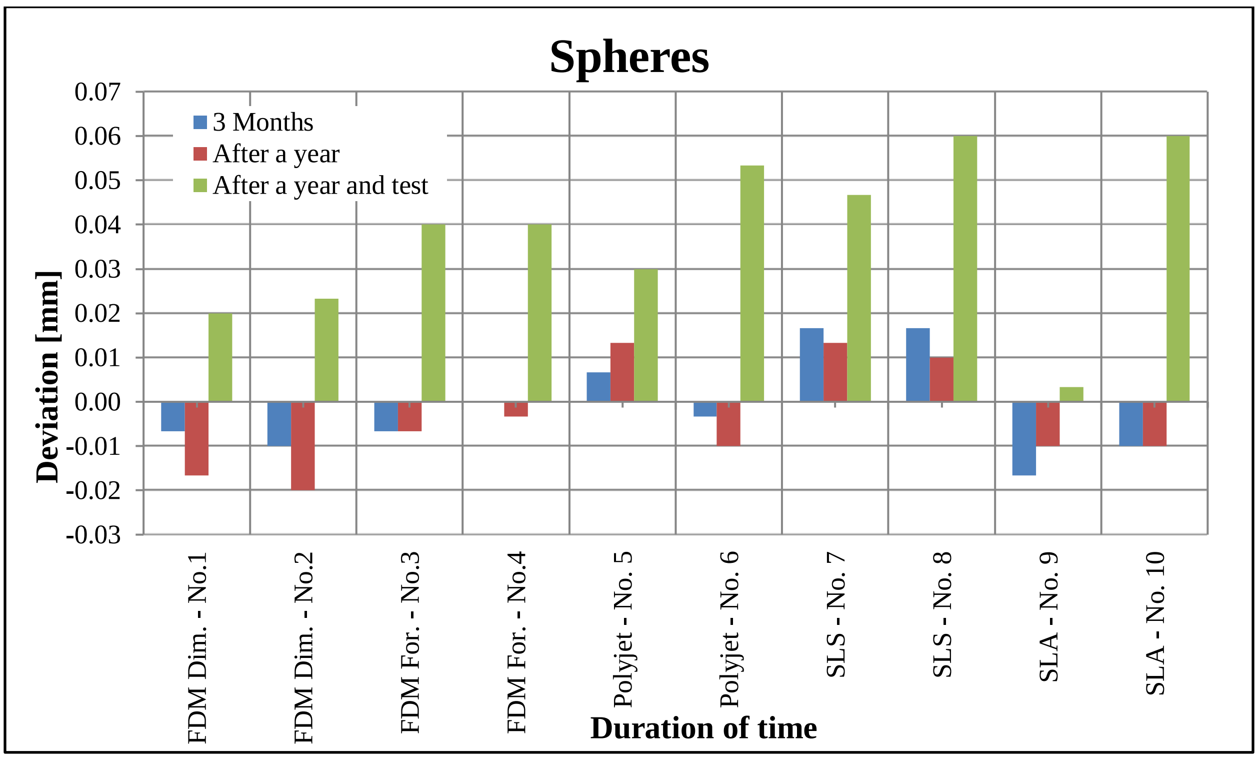


Figure 47 Average deviations of diameter of spheres with duration of time

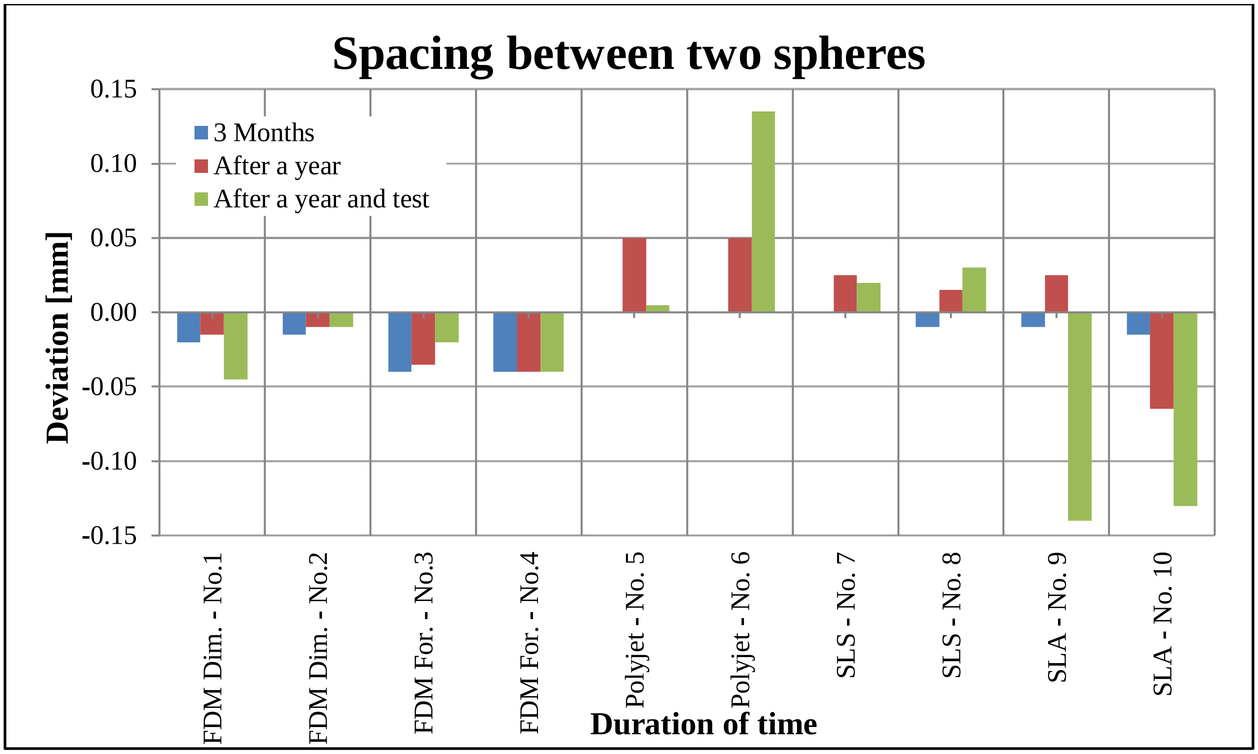


Figure 48 Average deviations of spacing between two spheres with duration of time

The above fig.48 demonstrates the average deviations of spacing between two spheres with duration of time after the 1st day of printing such as 3 months, after a year and after a year with test-1 & 2. From this figure it can be seen that in Polyjet-6, SLA-9 there were no changed the deviations above than ± 0.05 mm up to after a year it means good dimensional stability up to after a year but after used standard test-1 & 2 suddenly increased and decreased the deviation of dimensions more than ± 0.05 mm then observed there were no longer dimensional stability after a year with test-1 & 2. Additionally, in SLA-10 there was good dimensional stability up to 3 months but after a year and after a year with test-1 there were decreased the deviations of dimensions so that there were no good dimensional stability throughout the time. On the other hand, the remaining models as FDM Dimension-1 & 2, FDM Fortus-3 &4, Polyjet-5 and SLS-7 & 8 were good dimensional stability because there were no changed above than ± 0.05 mm throughout the time.

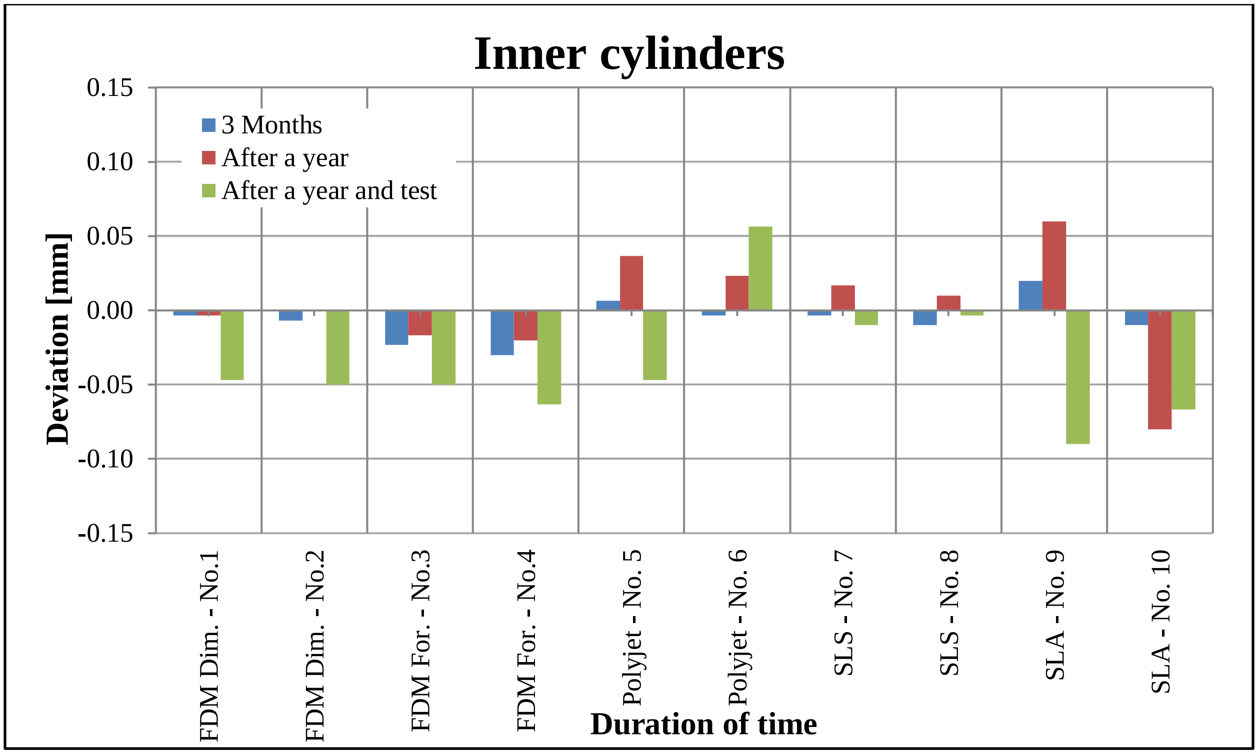


Figure 49 Average deviations of diameter of inner cylinders with duration of time

