



ARTICLE

Enhancing Mechanical Performance of FFF-Fabricated PEEK Using an Integrated GA-ANN and FEA for Mandible Fracture Application

Ashish Phogat¹, Akash Ahlawat¹, Virendra Singh² and Deepak Chhabra^{1,*}

¹Department of Mechanical Engineering, University Institute of Engineering and Technology, Maharshi Dayanand University, Rohtak, Haryana, India

²Department of Oral and Maxillofacial Surgery, Post Graduate Institute of Dental Sciences, Haryana, Rohtak, India

*Corresponding Author: Deepak Chhabra. Email: deepak.chhabra@mdurohtak.ac.in

Received: 13 February 2026; Accepted: 11 June 2026; Published: 23 July 2026

ABSTRACT: Polyether ether ketone (PEEK) is a radical filament with excellent strength equivalent to cortical bone and high thermal-mechanical properties. PEEK's acquisition is acceptable in the fabrication of cranio-maxillofacial implants because of its exceptional strength-to-weight ratio and biocompatibility. However, its implementation in fused filament fabrication (FFF) is impeded by the lack of a cohesive optimisation framework that involves varying vital parameters: layer height, infill density and two post-process parameters: annealing temperature, annealing time, which affect its mechanical performance. This research work introduces a comprehensive methodology that integrates experimental design, hybrid Genetic Algorithm Artificial Neural Network (GA-ANN) modelling and finite element analysis (FEA) to improve the tensile properties of FFF fabricated PEEK. A total of 32 specimens (ASTM D638-IV) have been fabricated as per the central composite design (CCD) and tested for tensile strength using the Universal Testing Machine (UTM UNITEK 94100). The maximum tensile strength of 58 MPa is achieved at a layer height of 0.1 mm, 60% infill density and an annealing temperature of 250°C for a duration of 2 h. A hybrid GA-ANN is introduced to optimise process parameters, where ANN is trained using the Levenberg-Marquardt algorithm, achieving high predictive accuracy ($R = 0.97375$). GA-ANN has enhanced the tensile strength up to 3.34% at 0.13 mm layer height and 53.977% infill percentage at an annealing temperature of 202.47°C, with an annealing time of 2 h. A maximum von-Mises stress of 61 MPa is obtained through FEA validation. Moreover, a force-based case study on plate-screw assembly of mandible under physiological loading shows a maximum deformation of 0.92 mm, suggesting an adequate fixation stiffness supporting the mechanical suitability of the fixation construct. The experimental, numerical and GA-ANN-predicted results are in good agreement.

KEYWORDS: Additive manufacturing; PEEK; GA-ANN hybrid model; FEA; mandible fracture

1 Introduction

Additive manufacturing (AM) has redefined recent production paradigms by enabling the fabrication of lightweight, complex, and customised components with nominal material waste and shorter lead times. The pursuit of replacing traditional metal products with lighter alternatives has led to the growing consideration of polymer-based surrogates. Metal surrogates provide a viable alternative to traditional components, such as low cost, lightweight, and noise [1]. Initially, plastic is a suitable choice for surrogacy due to its low cost and ease of fabrication of complex parts. However, industries found it challenging to replace metal with thermoplastic polymers because of their low mechanical properties [2]. With the emergence of high-performance polymers (HPP), industries have continued to struggle with the substitution of metal for

HPP owing to similar mechanical limitations [2]. Among these polymers, polyether-ether-ketone (PEEK), a semi-crystalline thermoplastic, stands out for its exceptional thermo-mechanical properties, as well as its radiation and chemical resistance [3–6]. Consequently, PEEK is suitable for structural components across various industries, including the automobile [7] and aerospace [8]. Additionally, PEEK is applicable in a range of biomedical applications, serving as an instrumental device like dental and surgical implants [9,10]. Various techniques have been utilised to fabricate PEEK, including machining, injection molding, and extrusion [11,12]. Recent advancements in additive manufacturing (AM), particularly through fused filament fabrication (FFF), showcase the potential of PEEK, offering benefits such as complex geometries and minimized production time. However, there are challenges to fabricating the PEEK as it has a high melting point and is more prone to warping, leading to manufacturing defects [13]. In certain conditions, due to rapid thermal incline, PEEK often induces residual stress and incomplete crystallisation, which impact the structural integrity and performance of fabricated parts [3,13]. In spite of the fact that many studies have examined the individual effects of FFF parameters and annealing on the properties of PEEK, their integrated investigation assessing their combined influence has not been accomplished [3,6]. Some examined blending PEEK with amorphous aPAEK-FDx improves Z-axis tensile strength, strain at break, and surface quality of FDM-printed parts by enhancing molecular chain diffusion, and incorporating rGO and cHAp into PEEK significantly enhances its mechanical strength, bioactivity, and osteogenic potential, making it suitable for biomedical implants, additionally incorporating partially compatible amorphous polymers into PEEK improves interlayer diffusion and entanglement, significantly enhancing interlayer strength in 3D-printed parts, it also confirms biocompatibility, supporting potential medical applications [14–16]. Furthermore, 3D-printed PEEK dental implants, fabricated via FFF with optimised raster angles ($45^{\circ}/-45^{\circ}$), demonstrated mechanical properties similar to natural tooth tissues, making PEEK a promising low-cost alternative to titanium and zirconia implants [17]. Some blends of PEEK/PEI with low-viscosity and low-molecular-weight PEEK151G showed improved strength, lower melt viscosity, and better 3D printability, indicating their potential for advanced additive manufacturing [18]. Whereas, adding 1 wt% mHNTs to a PEEK/PEI blend improves mechanical, thermal, and morphological properties. The uniform distribution of mHNTs improves tensile, flexural, hardness, impact, storage modulus, glass transition, and degradation temperatures [19]. The annealing markedly improves the compressive strength and modulus of 3D-printed PEEK, especially FCC designs, with hybrid FCC-Gyroid structures by alleviating residual stresses and enhancing bonding and mechanical performance, exhibiting a strength increase of up to 59.4% [20]. Moreover, the absence of standardised annealing protocols, specifically those optimised for the unique crystallisation behaviour of PEEK, limits the reproducibility and industrial adoption of additive manufacturing using this high-performance polymer [13]. Although optimisation using FEA and topology optimisation, and FFF enable the design of lightweight, comfortable, and structurally stable customised parts [21]. Also, ANN-GA hybrid model and MOGA-ANN minimise the surface roughness and enhance strength, wear resistance, and surface finish for industrial applications of 3D printed prototypes, and optimise the part quality [22,23]. However, previous studies primarily focus on isolated parameter effects and material modification, while an integrated framework combining process parameters, annealing behaviour, predictive modelling and validation remains limited. This study proposes a novel framework for integrating DOE, GA-ANN optimisation and FEA validation within a single framework for FFF-fabricated PEEK. Fig. 1 illustrates a thorough process. A total of 32 specimens are fabricated and tested, revealing a tensile strength of 58 MPa. The GA-ANN model predicts high accuracy ($R = 0.97375$) and identifies near-optimal settings that are consistent with experimental observations, while FEA correlation validates the mechanical response with a maximum von Mises stress of 61 MPa. Further, the medical relevance of the numerical framework is strengthened by a force-based case study to validate the finite element model under realistic loading conditions. Emphasis is placed on examining stress distribution at the plate-screw interfaces and evaluating stress transfer to

the surrounding bone, given their critical roles in mitigating stress shielding and implant-induced bone resorption. This work contributes to the development of reliable and enhanced additive manufacturing enactments for engineering applications involving advanced thermoplastics by synthesising experimental findings and conducting comparative evaluations.

