Study of compressive behaviour on 3D printed ABS polymer lattice structures infilled with epoxy and polyester resins

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Abstract: The 3D printing process is a design driven manufacturing process. The complex shaped structures can be produced in a short lead time with high precision percentage. The functionally graded polymer oriented cellular structures are possessing great energy absorbing ability. In recent years, the application of cellular structures are highly utilized in 3D printing process for developing functional prototypes without compromising strength to weight ratio. In this study, a novel approach to develop functionally graded uniformly open porous structures of fixed volumetric proportions are created and it is selectively infilled with polyester and epoxy resins. After curing process the samples were tested for analyzing the improvement of compressive behaviour. The results of the compressive behaviour were compared between non-porous structures, resin infilled porous structures and non-resin infilled lattice structures. The interface between the resin and the base material also exhibited good adherence which promises the usage of this methodology in creating more customized hybrid composite materials for the various applications by using 3D printing technique.

Keywords: Additive manufacturing, Fused deposition modelling (FDM), Lattice structures, infill of resins, ABS material, Compressive behaviour.

1. INTRODUCTION

It is important for industries to reduce the lead time, cost of the industrial products manufactured and to achieve the high strength to weight ratio of the products without compromising the build quality [1]. Additive manufacturing is one of the best solutions to satisfy the above requirements and with the help of additive manufacturing techniques highly energy absorbing, light weight and strong cellular structures can be created [2]. This process involves manufacturing of the product in layer by layer fashion [3]. As per Wohler’s report, the application of additive manufacturing widely spreads in many fields like tooling, consumer products, electronics, bio-medical implants, dental, motor vehicles, aerospace, industrial, military and architectural [4]. Cellular structures have been increasingly used in modern engineering and medical applications due to their advantageous mechanical and thermal
properties [5]. In addition, cellular structures are widely used in applications, like thermal insulation, shock or vibration damping, acoustic absorption, current collectors in battery electrodes, catalyst supports and biomedical implants [6]. The mechanical behaviour of cellular materials e.g. energy absorption capability and plateau load-deformation response mainly depends on the porosity and the material used for its fabrication [7]. For the same porosity, the yield strength could be increased and the build time shortened simultaneously by having a certain cell size control [8]. Additive manufacturing technology enables manufacturing of uniformly regular cellular structures which allows for accurate cell shape control to fulfill some chosen properties for individual applications [9]. The different types of uniformly regular cellular structures generally fabricated through AM process are honey comb, crisscross, triangular, circular and diamond [10]. The tooling produced with AM are suitable for low volume products, rapid changing high volume products and easily adapt design iterations, which are time consuming and expensive in tradition practices [11]. The significant advancement in Additive Manufacturing (AM) processes enables the fabrication of innovative parts, characterized by minimum weight and good mechanical properties [12]. The significant advancement in Additive Manufacturing (AM) processes enables the fabrication of innovative parts, characterized by minimum weight and good mechanical properties [13]. This AM process in general is classified into seven types [14]. However this project is mainly emphasized with the FDM type of manufacturing. FDM is highly used polymer based additive manufacturing technique used for creating many complex shaped structures [15].

The figure 1 shows the fishbone diagram of various 3D printing technologies.

![Fishbone Diagram of 3D Printing Technologies](image)

Figure 1. Various 3D printing technologies

2. METHODOLOGY

In this paper, we discuss a method of improving the mechanical strength of the 3D printed part with the help of resin infilling technique. The design of the part is made such that the volumetric proportions are 60% base material (ABS) and 40% resins filling void. A full solid ABS material is tested whose volume is completely made of ABS and two parts filled with resins of fixed volumetric proportions are tested and a part that is left void for the same proportions is also tested.

3. PRINTING AND INFILLING OF THE PART

3.1 Design for 3D Printing

The design of the 3D printed part is made with the ASTM standard for compression test of rigid polymers (ASTM D695) [16]. The designing of compressive test specimens were carried out using CATIA V5R20 software. The dimensions of the 3D printed parts are 38.1mm in diameter and 25.4mm
in length. Based on the design for the volumetric proportions mentioned earlier, the design is made such that the radius of the void is 4.55mm and has seven through holes in total volume. The figure 2 shows the designed CAD model of the part.

