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Experimental and Finite Element Analysis of 3D Printed Parts for Characterisation of Their Mechanical Behaviour

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Abstract: As an upcoming technology, Additive Manufacturing (AM) or 3D Printing has gained popularity due to its simplicity, reliability, and speed for product development. It gives design freedom to designers for designing and redesigning complex components so that they fit for their respective purposes. Though AM through its unique capabilities offers a wide scope to the designers, still the properties of the 3D printed components depend upon many process parameters like layer thickness, build orientation, infill density, and print speed. Therefore, the research works in the domain of Fused Deposition Modelling (FDM) are focused on the assessment of strengths of the printed parts through the characterisation of their mechanical behaviour. In this work, a review of variety of related works is presented, and a methodology is proposed in this regard as per the standards laid down, involving experimentations and validation through Finite Element Analysis (FEA). This will help the researchers to assess their designs by optimizing the process parameters for the specific objectives. Also, this work will motivate the designers to adopt the methodology while deploying AM printed parts for end use.

***Keywords**: Additive Manufacturing, Fused Deposition Modelling (FDM), Finite Element Analysis (FEA), Material Characterization, Optimization.*

1. Introduction:

Additive Manufacturing (AM) is an evolving technology that is useful for the production of lightweight parts with good strength and therefore finds a prominent place in the aerospace and automotive industries, as also for manufacturing intricate and complex medical and dental implants [1, 2]. The unique capabilities of AM viz. Shape, Hierarchical, Material, and Functional Complexity enable new opportunities for customization, very significant improvement in product performance, manufacturability, and lower overall manufacturing costs thus enabling design freedom [3]. The layer-by-layer deposition of material by using a CAD model which is exported as STL file, makes it possible for a designer to go beyond the conventional designs and explore the capabilities of the AM process to optimize the geometry of the product. The use of net shape manufacturing principle and no tooling requirements make AM the least expensive [4].

Fused Deposition Modelling (FDM) is an extrusion-based AM process used for design studies, rapid prototyping and non-critical spare parts production though having a few inherent disadvantages like the size of parts manufactured as well as surface and microstructural imperfections [5], geometrical and dimensional accuracy [6], need of surface structures [7], insufficient mechanical characteristics [8], and difficulty in creating components for end-use [4]. However, its application in structurally loaded components is limited, and the reason being cited that the engineers are sceptic due to a lack of knowledge about the expected lifetime and reliability of these components under stress, is valid [9].

Irrespective of the various materials used, FDM printed parts exhibit anisotropy, and porosity. The layer-by-layer deposition of extruded molten material makes it behave with an anisotropic property that is governed by the microstructure so produced [10,11]. As reported by Abouzaid et al [12], for the FDM-produced parts with good dimension accuracy due to positive airgap, porosity in the part is indispensable, and as reported by Al-Mharama et al the pores that emerge from AM are distributed into three critical locations in the structure viz. in the bulk material, between deposited layers, and at the fibre/matrix interface region for fibre composite materials processed by AM and the interlayer generated pores have a critical effect on the bond strength. The effect of process parameters of FDM on the tensile, compressive, and flexural strengths of the printed part, has been a focused domain of research since the outcomes help in arriving at the optimum values of the process parameters for a specific functional requirement of the part.

As proposed by Chia et al the large parameter space in AM requires more sophisticated approaches for optimisation rather than simple trial and error which

