Optimization of FDM 3D Printing Process Parameters on ABS based Bone Hammer using RSM Technique

Umesh Kumar Vates¹, Nand Jee Kanu²,³*, Eva Gupta⁴,⁵, Gyanendra Kumar Singh⁶, Naveen Anand Daniel¹, Bhupendra Prakash Sharma¹

¹Associate Professor, Mechanical Engineering, Amity University, Noida, India
²PhD Research Scholar, Mechanical Engineering, SVNIT, Surat, India
³Assistant Professor, Mechanical Engineering, JSPM Narhe Technical Campus, Pune, India
⁴PhD Research Scholar, ASET, Amity University, Noida, India.
⁵Assistant Professor, Electrical Engineering, TSSM’s Bhivrabai Sawant College of Engineering and Research, Pune, India
⁶Faculty, Mechanical Design and Manufacturing Engineering, Adama Science and Technology University, Adama, Ethiopia

*Corresponding Author Email: nandssm@gmail.com

Abstract. Rapid prototyping (RP) uses a cycle where a real model is made by explicitly adding material as thin cross-sectional layers. Fused deposition modelling (FDM) 3D printer is being use for synthesis of ABS based bone hammer. Response surface methodology (RSM) based L2⁷ design of experiment were adopted to perform the experiment using four influencing parameters such as layer thickness, infill percentage, orientation and nozzle temperature for the three responses deflection, hardness and weight. Response surface methodology was used for modelling and optimization of considered process parameters. In present investigation, it is evident that bone hammer fabrication process parameters have been optimized on data such as bone hammer weight 19.8091g, hardness 104.5921 BHN, and force of 15-degree deflection 36.0681 N has been produced with RSM prediction with influence of process parameters such as layer thickness 0.250 mm, infill percentage 63.3333, orientation 60-degree, nozzle temperature 240°C.

Keywords. RSM, RP, FDM, ABS, Additive Manufacturing, Bone Hammer Optimization

1. Introduction

1.1 An insight

It is well known that additive manufacturing technologies (AMT) become popular in manufacturing sectors since 1980s. Previous technology involving in layered construction of physical models based on a digital 3D solid model was stereo lithography. One of the other layered manufacturing methods invented in the 1980s is the technology of the deposition of molten thermoplastic material. In this recent technology, material feed in the form of a very thin solid plastic wire is generally passed through the nozzle where it is heated to a temperature at which it becomes an intermittent phase of solid and liquid interface. The material is distributed as per design cross-section of the current building model. Rapid
prototyping (RP) licenses engineers to make considerable models quickly rather than straightforward two-dimensional pictures, such models are even using for various huge purposes from passing on contemplations to partners and customers to testing of different pieces [1]. Other than this, RP offers a lot of various advantages, for instance, unambiguous data managing and limit, ability to make complex shapes and interlocking plans, freed from contraption/work piece garbage, nonappearance of molds, kicks the pail, establishments and models, mass customization. As of now, the prevalent RP estimates open market are entwined declaration illustrating (FDM), stereo lithography (SL), and explicit laser sintering (SLS), overlaid object creating 3D printing and solid ground mitigating (SGC). Regardless, the introduction of any RP association is assessed with respect to manufacture time, quality ascribes like surface disagreeableness and dimensional accuracy, mechanical and tribological properties, cost of creation and energy use. 

These display extents of RP measures are through and through influenced by their participation limits. We explored the effect of cooperation limits on the perimetric exactness of the FDM models. Also we investigated the effect of cycle limits on the physical properties of the FDM models. Define conditions for versatility, various strengths of the FDM models were made using response surface technological way of thinking and alluring quality limit approach was used to expect the ideal blend of cycle limits [2, 3]. Mathematical models were made and ideal structure course was settled using a graphical strategy. The paper presents exploratory delayed consequences of the models on picked mechanical properties like force at 15 degrees evasion, Brinell hardness, and weight at consistent volume 25. Tests were made using the estimation and arranged a lot using SolidWorks 2013 [4]. They were made on a 1200es machine understanding the joined testimony exhibiting advancement (FDM) in light of plan of investigation masterminded using MATLAB considering all likely outcomes with changing of variable components to get the best strong hammer printed. Added substance manufacturing measurements are used to make genuine models from three-dimensional (3D) PC upheld plan (CAD) math data. The article is based on layer-by-layer stacking, with supporting developments for overhanging math and sabotages being made where essential (measure subordinate). The circuit of reconfigurable parametric inside matrix structures subject to rough segments will change the mechanical properties, the material uses and the structure time. The models were arranged on the machine stage at different focuses to the printing course. Similarly, what's more we changed genuine components of the printer to improve progressed results like the layer thickness, Infill rate, Orientation, and Nozzle temperature. The material used for the advancement of tests was ABS [5-7]. All the testing part was done truly on machines under evaluated bearing from specialists. Wide genuine testing is done as the fragments worked by the FDM cooperation have anisotropic properties. The mechanical properties and dimensional-shaped accuracy of elements manufactured by the aforementioned technology depend on the direction of its position on the building platform, the layer thickness and the heat of the working chamber [8].