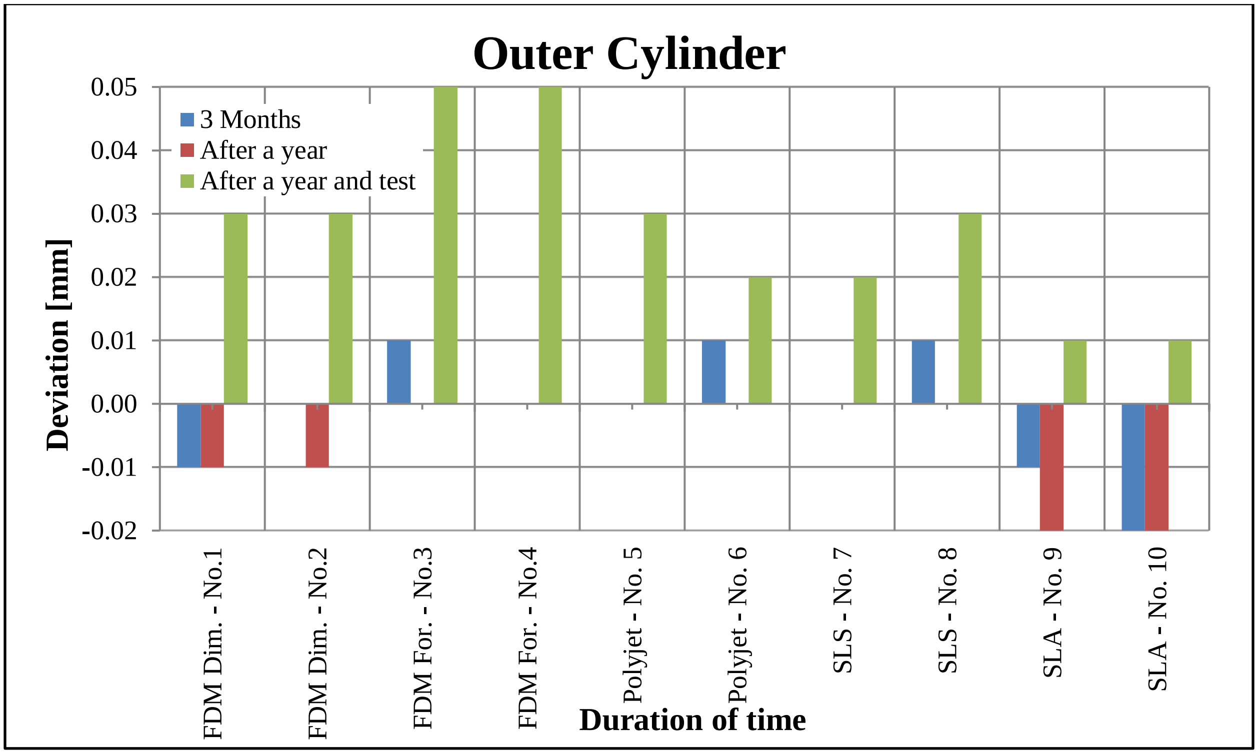


Figure 50 Average deviations of diameter of outer cylinder with duration of time

The above fig.49 and fig.50 depict the average deviations of inner and outer cylinders with duration of time.

From fig.49 shows that in FDM Fortus-4, Polyjey-6 and SLA-9 & 10 were changed the deviation more than ± 0.05 mm so that it considered as no longer dimensional stability throughout the time. Sometimes there were no changed above than ± 0.05 mm up to after a year but after the performed standard test-1 & 2 there were observed that no good dimensional stability in the models. Apart from this the models like as FDM Dimension-1 & 2, FDM Fortus-3, Polyjet-5 and SLS-7 &8 were no changed more than ± 0.05 mm deviations during all-time.

In fig.50 indicates that in outer cylinder there were minor changed or sometimes no any deviations up to after a year but then used the standard test-1 & 2 quickly changed the outer diameter of cylinder increase or decrease. It is clear from fig.50 there were no more changed above than ± 0.05 mm deviations during all-time it means good dimensional stability throughout time in all models.

Fig.51 presents about the average deviation of cylindricity with duration of time such as 3 months, after a year and after a year with test-1 & 2 compared with the 1st day of printing. From this figure it can be seen that in all models were minor changed less than ± 0.02 mm deviations and sometimes remain constant during all time.

The below fig.52 illustrates that the average deviation of surface flatness during the time as 3 months, after a year and after a year with test-1 & 2.It is clearly defined from the fig.52 in SLA-10 were constant value 0.02 mm deviation up to after a year but suddenly performed the standard test-1 then observed the deviations, it is noticeable peak value 0.29 mm deviation. Based on this, there was no good dimensional stability throughout the time. Furthermore, in SLA-9 was increasing the deviation day by day up to 0.10 mm during the time like 3 months, after a year and after a year with test-2.In polyjet-6 was no any deviation between 3 months and after a year but after the performed standard test-1 was increased the deviation up to 0.06 mm there could be said that no good surface flatness stability during all time. On other the side, the remaining all models there were no changed above than ± 0.05 mm deviation so that there were good dimensional stability during the time like 3 months, after a year and after a year with test-1 & 2.

