RE-CONSTRUCTION OF INDEX FINGER BONES BY USING ADDITIVE MANUFACTURING PROCESS WITH BIO-BASED ABS RESIN MATERIAL

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ABSTRACT: Additive Manufacturing is the modern technology to build complex designs in an easy, accurate, cost-effective, and customized manner, we can also create by remote manufacturing. This project aims to make artificial bones with customization of size, quick manufacturing, and cost-effectiveness using X-ray images SLA (Stereolithography) process with Bio-based ABS (Acrylonitrile butadiene styrene) resin material. Multiview X-ray images are used for the dimension's extraction. Next with extracted dimensions, CAD models of the bones were designed and assembled using Solidworks, then simulated the model by applying the pressure loads on the bones using Ansys Workbench. At the end, designed components which are in Stl file format are sliced using Ultimaker Cura. Finally, components are 3D printed by using SLA 3D printer with Bio-based ABS resin material.

Keywords: - Stereolithography; 3D printing; Bio-based ABS resin; X-ray images; Artificial bones.

INTRODUCTION:

3D printing technology is used to design complex geometries easily and, it is the most used technology over other processes like casting, welding, etc. We have many different types of 3D printing processes such as FDM (Fused Deposition Modelling) SLA (stereolithography), SLS (selective laser sintering), etc [1].

In the FDM process, plastic filaments are used as raw material, which is melted at a controlled temperature and material is deposited layer by layer to create the product. First, we have to create a 3D CAD file of the component and convert it to an STL file format, then the component is sliced using software like 3D Slicer, Cura, etc. The filament is loaded into the extruder of the 3D printer, then the extruder feeds the filament through the heated nozzle so that the filament is melted to liquid. The extruder follows the instructions of the software. It moves in multiple directions by depositing the melted liquid layer by layer on the build platform to obtain the required shape and size. We can control the part's infill density, orientation, and layer height.

In the SLS process powdered materials (metals or plastic) are used as raw materials. A high-power laser is used to selectively heat and sinter the powder by the instructions given by the software. The laser scans the cross-section of the component on a powder bed to form the required part layer by layer. This process is expensive and low resolution [1].

In the SLA process liquid resin is used as raw material, laser is used to convert liquid resin into solid to form a 3D model or required component. Creating a 3D CAD file, converting it to an STL (standard triangular format) file, and slicing are common in 3D printing processes. In this process, a 3D printer consists of a container filled with liquid resin. The laser beam guided by the mirror is reflected on the surface of the resin and gets hardened, now, the initial layer is created, and the platform is lowered slightly to create the next layer. This process goes on until the part is finished. In this project, I have used SLA (stereolithography) because it gives accurate results, biomechanical components are mainly manufactured using the SLA process [2] [3]. The following flow chart shows the chronology of the Stereolithography process,

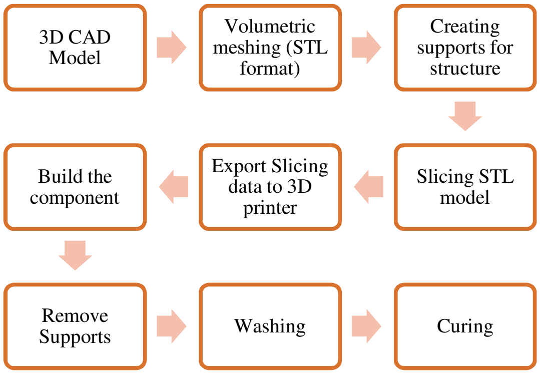


Chart 1: Process of Stereolithography [3]

Let us understand the basic anatomy of a human hand. There are twenty-seven bones in the human hand, eight are wrist bones (carpals), five are palm bones (metacarpals), and fourteen are finger bones (phalanges). Each finger has three phalanges proximal phalange, middle phalange, and distal phalange, except the thumb consists of two phalanges. Each phalange has a head shaft and base as shown in image 1. The phalanges are connected to ligaments, tendons, and muscles. Coordination of finger movements involves a combination of muscles, located in the forearm and hand.