There are papers in which authors analysed both selected mechanical properties, as well as the accuracy of elements manufactured using FDM. There are no studies concerning rheological tests in spite of current fact concerning to FDM, i.e., relaxation, especially in relation to process parameters such as printing direction. Samples were produced using FDM Technology. It is very important to determine the critical parameters of FDM and their values in regards to tensile strength. The impact of the degree of filling of the sample by model material was tested. Biodegradable material acrylonitrile butadiene styrene (ABS) was used to build the model. The study included 27 types of samples, which were printed along the three main axes: X, Y, Z and selected thickness of the combined layers. The amount of material wastage was kept in mind. The study confirmed the dependence of the mechanical properties of the selected printing direction during manufacturing [9-11]. Depending on the location of models on the working platform, different type of filling of support material was used. Based on the fact, support thickness was increased or decreased. Due to the fact that most of the elements of machines and mechanisms manufactured by additive technologies, they are subjected to a constant load, the research presented in this paper can be regarded as well founded. Additive manufacturing (AM) is a suitable name to portray the advances that assemble 3D protests by adding endless supply of material, regardless of whether the material is plastic, metal, concrete or human tissue and is an extraordinary way to deal with modern creation that empowers the production of lighter, more grounded parts and frameworks [3].
It gives expert looking item, on which the structure layers are hard to see, with noteworthy exactness and extensive assortment of materials than FDM. Fig. 1 is the 3D printing fishbone diagram for process. Metal additive manufacturing, components with complex plans, or those profiting by being light, for example, parts for airplanes, vehicles, trucks or clinical applications, will discover points of interest, while segments with basic plans, or where weight isn’t an issue, are better delivered utilizing customary, subtractive manufacturing. The aviation and clinical businesses are especially appropriate to see development. Fig. 2 indicates the 3D printing setup with nozzle.

1.2. AM materials

Materials for additive manufacturing are mentioned below:
Thermoplastics: Thermoplastic polymers remain the most famous class of additive manufacturing. Polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and polycarbonate (PC) each offer unmistakable favourable circumstances in various applications. Water-solvent polyvinyl alcohol (PVA) is normally used to make impermanent help structures.
Metals: Many metals and its compounds are utilized in additive manufacturing, as valuable metals such as silver, gold, treated steel and titanium. Fig. 3 indicates the traditional and additive manufacturing.
Ceramics: An assortment of earthenware production has additionally been utilized in additive manufacturing, including zirconia, alumina and tricalcium phosphate. Similarly, substitute layers of powdered glass and glue are prepared together to make altogether new classes of glass items.
Biochemical: Biochemical medical care applications incorporate the utilization of solidified material from silicon, calcium phosphate and zinc to help bone structures as new bone development happens. Analysts are additionally investigating the utilization of bio-inks created from undifferentiated cells to frame everything from veins to bladders and past.
Figure 3: Traditional v/s additive manufacturing

The impediment organizations face while examining additive manufacturing is the expense. New advances have made the expense considerably moderate, for a solid modern machine. Since additive manufacturing diminishes capital it is expected to scale up creation without rolling out significant enhancement, makers might have the option to push up and benefit of their plan of action. Revised version of product easily available: AM is something beyond making an actual item, but is tied in with carrying plan and development to the front line. In manufacturing, altering a plan during creation increases critical cost or time delays as tooling on a creation line is changed out. Additive manufacturing takes care of this issue by moving ceaselessly from static plans and empowering specialists to deliver various renditions of a solitary plan in a financially savvy way [1-14]. AM will not intrude on business tasks as there are wide assortment of preparing programs accessible for originators and makers at all degrees of comprehension. Reduction in waste production: AM creates less waste than customary manufacturing. The eliminated material is typically fuel or shavings that can't be reused and end up as waste. Contrasted and conventional manufacturing measures, additive manufacturing can essentially decrease energy use by utilizing less material and disposing of steps in the creation cycle.