![Figure 2. CAD Model design using CATIA V5.](image)

3.2 Fabrication of Compressive test specimens

The mode of 3D printing is the fused deposition modelling which belongs to the material extrusion family. Here ABS and PLA are the most commonly used printing material. Here for printing the part, infill pattern is chosen to be hexagonal and the infill density is 100%. Other standard parameters like layer height, number of perimeter shell, and the print speed are unchanged and are constant [17, 21]. The extrusion temperature for the filament drawn is 230°C. The properties of the 3D printer used in this study is stated in table 1. The images of the fabricated specimens are shown in figure 3 as follows.

![Figure 3. Fabricated parts.](image)

3.3 Infilling of resins

This study involves two resins namely epoxy and the polyester resin. Although various resins are available for filling the voids, these two are selected based on their meritorious properties, availability and their relatively low cost of nature. These resins are added carefully to the voids only through the manual means [18, 23].

3.3.1 Epoxy resin and Polyester resin preparation

Epoxy resin and polyester resin are mixed with hardener at 2:1 proportion in room temperature. The resin and hardener undergo chemical reaction. This reaction takes until molecular cross linkage occurs. This time is known as curing time. Polyester is an adequate adhesive but not as good as epoxy [19, 22]. As a general rule, the strength of a polyester bond will be around 20 percent weaker than the same bond made with epoxy resins. Polyester resins and MEKP (Methyl Ethyl Ketone Peroxide) catalyst is used as hardener. The mixing proportions used are 30ml of resin and 20 drops of MEKP.
Table 1. Parameters set for 3D printing

| Printing Parameters   | Options Used | Units     |
|-----------------------|--------------|-----------|
| Layer Height          | 0.18         | mm        |
| Number of Perimeter Shell | 4          | -         |
| Fill Density          | 100          | %         |
| Fill Pattern          | Hexagonal    | -         |
| Print Speed           | 40           | mm/sec    |
| Travel Speed          | 60           | mm/sec    |
| Extruder Temperature  | 230          | Degree Celsius |

For epoxy and polyester resin the added ratio of resin to hardener is 2:1 and this mixture is allowed to cure for about 24 hours. The figure 4 shows the preparation of resins by mixing with hardener. Though epoxy is general resin without any solvent, the polyester would have very strong smell due to the vaporization of the solvent present in them during the times of curing. To accelerate the phase of curing hardeners are used. The figure 5 shows the cured parts after 24 hours.

Table 2. Curing time and mixing ratios

| Resins | Mixing Proportion | Curing Time (Hours) |
|--------|-------------------|---------------------|
|        | Resin (ml)         | Hardener (ml)       |                     |
| Epoxy  | 200                | 100                 | 24                  |
| Polyester | 300              | 150                 | 24                  |

Figure 4. Preparation of resins.
Figure 5. Specimens after curing

4. TESTING OF SAMPLES
The compression testing is carried out as per ASTM D695 standard at room temperature by using Instron UK compression tester. The ASTM D659 standard is generally used for the rigid plastics [20]. Any plastic under compression will have three phases namely the plastic phase, plateau phase, and the densification phase. The point of conversion of plastic to plateau is called the yield point after which the material disobeys hook’s law. At the plateau phase excessive bulging of the material along the length is seen significantly. At the densification stage the material completely disorients and breaks down. The figure 6 shows the specimen after compression test.

4.1 Quality of Interface region

The video measuring system was used to ensure the infill quality and it was clearly found that both the resins were perfectly bonded with the base material in the interface region and also the resins infilled the pores without any voids. The figure 7 depicts the enlarged view of quality at interface.

Figure 6. Specimens after compression test
5. RESULTS AND DISCUSSION
The compression test was done for all the four parts and their values are compared. The resulting load vs elongation graph for the various parts are shown in figures 8, 9, 10, 11 respectively. The addition of epoxy to ABS parts had improved the strength of the manufactured part for about 25.5%. Epoxy is strong and has great compressive strength. In general thermosetting polymers exhibit more strength than thermoplastic polymer. So this combination provides higher strength than the solid part. The addition of polyester to ABS parts had improved the strength of the manufactured part to about 12.9%. Polyester resins have compressive strength of 94mpa. Polyester resins filled parts have less strength than epoxy and more strength than hollow parts. Addition of polyester resins to ABS have strength improvement than hollow parts but less than epoxy.
Figure 9. Load (KN) vs Elongation (%) of epoxy filled ABS

Figure 10. Load (KN) vs Elongation (%) of polyester filled ABS

Figure 11. Load (KN) vs Elongation (%) of void ABS

From the above graphs the values of stress and strain are calculated. Comparing this with the stress-strain graph the yield and the ultimate stress values are found and are given below in the table 3. The figure 12, 13 and 14 shows the comparison of yield stress, ultimate stress and overall comparison between various specimens used in this study.