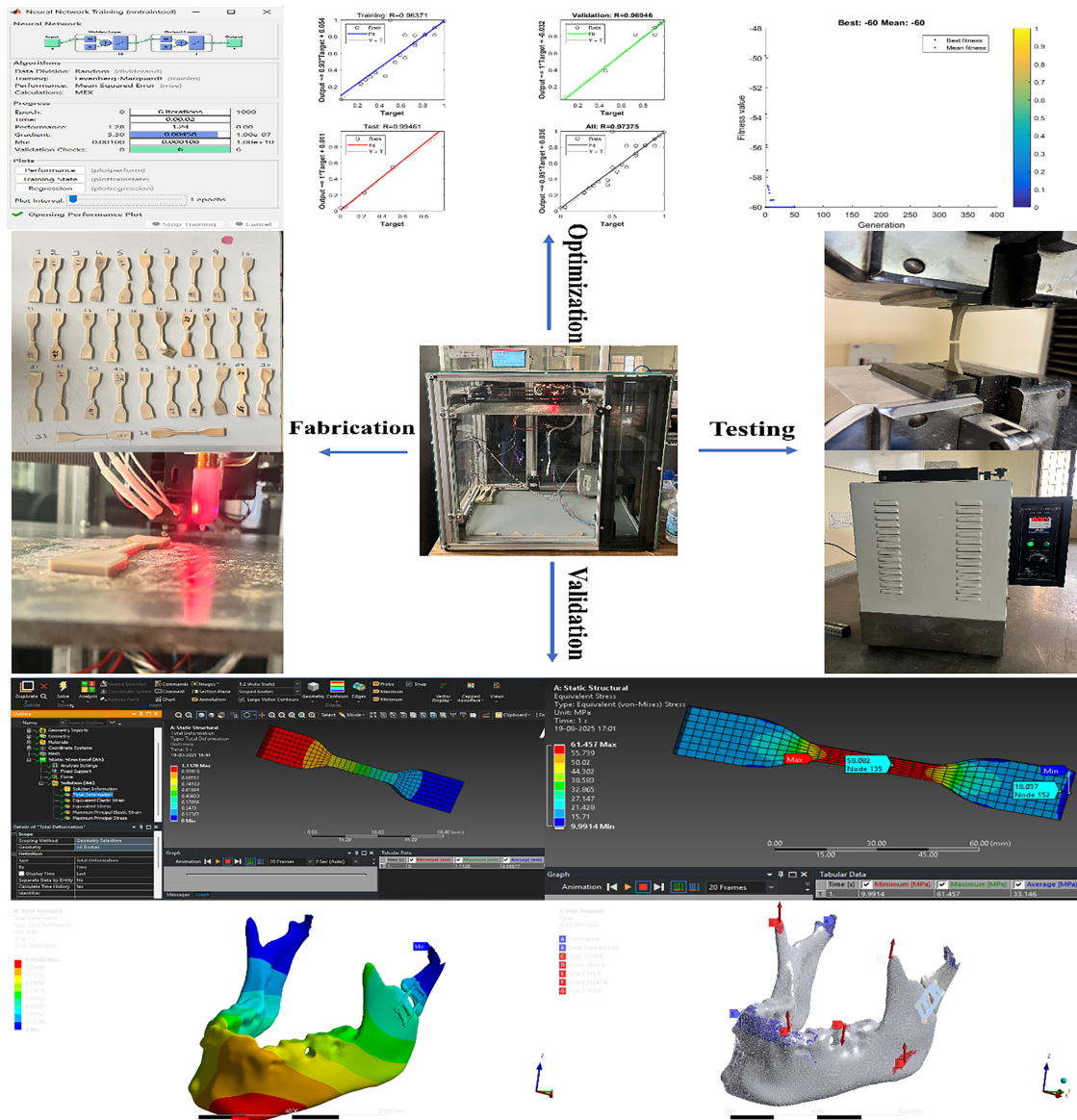


Figure 1: The thorough process of manufacturing, testing, and validation using a hybrid tool.

2 Materials and Methods

2.1 Material

ThermaXTM PEEK by 3DXTech, Michigan, USA, is used to fabricate all PEEK test specimens having a diameter of 1.75 ± 0.05 mm. PEEK has high thermal properties, inherent flame resistance, and enduring hydrolytic stability. The melting and glass transition temperatures given by the supplier are 343°C and 143°C .

2.2 Fused Filament Fabrication Process

An FFF printer custom-built for the fabrication of PEEK thermoplastic using an open-source Duet 3d motherboard is utilised to make tensile specimens of PEEK material, shown in Fig. 2a. The printer can extrude high-performance materials such as PEEK and ULTEM with a nozzle temperature of 500°C. The printer includes a 120°C heated chamber and a 140°C heated bed. Moreover, the printer possesses a build volume of $300 \text{ mm}^3 \times 150 \text{ mm}^3 \times 145 \text{ mm}^3$ and is capable of printing layer heights as minimal as 0.05 mm. The printer has a 0.4 mm diameter hardened steel nozzle and a 316 L stainless steel heated bed with a core xy setup. Test specimens are fabricated according to American Society for Testing and Materials D638 Type IV and design in PTC CREO 1.0, having an overall length and width of 115 and 119 mm, the grips distance is 65 mm, and the gauge length is 25 mm, where the radius of the curved part and the outer part is 14 and 25 mm respectively and a thickness of 4 mm as shown in Fig. 2b. Then, Ultimaker Cura, a free online software, is used to slice the model and generate G-code. The process parameters that have been taken are in Table 1. Only two process parameters are varied while slicing: layer height and infill percentage. Whereas others are taken as constant for all the specimens, such as raster angle (45°), printing orientation (flat horizontally). The layer height is set to 0.10, 0.15, and 0.20 mm for slicing the specimen, and the infill percentage is set to 20%, 40% and 60%. The infill pattern is taken as a gyroid, whereas the printing speed is taken as 25 mm/s for all the test models. However, the nozzle temperature, heated bed temperature, and chamber temperature are taken as 400°C, 135°C, and 100°C, respectively. On the other hand, two post-processing parameters are also taken for all the specimens: annealing temperature and annealing time. Those are also varying, annealing temperature is set to 150°C, 200°C, and 250°C, and the annealing time is set to 2, 3, and 4 h, individually, a total of 32 samples are prepared as shown in Table 2. According to Design of Experiment (DOE), using the face-centred central composition design method, only 30 samples are there, but two more tests were added later to the list for cross verification. Since PEEK is difficult to print even with a heated chamber and a PVA glue on the heat bed, PEEK is first dried in the Creality filament drier for 4 h prior to printing. Consequently, the specimen remained flat on the bed plate and is firmly attached to the heated bed with nano polymer adhesive, preventing warping during fabrication, as shown in Fig. 2c.

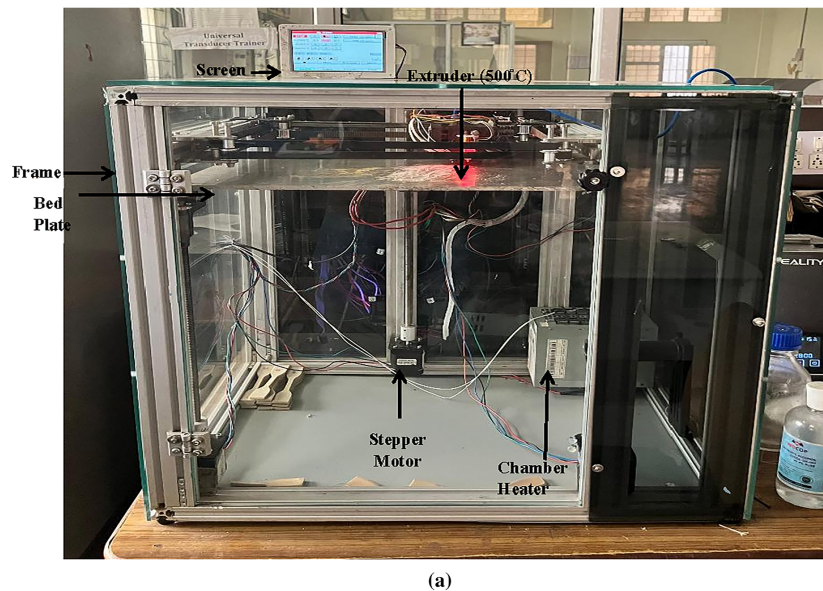


Figure 2: (Continued)