1.3 Response surface methodology

Response surface methodology technique (RSMT) researches the associations between a couple of educational variables and in any event one response factors. The standard considered RSM is to use a gathering of arranged investigations to obtain an ideal response. RSM could be used to increase the formation of a phenomenal substance by smoothing out of operational segments. Maybe than customary methodologies, the association among measure variables can be directed by authentic techniques.

1.4 Fused Filament Fabrication (FFF)

It is also known fused deposition modeling (FDM), sometimes referred as filament freeform fabrication, and is a 3D printing measure that uses a constant fiber of a thermoplastic material. Fiber is dealt with from a colossal spool through a moving, warmed printer extruder head, and is kept on the creating work. The speed of the extruder head may similarly be controlled to respite and start declaration and design a barged in on plane without hanging or spilling between sections. "Consolidated fiber fabricate" was created by the people from the RepRap errand to give an articulation that would be genuinely unconstrained in its usage, given brand names covering "entwined declaration showing". The 3D printer head or 3D printer extruder is a part in material ejection added substance creating at risk for rough material mellowing and outlining it into a relentless profile [15, 16]. A wide arrangement of fiber materials are removed, including thermoplastics.
2 Materials and Methods

2.1 Introduction

ABS is an impact-resistant engineering thermoplastic and amorphous polymer. ABS is made up of three monomers: acrylonitrile, butadiene and styrene as structure of molecules given in Fig. 4. Acrylonitrile: It is a synthetic monomer produced from propylene and ammonia. The component contributes to ABS chemical resistance & heat stability. Butadiene: It is produced as a by-product of ethylene production from steam crackers. The component delivers toughness and impact strength to ABS polymer. Styrene: It is manufactured by dehydrogenation of ethyl benzene. It provides rigidity and process ability to ABS plastic, ABS is produced by emulsion or continuous mass technique. The chemical formula of acrylonitrile butadiene styrene is \((C_8H_8·C_4H_6·C_3H_3N)n\). The natural material is an opaque ivory color and is readily colored with pigments or dyes.

ABS is a strong and durable, chemically resistant resin but gets easily attacked by polar solvents. It offers greater impact properties and slightly higher heat distortion temperature than HIPS [17-19]. Acrylonitrile butadiene styrene has a broad processing window and can be processed on most standard machinery. It can be injection-molded, blow-molded, or extruded. It has a low melting temperature making it particularly suitable for processing by FDM based 3D printing machine. ABS falls between standard resins and often meets all the desire properties at a reasonable price-cost effectiveness. Key suppliers of ABS plastics include: SABIC, RTP Company, LG Chem, Ineos etc. 3D Printing ABS grades are readily available from 3D Systems, Stratasys, Techmer Engineered Solution.

![Molecular structure of ABS](image.png)

**Figure 4:** Molecular structure of ABS

2.2 Properties of ABS

Mechanical properties:

- High rigidity
- Good impact resistance, even at low temperatures
- Good insulating properties
- Good weldability
- Good abrasion and strain resistance
- High dimensional stability (Mechanically strong and stable over time)
- High surface brightness and excellent surface aspect

Chemical properties:

- Very good resistance to diluted acid and alkalis
- Moderate resistance to aliphatic hydrocarbons
- Poor resistance to aromatic hydrocarbons, halogenated Hydrocarbons and alcohols
Mechanical and electrical properties of ABS plastics have been explored in Table 1 as standard to enable understanding bone hammer requirement.

**Table 1: Properties of ABS**

| Mechanical properties          | Elongation at break | 10 - 50 % |
|--------------------------------|---------------------|-----------|
| Flexibility (flexural modulus) | 1.6 - 2.4 GPa       |           |
| Hardness Shore D               | 100                 |           |
| Strength at yield (tensile)    | 29.6 - 48 MPa       |           |
| Toughness (Notched Izod Impact at room temperature) | 200 - 215 J/m | |

**Electrical properties:**

| Arc resistance | 60 - 120 sec |
|---------------|-------------|
| Dielectric constant | 2.7 - 3.2 |
| Dielectric strength | 15.7 - 34 kV/mm |
| Volume resistivity | 14 - 16 x 10$^{15}$ Ohm.cm |