Image 1: Anterior view of Index finger bones

Nowadays the number of cases of fractures has increased due to war, accidents, or birth defects. Artificial bones are made for the replacement of fractured bones. However, replacement of the bones costs more for both material and replacement. The average cost of a prosthetic hand is about USD 25000 to USD 75000 depending upon the material type. USD 4000 to USD 8000 for fingers. So, the main aim of this project is to design artificial bones at an efficient cost and customize the sizes of the bones according to the requirements. Customization and cost efficiency can be obtained using 3D printing technology. Here chart 2 shows the process of reconstruction of artificial bones, using a 3D printing process [4].

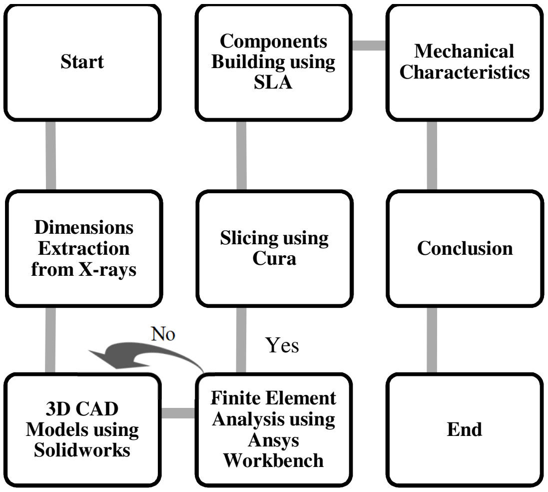


Chart 2: **Process of Re-Construction of Artificial Bones using 3D-printing process**

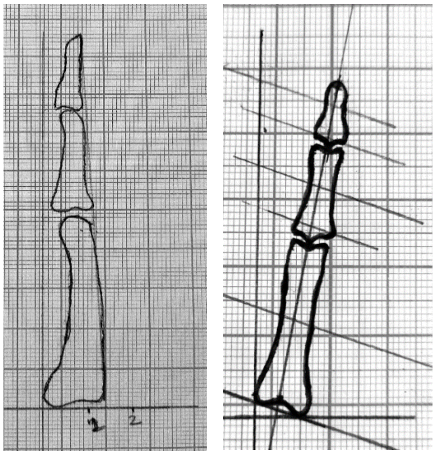
<u>DIMENSIONS EXTRACTION FROM X-RAYS</u>:

The dimensions can be obtained easily from the CT-Scan (Computed Tomography scan), and MRI (Magnetic Resonance Imaging). Still, the main disadvantage of these processes is, that radiation emitted by these devices is hazardous to health. So, I have used multiple X-rays and the point-based method, in this method multiple points are located and matched the points by using multiple views of the X-ray images, so front and lateral views of the X-ray images are used to extract the dimensions. Image 2 shows the lateral view and front view of the Index finger [5] [6].

In these images, lateral view (1a) is mirrored. First, clamp the graph paper so that the X-ray axis should coincide with any one axis of the graph paper. Now outline the finger bones on graph paper, for better results use an LED illuminator. Now I have the outline of index finger bones on the graphs. The outlines on the graphs are shown in image 3. After outlining on graphs points should be marked on the outline so that either X-axis or Y-axis should coincide with the starting or ending point of the outline as shown in image 3. Now using the drafter, draw a vertical line joining the midpoints of each bone (proximal, middle, and distal phalanges) on the front view outline (image 3b). Now the drafter is set at an angle perpendicular to the vertical line. Now draw multiple horizontal lines that are parallel to each other so that the dimensions are to be measured (image 3b). We can measure the length and width using image 3b and the same process is followed for extracting the thickness using image 3a. Multiple graphs are drawn and those graphs' average values are considered the final dimensions. The tables (1,2) below show the maximum dimensions of each phalange. By using this process, the design is made with an error of 1mm-3mm.