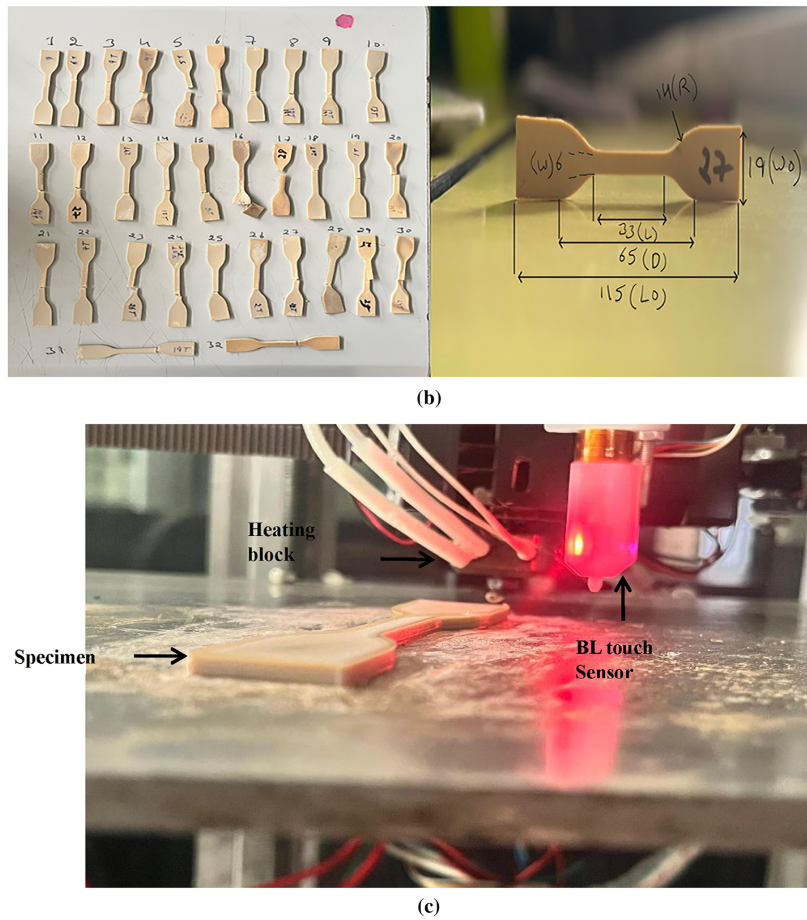


Figure 2: (a) FFF custom-built core xy PEEK Printer. (b) PEEK specimens. (c) PEEK fabrication.

Table 1: Process parameters taken in slicing the specimens.

Process Parameter	Value
Nozzle temperature (°C)	400
Bed temperature (°C)	135
Infill density (%)	20–60
Layer height (mm)	0.10–0.20
Printing speed (mm/s)	25
Chamber temperature (°C)	100
Raster angle (°)	±45
Infill pattern	Gyroid
Printing Orientation	Flat horizontally on to the plate

Table 2: Experimental run.

Run	Layer Height (mm)	Infill Density (%)	Annealing Temperature (°C)	Annealing Time (hr)
1	0.15	40	200	3
2	0.15	40	200	3
3	0.20	20	250	4
4	0.15	40	250	3
5	0.15	20	200	3
6	0.10	20	250	4
7	0.15	40	200	2
8	0.10	20	150	2
9	0.20	20	150	2
10	0.10	60	150	2
11	0.20	60	250	4
12	0.10	40	200	3
13	0.15	40	200	3
14	0.20	40	200	3
15	0.15	40	200	3
16	0.15	40	150	3
17	0.20	60	150	2
18	0.20	20	250	2
19	0.15	40	200	3
20	0.10	60	150	4
21	0.10	20	250	2
22	0.10	20	150	4
23	0.15	40	200	3
24	0.10	60	250	4
25	0.20	60	250	2
26	0.20	60	150	4
27	0.10	60	250	2
28	0.15	60	200	3
29	0.15	40	200	4
30	0.20	20	150	4
31	0.10	60	200	3
32	0.20	60	200	3

2.3 Annealing

All the tensile test pieces are annealed in the muffle furnace. The make of the machine is Shivam Instrument Delhi, and the model is Muffle Furnace, as shown in [Fig. 3a](#). The maximum working temperature of the Muffle furnace is 1100°C. All the test specimens are annealed according to the experimental run with different annealing temperatures of 150°C, 200°C, and 250°C, and different annealing times of 2, 3, and 4 h, independently as shown in [Fig. 3b](#). All samples are annealed independently at different temperatures and for different times. PEEK samples are placed directly inside the furnace and annealed. After annealing to a

specific temperature, samples are allowed to cool at room temperature and tested for tensile strength on a UTM machine.

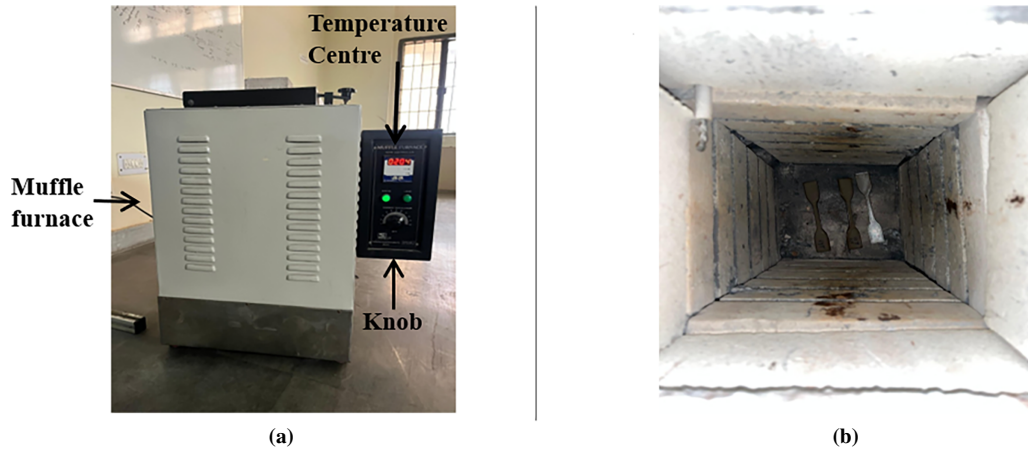


Figure 3: (a) Muffle furnace. (b) PEEK annealing.

2.4 Test Setup

An electromechanical UTM is utilised to test the tensile strength of the fabricated PEEK samples. The maker of UTM is Fuel Instruments & Engineers Pvt. Ltd., and the model is the UNITEK 94,100. The load range of the machine is between 0–100 KN, and the Load Measuring Accuracy of +1% from 2% to 100% of the load cell used. All the models are tested at room temperature, and the custom fixture is installed on the machine to hold the test specimens in place and to perform the tensile strength test, as shown in Fig. 4.

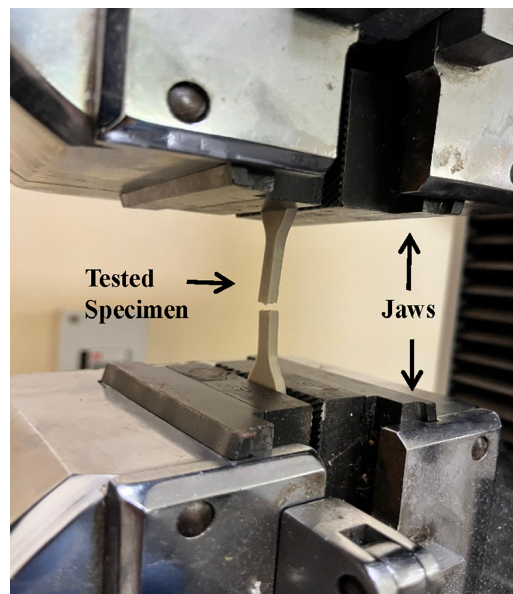


Figure 4: Tensile testing on UTM.

2.5 Finite Element Analysis

Initially, the test specimens are modelled in PTC Creo and saved as a step file, after which they are presented to Ansys Workbench for finite element analysis. The static structural module is selected, and the desired isotropic properties of the material, such as Young's modulus, Poisson's ratio, and density, are selected through the engineering data as in Table 3 and opened into the SpaceClaim or geometry structure to check for any faces or edges errors in the specimen and repaired for better mesh, followed by the Model tab.