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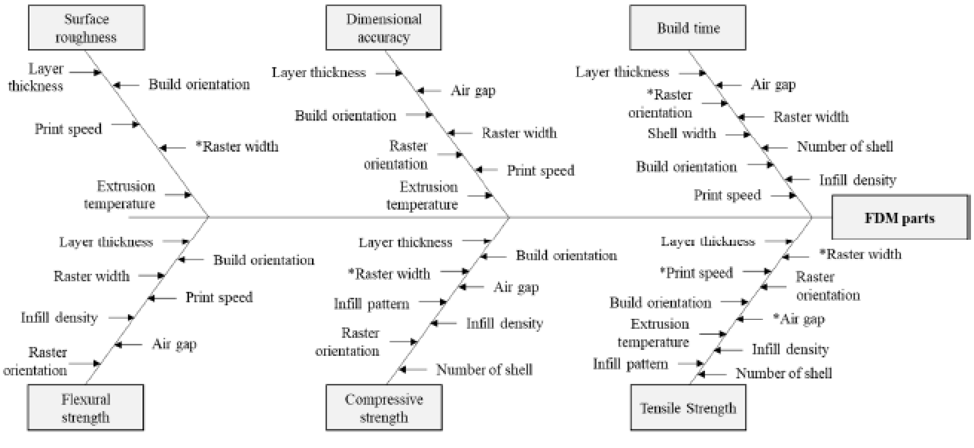
begins by identifying a suitable processing map for a given material and combination of parameters within the near-zero defects processing regions. Many research works on optimisation of process parameters have been carried out for different materials by considering specific process parameters and their effects [15,16,17]. Moreover, exhaustive reviews of such kind of works have been made by Dey and Yodo [18], Mohamed et al [19], Kristiawan et al [20], Suniya and Verma [4], and Potdar and Joshi [8].

A fishbone diagram indicating the effect of process parameters on the strengths of FDM printed parts, is reproduced from [18], and shown in figure 1.



* Indicates still unknown whether a parameter is significant for a part characteristic or not

Fig 1: A fishbone diagram to illustrate the main effect of process parameters on FDM [18].

In addition to the above, creep property especially for polymers which are sensitive to temperature and strain rate plays a crucial role in performance of plastic parts [19]. As mentioned by Oguz [21], the creep behaviour of polymers is significant in industrial applications where dimensional stability is essential and therefore parts should be designed accordingly. Moreover, deployment of FDM printed parts in structural and load-bearing applications make them to face fatigue due to cyclic stress which leads to catastrophic failure at a lower stress than in case for the normal static mechanical loading, as referred by Shanmugam et al [22]. As such the fishbone diagram depicted in figure 1, needs to be modified to account for the effect for creep, and fatigue as well.

To summarize, in view of the polymer material properties, process parameters, and defects observed in FDM printed parts, their mechanical strength characterisation is essential to ensure their fitness for purpose, and long life. This can be done through laboratory experiments by using appropriate setups and following the existing standards, however, it is required to validate the results so arrived at. Finite Element Analysis (FEA) has been in use for past many years, and validation through simulation of elasto-plastic behaviour can be done by creating near realistic models.

2. Previous works on mechanical characterisation of 3D printed parts:

2.1. Need of research:

The necessity of research on mechanical characterisation of 3D printed parts, is due to a shift of 3D printing from prototyping to manufacturing of the final product, with a view to achieve the necessary mechanical properties to meet the performance criteria [23]. However, the assessment of mechanical strength of FDM printed parts is a challenging work since in their basic form, polymers exhibit a range of mechanical behaviours and properties from the phases of elastic solid to viscous liquid, and these depend on the material constituents, their structure, temperature, frequency and time scale at which analysis is done [24]. Moreover, the classical methods of mechanical characterisation relied upon for additively manufactured parts, were all developed for solid and homogeneous samples produced conventionally and besides that, many different types of emerging 3D printing processes demand to develop criteria for more advanced fields of material mechanics [25].

Lack of specific guidance to quantify the tensile strength of AM products has been a concern [15].

Apart from the above, in the FDM printed parts the microstructural anisotropy and the inherent interlayer voids i.e., porosity inside their structure, reported as drawbacks by Cardoso et al [26], are required to be considered while determining the mechanical properties correctly. This is supported by way of reporting by Dizon et al [27] that in FDM there is a large part-to-part and intra-part variations of the mechanical anisotropy and it is largest approximately at 50% among all AM techniques. In this concern, Garzon-Hernandez et al [28] too in their work related to FDM components have related mechanical anisotropy and void density i.e. porosity with the process parameters. While dealing with porosity, to improve the structural performance of AM oriented porous structures, design optimisation involving Topology Optimisation was performed by Zhao et al [29] on a FDM printed cantilever beam by comparing with an established method, through numerical analyses and mechanical testing. Such approaches can be considered while undertaking the work of mechanical characterisation. Nevertheless, it is observed that in most of the research works, references or revelations on drawbacks of FDM, are not found prominently.