### 2.3 Printing process

- Fused filament fabrication (FFF) is the additive manufacturing bases technology; a fine plastic material filament is generally fed in to the influence of heated and moving head that melts and extrudes it to depositing layer-by-layer and form desired shape. Each layer is deposited over the layer with help of moving platform. Additional vertical support structures are required to sustain overhanging part during printing.
- FFF operated with software but requires STL file (stereolithography file format). It is also requiring support structures for holding the part [20].
- Nozzle is capable to move in both vertical and horizontal directions with given mechanical range which moves in the XY plane. Process: 1 – 3D Printer Extruder, 2 – deposited material (modelled part), 3 – controlled movable table
- Thin bead of deposited extruded plastic metal (called road) generally solidifies quickly and get rigid collapse with substrate just after movement of nozzle on table
- Servo motors are employed for extrusion head movement as the specified geometry.
- Platform is lowered in the z direction just after the completion of one layer in order to start the next layer. Such process is generally continuing till the complete fabrication of substrate.
- Thermal environment is very important control parameter for adequate bonding between the successive layers. It should be maintaining below the melting point [21].
- Materials such as Polylactic acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC), Polyamide (PA), Polystyrene (PS), and lignin, rubber may be applied on FDM also for fabrication of substrate as per design geometrical consideration. [22]. In addition, even the colour of a given thermoplastic material may affect the strength of the printed object
- During the synthesis of substrate, it is verdict that inert gas like nitrogen or argon significantly impacts on layer adhesion capabilities and mechanical properties of the 3D printed objects.

### 2.4 Process Parameters

The following are the most critical parameters generally found in literatures such as orientation, nozzle temperature (degree Celsius), printing speed (mm/s), infill density, shell thickness and layer thickness etc. In the present investigation, the process parameters are orientation, nozzle temperature, infill percentage and layer thickness.
2.5 Design of experiment

- Nozzle temp is measured as degree centigrade (ranging from 220-230-240) represented by -1, 0, 1.
- Steel ball intender for brinell hardness test was 1.58mm and constant load was 100 kg.
- Layer thickness is the layer height of each successive addition of material in AM (ranging from 0.15-0.2-0.25) represented by -1, 0, 1.
- The density of the pattern to be printed is known as infill percentage (ranging from 30-60-90) represented by -1, 0, 1.
- Orientation directly governs the productivity, part quality and cost of manufacturing (ranging from 50-55-60) represented by -1, 0, 1.

2.6 CAD model of bone hammer

Fig. 5 is the CAD model of different parts of bone hammer. It has been designed as per requirement in biomedical field. Lot of questioner’s float entire group of patient and doctors then after design factors were decided.

![Figure 5: Different portion of Bone hammer](a) (b) (c) (d)

3. RSM Modelling

- RSM based design of experiments (DOE) was conducted at three level input parameters using FDM 3D printing in different grade of ABS materials.
- Strength and bend test will be conducted on 3D printed bone hammer in each of the specimen. [2, 3]
- Using the experimental data responses have been predicted using RSM modelling.
- RSM is the technique which works based on integration of algorithms [23].
- Predicted and experimental responses were compared for error removal.
Table 2: Experimental Data