Table 3: Material properties of PEEK.

PEEK Material Isotropic Properties	Values
Young's Modulus	3600 MPa
Poisson's Ratio	0.3
Bulk Modulus	3000 MPa
Shear Modulus	1384.6 MPa

The specimen opened in the geometry is automatically transferred to the model tab, where its material properties, as initially recorded in the engineering library, are selected. Mesh generation commenced with the default element size for simplicity; however, smaller element sizes resulted in increased mesh generation time. Subsequently, the explicit menu is utilised to define boundary conditions: one end of the specimen is fixed while displacement is applied at the opposite end using a component factor and opposing axis for tensile analysis, ultimately solving for total deformation and stress as in Fig. 5.

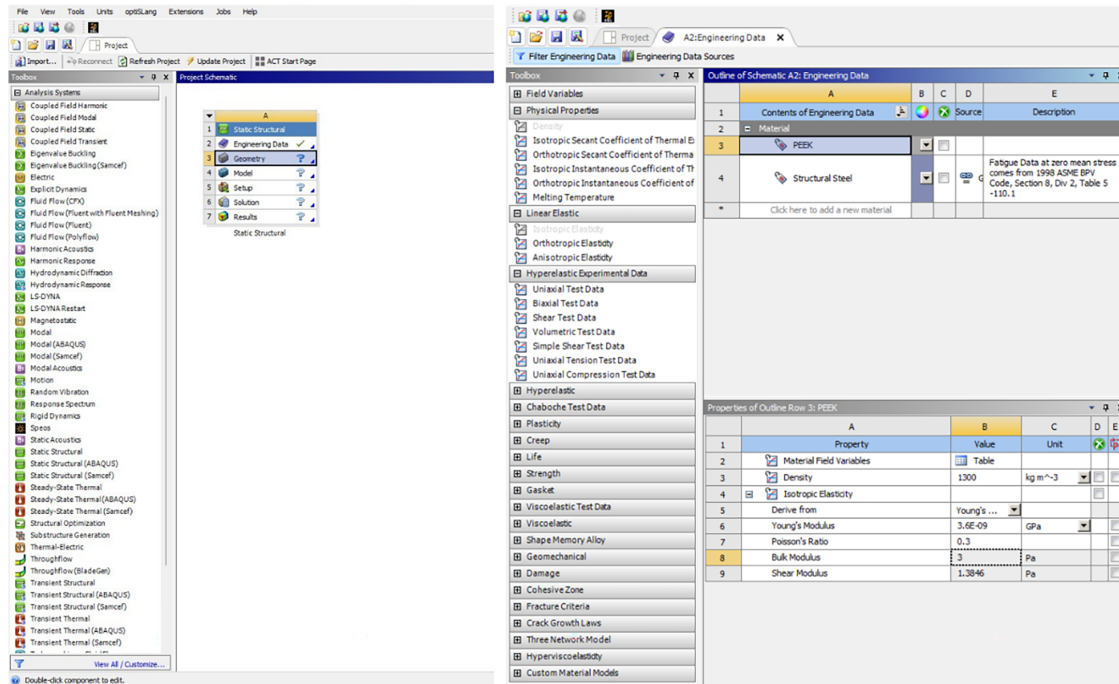


Figure 5: Material selection in Ansys.

Case Study of Fractured Mandible

Further, a force-based case study was incorporated following the primary finite element analysis. A finite element model of a PEEK cranio-maxillofacial fixation plate was developed using the Cone Beam Computed Tomography (CBCT) of the patient and converted into 3d model using Mimics software as shown in Fig. 6.

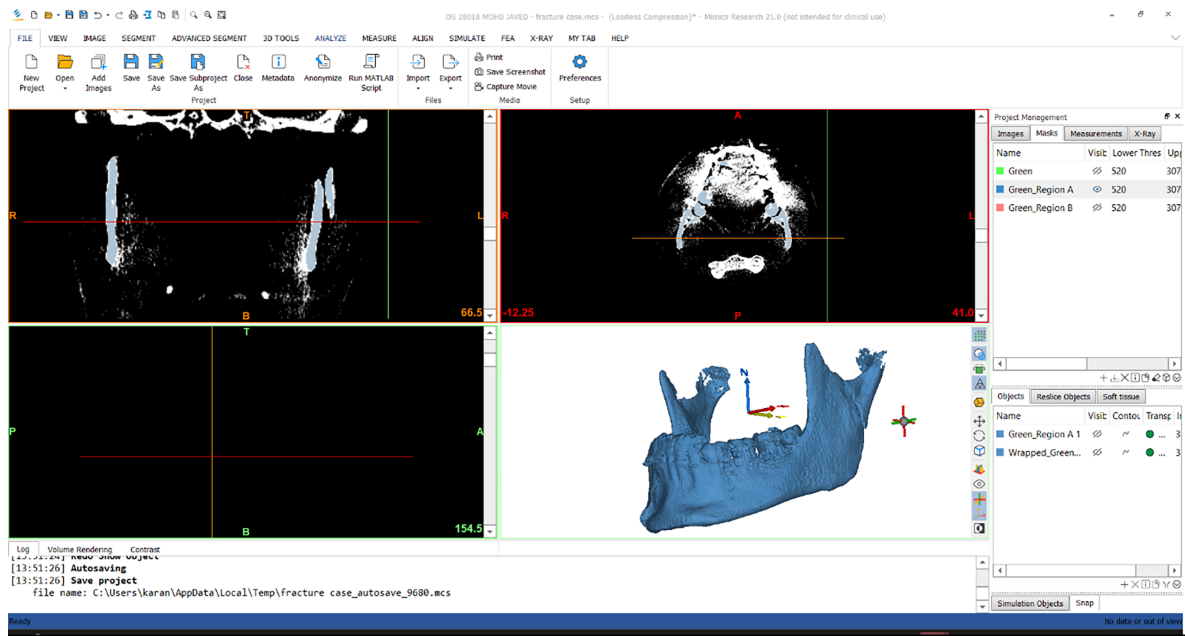


Figure 6: 3D model converted from CBCT.

The same material properties (for fixation plate, screw, and condyle part) and contact definitions are retained to ensure methodological consistency. The model consists of seven interacting bodies, including bone, fixation plate, and screws with bonded and frictional contact interfaces defined using an augmented Lagrange formulation and a friction coefficient of 0.3. A refined volumetric mesh comprising 701,157 nodes and 400,444 elements is employed to accurately capture stress and deformation gradients in regions of geometric and material discontinuity. Static structural analysis is performed using a Mechanical APDL solver under quasi-static assumptions. Boundary conditions included fixed and elastic supports to represent anatomical constraints, while external forces of approximately 100 N were applied at multiple locations, in addition to a peak force of 400 N acting along the global Z-direction to simulate a critical loading scenario as shown in Fig. 7. The applied load of 400 N is a physiologically relevant chewing force, as normal mastication ranges from 20–120 N, while posterior bite forces can reach 400–800 N and FEA studies commonly use 200–400 N to simulate functional loading conditions [24,25]. All loads are applied incrementally over a single time step to ensure numerical stability and convergence. However, the biomechanical model uses simplified assumptions and requires further validation.

3 Results and Discussions

A set of 32 specimens is tested for tensile strength in the UTM UNITEK 94,100 at room temperature, fabricated using a FFF printer. The result of the tensile strength is recorded in Table 4. All the samples are fabricated with varying layer heights and infill densities, but all other parameters remained constant. However, as a post-processing and an essential parameter, annealing with various temperatures and time spans is performed on all the specimens to maximise the tensile strength of the PEEK material. The maximum

tensile strength recorded is 58 MPa under the conditions of a 0.1 mm layer height, 60% infill density, an annealing temperature of 250°C, and a duration of 2 h, as shown in Fig. 8. However, consistent tensile strength of 52–57 MPa is achieved with 0.1–0.15 mm layer height, 40%–60% infill, and moderate annealing temperature of 200°C for 2–3 h. Additionally, the mechanical properties of PEEK are greatly affected by three parameters: layer height, annealing temperature, and infill density. To assess the influence of these parameters statistically, an ANOVA-based significant Model is generated. Among these parameters, infill density (B) was identified as the most significant parameter, as shown in Table 5.