On the basis of literature survey, the research works related to assessment of strengths of AM manufactured parts can be broadly categorised as follows:

1. a) Basic works for finding tensile, compressive or flexural strengths.

   b) Comparisons of the strengths of various polymers.

   c) Comparisons of the strengths of the 3D printed parts with those conventionally

   manufactured say by Injection Moulding.

2. Validation of experimental values of strength with Finite Element Analysis (FEA).

3. Application oriented research.

Apart from the above, reviews of the research works relevant to mechanical characterisation of 3D printed parts were also found. All the above mentioned works are discussed in the following section highlighting their contributions.

2.2. Contributions of researchers:

It is important to understand the philosophy of the researchers while dealing with the mechanical strength of FDM processed parts, as also the trend of the research so that the research gaps can be identified. The objectives and findings are given in brief for all the related research from the year 2003 to 2023, i.e for the time horizon of past 20 years.

In 2015, Mohamed et al [19] have reviewed some research works on static and dynamic mechanical properties along with the effects of process parameters on other quality characteristics, and concluded that there were still no perfect optimal conditions for all types of parts and materials and the properties of FDM fabricated parts can be controlled by the selected build styles and other FDM parameters. They further emphasised on research related to optimisation of FDM process variables for thermal, chemical, and dynamic mechanical properties of FDM parts in all material forms, and stressed that study on effects of process parameters need to be extended to hardness, creep, vibration, porosity, and stress strain behaviour at high strain-stress loading conditions among other ones. Physical constraints imposed on FDM machine are also cited which render FDM process parameters optimisation complicated.

Simultaneous evaluation of the effects of five FDM process parameters (control factors) on the quality performances like hardness and tensile stress among others by using Taguchi's L27 orthogonal array design of experiments to test parts of PLA with polycarbonate fortification, was done by Enemuoh et al [16] using a dog bone sample as per ASTM D638 Type IV. Signal-to-noise ratio mean effect analysis, and analysis of variance (ANOVA) were used by ignoring interaction effects among the control factors, to conclude that infill density has the highest effect on tensile strength whereas layer thickness has highest effect on hardness.

Apart from the effects of process parameters on tensile strength of the FDM printed parts, Gordelier et al [15] reviewed the effects of standards adopted in research works and effects of material selection on tensile strength, as well as citing results of comparative studies involving different materials, and samples manufactured by injection moulding. While reviewing the research on experimentations, they raised an issue related to premature failure of the hour glass specimens at the bend radius outside the gauge length due to stress concentrations claimed to be intensified by FDM technique, and revealed that despite of this fact the data from the investigations were reported as valid results, and only limited number of studies published images of failed specimens. In this connection they suggested to refer test standards for other materials that have similar anisotropy issue, like fibre reinforced composites.

Though Dizon et al. [27], reported various works on testing mechanical properties of parts printed using different AM technologies, commonly used ASTM and ISO test standards have been mentioned besides discussing issues like overcoming the limitations of using FEA for approximation of mechanical properties of AM printed parts. They posed questions related to standardization of test methods, which will provoke researchers for future works.

Popescu et al [30] made a review in 2018 for knowing the relevance of research of setting the process parameters on mechanical behaviour of products so as to apply them in real life applications and pointed out that mechanical properties' optimisation should be performed by considering complex combination of material, machine, and manufacturing conditions instead of focussing solely on setting of process parameters. As their review laid a thrust on need of evaluating the mechanical performances of FDM end-parts and their suitability for particular application, they raised an issue of impact of sterilisation on mechanical properties of medical field instruments, implants, etc. and how process parameters can be optimised from this perspective. Also issues of results which will be obtained with intra-3D- printer variability for same set of parameters, and inadequate study of effect of parameters like nozzle, and bed temperature are mentioned in the review.

In 2019, Dey and Yodo [18] presented current and future research trends on FDM process parameters optimisation and their influence on part characteristics by reviewing research since the year 2005. Various statistical tools used by researchers are mentioned in their work, and summary of research analysis on effect of process parameters on mechanical properties of parts has been inter alia made. The feature of this referred work is that researches on mechanical characterisation by way of investigating range of characteristics like lattice structure, material volume, support volume, modulus of rupture, thermal conductivity, mechanical damping, storage modulus, etc. have been mentioned along with the concerned process parameters and the methods or tools deployed. They concluded that there is still limited research that compares the mechanical properties of parts produced from different materials, and that more parameters are needed to be analysed simultaneously to know cumulative effect on flexural strength. Further, one more research gap identified is that complex part geometry and process parameters are to be considered together for improving part characteristics, besides considering the uncertainties in FDM process. They recommended use of machine learning and image processing for predicting the part characteristics.