(1a) **(1b)**

Image 2: Lateral and Front view of the left-hand Index Finger Bones



(3a) **(3b)**

Image 3: Outline of index finger bones on graphs

All dimensions in mm.	**Iteration 1 (Depth)**	**Iteration 2 (Depth)**	**Iteration 3 (Depth)**	**Average**
Proximal Phalanx	10	09	08	**09**
Middle Phalanx	08	06	07	**07**
Distal Phalanx	07	05	06	**06**

Table 1: Dimensions from Lateral View Outline

All dimensions in mm.	Iteration 1		Iteration 2		Iteration 3		Average	
	Length	Width	Length	Width	Length	Width	Length	Width
Proximal Phalanx	44	13	43	12	45	14	**44**	**13**
Middle Phalanx	27	11	25	09	26	10	**26**	**10**
Distal Phalanx	16	07	18	08	20	09	**18**	**08**

Table 2: Dimensions from Front View Outline

<u>3D CAD MODELS USING SOLIDWORKS</u>:

We have many CAD software like Auto-CAD, Solidworks, Catia, Fusion 360, etc. I used Solidworks to make CAD model of bones because Solidworks is user-friendly and easy to use. So, I have 2D images along with the dimensions, starting with creating a CAD model of the proximal phalange. As I have mentioned Solidworks is a user-friendly and easy-to-use software for designing. Image 4 is the CAD model of the proximal phalange made by using simple commands rectangle > extrude boss/base > spline > cut extrude > circle > fillet. Some other features like Smart dimensions and convert entities are used according to our requirements. Note: sketch plane to be selected accordingly for all phalanges.

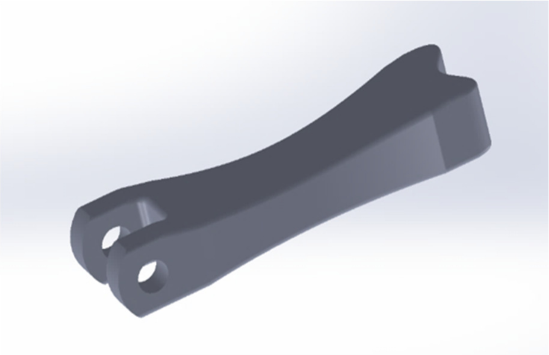


Image 4: CAD model of the proximal phalange

I created a slot on the head of the bone so that the base of the middle phalange mates with the proximal. Let's discuss more in the assembly. Slots are created by using the cut extrude command. Pins/screws are used for joining phalanges.

The middle phalange consists of a slot on the head for the distal phalange and a slot at the base for proximal phalange. Commands used for designing all the phalanges are the same. The middle phalange behaves like an intermediate and supports the phalange for both proximal and distal phalanges. Image 5 is the CAD model of the middle phalange. All the features are used accordingly based on extracted dimensions.

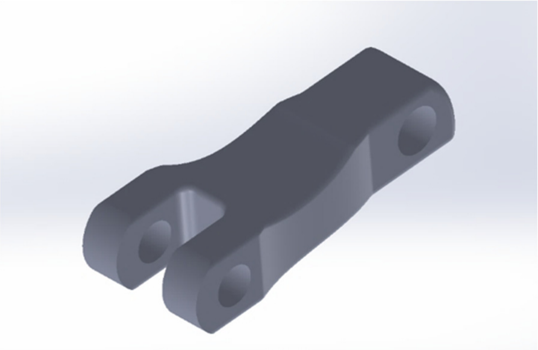


Image 5: CAD model of Middle phalange

The distal phalange is the topmost bone of the finger and the size of this bone is small compared to the other two phalanges. The force/pressure is observed by this phalange when a force is applied by the finger, so a simulation (Ansys) is made by applying the loads on the distal phalange. However, the bases of the middle and distal phalanges are neglected because slots are made so that both the phalanges are joined with the pins.