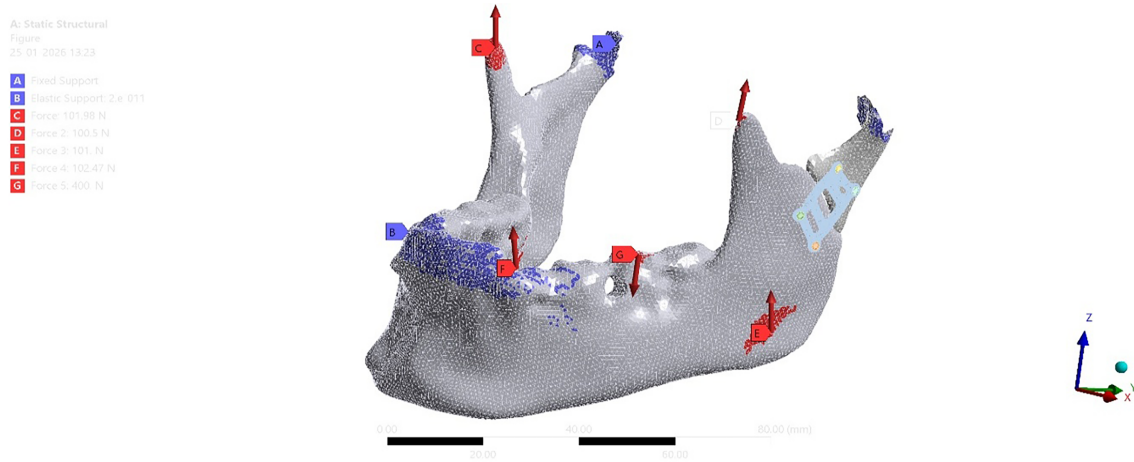


Figure 7: Boundary condition on patient's fractured mandible.

Table 4: Experimental results.

Run	Layer Height (mm)	Infill Density (%)	Annealing Temperature (°C)	Annealing Time (hr)	Tensile Strength (MPa)
1	0.15	40	200	3	56
2	0.15	40	200	3	56
3	0.20	20	250	4	41
4	0.15	40	250	3	52
5	0.15	20	200	3	37
6	0.10	20	250	4	41
7	0.15	40	200	2	50
8	0.10	20	150	2	47
9	0.20	20	150	2	42
10	0.10	60	150	2	47
11	0.20	60	250	4	46
12	0.10	40	200	3	52
13	0.15	40	200	3	56
14	0.20	40	200	3	56
15	0.15	40	200	3	54
16	0.15	40	150	3	46
17	0.20	60	150	2	52
18	0.20	20	250	2	36

(Continued)

Table 4 (continued)

Run	Layer Height (mm)	Infill Density (%)	Annealing Temperature (°C)	Annealing Time (hr)	Tensile Strength (MPa)
19	0.15	40	200	3	50
20	0.10	60	150	4	56
21	0.10	20	250	2	48
22	0.10	20	150	4	37
23	0.15	40	200	3	52
24	0.10	60	250	4	43
25	0.20	60	250	2	44
26	0.20	60	150	4	49
27	0.10	60	250	2	58
28	0.15	60	200	3	57
29	0.15	40	200	4	50
30	0.20	20	150	4	41
31	0.10	60	200	3	52
32	0.20	60	200	3	48

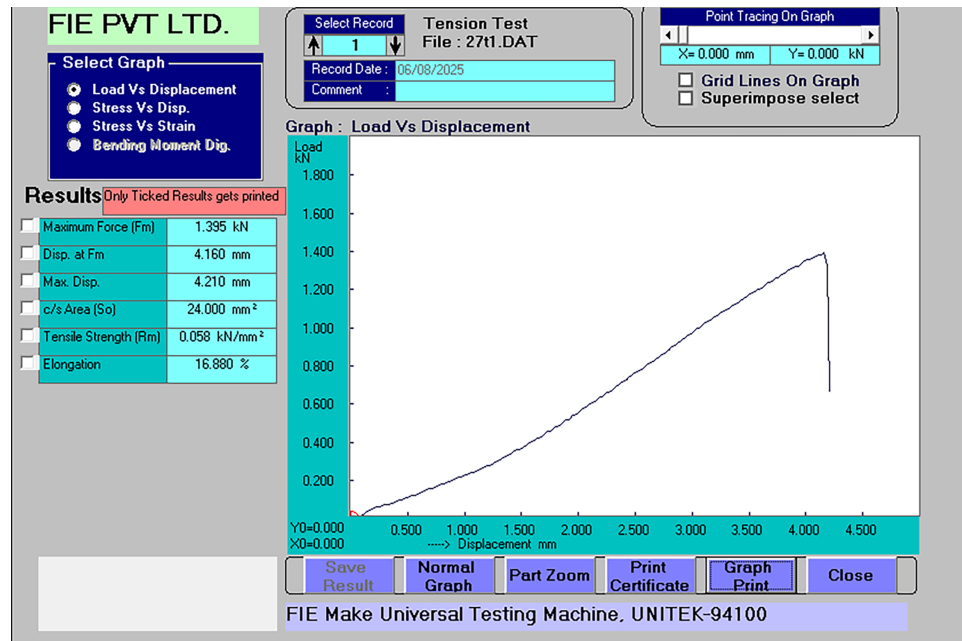


Figure 8: Tensile test result.

Table 5: ANOVA statistics.

Source	Sum of Squares	df	Mean Square	F-Value	p-Value	
Model	855.88	14	61.13	2.64	0.0359	Significant
A-layer thickness	26.89	1	26.89	1.16	0.2979	
B-Infill density	373.56	1	373.56	16.16	0.0011	
C-Annealing temperature	3.56	1	3.56	0.1538	0.7005	
D-Annealing time	14.22	1	14.22	0.6152	0.4451	
AB	0.0000	1	0.0000	0.0000	1.0000	
AC	25.00	1	25.00	1.08	0.3149	
AD	42.25	1	42.25	1.83	0.1965	
BC	9.00	1	9.00	0.3893	0.5420	
BD	2.25	1	2.25	0.0973	0.7594	
CD	6.25	1	6.25	0.2703	0.6107	
A ²	7.50	1	7.50	0.3245	0.5773	
B ²	72.73	1	72.73	3.15	0.0964	
C ²	28.19	1	28.19	1.22	0.2869	
D ²	0.2305	1	0.2305	0.0100	0.9218	
Residual	346.78	15	23.12			
Lack of Fit	308.78	10	30.88	4.06	0.0676	Not significant
Pure Error	38.00	5	7.60			
Cor Total	1202.67	29				

This affects the tensile strength, as evidenced by its high F-value (16.16) and very low p -value (0.0011), showing the model is significant and the lack of fit was not significant. In contrast, layer thickness, annealing temperature, annealing time and most interaction terms showed p -values greater than 0.05, indicating comparatively lower statistical significance within the studied range.

These vital parameters are validated and optimized using a hybrid tool. The ANN [26,27] is trained using the Levenberg-Marquardt algorithm with 32 parameter sets: infill density, layer height, annealing temperature, and annealing time. Fig. 9a shows that the best overall R is 0.97375, while training, validation, and testing had R values of 0.96371, 0.96946, and 0.99461, respectively. The best validation performance is 0.012097 at epoch 4 as shown in Fig. 9b.

The Genetic Algorithm's parameters are as follows: a population size of 200, an elite count of 0.05, a crossover fraction of 0.8, a two-point crossover function, uniform mutation, and a stopping criterion of 200 generations [28,29]. Using a DOE-generated experimental run, the upper and lower bounds yield optimised values of 0.13 mm layer height and 53.977% infill percentage at an annealing temperature of 202.47°C, with an annealing duration of 2 h, as illustrated in Table 6 and Fig. 10a. The optimal fitness in GA-ANN is depicted in Fig. 10b. The GA objective function was formulated by a trained ANN Model to maximise tensile strength under feasible constraints, lower bound (0.1, 20, 150, 2) and upper bound (0.2, 60, 250, 4).