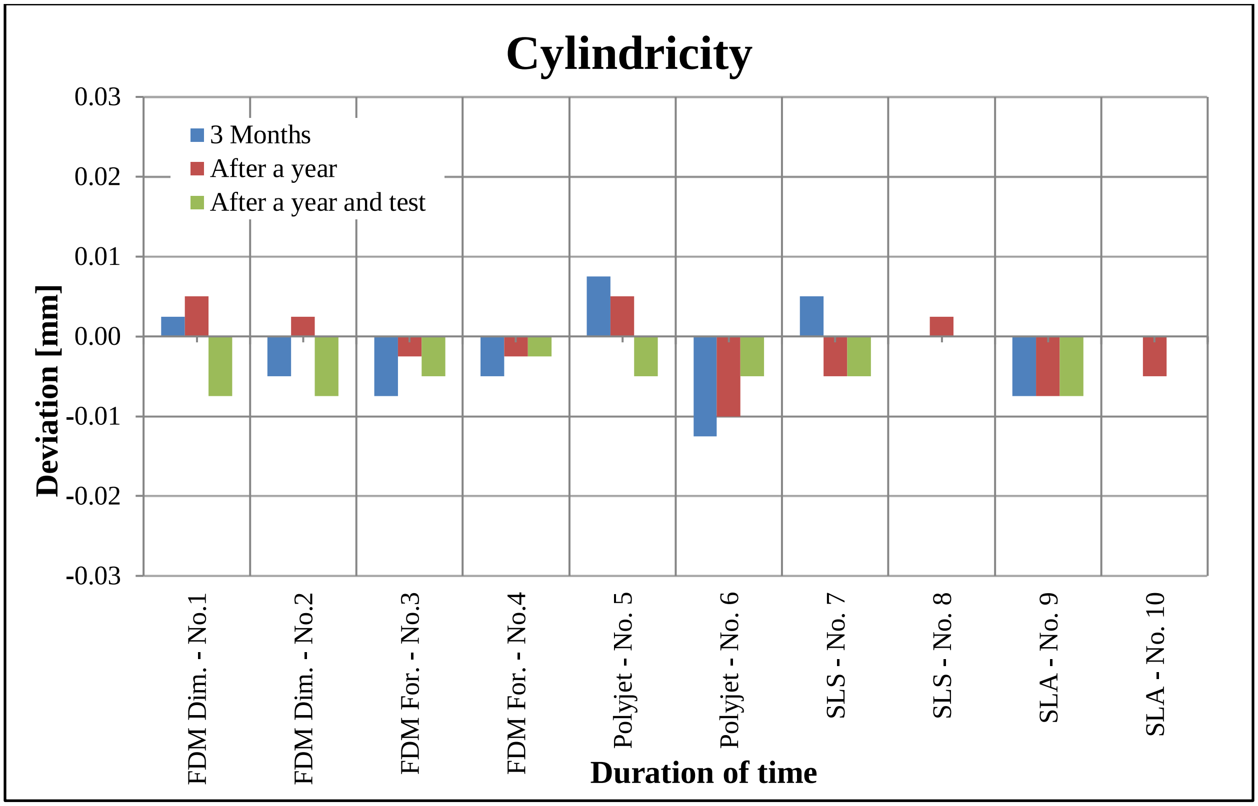


Figure 51 Average deviations of cylindricity with duration of time

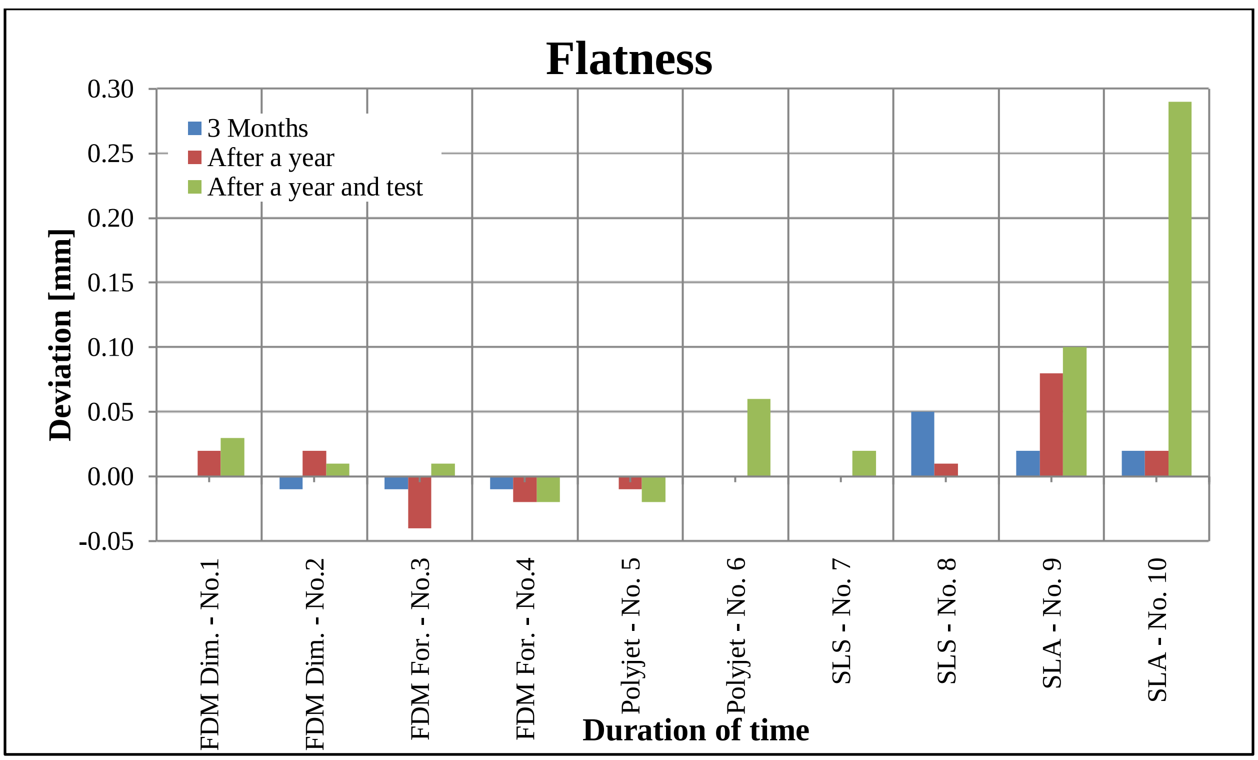


Figure 52 Average deviations of flatness with duration of time

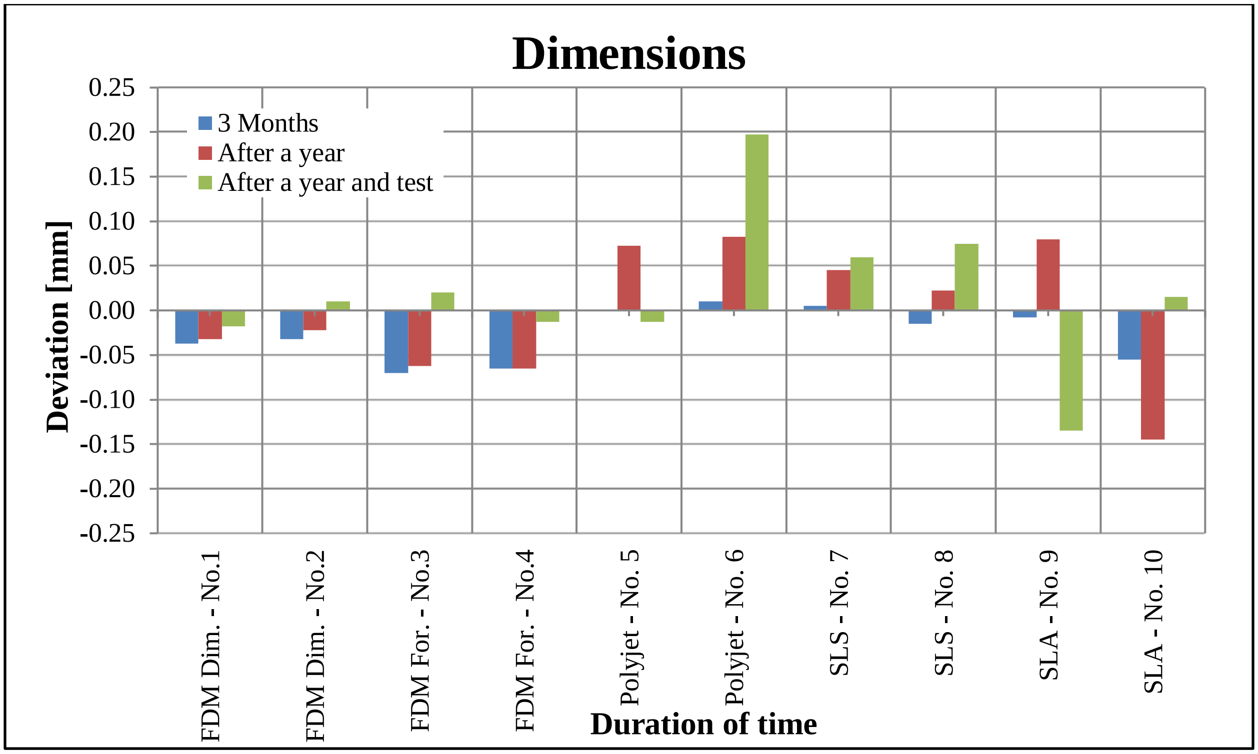


Figure 53 Average deviations of dimensions with duration of time

The above fig.53 represents that the average deviations of horizontal and vertical dimensions during the time such as 3 months, after a year and after a year with test-1 & 2. As can be seen from figure in Polyjet-6 and SLA-9 were same changed the deviation up to 0.08 mm between 3 months and after a year then performed the standard test-1 & 2 were rapidly increased and decreased the deviation up to +0.20 and -0.14 respectively. Based on this result there were no good dimensional stability in horizontal and vertical dimensions throughout the time. In addition, SLS-7 & 8 were increasing the deviations day by day up to 0.07 & 0.08 mm so that in this models were no good horizontal and vertical dimensions stability during all-time. Furthermore, in FDM Dimension-3 & 4, Polyjet-5 and SLA-10 were changed the deviation above than ± 0.05 mm up to after a year then performed the standard test-1 & 2 were suddenly decreased and reached the deviations under the ± 0.05 mm so that it means there were no good dimensional stability during all-time. In the last remaining models like FDM Dimension-1 & 2 were no changed more than ± 0.05 mm deviations, there were good dimensional stability throughout all time.

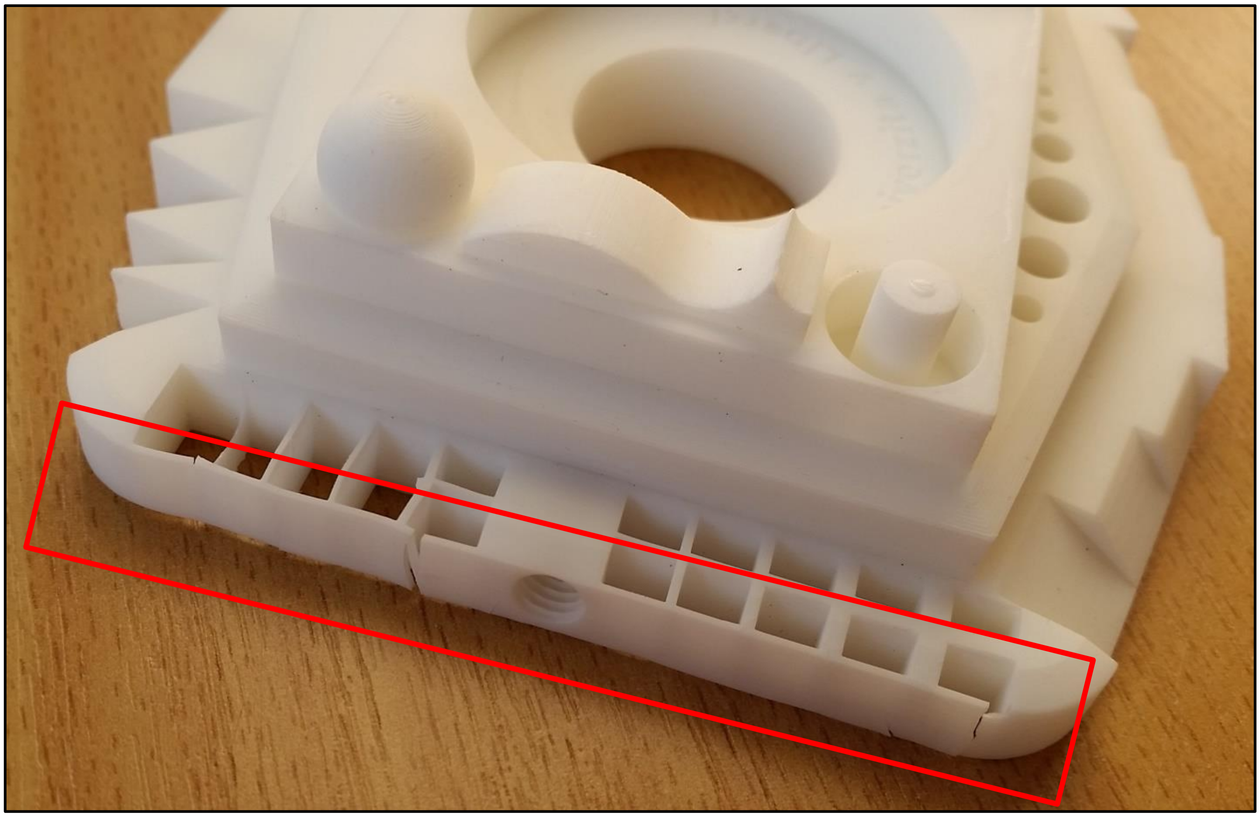


Figure 54 The result of model SLA No.10 after a year with test-1

In the end we got the result of model SLA No.10 after a year with test-1 as shown in fig.54. It is clear from fig.54 and marked the area was the cracked after performed the test of temperature and humidity.