In a recently done review work by Suniya and Verma [4] in 2023, a summary of twenty-one major research works on optimisation of process parameters of FDM parts is given with a mention of nineteen optimisation techniques deployed therein using different materials, besides giving respective process parameters investigated for various mechanical performance parameters. They concluded that few researches are reported that studied flexural strength, and also there is further scope in research of multi-objective optimisation of process parameters to improve mechanical properties of FDM parts.

Kristiawan et al [20] reviewed various factors influencing mechanical characteristics of FDM parts by revealing the relationship of each part of FDM process, from the extrusion of raw materials to the printing process and mentioned four critical aspects in this regard. Thus, an emphasis has been made that material of filament and process of making filament can also be a variable to improve mechanical properties.

Rajan et al [7] discussed mechanical investigations carried out for different materials, process parameters, properties, and potential application of FDM They also discussed the advanced materials used in FDM and various parameters optimisation to achieve maximum mechanical properties, and advocated for reinforcing fibres with polymers to improve them.

Abouzaid et al [12] stated that predicting and controlling mechanical characteristics of FDM printed parts is crucial for their final use and focussed on extrusion temperature dependent effect on anisotropy, porosity, and decrease in cohesiveness between the deposited filaments, by citing previous works. They have presented mechanical properties viz. uniaxial tensile strength, Young’s modulus, and fracture toughness of different FDM-made polymer composites depending on printing temperature.

The study of Bodur et al [6] focused on the effect of infill pattern geometry and its percentage on the actual infill percentage, mass and density of FDM manufactured eco-PLA parts as per ISO 10791-7, by using industrial Computed Tomography and observed the internal lattice structure and pattern-to-pore ratio. They opined that the errors in manufactured infill pattern can lead to density variations, and changes in mechanical properties of the printed parts.

Effect of infill and nozzle diameter on pore size and porosity of FDM printed parts with rectilinear pattern was studied by Buj-Corral et al [31], in which the experimental pore size and porosity values obtained by X-ray Tomography were compared with theoretical and simulated ones, by using a PLA prismatic sample. Variations of pore size and porosity with infill and nozzle diameter, have been found out in their work.

In a most recent study, Potdar and Joshi [8] while reviewing researches on process parameters’ effect on mechanical characteristics of FDM parts, pointed out that in literature the data related to strength improvement is scarcely found, and that compromise must be found for parameter optimisation on case-to-case basis. It was concluded that for determining effects of extrusion temperature, printing speed and layer thickness on flexural strength in-depth research is required, and additional research is needed to evaluate shear strength and impact strength for determining service life of components, as also to know effects of more complex shapes.

Oguz [21] presented a literature survey of earlier works carried out to investigate creep behaviour of FDM parts, and investigated creep behaviour of different test specimens made of respective six types of polymers, under the effect of three ambient temperatures and two stress levels. ASTM D638 Type IV, and ASTM D2990-17 were followed, and the FDM printed parts were machined by CNC Milling for giving final dimensions. It was found that load is more effective parameter than temperature for creep, and that PLA has worst and PC has best resistance against creep.

Garzon-Hernandez et al [28] have taken a step further by formulating a new continuum hyperelastic constitutive model for finite deformation of FDM parts which accounts for non-linear response and anisotropic hyperelasticity related to porosity among others and accounts for both material and printing dependencies. For validation, prior experimentation is done by using thin rectangular specimen, and an agreement on values was found on various counts for uniaxial loading for tensile test. Thus, a new proposition has been made in the field of mechanical performance of FDM printed parts.