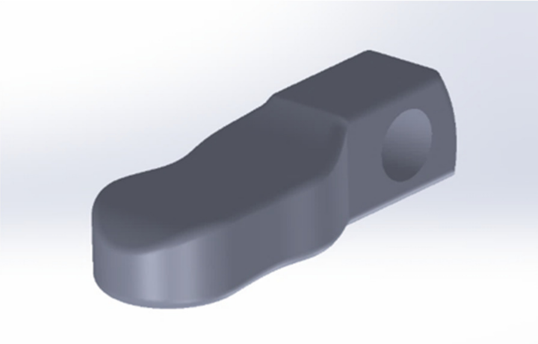


Image 6: CAD model of Distal phalange

All three phalanges were designed by taking the dimensions of the head and shaft of the bones and assembled using Solidworks software. Commands like mate, toolbox, and cylindrical pins of Indian standard are used for the assembly (image 7). The assembly is done in such a way that the slot of the proximal phalange is mated with the base slot of a middle phalange, and the head slot of the middle phalange is mated with a slot of the distal phalange. Then cylindrical pins of Indian standards are used from a toolbox (Solidworks). Dimensions are made according to the requirements. Save the file in both (IGS) and (SLDASM) formats.

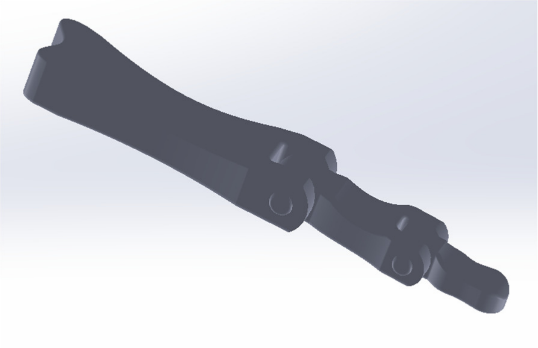


Image 7: Assembly of Phalanges

<u>FINITE ELEMENT ANALYSIS USING ANSYS</u>:

We have many software's for analysis, and I have used Ansys software for simulation. The process of simulation in the Ansys workbench is carried out by following steps,

Step 1: Assigning material properties according to requirements and type of simulation.

Step 2: Import the assembled geometry that is saved as .IGS format.

Step 3: Meshing the components (Auto meshing).

Step 4: Assigning boundary conditions.

Step 5: Applying the loads (point/pressure loads).

Step 6: Solve the results.

I have used the Bio-based ABS material, and the static structural simulation is made on the designed model, for this type of simulation. I need Young's modulus and the poisons ratio for this simulation. Young's modulus of Bio-based ABS material is assigned as 2300 Mpa and the poisons ratio is 0.36 [9].

The same values are assigned in the Ansys workbench. Now import the geometry which is saved in IGS format. Next, go with the model tab then Ansys Mechanical gets started, now go to mesh and click on generate Mesh, meshing is generated automatically, assign fixed support properties at the base of the proximal phalange, and apply pressure load on the tip of the distal phalange. Select the solutions like equivalent (von- Mises) stress and total deformation in the solution section then click on solve to obtain the solution.

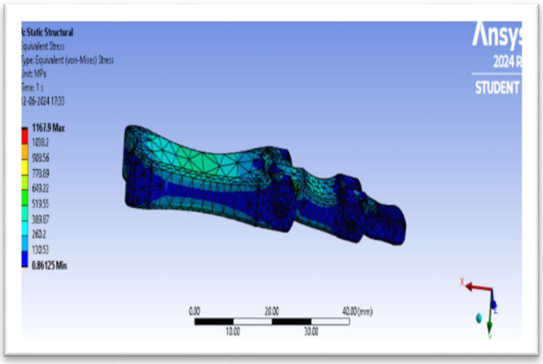


Image 8: Equivalent Stress

	Minimum	Average	Maximum
Stress in (Mpa)	0.861	104.5	1165.2

Multiple simulations are to be made using the multiple outlines i.e. by changing the dimensions of the components multiple simulations are made, then select an optimal result.