Overall, based on experiment and analysis I can say that the models of Polyjet-6 and SLA-10 were less changed between 3 months and after a year but after a year performed the test-1 higher humidity and temperature there were suddenly big changed in dimension because of material properties, water absorption in humidity and also considerable parameters based on theory like weight loss, fracture the structure, shrinkage of material and cyclic dimensional changes occur. On another side in model SLA-9 was also changed after a year with performed the test-2 UV lighting. Due to UV lighting we can notice the changeable parameters based on theory like reduced ductility, color changes, cracking and a reduction in toughness. These all changed above than 0.05 mm deviations during the time. Apart from this the remaining all models having another divisions of less than 0.05 mm deviation there were changed because of measurement errors and before scanning the layer of spray painting.

10. Conclusion

The main theme of thesis was to inspect the dimensional stability of models produced by additive technologies such as FDM, Polyjet, SLS and SLA with different structure of 3D printing. Models were scanned and inspected by 3D contactless scanner ATOS II 400 and GOM Inspect Professional V8 respectively. These scanning and inspection were performed with duration of time like 3 months, after a year and after a year with standard test-1 (Humidity and Temperature) and Standard test-2 (UV lighting).

While doing the experiment and analysis, firstly the models were fully scanned by scanner, and then some parameters like diameter of spheres, spacing between two spheres, diameter of inner and outer cylinders, cylindricity, surface flatness and horizontal & vertical dimensions were measured by GOM Inspect Professional V8 with duration of time. Additionally, these measurement data were compared with CAD and the first day of printing. Based on these comparison data, the deviations were divided into two groups. The deviation values less than 0.05 mm could be considered as measurement errors, layer of spray painting and values more than 0.05 mm it was recognized by there are no good dimensional stability with duration of time.

Overall, all the measured parameters were increasing the deviation (more than 0.05 mm) day by day in Polyjet-6 so that it can be concluded that they had no longer good dimensional stability with duration of time. Whereas the deviation values of spacing between two spheres and diameter of inner cylinders were decreasing day by day more than 0.05 mm in SLA-10. Moreover, the deviation values of flatness were under 0.05 mm till a year but after the examining the model by test-1 there was notice a pick value of deviation more than 0.05 mm. The values of horizontal & vertical dimensions were also decreased up to a year and there were found no deviation after evaluating the model with standard test-1. The diameters of spheres values of SLA-10 were remained constant up to a year but once standard test-1 was performed there was witnessed sudden increase in deviation up to 0.06 mm. While all of the above mentioned dimensions were changed in polyjet-6 and SLA-10 which means there were no longer good dimensional stability. The reasons of poor dimensional stability could be some change in material properties, weight loss, water absorption and shrinkage of surface material due to performed standard test-1 of humidity and temperature.

On the contrary in SLA-9, the deviation values of spacing between two spheres and diameter of inner cylinders were not changed more than ± 0.05 mm but after conducting standard test-2 these values were suddenly decreased up to -0.14 mm and +0.09 mm deviation respectively. In addition, the values of flatness' deviation were increasing day by day (more than 0.05 mm deviation throughout all time). The amounts of deviation in horizontal and vertical dimensions were increased up to a year but there were suddenly decreased up to -0.14 mm deviation after performing test-2. Remaining all the parameters such as diameter of spheres, diameter of outer cylinder and cylindricity had no change more than 0.05 mm deviation. Based on this analysis and theory, as the standard test-2 of UV lighting was performed, it could be said that in SLA-9 there were no longer good dimensional stability during the time because of the change in material properties, reduced ductility, surface color and cracking.

Apart from this remaining all models such as FDM Dimension-1 & 2, FDM Fortus-3 & 4, Polyjet-5 and SLS-7 & 8, there were no change in the deviation more than ± 0.05 mm throughout all time. Therefore, it could be said that there were good dimensional stability.

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Appendix

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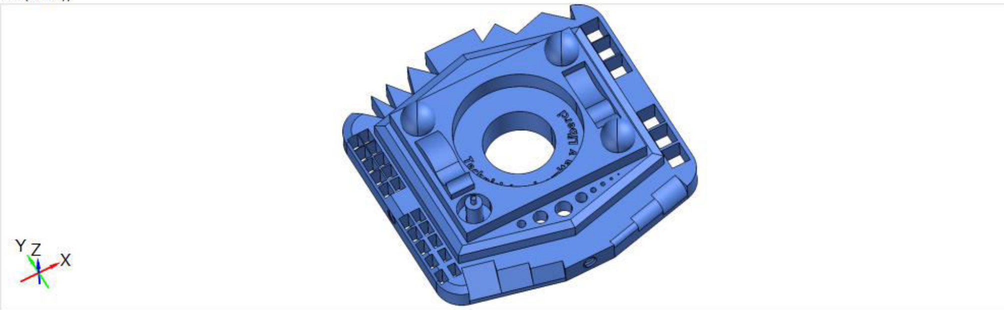
KATEDRA
VÝROBNÍCH SYSTÉMŮ
A AUTOMATIZACE

Inspection

GM (1st day)



Prealignment 1 | Length unit: mm

Inspector:	Soni Rakeshkumar	**Part**:	Etalon
Company:	Technical university of Liberec	**Part no.**:	10
Department:	www.ksa.tul.cz	**Version**:	SLA Ultra - Out side
Location:	Liberec	**Charge no.**:	
Date:	6.2.2018	**System**:	ATOS - GOM Inspect Pro v8
Project:			

Etalon 10 SLA Ultra - Out side 1/22

Generated with GOM Inspect Professional V8

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KATEDRA
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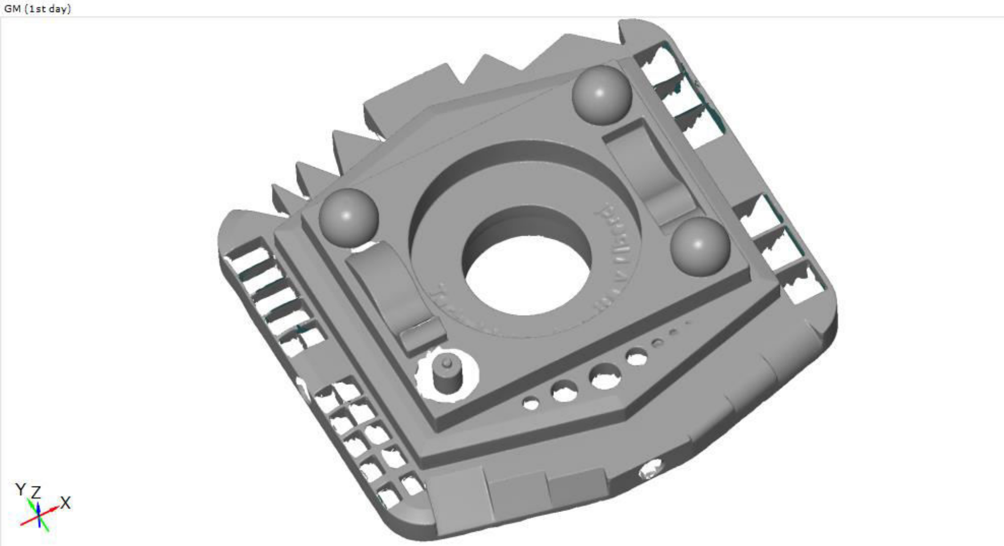
A AUTOMATIZACE

Mesh (actual model)

GM (1st day)



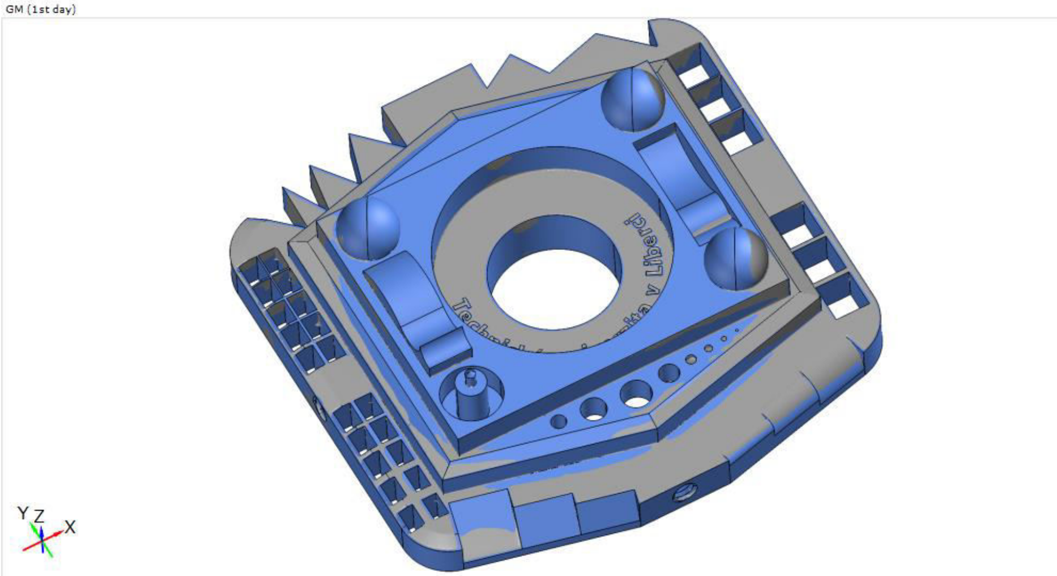
Prealignment 1 | Length unit: mm

Etalon 10 SLA Ultra - Out side 2/22

Generated with GOM Inspect Professional V8

CAD (blue) & Mesh (grey)