Abbot et al [32] have carried out comparative study for FDM printed cubes of various materials by conducting physical tests under compressive loadings across the two different layering axes and through simulations by FEA. They arrived at the conclusions that large discrepancy existed between the results of said methods due to compactness and porosity difference of physical and modelled parts, and that the design of 3D parts has strong dependence on application of the parts. Kaveloglu and Temiz [33] performed an experimental and FEA of honeycomb structures of PLA and ABS samples by putting them under axial compression, and selecting cell size and wall thickness as parameters. They found that in terms of elastic buckling, plastic buckling and cell wall crush, the deformation of samples was similar in both experimentation and FEA, and that ABS samples yielded more stable results compared to PLA samples. Birosz et al [34] gave the determined material properties, as the input to FEM analysis for simulation of a compressor wheel to investigate creep properties. Thus, a complex geometry component was simulated with the tested parameters, after concluding that creep in FEM modelling shows deviation in acceptable range, from value measured through test.

Mishra et al [35] studied the effect of layer thickness on impact, flexural, and tensile strength of FDM printed Polyamide specimen and prediction through FEM by making an assumption that the printed layer thickness will not change after printing. Moreover, the bending and tensile simulations are done with the assumptions of elasto-plastic deformation under 3-point bending, and uniaxial loads respectively to get corresponding average prediction accuracy of 87% and 94%. In context of these works, it is pertinent to state that to deal with the anisotropy exhibited by the 3D printed parts, it is suggested that an extremely fine mesh i.e. element dimensions much smaller than the filament cross section, should be used to represent the microstructure accurately [36].

As regards to the end use 3D printed parts or applications of 3D printed parts in real life conditions, their mechanical characterisation has been reported in some works. Shu et al [37] validated FE models of PLA temporomandibular joint by physically testing 3D printed models under five pressure forces. In this test, ten strain rosettes were deployed on the mandible for measuring horizontal and vertical strains and inter alia a difference of 4.92% was found between the two results. In another study Provaggi et al [38] with an objective to cut down product design and development time, demonstrated that FDM assisted FEA can be used for predicting the performance of a lumbar cage design. In this work the lumbar cage was printed with three materials, three infill densities and three infill patterns and the results of mechanical tests viz. compressive modulus, and compressive yield strength were used for FEA to optimise manufacturing parameters for withstanding maximum load with minimum material and manufacturing time.

A novel work was carried out by Sedlak et al [39], in which tensile, and Shore D hardness tests were done on samples of four polymer materials in their non-degenerate state and post exposure to four degradation effects viz. humidity, temperature, UV radiation, and weather condition. The results of this study guides for selection of appropriate material for specific applications.

From the above literature survey, a trend of research in the domain of mechanical characterisation can be noticed. In most of the works, the standards for testing polymers have been used by the researchers, and in few the test standards adopted have not been revealed. In some works, the deviations from the standards in terms of size/geometry of the specimen deployed in the experiments are also not mentioned. Moreover, the prominent assumptions made by them have not been stated. Apart from this, while pointing out that for some process parameters, non-conclusive results have been found in literature, Syrlybayev et al [40] opine that for optimising the best parameters it is required to have a case specific trade-off solution. Further, they brought forth shortcomings in research viz. divergent data on the effect of layer thickness, absence of proper metrics, limited availability of data on the effect of nozzle diameter, and different results related to optimal orientations, and raster angles for different strengths.

In the present work, a research gap in form of non-availability of comparison or validation of results by using two or more different statistical techniques in the literature, is identified as per the best knowledge of the authors, which if performed, would give a further idea of degree of correctness or corroboration of the results. This is utmost required in cases of the structural components, and also for those put to dynamic loadings. Similarly, the validation of experimental results by means of another experimental method(s), also could not be seen.

In engineering, most of the validations of the results obtained by experimentations are done by using Finite Element Analysis, however, not in many works reviewed here, this was practiced. Further, researchers are expected to reveal the failure zones of the specimen used clearly so as to authenticate the validity of their experiments. In addition, only few researchers cited the difficulties faced by certain limitations of FDM process while discussing the modality of experiments conducted.

All the above observations should give an insight to the researchers and motivate them for further works.

4. Mechanical Characterisation Process:

4.1 Use of Test Standards: Though lack of supporting framework and guidelines for AM processes are not available, for quantifying strengths of FDM printed parts the ASTM standards are used for carrying out the experimentations for evaluating tensile, flexural, and impact strengths though they are meant for polymers. The test standards are also available for investigating creep behaviour, and fatigue. In some of the researches, ISO and DIN standards are also used alternatively, and some specific purpose standards like Boeing BSS 7260 and SACMA SRM 1R-94 are followed which are used for composite materials.