| Sample No | Layer Thickness (mm) | Infill (%) | Orientation (degree) | Nozzle Temp. (°C) | Deflection on 15 degree | Brinell Hardness (BHN) | Weight (g) |
|-----------|----------------------|------------|----------------------|-------------------|------------------------|------------------------|------------|
| 1         | 0.250                | 60         | 60                   | 230               | 42                     | 96                     | 16.4331    |
| 2         | 0.200                | 30         | 50                   | 220               | 37                     | 86                     | 10.0866    |
| 3         | 0.150                | 90         | 50                   | 230               | 41                     | 83                     | 20.2629    |
| 4         | 0.200                | 30         | 60                   | 230               | 35                     | 16                     | 16.3535    |
| 5         | 0.250                | 60         | 50                   | 220               | 52                     | 86                     | 15.8180    |
| 6         | 0.200                | 90         | 50                   | 220               | 46                     | 34                     | 19.3400    |
| 7         | 0.150                | 60         | 50                   | 240               | 53                     | 97                     | 16.3102    |
| 8         | 0.200                | 90         | 55                   | 230               | 55                     | 100                    | 17.0400    |
| 9         | 0.200                | 60         | 50                   | 230               | 52                     | 100                    | 14.8900    |
| 10        | 0.150                | 60         | 50                   | 220               | 30                     | 97                     | 16.0900    |
| 11        | 0.250                | 30         | 50                   | 230               | 32                     | 57                     | 11.9700    |
| 12        | 0.200                | 90         | 50                   | 240               | 58                     | 89                     | 11.9700    |
| 13        | 0.200                | 30         | 55                   | 220               | 33                     | 105                    | 20.3900    |
| 14        | 0.200                | 60         | 55                   | 230               | 48                     | 96                     | 11.2208    |
| 15        | 0.200                | 90         | 60                   | 230               | 46                     | 101                    | 20.4858    |
| 16        | 0.250                | 60         | 50                   | 240               | 44                     | 104                    | 20.1800    |
| 17        | 0.150                | 30         | 50                   | 230               | 46                     | 103                    | 16.5224    |
| 18        | 0.250                | 90         | 50                   | 230               | 44                     | 87                     | 11.4500    |
| 19        | 0.200                | 60         | 50                   | 230               | 33                     | 90                     | 19.5600    |
| 20        | 0.200                | 60         | 60                   | 220               | 53                     | 90                     | 16.0140    |
| 21        | 0.200                | 30         | 55                   | 240               | 43                     | 89                     | 15.8000    |
| 22        | 0.150                | 60         | 60                   | 230               | 48                     | 88                     | 12.1203    |
| 23        | 0.200                | 60         | 55                   | 220               | 28                     | 93                     | 16.3400    |
| 24        | 0.250                | 60         | 60                   | 230               | 42                     | 100                    | 16.2400    |
| 25        | 0.200                | 60         | 50                   | 230               | 47                     | 89                     | 16.0081    |
| 26        | 0.150                | 60         | 55                   | 230               | 55                     | 100                    | 16.0200    |
| 27        | 0.200                | 60         | 60                   | 230               | 36                     | 81                     | 16.5000    |

Figure 6 3D printed bone hammer

Bone hammers have been manufactured through FDM 3D printer as per the design of experiment listed in Table 2 which is being expressed in Fig. 6. It has been fabricated on FDM 3D printed bone hammer.
It is very clear from Fig. 7 that bone hammer weight increasing with increase of layer thickness, infill percentage and nozzle temperature. Hardness is also proportional to the nozzle temperature. Deflection of bone hammer is also proportional to the infill percentage and nozzle temperature. All the interaction plots (Fig. 7) are self-explanatory and verifying the main effect plots. It is evident from Fig. 7 that high nozzle temp.; infill percent and low layer thickness are responsible to increase weight of bone hammer. However, hardness increase with low thickness of layer at high nozzle temperature also high deflection occurs at low infill percentage [24-30].

![Main Effects Plot for Bone hammer weight (g)](image1)
![Main Effects Plot for Hardness(BHN)](image2)
![Main Effects Plot for Force for 15 deg. Deflection (K)](image3)
![Interaction Plot for Bone hammer weight (g)](image4)

**Figure 7:** Main effect plot of bone hammer process parameters

4. **Optimization of process parameters**

Fig. 8 indicates that optimal process parameters layer thickness 0.250, infill percent 63.3333, orientation 60 and nozzle temperature 240 are the best suited to produce quality bone hammer with economical consideration. Present optimization plot has been plotted on composite desirability 'D' 0.8795 which indicates the probability to achieve such responses. It was again tested with conducting experiment by considering optimal parameters; the result was almost same as having bone hammer weight 20.3045g, hardness 105.5653 BHN, and force at 15 degree deflection 35.4471 N with 1.64 percent error.
5. Conclusions

It is evident that 3D printing technology is the alternate way throughout product development which can reduce design risk and, result in better quality of products. Main competitor materials of 3D printing are ABS and PLA. Unlike PLA, ABS is a renewably derived plastic. It is therefore biodegradable and biocompatible whereas PLA is only biocompatible. However, ABS is 100% recyclable, non-toxic and harmless. Best quality of bone hammer responses (having bone hammer weight 19.8091g, hardness 104.5921 BHN, and force at 15 degree deflection 36.0681 N has been produced with RSM prediction with influence of process parameters (layer thickness 0.250, infill percentage 63.3333, orientation 60 degree, nozzle temperature 240°C). RSM is the best suitable technique through which further prediction may be done for biomedical equipment manufacturing. Response surface methodology (RSM) allows researcher to approximate the behavior of a process in the vicinity of the optimum.  Rapid prototyping, on the same platform as production, aids quick progression of novel designs and features. Economically feasible to print multiple custom designs in one build [31-35].