Table 3. Yield stress and ultimate stress of the specimens

| Category of Specimens           | Yield Stress (MPa) | Ultimate Stress (Mpa) |
|---------------------------------|--------------------|-----------------------|
| Solid Sample                    | 31.19              | 50.96                 |
| Epoxy Filled ABS Sample        | 41.9               | 85.72                 |
| Polyester Filled ABS Sample    | 35.82              | 61.85                 |
| Void ABS Sample                | 23.86              | 51.43                 |
6. CONCLUSION
The open non-stochastic circular cellular structure was designed in cuboid shape as per ASTM standards. The specimens were designed in the volumetric composition of 60% base material density and 40% void density which was filled later with epoxy and polyester resins. This study was carried out as a pre-indicative study to verify the compatibility of creating hybrid functionally graded material which is to be used for direct functional end tooling applications. Four types of specimens which is of different volumetric compositions were tested and the results were inferred. The compression test were carried out to examine the energy absorbing ability of the functionally graded material. The results of this study are concluded as follows.
This novel technique of infilling resins into the additive manufactured cellular structures showed a good bonding interface and also proven to be a better technique in producing functionally graded materials.

Two types of resins were used in this study (Epoxy – Thermosetting resin) and (Polyester – Thermosetting resin). The base material is ABS (Thermoplastic). The interface layer of ABS-EPOXY and ABS-POLYESTER is good and this promises the possibility of more studies can be carried out by using different materials in future.

The ABS-EPOXY composition provided higher absorbing capability than ABS-POLYESTER and from other specimens which shows the addition of thermosetting resin reinforced the properties of thermoplastic base material significantly.

The specimen without any infilled resin (void part) has reduced strength due to less resistance offered by the air.

The 100% density solid ABS part shows reduced strength than functionally graded structures which promises the utilization of this study in creating customized applications.

This method of resin addition to strengthen the polymer parts may be further studied under two methods. Firstly, multiple layers of resins may be coated to a certain thickness which would enhance the impact and scratch resistance of the part. Secondly, the resin addition instead of manual method can be done by protected vacuum condition method along with the printing of the base material.

REFERENCES

1. Olga Ivanova Christopher Williams Thomas Campbell, (2013), “Additive manufacturing (AM) and nanotechnology: promises and challenges”, Rapid Prototyping Journal, Vol. 19 Issue 5 pp. 353 - 364
2. Mehrdad Mohsenizadeh, Federico Gasbarri, Michael Munther, Ali Beheshti, Keivan Davami, “Additively-manufactured lightweight Metamaterials for energy absorption”, Materials and Design 139 (2018) 521–530.
3. D.W. Gibson, Rosen, B. Stucker, “Additive manufacturing technologies: rapid prototyping to direct digital manufacturing” Springer, New York, 2010.
4. Chunlei Qiu, Sheng Yue, Nicholas J.E. Adkins, Mark Ward, Hany Hassanin, Peter D. Lee, Philip J. Withers and Moataz M. Attallah “Influence of processing conditions on strut structure and compressive properties of cellular lattice structures fabricated by selective laser melting”, Materials Science & Engineering, 2015, Vol. 628, pp. 188–197.
5. MatejVesenjak, Lovre Krstulovi Opara, Zoran Ren and Zeljko Domazet, “Cell shape effect evaluation of polyamide cellular structures”, Polymer Testing, Vol. 29, 2010, pp. 991–994.
6. Iyibilgin, O., Yigit, C., and Leu, M.C, “Experimental investigation of different cellular lattice structures manufactured by fused deposition modeling”, Proceedings of Solid Freeform Fabrication Symposium, Austin, TX, 2013, pp. 895-907.
7. Sathishkumar N, Sugavaneswaran M, Arumaikkannu G, “Investigation of sparse mode build style on material consumption, build time and compressive behaviour of additive manufactured cellular structures”, 6th International & 27th All India Manufacturing Technology, Design and Research Conference (AIMTDR-2016), December 16-18, 2016 at College of Engineering,, Pune, Maharashtra, INDIA, ISBN:9789386256270.
8. Cerardi, Caneri M., Meneghello R., Concheri G., Ricotta M “Mechanical characterization of polyamide cellular structures fabricated using selective laser sintering technologies”, Materials and Design, Vol. 46, 2013, pp. 910–915.
9. Sathishkumar, N., Arunkumar, N., Balamurugan, L., Sabarish, L., & Joseph, A. S. S. (2020). Investigation of Mechanical Behaviour and Surface Roughness Properties on Copper Electroplated FDM High Impact Polystyrene Parts. In Advances in Additive Manufacturing and Joining (pp. 287-300). Springer, Singapore.
10. Balamurugan, L., N. Sathishkumar, N. Arunkumar, and G. Aravind. "Investigation of mechanical behaviour and surface roughness properties on electroplated FDM ABS parts." *Int. J. Eng. Res. Mech. Civ. Eng* 2 (2017): 60-67.