Even though the test standards are available, deviations from them are witnessed in many works on account of certain observations. More prominent is the change in geometry of the specimen used in the experiments, in some cases the reasons are given while in others no comments are made. Secondly, as mentioned in earlier section, failures of specimens outside the gauge length are considered as valid and that rarely the failed specimens are displayed as reported by Gordelier et al [15]. Such type of practices may give the results which are not authentic and relying upon them for further course of work, will lead to skewed results.

For these reasons, a generic holistic process for material characterisation of AM printed parts is required which is proposed in the next subsection though FDM has been referred in the preceding sections.

4.2 Holistic process for material characterisation:

For mechanical characterisation of an AM printed part, first of all objectives need to be set depending on its functional roles by taking into account whether it is a prototype or an end use product, what are the priorities e.g. light weight, resilience to dynamic loads, etc. Accordingly, the mechanical properties to be tested in conjunction with the part material and the AM process, need to be finalised. Subsequent to this, optimisation of either the specimen part design or process parameters or both need to be done by using various techniques, say topology optimisation may be used for optimising part geometry and, statistical techniques may be deployed for selected process parameters optimisation.

Once the said optimisations are performed, the part can be printed and subjected to the experimentations by following the standards laid and observing the values of the desired mechanical properties and also the failure patterns, if any. Assumptions made on various counts during the experimentations should be reasonably based, say if the specimen shape and size deviates from that prescribed by the standards, proper approximations must be considered. On the other hand, if the part is an end use part, the working conditions are different than the test conditions for which necessary compensations must be made. Repetitive tests should be done on similar specimen/part to ensure nearly same values.

The values or scenario of failure so observed in the experimentations need to be validated by conducting FEA using a standard software. The assumptions made as referred above need to be considered while performing the modelling for FEA. Once the validation is done, the same can be used for further work, and the part can be deployed for use if it is an end use product, else an assessment need to be done. Again, the selection of material, part design and / or selection of parameters and their optimizations will be required till the time the experimental values and simulation values closely agree. A flowchart depicted in figure 2, shows these steps.

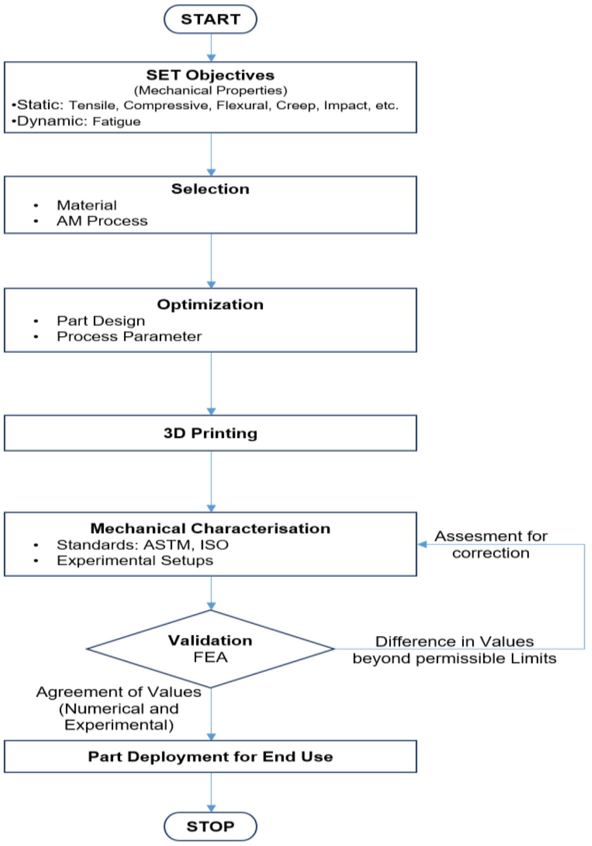


Fig 2: Flow chart for holistic process of mechanical characterisation of 3D printed parts

5. Experimentation:

In this research work, a sample spanner is 3D printed using Acrylonitrile Butadiene Styrene (ABS) material, on a Pratham 3.0 Fused Filament Fabrication machine i.e. through FDM process, with the following process parameters:

Layer thickness = 0.15 mm

Orientation = 0 degree, 45 degrees, and 90 degrees

Infill density = 20%, 50%, and 80%

Print speed=60 mm/s

Infill pattern- Honeycomb

Thus, in all, nine samples were printed with the above settings. For finding out the mechanical strength of the spanner i.e. its ability to bear the torque before failure, a digital torque test machine deployed for industrial quality assurance at Taparia Tools Ltd., Nashik, was used. The experimental setup is shown in figure 4, on which the spanner was tested across the flats. The Double Ended Open Jaw Spanners are generally conforming to Indian Standard Specifications IS 2028 : 2004 & IS 6131 : 1980, and tested accordingly. After the tests, the values of torque, and patterns of failure which were the outcome of variations in process parameters, were noted.

The failure modes were found similar to that of metal spanner, which indicates that even though the printed part exhibits anisotropy, its behaviour remains the same under the applied torque.

Fig. 4 Experimental setup for testing the spanners

Assuming the same test conditions, FEA trials were carried out on the modelled spanner with ABS material using ANSYS software by considering the concerned isotropic material properties. As shown in Figure 5, the areas of failure were seen exactly in a similar region as per the analysis and history of failures of metal spanners as per the manufacturer's failure data.

The difference in values in both the methods is attributed to the anisotropy, and porosity of the FDM printed parts due to the internal layering effects.

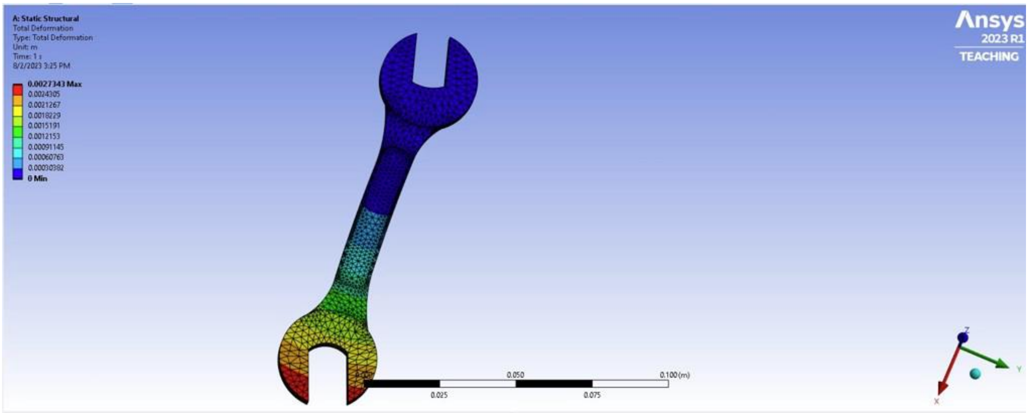


Fig. 5 Finite Element Analysis of the spanner

6. Conclusion:

In the present work, the necessity of the mechanical characterisation of FDM parts, the associated issues to be considered while performing the same, and the findings of different types of earlier related researches have been discussed to know the trend of research, gaps in research and scope for future works. On the basis of the said literature study, a holistic procedure has been proposed in this work by providing the flowchart for effectively carrying out the mechanical characterisation. This paper also attempts to bridge the processes viz. optimization of the process parameters, and mechanical characterisation.

An experimentation has been demonstrated in which an end-use product- a spanner was tested using industry grade setup and applicable standards. The validation of the said test was shown as performed through FEA software. Thus, the mechanical characterisation in terms of the torque bearing ability by the spanner was attempted by varying the process parameters of FDM.

In this work, it has been observed that few more aspects of FDM, like the effect of support structures, heat transfer mechanism, uncertainties in the process, etc. also need to be taken into account besides the process parameters, which may have a substantial effect on the strength of the printed components. One important insight got here is that mechanical characterisation can't be considered in isolation by ignoring the technique like Topology Optimisation of scaffolds and lattices to improve toughness. Also, the post processing techniques which enhance the microstructure, release residual stress, and improve surface finish, should be considered. Further, effects of Functionally Grade Materials, and part geometry affiliated local stress concentration, can be stated as sub-domains of the present research which need to be explored.

To summarize, 360 degrees efforts are required to arrive holistically at the mechanical characterisation of FDM printed parts.

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