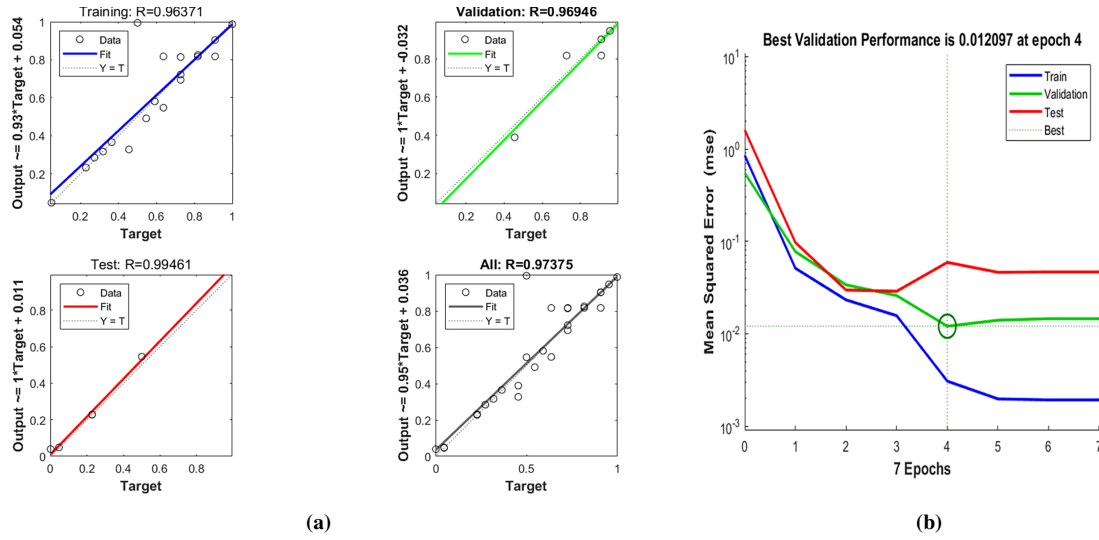


Figure 9: (a) Regression output of ANN. (b) MSE plot.

Table 6: GA-ANN optimised values.

Sr. No.	Layer Height (mm)	Infill Density (%)	Annealing Temperature ($^{\circ}\text{C}$)	Annealing Time (hr)	Result (MPa)
1	0.137	53.977	202.47	2.071	60

Final point:					
1	2	3	4		
	0.137	53.977	202.477	2.071	

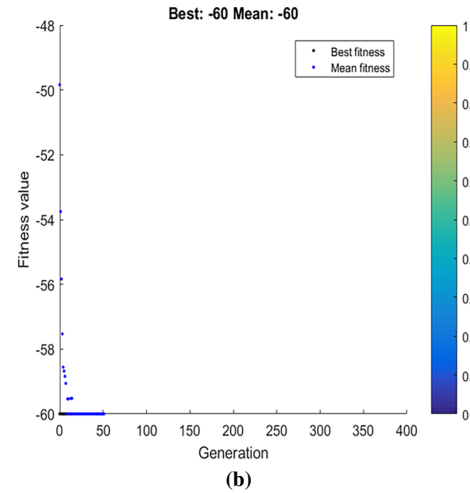


Figure 10: (a) GA-ANN validated values. (b) Best fitness value.

3.1 Validation of FEA Correlation & GA-ANN

To validate the hybrid model, the optimised parameters have been fabricated to confirm the forecasted specimens for the same parameters, and the percentage error of GA-ANN for the same is 0.84% and for the FEA is 2.34% as shown in Table 7. The small deviation between experimental, GA-ANN and FEA results is due to inherent process variability in FFF fabrication, modeling approximations in ANN, FEA as well

as experimental uncertainties. These differences are within acceptable limits and indicate good agreement among the experimental, GA-ANN and FEA.

Table 7: Validation data for GA-ANN and FEA.

Sr. No	Layer Height (mm)	Infill Density (%)	Annealing Temperature (°C)	Annealing Time (hr)	Result as Per GA-ANN (MPa)	Result as Per FEA Correlation (MPa)	Experimental Validation Result by UTM (MPa)	Percentage Error between GA-ANN & Experimental (%)	Percentage Error between FEA and Experimental (%)
1	0.137	53.977	202.47	2.071	60	58.08	59.5	0.84	2.38

The FEA using Ansys confirms the validated experimental value using static structures, and the maximum Von Mises stress is recorded as 61 MPa.

The experimental run is being validated with finite element analysis for strain, equivalent (von Mises) stress, and total deformation. After uploading the specimen geometry to the model analysis, a fixed support is applied to one end, and a force is applied to the other. Determine the total deformation and stress after applying a force of 1.4 KN. The highest von Mises stress is 61 MPa. However, the PEEK specimen exhibited a value of 58.08 MPa in the FEA at the midway of the Mesh nodes where it broke during the validated experimental UTM tensile test, as shown in Fig. 11, beside the maximum validated value of 59.5 MPa recorded during the UTM tensile test. Fig. 12 illustrates the total deformation, stress, strain, and the maximum and minimum values at the nodes of the mesh.

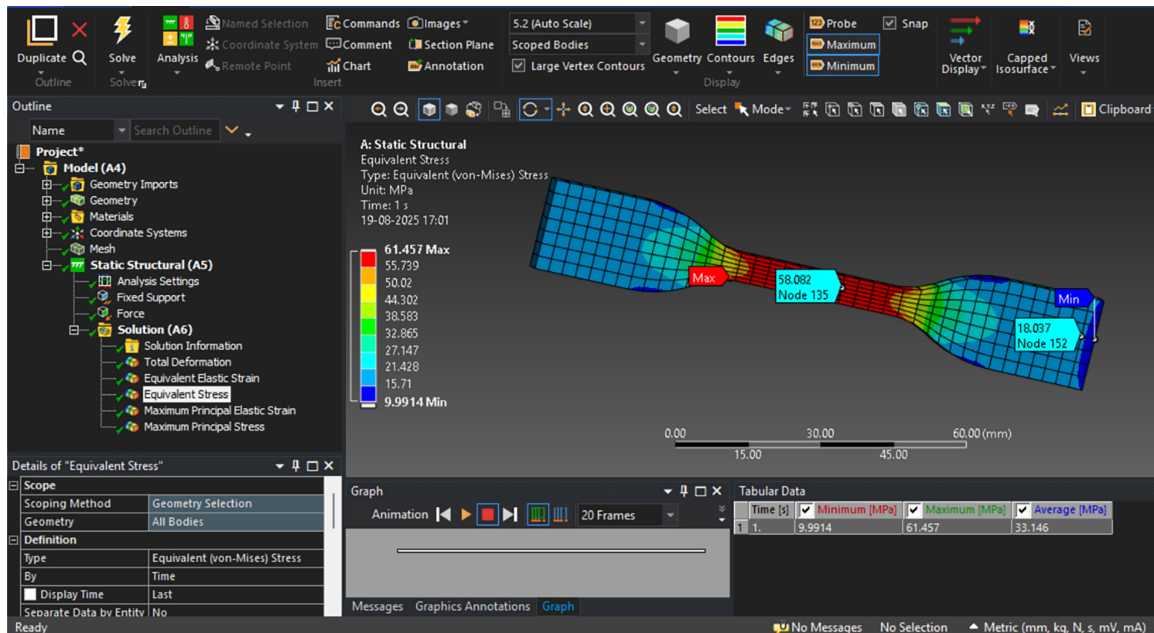


Figure 11: FEA result.