Note: Simulated at 10 Mpa of pressure

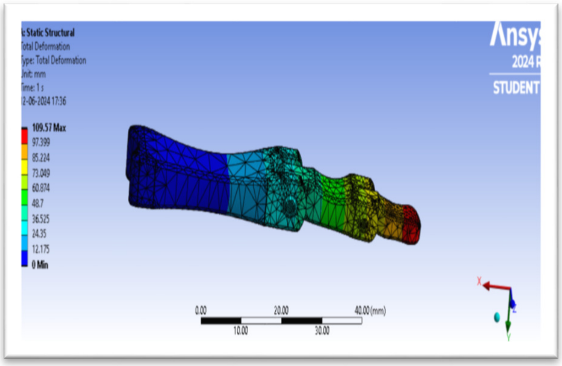


Image 9: Total Deformation

	Minimum	Average	Maximum
Deformation in (mm)	0	46.148	109.55

SLICING USING ULTIMAKER CURA:

Ultimaker Cura is a slicing software used in 3D printing. Slicing software is crucial in 3D printing because it converts the 3D models into G-codes (instructions). The CAD model which is saved in STL format is to be imported into Cura and the position of a model on the virtual build platform, then adjust size, orientation, and placement of the model. We can adjust line width, infill density, layer height, wall thickness, printing temperature, specific thickness and more [7].

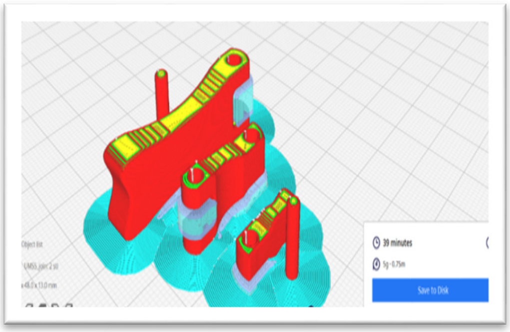


Image 10: Sliced components (Ultimaker Cura)

the estimation time for building the components is shown at the right bottom of the screen, we can also automate the process by using commands for tools and scripts. Transfer the sliced data from the Ultimaker Cura to the printer.

COMPONENTS BUILDING USING SLA:

3D CAD files are converted to STL format and data of sliced STL files is to be exported to a 3D printer. In this process, I have used a Form-3B printer which is designed and developed by Form Labs. This printer is capable of designing using bio-based materials. Form 3B is a desktop 3D printer engineered for the healthcare industry. This printer can create patients-specific parts virtually and mainly benefits medical and dental personnel.

This printer is bio-compatible with a variety of SLA materials**.** Workflow validated for Food and Drug Administration (FDA) processes, safeguard in medical uses. This printer has hands-free resin dispensing coupled with ease of use for printing with software that optimizes clinical workflow [8].

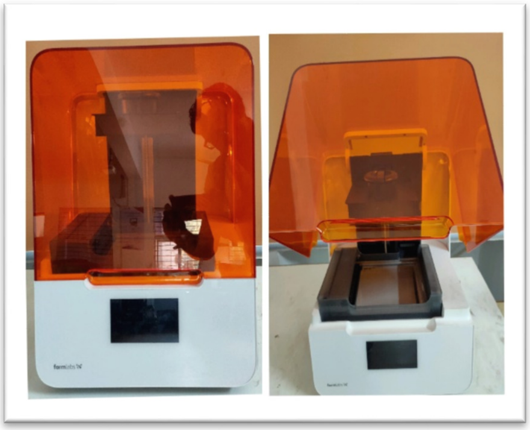


Image 11: Form 3B Printer

Resin should be selected by considering factors like flexibility, strength, and other required properties that match the particular prerequisites of the components. A calibration check is to be performed before the printing process is started. Make sure that the printer's laser and build platform of the 3D printer are precisely adjusted for printing accurately. The printer is connected to the local networks so that it can be monitored remotely and send print components. Import the 3D models into the Ultimaker Cura or preform software, adjustments like print orientation, supports for a structure, print speed and more required modifications to be made that are necessary for the printing. The Ultimaker Cura slices the 3D models which are in STL format into several thin layers, all those layers were built by the 3D printer. Transfer the output data of Ultimaker Cura to the printer then the laser of the 3D printer cures (hardens) the ABS resin and the build platform slowly rises additionally to allow the next layer to build**.** When the component is printed completely, that component is placed into an IPA (Iso Propyl Alcohol) so that the resin left without curing is washed away, after removing the component from an IPA, it is placed into a UV curing chamber to achieve the required/final mechanical properties. Supports which was added during the process should be removed carefully without affecting the main component. After curing there are other post-processing like sanding and other processes, which are essential to smooth out the surface of the printed components and for smooth assembling like pins in the case of multiple components. printed components are assembled, and a final check-up for a component is made then make sure it is ready for use.