11. Sugavaneswaran M., Rajesh N., Sathishkumar N. (2020) Design of Robot Gripper with Topology Optimization and Its Fabrication Using Additive Manufacturing. In: Shunmugam M., Kanthababu M. (eds) Advances in Additive Manufacturing and Joining. Lecture Notes on Multidisciplinary Industrial Engineering. Springer, Singapore.

12. Prithivirajan R., Sugavaneswaran M., Sathishkumar N. and Arumaikkannu G. (2019), "Metal bellow hydroforming using additive manufactured die: a case study", Rapid Prototyping Journal, Vol. 25 No. 4, pp. 765-774.

13. Sugavaneswaran M., Rajesh N., Sathishkumar N. (2020) Design of Robot Gripper with Topology Optimization and Its Fabrication Using Additive Manufacturing. In: Shunmugam M., Kanthababu M. (eds) Advances in Additive Manufacturing and Joining. Lecture Notes on Multidisciplinary Industrial Engineering. Springer, Singapore.

14. Prithivirajan R., Sugavaneswaran M., Sathishkumar N. and Arumaikkannu G. (2019), "Metal bellow hydroforming using additive manufactured die: a case study", Rapid Prototyping Journal, Vol. 25 No. 4, pp. 765-774.

15. Afshara M, Pourkamali Anarakia A, Montazeriana H, Kadkhodapour J, “Additive manufacturing and mechanical characterization of graded porosity scaffolds designed based on triply periodic minimal surface architectures”, *Journal of the mechanical behavior of biomedical materials*, Vol.62, 2016, pp. 481–494.

16. Xiaojian Wang, Shaqing Xu, Shiwei Zhou, Wei Xu, Martin Leary, Peter Choong, M. Qian, Milan Brandt, Yi Min Xie, “Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: A review”, *Biomaterials*, Vol. 83, 2016, pp.127-141.

17. L.J. Gibson, M.F. Ashby, Cellular Solids: Structure and Properties. *Cambridge university press*, 1997.

18. Arun, M., N. Sathishkumar, K. Nithesh Kumar, S. S. Ajai, and S. Aswin. "Development of patient specific bio-polymer incisor teeth by 3D printing process: A case study." *Materials Today: Proceedings* (2020).

19. Ashby, M.F., Evans, A., Fleck, N. A., Gibson, L. J., Hutchinson, J. W., and Wadley, H. N. G., “Metal Foams: A Design Guide”. *Woburn, MA: Butterworth-Heinemann*, 2000.

20. Rasoul Mahshid, Hans Nørgaard Hansen, Klaus Loft Hojbjerg, “Strength analysis and modeling of cellular lattice structures manufactured using selective laser melting for tooling applications”, *Materials and Design*, Vol. 104, 2016, pp. 276–283.

21. Sathishkumar, N., Naren Vivekanandan, L. Balamurugan, N. Arunkumar, and Ijaz Ahamed. "Mechanical Properties of Triply Periodic Minimal Surface based lattices made by Polyjet Printing." *Materials Today: Proceedings*. Vol. 22 (2020): 2934-2940.

22. ASTM F2792-12a, “Standard Terminology for Additive Manufacturing Technologies”, ASTM International, West Conshohocken, PA, 2012.

23. Sathishkumar, N., Udayakumar, ASM., Vincent, B., Ashok Kumar, V., “Study and analysis of 3D printed FDM components by non-destructive testing techniques”. *International Journal of Research and Review*. Vol. 7, Issue 5, 2020, pp. 217-222.