References

[1] El-Gizawy AS, Cardona J, Graybill B 2010. An integrated approach for characterization of properties and meso-structure of fused deposition modeling ULTEM 9085 products. International SAMPE Symposium and exhibition.
[2] Kanu,N.J; Gupta,E; Vates, U.K; and Singh,G.K; 2019 An insight into biomimetic 4D printing, RSC Adv., 9, 38209
[3] Ahn SH, Montero M, Odell D, Roundy S, Wright PK. 2002 Anisotropic material properties of fused deposition modelling ABS. Rapid Prototyping Journal; p. 248–257.
[4] Daniel, N.A; Singh,N.K; Vates,U.K; Sharma, B.P; and Sivaraos 2019 Optimization of Critical Parameters of EDD Steel in Die Cavity Manufacturing, Advances in Industrial and Production Engineering, Springer Nature Singapore Pte Ltd., Lecture Notes in Mechanical Engineering, pp 357-363.
[5] Saqib S, Urbanic, R.J.2011 An experimental study to determine geometric and dimensional accuracy impact factors for fused deposition modelled parts. 4th International Conference on Changeable Agile, Reconfigurable and Virtual Production; p. 293-298.
[6] Alexander, P., Allen, S., Dutta, D., 1998. Part orientation and build cost determination in layered manufacturing. Computer-Aided Design, Vol 30, No 5, pp. 343-356.

[7] Cz. Kundera, T. Kozior 2014, Research of the Elastic Properties of Bellows Made in SLS Technology, Advanced Materials Research, Volume 874 pp. 77-81.

[8] Bonten C. Kunststofftechnik: Einfuehrung und Grundlagen 2021, Characterization of FDM printed product: A review, polymers, 124 (2) p. 252-264.

[9] Khangarot H, Sharma, S, Vates, U.K, Singh, G.K, & Kumar, V; 2018. “Optimization of Surface Grinding Process Parameters Through RSM” Proceedings of the International Conference on Modern Research in Aerospace Engineering pp 291-302, Print ISBN: 978-981-10-5848-6, Online ISBN: 978-981-10-5849-3, Springer, Singapore.

[10] Turner BN, Strong B, Gold SA. 2014 A review of melt extrusion additive manufacturing processes: I. Process design and modeling. Rapid Prototyping Journal; 20/3:192-204.

[11] Rodriguez JF, Thomas JP, Renaud JE. 2001 Mechanical behavior of acrylonitrile butadiene styrene fused deposition materials. Experimental Investigation. Rapid Prototyping Journal; p.148-158.

[12] Cz. Kundera, 2013, Seals of rotating systems, Monograph M53, Kielce University of Technology, Kielce, p. 286-294.

[13] Cz. Kundera, J. Bochnia 2014, Investigating the stress relaxation of photopolymer O-ring seal models, Rapid Prototyping Journal, 20 (6) 533-540.

[14] Inspekt Mini. 2011 Universal Testing Machine Inspekt mini 3kN - User’s Guide, Hegewald & Peschke, Meß- und Prüftechnik GmbH 5- p.1-478.

[15] Villalpando L. 2013 Characterization of parametric internal structures for components built by fused deposition modeling. Electronic Theses and Dissertations: University of Windsor.

[16] Agarwala MK, Jamalabad VR, Langrana NA, Safari A 1996, Whalen PJ, Danforth SC. Structural quality of parts processed by fused deposition. Rapid Prototyping Journal p. 4-19.

[17] L. Koch, A. Deiwick and B. Chichkov, 2018 Laser-Based Cell Printing, 3D Printing and Biofabrication, Springer International Publishing, Cham, pp. 303–329.

[18] Hopkinson, N., Dickens, P., 2003. Analysis of rapid manufacturing using layer manufacturing processes for production. Proc.Instn Mech.Engrs Vol.217 Part C.

[19] Anitha R, Arunachalam S, Radhakrishnan P. 2001. Critical parameters influencing the quality of prototypes infused deposition modelling. Journal of Materials Processing Technology. p. 385-388.

[20] J. Skrzypek,1986, High Strain Rate Thermo-Inelasticity of Damaged AISI 316H, Plasticity and creep, PWN, Warsaw p. 628-637.