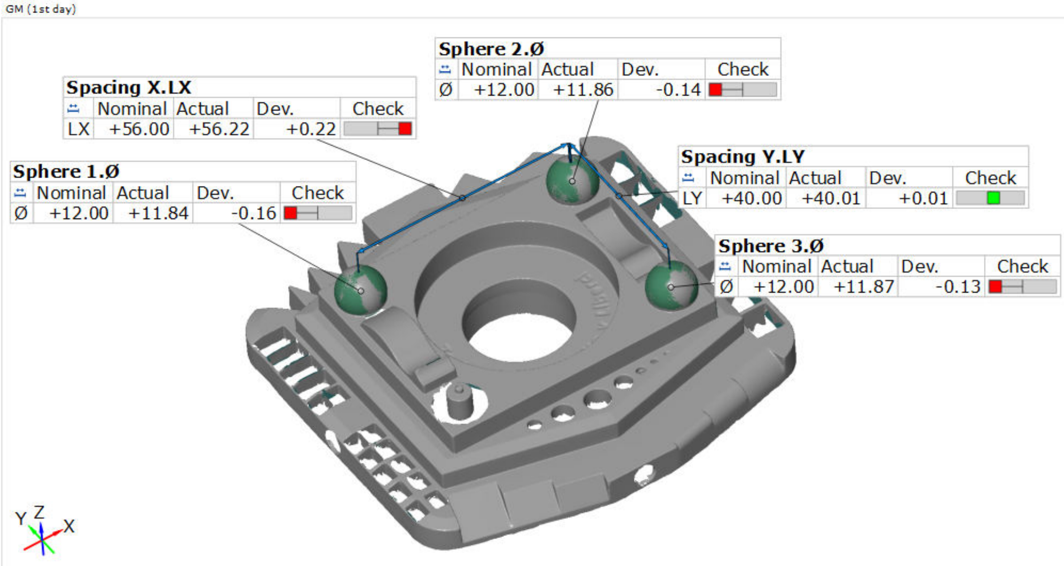
GM (1st day)



Prealignment 1 Length unit: mm

Sphere

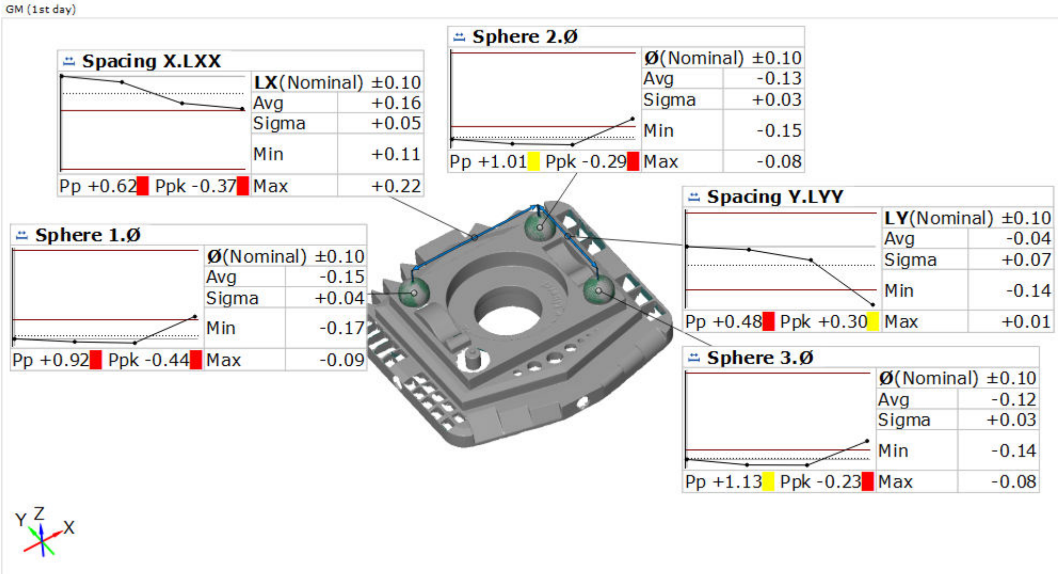
GM (1st day)



Prealignment 1 Length unit: mm

Sphere (Trend)

GM (1st day)



Prealignment 1 Length unit: mm

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KATEDRA VÝROBNÍCH SYSTÉMŮ A AUTOMATIZACE

Sphere (Statistics)

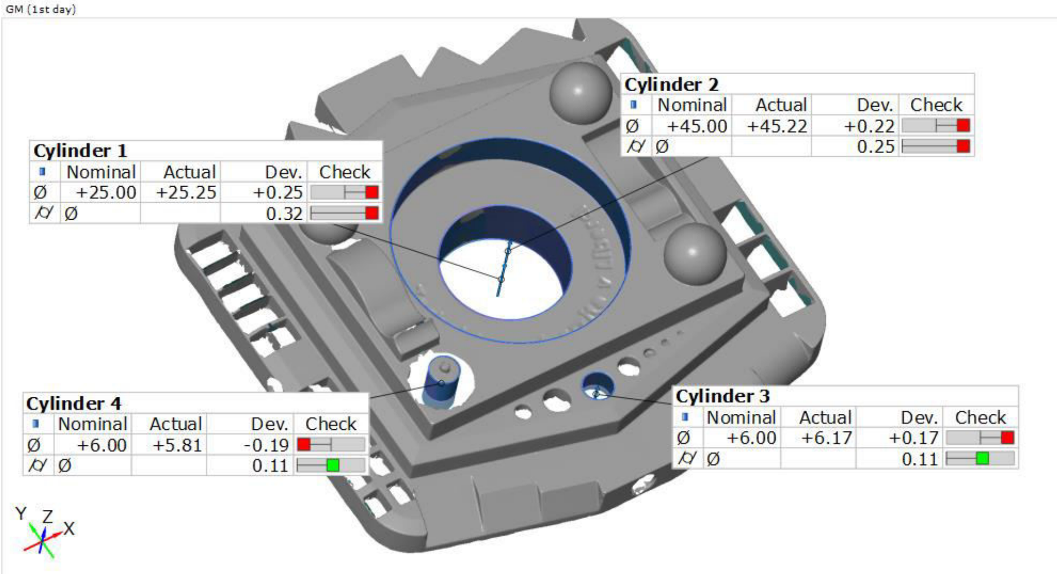
GM (1st day)

Element	Property	Nominal	Actual	Tol -	Tol +	Dev	Avg	Sigma	Range	Min	Max	Pp	PpK	Count
Sphere 1	Ø	+12.00	+11.84	-0.10	+0.10	-0.16	-0.15	+0.04	+0.08	-0.17	-0.09	+0.92	-0.44	4
Sphere 2	Ø	+12.00	+11.86	-0.10	+0.10	-0.14	-0.13	+0.03	+0.07	-0.15	-0.08	+1.01	-0.29	4
Sphere 3	Ø	+12.00	+11.87	-0.10	+0.10	-0.13	-0.12	+0.03	+0.06	-0.14	-0.08	+1.13	-0.23	4
Spacing X	LX	+56.00	+56.22	-0.10	+0.10	+0.22	+0.16	+0.05	+0.11	+0.11	+0.22	+0.62	-0.37	4
Spacing Y	LY	+40.00	+40.01	-0.10	+0.10	+0.01	-0.04	+0.07	+0.15	-0.14	+0.01	+0.48	+0.30	4

Prealignment 1 Length unit: mm

Cilinder

GM (1st day)



Prealignment 1 Length unit: mm

Etalon 10 SLA Ultra - Out side 7/22

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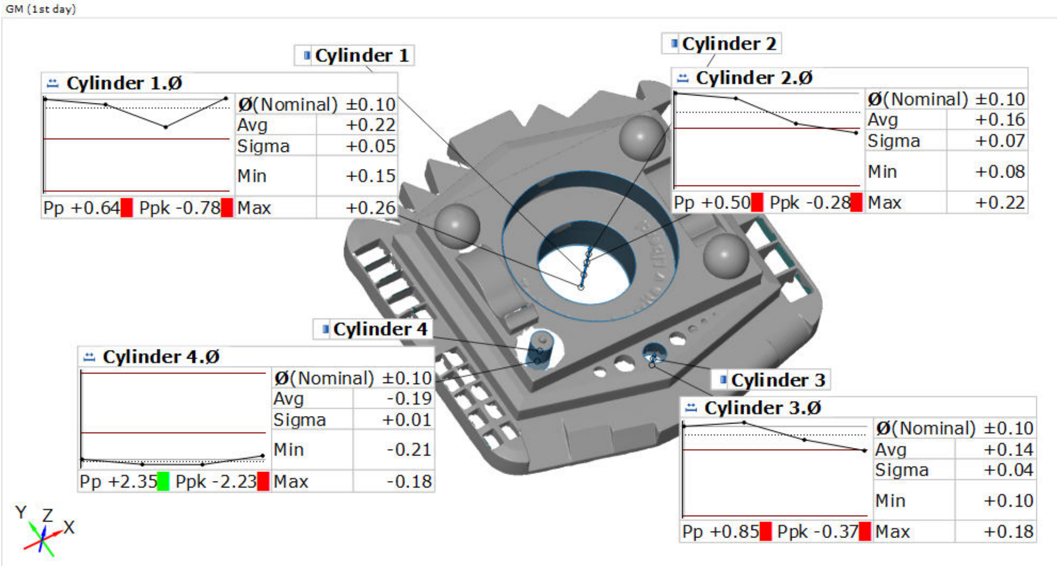
Cilinder (Trend)