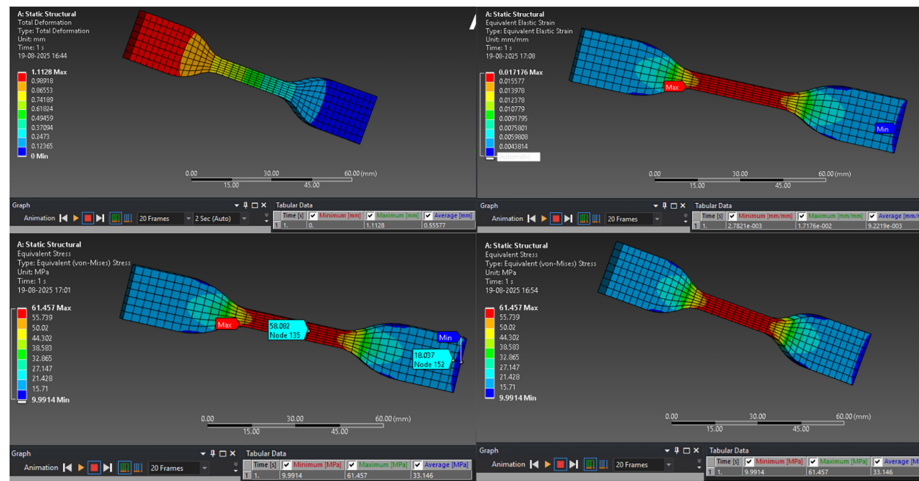


Figure 12: Illustrate the total deformation, stress, and strain.

3.2 Finite Element Model Validation for Application

The force-based case deciphers the optimized tensile response to practical application. The model underwent validation through material property verification, deformation assessment, and stress distribution analysis under physiologically representative boundary conditions [30,31]. The predicted von Mises stress within the fixation plate remained below PEEK's elastic threshold (100 MPa), confirming safe elastic behaviour without risk of plastic deformation. As shown in Fig. 13, aligning with clinically acceptable displacements (less than 1 mm) reported for fixation constructs [32,33] a maximum total deformation of 0.92 mm is observed. At plate–screw contact interfaces, peak intensities indicated through stress maps highlighted reduced stress in surrounding bone regions, while the remaining structure experienced comparatively low stress levels. This congruous distribution aligns with previously reported biomechanical analyses, minimising stress shielding and the potential for bone resorption [34] and high localised stresses near implant interfaces were observed under elevated loading conditions [35,36]. This approach is primarily intended for the treatment of minor mandibular condylar fractures and localized defects rather than extensive mandibular reconstruction.

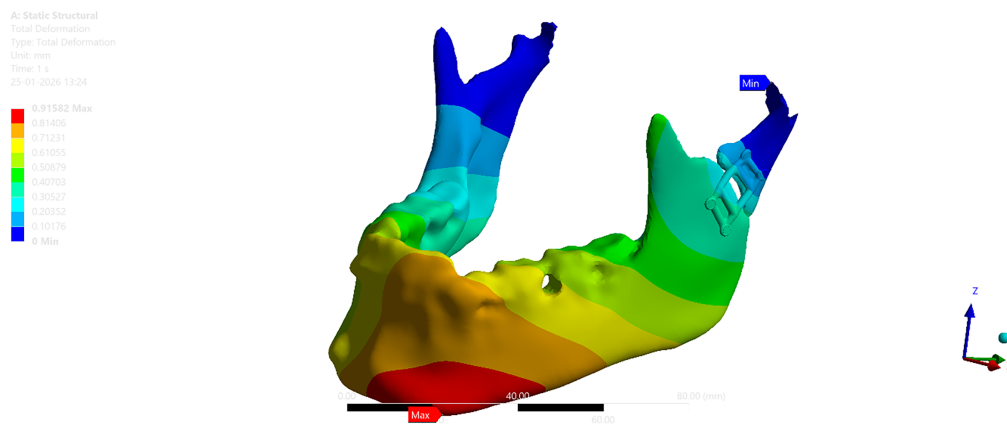


Figure 13: Total deformation.

4 Conclusion

This work establishes that the mechanical performance of 3D-printed PEEK is significantly impacted by the synergistic effects of layer height, infill density, and annealing temperatures. The maximum tensile strength of 58 MPa is achieved at a layer height of 0.1 mm, 60% infill density, an annealing temperature of 250°C and a duration of 2 h, while consistent values of 52–57 MPa are observed with 0.1–0.15 mm layer height, 40%–60% infill and moderate annealing (200°C, 2–3 h). The GA-ANN hybrid optimisation framework maximises the tensile result and predictive capability ($R = 0.97375$), producing optimised parameters that closely match experimental results at 0.13 mm layer height and 53.977% infill percentage at an annealing temperature of 202.47°C, with an annealing duration of 2 h, corresponding to 60 MPa. Furthermore, the FEA (maximum von Mises stress of 61 MPa) supported the optimised experimental findings, a force-based case study validation under realistic loading scenarios and demonstrated the validity of both the optimisation model and experimental methodology. Stress concentrations are predominantly localised at the plate–screw interfaces, and reduced stress transmission to the surrounding bone indicates a diminished risk of stress shielding and implant-induced bone resorption. The mechanical performance of the biocompatible PEEK material in the proposed study demonstrated that it is suitable for the treatment of minor mandibular condylar fractures rather than the whole mandible condyle. A systematic approach to reducing the number of experimental trials while optimising performance is especially useful for materials like PEEK, where experimentation is expensive and time-consuming.

Despite encouraging findings, certain limitations, such as anisotropic behaviour and the absence of microstructural validation, highlight the need for further research. Future study should incorporate experimental validation of FFF-induced anisotropy, fatigue loading, and patient-specific boundary conditions to further strengthen the clinical translatability of additively manufactured PEEK fixation systems.

Acknowledgement: Authors duly acknowledge Maharshi Dayanand University, Rohtak, India, for providing FFF printer and workshop/laboratory facilities.

Funding Statement: This research was funded by the Haryana State Council for Science, Innovation and Technology [HSCSIT/R&D/2025/598].

Author Contributions: Conceptualization, Ashish Phogat and Deepak Chhabra; Data curation, Ashish Phogat, Akash Ahlawat and Deepak Chhabra; Funding acquisition, Virendra Singh and Deepak Chhabra; Investigation, Ashish Phogat and Deepak Chhabra; Methodology, Ashish Phogat and Deepak Chhabra; Project administration, Deepak Chhabra; Resources, Virendra Singh and Deepak Chhabra; Supervision, Deepak Chhabra; Validation, Ashish Phogat, Akash Ahlawat and Deepak Chhabra; Visualization, Ashish Phogat and Deepak Chhabra; Writing—original draft, Ashish Phogat; Writing—review & editing, Akash Ahlawat and Virendra Singh. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: Data available on request from the author.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

AM	Additive Manufacturing
FFF	Fused Filament Fabrication
PEEK	Polyetherether Ketone
HPP	High-Performance Polymer

DOE	Design of Experiment
CCD	Central Composite Design
ANN	Artificial Neural Network
GA	Genetic Algorithm
GA-ANN	Hybrid Genetic Algorithm–Artificial Neural Network
FEA	Finite Element Analysis
UTM	Universal Testing Machine
CBCT	Cone Beam Computed Tomography
APDL	Ansys Parametric Design Language