[21] Sahu, K.L; Kumar,N; Singh,A; Daniel, N A; and Vates, U.K; 2020 ‘Investigation of Laser- MIG hybrid welding performances in Al alloys with influence of Ar-He-Ne mix shielding’ Review’ 2nd International Conference on Future Learning Aspects of Mechanical Engineering (FLAME) Department of Mechanical Engineering Amity University Uttar Pradesh (India)

[22] ISO 3384: 2002, Rubber, vulcanized or thermoplastic compression at ambient and at elevated temperatures.

[23] UK Vates, N.A.Daniel, Dr.N.K.Singh, Parametric Optimization & Simulation of Mild Steel Cup in Deep Drawing using LS-Dyna, International Journal of Applied Engineering Research 10 (9), 24479-24489, 2015.

[24] Ayushi, UK Vates, S Mishra, NJ Kanu, Biomimetic 4D printed materials: A state-of-the-art review on concepts, opportunities, and challenges. Materials Today: Proceedings. 47 (2021) 3313-3319. https://doi.org/10.1016/j.matpr.2021.07.148.

[25] NJ Kanu, Modeling of stress wave propagation in matrix cracked laminates. AIP Advances. 11 (2021) 085217. https://doi.org/10.1063/5.0057749.

[26] NJ Kanu, D Patwardhan, E Gupta, UK Vates, GK Singh, Numerical investigations of stress-deformation responses in fractured paediatric bones with prosthetic bone plates. IOP Conference Series: Materials Science and Engineering. 814 (2020) 012038. https://doi.org/10.1088/1757-899X/814/1/012038.
[27] A Lal, NJ Kanu, The nonlinear deflection response of CNT/nanoclay reinforced polymer hybrid composite plate under different loading conditions. IOP Conference Series: Materials Science and Engineering. 814 (2020) 012033. https://doi.org/10.1088/1757-899X/814/1/012033.

[28] NJ Kanu, E Gupta, UK Vates, GK Singh, Self-healing composites: A state-of-the-art review. Composites Part A: Applied Science and Manufacturing. 121 (2019) 474-486. https://doi.org/10.1016/j.compositesa.2019.04.012.

[29] N Jain, E Gupta, NJ Kanu, Plethora of Carbon nanotubes applications in various fields–A state-of-the-art-review. Smart Science. (2021). https://doi.org/10.1080/23080477.2021.1940752.

[30] NJ Kanu, S Bapat, H Deodhar, E Gupta, GK Singh, UK Vates, GC Verma, V Pandey, An Insight into Processing and Properties of Smart Carbon Nanotubes Reinforced Nanocomposites. Smart Science. (2021). https://doi.org/10.1080/23080477.2021.1972913.

[31] CM Asre, VK Kurkute, NJ Kanu, Power generation with the application of vortex wind turbine. Materials Today: Proceedings. (2021). https://doi.org/10.1016/j.matpr.2021.08.228.

[32] MA Kumbhalkar, KS Rambhad, NJ Kanu, An insight into biomechanical study for replacement of knee joint. Materials Today: Proceedings. 47 (2021) 2957-2965. https://doi.org/10.1016/j.matpr.2021.05.202.

[33] M.A. Kumbhalkar, D. T. Rangari, R. D. Pawar, R. A. Phadtare, K. R. Raut, A. N. Nagre, “Finite Element Analysis of Knee Joint with Special Emphasis on Patellar Implant”, Trends in Mechanical and Biomedical Design” in book series of Lecture Notes in Mechanical Engineering, pp 319-333, 2020. ISBN 978-981-15-4487-3. https://doi.org/10.1007/978-981-15-4488-0_29

[34] M A Kumbhalkar, P H Jaiswal, H M Bansod, “Design and Manufacturing of Knee Joint using CAD/CAM and Rapid Prototyping” published in Journal of The Institution of Engineers (India), Mechanical Engineering, 25-28, Volume 92, April 18, 2011.

[35] M. A. Kumbhalkar, Umesh Nawghare, Rupesh Ghode, Yogesh Deshmukh, Bhushan Armalkar “Modeling and Finite Element Analysis of Knee Prosthesis with and without Implant”, published in Universal Journal of Computational Mathematics, Vol. 1(2), Horizon Research Publishing, USA, pp. 56–66, 2013. https://doi.org/10.13189/ujcmj.2013.010204.24.