GM (1st day)



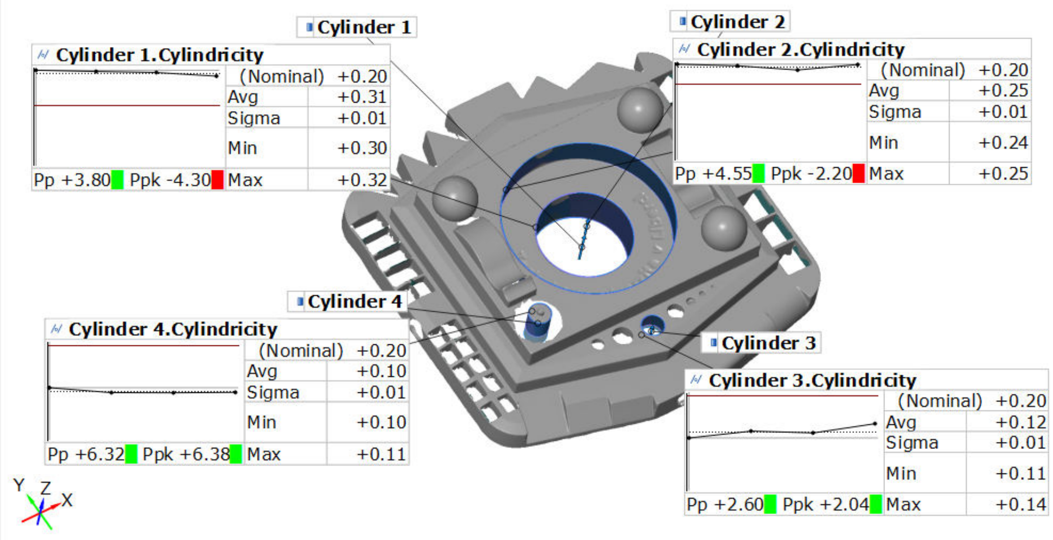
Prealignment 1 Length unit: mm

Etalon 10 SLA Ultra - Out side 8/22

Generated with GOM Inspect Professional V8

Cilinder (Trend)

GM (1st day)



Prealignment 1 Length unit: mm

Cilinder (Statistics)

GM (1st day)

Element	Property	Nominal	Actual	Tol -	Tol +	Dev	Avg	Sigma	Range	Min	Max	Pp	PpK	Count
Cylinder 1	Ø	+25.00	+25.25	-0.10	+0.10	+0.25	+0.22	+0.05	+0.11	+0.15	+0.26	+0.64	-0.78	4
Cylinder 2	Ø	+45.00	+45.22	-0.10	+0.10	+0.22	+0.16	+0.07	+0.14	+0.08	+0.22	+0.50	-0.28	4
Cylinder 3	Ø	+6.00	+6.17	-0.10	+0.10	+0.17	+0.14	+0.04	+0.09	+0.10	+0.18	+0.85	-0.37	4
Cylinder 4	Ø	+6.00	+5.81	-0.10	+0.10	-0.19	-0.19	+0.01	+0.03	-0.21	-0.18	+2.35	-2.23	4
Cylinder 4	⌭	+0.00	+0.11	+0.00	+0.20	+0.11	+0.10	+0.01	+0.01	+0.10	+0.11	+6.32	+6.38	4
Cylinder 1	⌭	+0.00	+0.32	+0.00	+0.20	+0.32	+0.31	+0.01	+0.02	+0.30	+0.32	+3.80	-4.30	4
Cylinder 2	⌭	+0.00	+0.25	+0.00	+0.20	+0.25	+0.25	+0.01	+0.02	+0.24	+0.25	+4.55	-2.20	4
Cylinder 3	⌭	+0.00	+0.11	+0.00	+0.20	+0.11	+0.12	+0.01	+0.03	+0.11	+0.14	+2.60	+2.04	4

Prealignment 1 Length unit: mm

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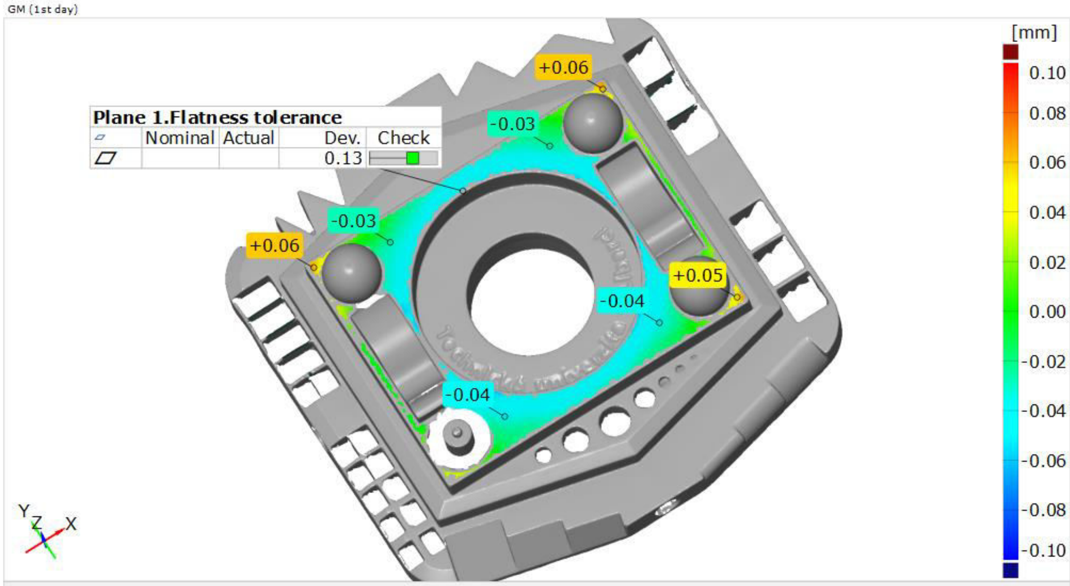
Flatness

GM (1st day)



Prealignment 1 — Length unit: mm

Etalon 10 SLA Ultra - Out side — 11/22

Generated with GOM Inspect Professional V8

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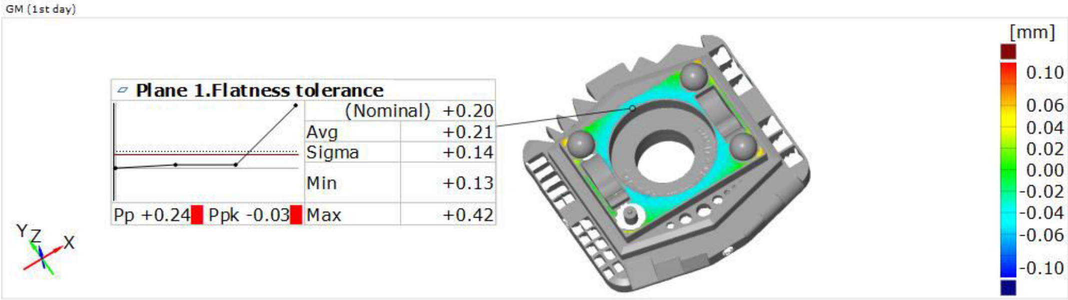
Flatness (Trend)

GM (1st day)



Element	Property	Tol -	Tol +	Dev	Dev	Dev	Dev
Plane 1	⏥	+0.00	+0.20	+0.13	+0.15	+0.15	+0.42

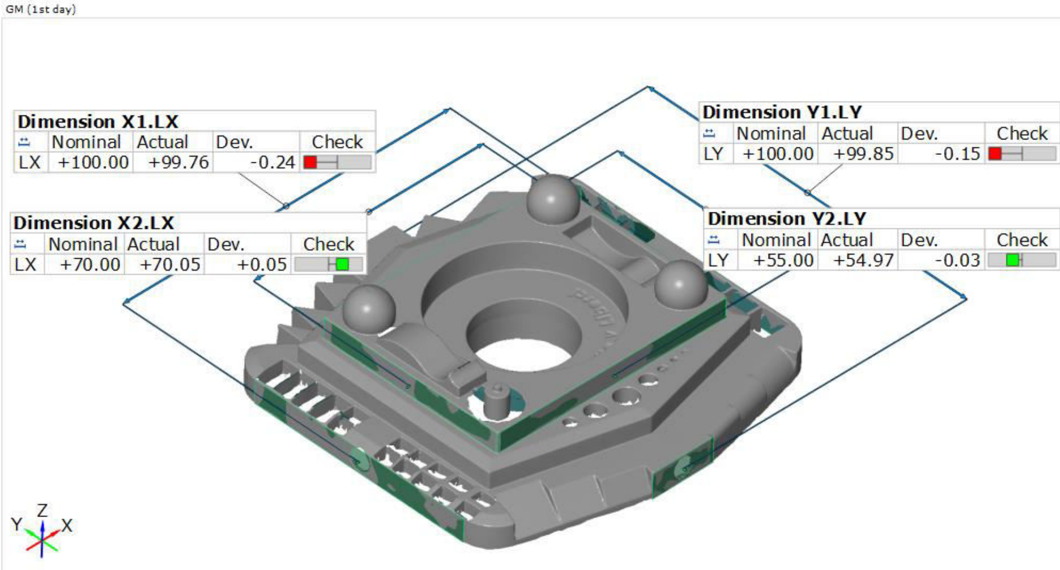
Prealignment 1 — Length unit: mm

Etalon 10 SLA Ultra - Out side — 12/22

Generated with GOM Inspect Professional V8

Dimension

GM (1st day)