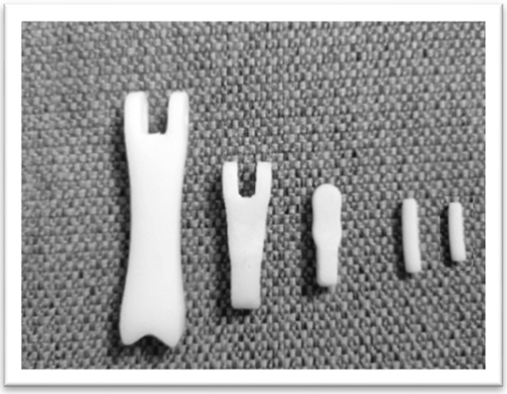


Image 12: Front View of Printed Components

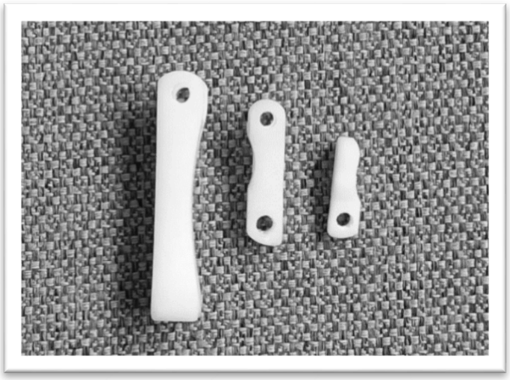


Image 13: Lateral View of Printed Components

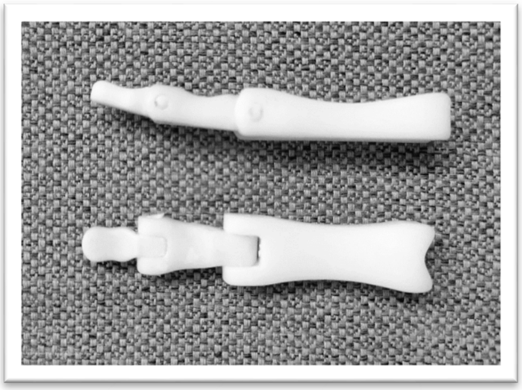


Image 14: Assembled 3D-Printed components

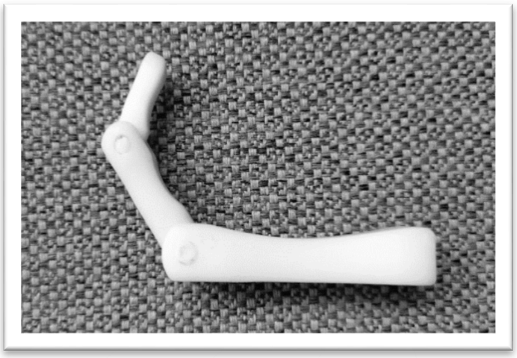


Image 14: Folding of 3D-printed components

The components are printed and assembled shown in the images above then in the following steps, mechanical properties like the Compression test and Hardness test are to be tested.

<u>MECHANICAL CHARACTERISTICS</u>:

Mechanical characterization describes the properties of materials like strength, behaviour under different conditions, and elasticity simplifying knowledgeable decisions in engineering and advanced innovations.

Compression Test:

The compression test is important for 3D-printed components because it determines the material's behaviour under compression load. It measures parameters like stress, strain, and deformation under compression. Through this test, we can understand how much load a component can withstand and to maintain the shape under pressure.