References

1. Lu K. The future of metals. *Science*. 2010;328(5976):319–20. doi:10.1126/science.1185866.
2. Bertagna S, Braidotti L, Laurini E, Marinò A, Priol S, Bucci V. Thermoplastic materials for the metal replacement of non-structural components in marine engines. *Appl Sci*. 2022;12(17):8766. doi:10.3390/app12178766.
3. Wang P, Zou B, Xiao H, Ding S, Huang C. Investigation on mechanical properties of 3D printed PEEK components. *J Mater Process Technol*. 2019;271:62–70.
4. Abderrafai Y, Diouf-Lewis A, Sosa-Rey F, Farahani RD, Piccirelli N, Lévesque M, et al. Additive manufacturing and characterization of high temperature thermoplastic blends for potential aerospace applications. *Compos Sci Technol*. 2023;231(5):109839. doi:10.1016/j.compscitech.2022.109839.
5. Baek I, Lim CM, Park KY, Ryu BK. Enhanced metal coating adhesion by surface modification of 3D printed PEKKs. *Coatings*. 2022;12(6):854. doi:10.3390/coatings12060854.
6. Hoskins TJ, Dearn KD, Kukureka SN. Mechanical performance of PEEK produced by additive manufacturing. *Polym Test*. 2018;70(2):511–9. doi:10.1016/j.polymertesting.2018.08.008.
7. Gebrehiwet L, Abate E, Negussie Y, Teklehaymanot T, Abeselom E. Application of composite materials in aerospace & automotive industry. *Int J Adv Eng Manag*. 2023;5(3):697–723.
8. Shekar RI, Kotresh TM, Rao PMD, Kumar K. Properties of high modulus PEEK yarns for aerospace applications. *J Appl Polym Sci*. 2009;112(4):2497–510. doi:10.1002/app.29765.
9. Senra MR, Marques MFV, Monteiro SN. Poly (ether-ether-ketone) for biomedical applications: from enhancing bioactivity to reinforced-bioactive composites—an overview. *Polymers*. 2023;15(2):373. doi:10.3390/polym15020373.
10. Verma S, Sharma N, Kango S, Sharma S. Developments of PEEK (Polyetheretherketone) as a biomedical material: a focused review. *Eur Polym J*. 2021;147:110295. doi:10.1016/j.eurpolymj.2021.110295.
11. Li T, Song Z, Yang X, Du J. Influence of processing parameters on the mechanical properties of PEEK plates by hot compression molding. *Materials*. 2022;16(1):36. doi:10.3390/ma16010036.
12. Xu J, Huang X, Davim JP, Ji M, Chen M. On the machining behavior of carbon fiber reinforced polyimide and PEEK thermoplastic composites. *Polym Compos*. 2020;41(9):3649–63. doi:10.1002/pc.25663.
13. Gao R, Xie J, Yang J, Zhuo C, Fu J, Zhao P. Research on the fused deposition modeling of polyether ether ketone. *Polymers*. 2021;13(14):2344. doi:10.3390/polym13142344.
14. Yang Y, Jiang B, Shang Y, Xu Q, He J, Li X, et al. The effect of 3D printing fluorene-containing poly (aryl ether ketone)/poly (ether ketone) blends on interlayer strength. *Polymer*. 2023;289(15):126497. doi:10.1016/j.polymer.2023.126497.
15. Oladapo BI, Zahedi SA, Ismail SO. Mechanical performances of hip implant design and fabrication with PEEK composite. *Polymer*. 2021;227(1):123865. doi:10.1016/j.polymer.2021.123865.
16. Yang Y, Jiang B, Liu H, Zhao T, Yu C, Yang B, et al. Compatibility-driven modulation of mechanical property in 3D printed PEEK blends. *Polymer*. 2025;333(1):128648. doi:10.1016/j.polymer.2025.128648.
17. Reddy KUK, Verma PC, Rath A, Saravanan P. A comprehensive mechanical characterization of as-printed and saliva soaked 3D printed PEEK specimens for low-cost dental implant applications. *Mater Today Commun*. 2023;36(6):106438. doi:10.1016/j.mtcomm.2023.106438.

18. Bozkurt YE, Kincal C, Solak N, Cebeci H. Tailoring viscosity and processability properties of PEEK/PEI blends for 3D printing: the influence of molecular weight. *Mater Today Commun.* 2025;49:113826. doi:10.1016/j.mtcomm.2025.113826.
19. Ahamad A, Kumar P. Mechanical and thermal performance of PEEK/PEI blend matrix reinforced with surface modified halloysite nanotubes. *J Thermoplast Compos Mater.* 2023;36(2):657–72. doi:10.1177/08927057211028629.
20. Wang Z, Yang L, Dong C, Zhang B, Zhang Z. Isothermal annealing effects on compression performances of polyether-ether-ketone lattice structures prepared via material extrusion additive manufacturing. *Mater Today Commun.* 2025;47(9-12):112993. doi:10.1016/j.mtcomm.2025.112993.
21. Kumar A, Chhabra D. Multidisciplinary topology and material optimization approach for developing patient-specific limb orthosis using 3D printing. *Rapid Prototyp J.* 2023;29(8):1757–71. doi:10.1108/rpj-12-2022-0435.
22. Alateyah AI, El-Taybany Y, El-Sanabary S, El-Garaihy WH, Kouta H. Experimental investigation and optimization of turning polymers using RSM, GA, hybrid FFD-GA, and MOGA methods. *Polymers.* 2022;14(17):3585. doi:10.3390/polym14173585.
23. Sagar P. Hybrid GA-ANN and GA-ANFIS soft computing approaches for optimizing tensile strength in magnesium-based composites fabricated via friction stir processing. *Mater Today Commun.* 2025;44(4):112083. doi:10.1016/j.mtcomm.2025.112083.
24. Ferrario VF, Sforza C, Zanotti G, Tartaglia GM. Maximal bite forces in healthy young adults as predicted by surface electromyography. *J Dent.* 2004;32(6):451–7. doi:10.1016/j.jdent.2004.02.009.
25. van Eijden TM. Biomechanics of the mandible. *Crit Rev Oral Biol Med.* 2000;11(1):123–36. doi:10.1177/10454411000110010101.
26. Phogat A, Chhabra D, Sindhu V, Ahlawat A. Analysis of wear assessment of FDM printed specimens with PLA, multi-material and ABS via hybrid algorithms. *Mater Today Proc.* 2022;62(2):37–43. doi:10.1016/j.matpr.2022.01.429.
27. Ahlawat A, Phogat A, Punia U, Chhikara A, Dhingra AK, Garg RK, et al. Innovative optimization of mechanical performance in carbon fiber-reinforced nylon composite using artificial neural networks and multi-objective genetic algorithms. *J Mater Eng Perform.* 2025;34(20):23031–44. doi:10.1007/s11665-025-10973-5.
28. Sagar P, Kumar G, Garg HC, Huang Y, Khanna SK. Analysis of wear assessment of FDM-printed ABS specimens using hybrid artificial intelligent soft computing techniques. *JOM.* 2025;77(11):8876–94. doi:10.1007/s11837-025-07709-0.
29. Ahlawat A, Phogat A, Yadav M, Sahdev RK, Dhingra AK, Chhabra D. Fabrication and analysis of ABS-HDPE-PC composite polymer filament used for FDM printing using hybrid algorithm. *Int J Interact Des Manuf Ijidem.* 2023;17(6):3199–209. doi:10.1007/s12008-023-01389-3.
30. Geng JP, Tan KB, Liu GR. Application of finite element analysis in implant dentistry: a review of the literature. *J Prosthet Dent.* 2001;85(6):585–98. doi:10.1067/mpd.2001.115251.
31. Lovald ST, Wagner JD, Baack B. Biomechanical optimization of bone plates used in rigid fixation of mandibular fractures. *J Oral Maxillofac Surg.* 2009;67(5):973–85. doi:10.1016/j.joms.2008.12.032.
32. Kurtz SM, Devine JN. PEEK biomaterials in trauma, orthopedic, and spinal implants. *Biomaterials.* 2007;28(32):4845–69. doi:10.1016/j.biomaterials.2007.07.013.
33. Schwitalla A, Müller WD. PEEK dental implants: a review of the literature. *J Oral Implant.* 2013;39(6):743–9. doi:10.1563/aaid-joi-d-11-00002.
34. Koriath TW, Hannam AG. Deformation of the human mandible during simulated tooth clenching. *J Dent Res.* 1994;73(1):56–66. doi:10.1177/00220345940730010801.
35. Seong WJ, Kim UK, Swift JQ, Heo YC, Hodges JS, Ko CC. Elastic properties and apparent density of human edentulous maxilla and mandible. *Int J Oral Maxillofac Surg.* 2009;38(10):1088–93. doi:10.1016/j.ijom.2009.06.025.
36. Yang F, Liu D, Yin W, Yuan C, Hu Y, Xu J, et al. Three-dimensional finite element analysis of the biomechanical behaviour of different dental implants under immediate loading during three masticatory cycles. *Heliyon.* 2024;10(11):e32616. doi:10.1016/j.heliyon.2024.e32616.