Dimension X1.LX

	Nominal	Actual	Dev.	Check
LX	+100.00	+99.76	-0.24	

Dimension X2.LX

	Nominal	Actual	Dev.	Check
LX	+70.00	+70.05	+0.05	

Dimension Y1.LY

	Nominal	Actual	Dev.	Check
LY	+100.00	+99.85	-0.15	

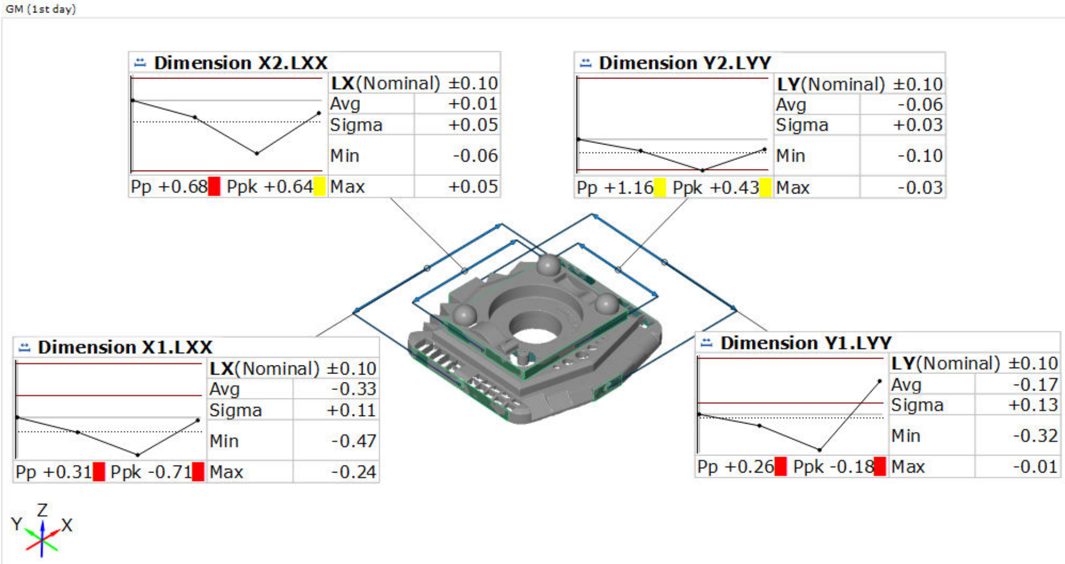
Dimension Y2.LY

	Nominal	Actual	Dev.	Check
LY	+55.00	+54.97	-0.03	

Prealignment 1 Length unit: mm

Dimension (Trend)

GM (1st day)



Dimension X2.LXX

LX(Nominal)	±0.10
Avg	+0.01
Sigma	+0.05
Min	-0.06
Max	+0.05

Pp +0.68 Ppk +0.64

Dimension Y2.LYY

LY(Nominal)	±0.10
Avg	-0.06
Sigma	+0.03
Min	-0.10
Max	-0.03

Pp +1.16 Ppk +0.43

Dimension X1.LXX

LX(Nominal)	±0.10
Avg	-0.33
Sigma	+0.11
Min	-0.47
Max	-0.24

Pp +0.31 Ppk -0.71

Dimension Y1.LYY

LY(Nominal)	±0.10
Avg	-0.17
Sigma	+0.13
Min	-0.32
Max	-0.01

Pp +0.26 Ppk -0.18

Prealignment 1 Length unit: mm

Dimension (statistics)

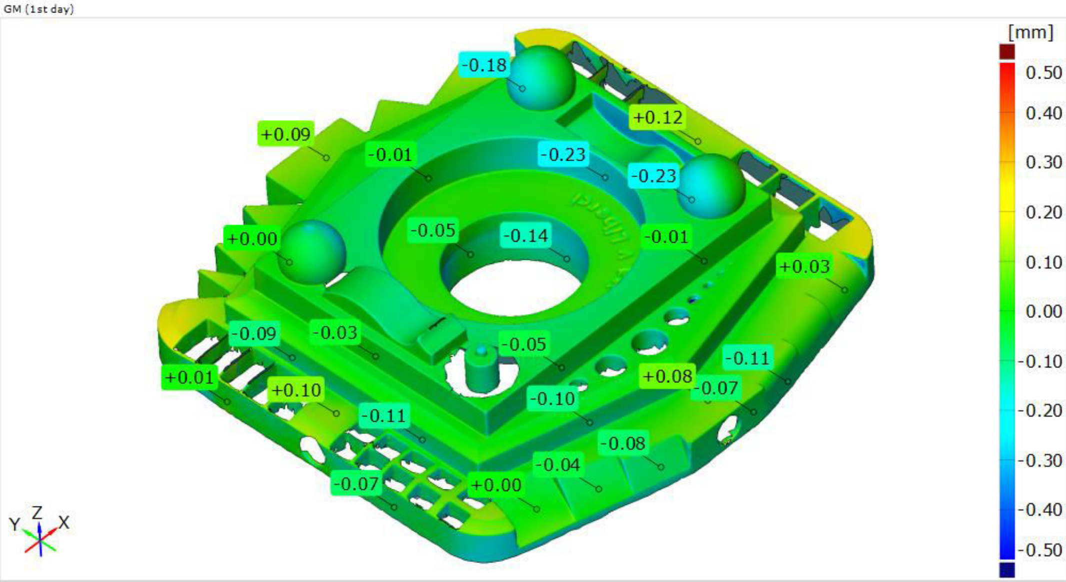
GM (1st day)

Element	Property	Nominal	Actual	Tol -	Tol +	Dev	Avg	Sigma	Range	Min	Max	Pp	PpK	Count
Dimension X1	LX	+100.00	+99.76	-0.10	+0.10	-0.24	-0.33	+0.11	+0.23	-0.47	-0.24	+0.31	-0.71	4
Dimension X2	LX	+70.00	+70.05	-0.10	+0.10	+0.05	+0.01	+0.05	+0.11	-0.06	+0.05	+0.68	+0.64	4
Dimension Y1	LY	+100.00	+99.85	-0.10	+0.10	-0.15	-0.17	+0.13	+0.31	-0.32	-0.01	+0.26	-0.18	4
Dimension Y2	LY	+55.00	+54.97	-0.10	+0.10	-0.03	-0.06	+0.03	+0.07	-0.10	-0.03	+1.16	+0.43	4

Prealignment 1 Length unit: mm

Surface comparison

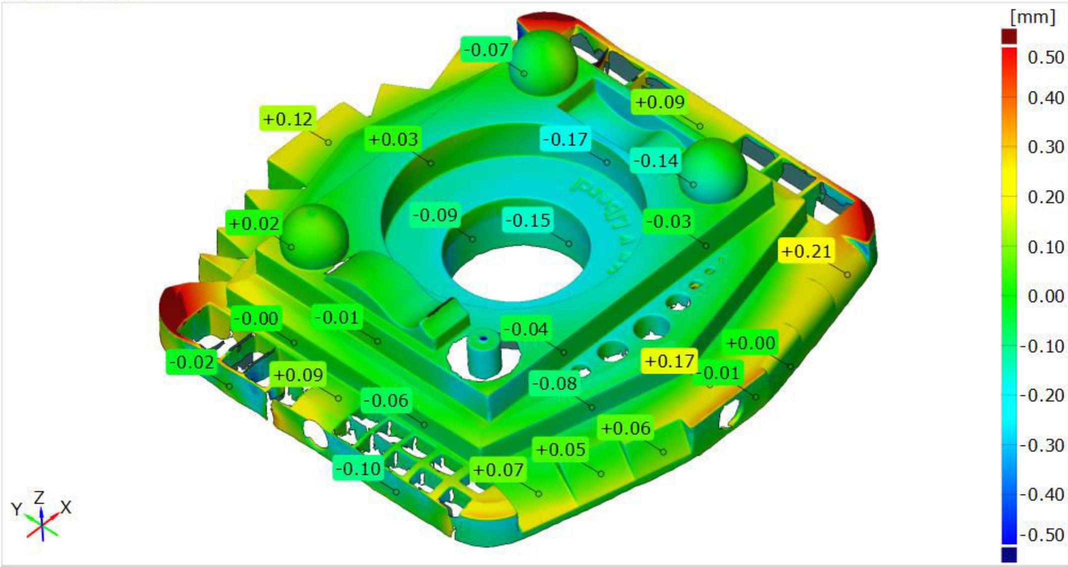
GM (1st day)



Prealignment 1 Length unit: mm

Surface comparison

Test (after a year and test)



Prealignment 1 Length unit: mm

Etalon 10 SLA Ultra - Out side Test 2 17/22

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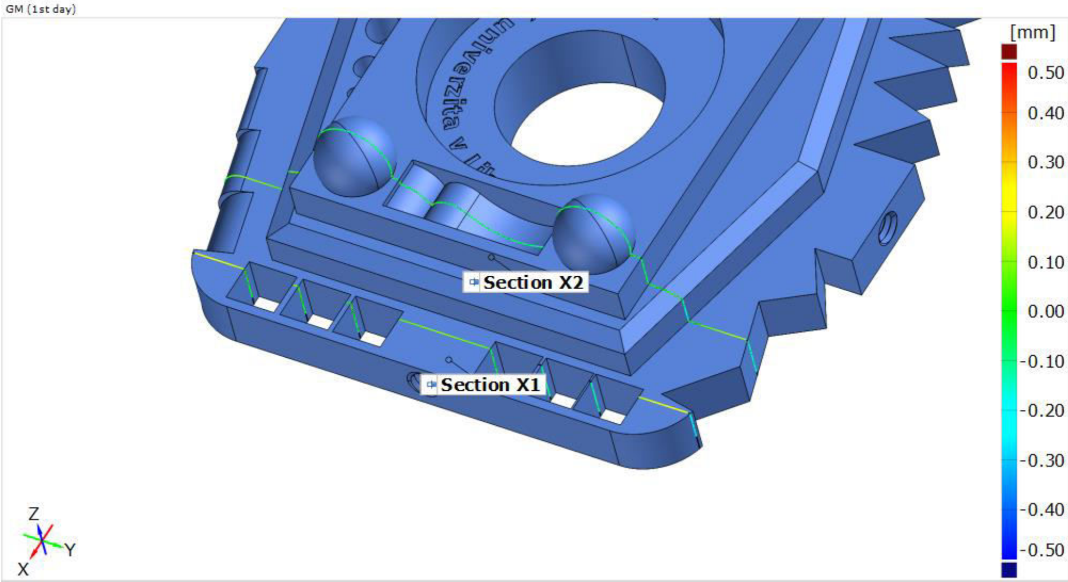
Position of Sections