S No.	Load (KN)	Displace-ment (mm)	Compress-ion Stress (Mpa)	Compress-ion Strain	Modu-lus in Compre ssion (Mpa)
1	0.1	2.8	0.2604	0.0875	2.976
2	3.4	4	8.8542	0.125	70.8336
3	4.5	5.4	11.7188	0.1688	69.4241

Table 3: Compression Test Output

<u>Calculation</u>:

The height and width of the specimen 32 mm X12 mm

$$\text{So, Area } A = 32 \times 12 = 384 \text{ mm}^2$$

Trial-1

Compression Stress (σ) $= F/A = 0.1\times10^3 / 384$

$= 0.2604 \text{ N/mm}^2$

Compression Strain (ϵ) $= \delta / L = 2.8 / 32$

$= 0.0875$

Modulus of Compression (E) $= \sigma / \epsilon = 0.2604 / 0.0875$

$= 2.976 \text{ N / mm}^2$

Similarly, trail 2 and trail 3 are calculated the output values are tabulated. The component is broken at 4.6 KN of compression load. This output shows that the component can withstand approximately 4-10 Kg's load.

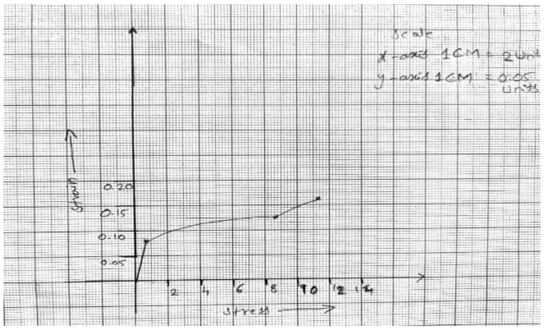


Image 15: Stress-Strain in compression

With the stress-strain graph, we can understand material behaviour under loads in this experiment maximum modulus in compression is obtained at 70.83 Mpa at $\sigma = 8.8542$ N/mm^2 and $\epsilon = 0.125$ which means the component has a moderate load-bearing capacity and long-term performance.

Hardness Test:

Measuring the hardness of 3D printed components is a method used to control the material's ability to resist deformation or indentation. An indenter applies a specific force against the surface of the component. Then measure the depth or size of the indentation after the usual time. Now calculate the hardness value according to the indentation. Rockwell hardness testing apparatus contains different scales (A, B, C…), these scales are used accordingly based on the type of indenter, like a ball indentor is used for soft materials (HRB) and a diamond-coated indentor is used for hard materials (HRC) [10].

S No.	Material	Indenter Type	Material Thickness (mm)	KgF	Load (Kg)	HRB
1	Cured Resin	Ball	04	10	60	54
2	Cured Resin	Ball	04	10	100	63
3	Cured Resin	Ball	04	10	150	78

Table 4: Rockwell Hardness Test Output

Calculation:

Average Rockwell Hardness number (RHN)

$= 54+63+78 = 195 \qquad = 195/3 = 65$ HRB

The HRB is 65 which means, the material has wear resistance that can withstand certain impacts which is crucial for the structure of bones. It will also have balancing strength and flexibility for shock absorption, and load distribution.

RESULTS & CONCLUSION:

The 3D-printed Index finger bones are designed with bio-based ABS resin using the SLA process. The dimensions of the bones are extracted using multiple radiographic images (X-ray). As this project aims for cost-efficiency, the artificial index finger bones in this project cost around $ 12-15 USD for reconstruction. Bio-based ABS resin has good Hardness as it has obtained RHN 65. The 3D-printed bones can resist the approximate weight of up to 0.1KN. These 3D-printed artificial bones can be used for temporary replacements, pre-operation planning, training, and they can also be used for permanent replacements with care. The development of bio-based artificial bones represents the advancement of biomaterials and Implantations.

FUTURE SCOPE:

Before the implantation of artificial bones for patients, both the pathology team and engineering team should conduct several trials. The 3D printing process can be used for designing artificial bones, and further research should be conducted for the direct replacement of artificial bones for humans and animals using Bio-based ABS resin. The continuation of research using bio-based materials and 3D printing technology could lead to more improvements in the strength and efficiency of artificial bones.

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