GM (1st day)



Prealignment 1 Length unit: mm

Etalon 10 SLA Ultra - Out side 18/22

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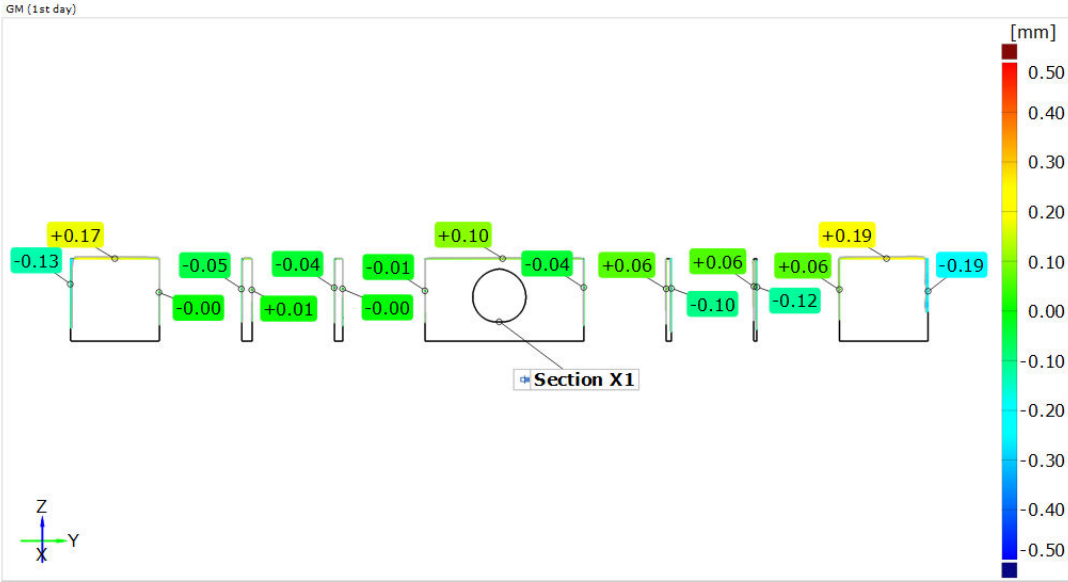
Section X1

GM (1st day)



Prealignment 1 Length unit: mm

Etalon 10 SLA Ultra - Out side 19/22

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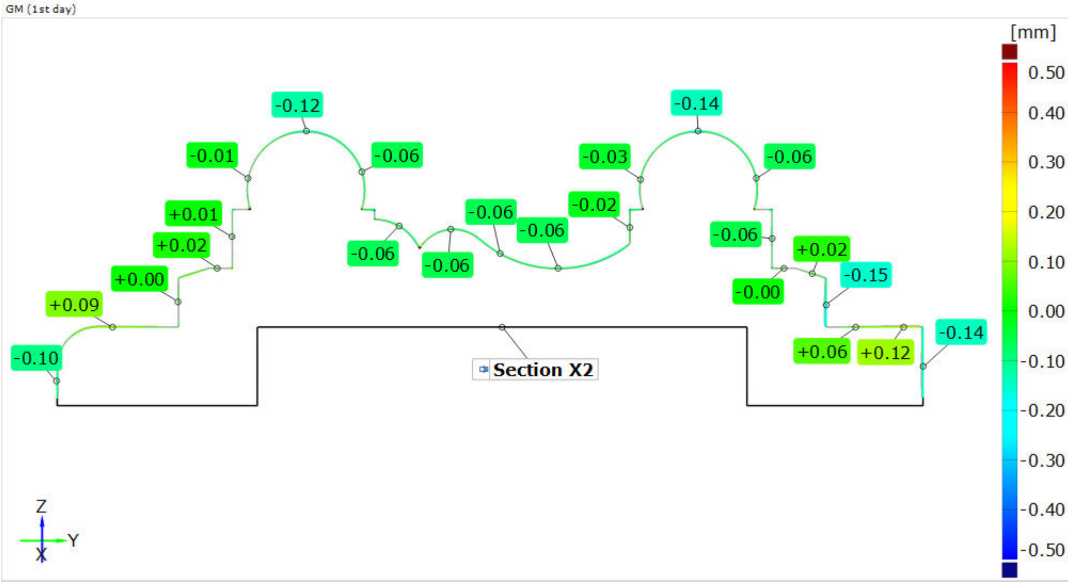
Section X2

GM (1st day)



Prealignment 1 Length unit: mm

Etalon 10 SLA Ultra - Out side 20/22

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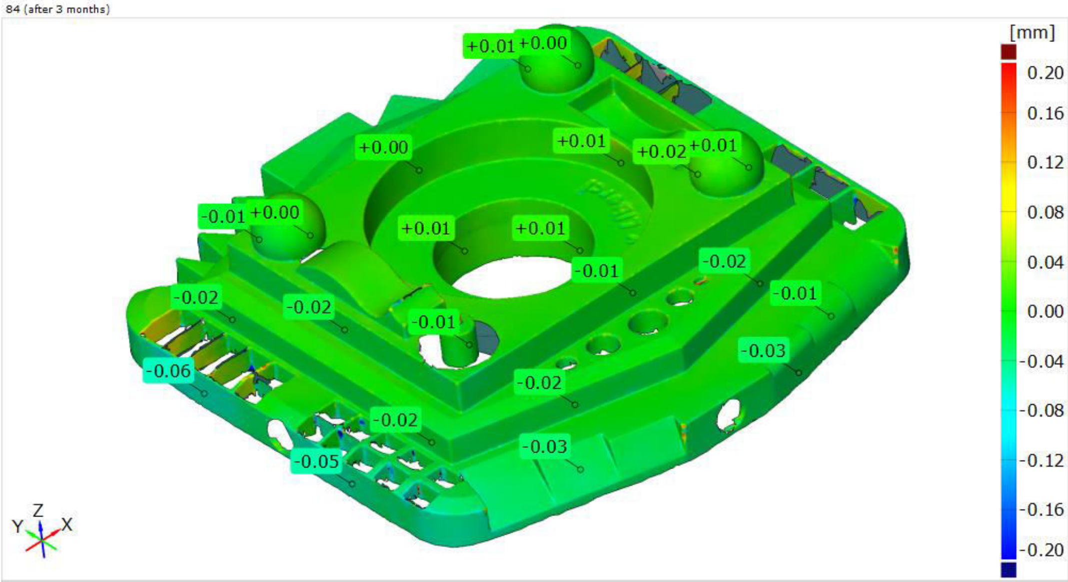
Surface comparison on 1st day

84 (after 3 months)



Prealignment 1 Length unit: mm

Etalon 10 SLA Ultra - Out side 21/22

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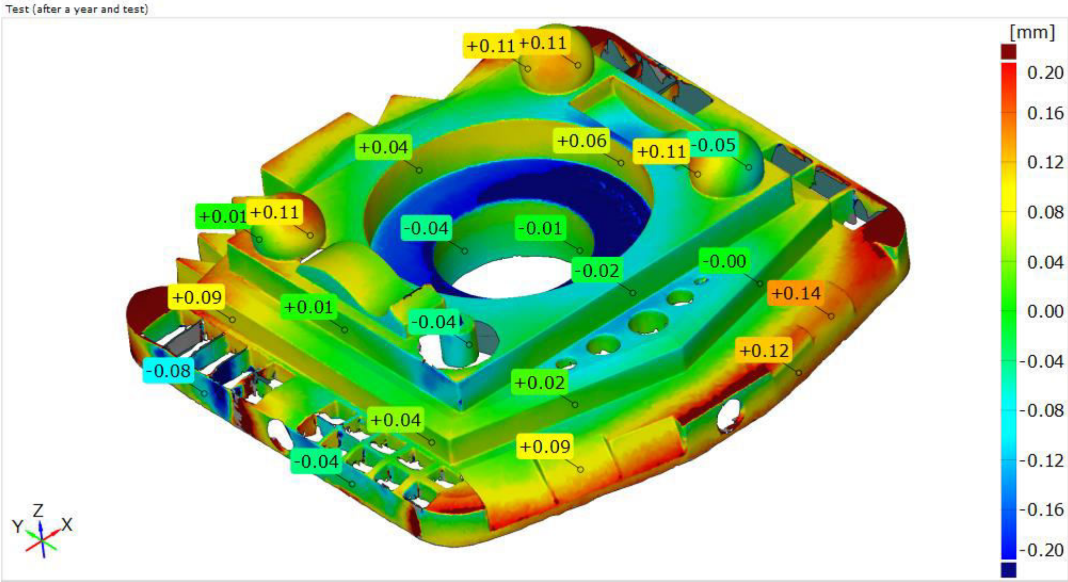
Surface comparison on 1st day

Test (after a year and test)



Prealignment 1 Length unit: mm

Etalon 10 SLA Ultra - Out side Test 2 22/22

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