

**EXPERIMENTAL INVESTIGATIONS INTO ULTRASONIC ASSISTED
3D PRINTING OF CARBON FIBER POLYMER COMPOSITES**

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3D PRINTING OF CARBON FIBER POLYMER COMPOSITES**

by

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Submitted

in fulfilment of the requirement of the degree of Doctor of Philosophy

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Dedicated to
My parents and Almighty

Certificate

This is to certify that the thesis entitled '**Experimental investigations into ultrasonic assisted 3D printing of carbon fiber polymer composites**' submitted by **Mr. Naveen Kumar Verma** to the **Indian Institute of Technology, Delhi** for the award of the degree of *Doctor of Philosophy*, is a record of the original bonafide research work carried out by him under my guidance and supervision. The results contained in it have not been submitted in part or full to any other institute or university for the award of any degree/diploma.

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(Naveen Kumar Verma)

Abstract

The increasing demand for lightweight, high strength, and cost effective components in sectors such as aerospace, automotive, and defence has propelled the advancement of high-performance polymer matrix composites. Among various manufacturing methods, Additive Manufacturing (AM) notably fused deposition modeling (FDM) has gained prominence due to its layer-by-layer fabrication approach that enables mass customization, reduced material waste, and geometrical freedom. However, conventional FDM processes suffer from persistent challenges such as insufficient interlayer adhesion, high anisotropy, micro void formation, and poor fiber distribution, all of which degrade the structural integrity and mechanical performance of carbon fiber polymer composites (CFPCs), particularly for load bearing applications.

To overcome these limitations, this doctoral research presents the design and development of an integrated ultrasonic assisted 3D printing (UA-3DP) system tailored for carbon fiber polymer composites, along with its comprehensive evaluation. The primary aim was to design and develop an ultrasonic assistance system within the FDM setup that could deliver precisely controlled excitation in the X-direction (parallel to the deposition path) and Z-direction (vertical to the build platform). This strategic integration of ultrasonic energy was intended to enhance fiber matrix adhesion, promote molecular mobility, improve fiber dispersion, and achieve superior layer to layer bonding.

The study proceeded with a structured experimental framework involving the optimization of baseline FDM parameters including infill density (ID), wall layers (WL), and layer height (LH) through full factorial experimentation and ANOVA based statistical analysis. This provided a robust reference point for analysing the individual and interactive effects of ultrasonic process

parameters, namely ultrasonic frequency (37.5 kHz and 42.5 kHz), power ratio (0% to 100%), and ultrasonic directionality on the mechanical and morphological properties of CFPC parts.

Extensive experimental trials revealed that ultrasonic excitation particularly in the X-direction at 42.5 kHz and 100% power produced the most substantial mechanical enhancements. Comparative testing showed maximum improvements of 52.30% in tensile strength, 50.66% in impact strength and 53.35% in flexural strength clearly surpassing the performance of parts fabricated using conventional FDM. These improvements were attributed to multiple synergistic effects: increased interlayer polymer chain entanglement, effective fiber distribution, reduced porosity, and enhanced interfacial fusion. Moreover, microstructural investigations using scanning electron microscopy (SEM) and non-destructive structural evaluations through computed tomography (CT) imaging confirmed denser, more uniform internal morphology and fewer defects in the ultrasonically assisted prints. Although Z-direction ultrasonic excitation also yielded improvements especially in the early build layers its efficacy diminished at greater build heights due to energy attenuation and limited penetration.

To assess real world applicability, a case study was also conducted involving the 3D printing of functional helical gears used in automotive power window motors. Gears fabricated with the UA-3DP approach were evaluated for torque-bearing capacity via breaking torque tests, showing marked superiority in strength and durability. The X-direction ultrasonically assisted gears exhibited a breaking torque of 45.4 Nm, compared to 31.0 Nm for conventional prints, a 46.1% increase in bending stress resistance. Notably, the performance of these parts approached that of compression moulded commercial gears, thereby validating the feasibility of UA-3DP for end-use, high-load applications.

The overall findings demonstrate that directional ultrasonic vibration especially when applied along the deposition path (X-axis) is a decisive parameter for realizing high strength, defect minimized, and structurally isotropic CFPC components. This research not only establishes the mechanical and structural merits of ultrasonic assisted 3D printing but also provides critical process design insights for its industrial scalability. The work further lays the foundation for future development of adaptive, closed loop UA-3DP systems, capable of real-time modulation of ultrasonic parameters in response to geometric and material complexities.

By bridging the gap between rapid prototyping and production grade manufacturing, this thesis significantly contributes to the field of advanced composite additive manufacturing, offering a novel route to fabricate next-generation structural components with tailored mechanical properties and enhanced reliability.

Keywords: Ultrasonic assisted 3D Printing (UA-3DP), Carbon fiber polymer composites (CFPCs), Fused deposition modeling (FDM), Directional ultrasonic vibration, Interlayer adhesion, Mechanical properties, SEM, CT imaging, Process optimization, Functional gears, Bending stress, Structural additive manufacturing.

सारांश

विमानन, ऑटोमोटिव और रक्षा जैसे क्षेत्रों में हल्के, उच्च-शक्ति वाले और लागत प्रभावी घटकों की बढ़ती माँग ने उच्च प्रदर्शन वाले पॉलिमर मैट्रिक्स कम्पोज़िट्स के विकास को तेज़ किया है। विभिन्न निर्माण विधियों में, ऐडिटिव मैनुफैक्चरिंग (AM), विशेष रूप से फ्यूज्ड डिपॉज़िशन मॉडलिंग (FDM), अपने लेयर-बाय-लेयर निर्माण दृष्टिकोण के कारण महत्वपूर्ण बन गई है, जो मास कस्टमाइज़ेशन, कम सामग्री अपव्यय और जटिल ज्यामितीय आकृतियों के निर्माण को संभव बनाती है। हालांकि, पारंपरिक FDM प्रक्रियाएँ अभी भी कुछ जटिल चुनौतियों से ग्रस्त हैं, जैसे कि अपर्याप्त इंटरलेयर बॉन्डिंग, अधिक दिशा-निर्भरता (anisotropy), माइक्रो-वॉयड का निर्माण, और असंगत फाइबर अभिविन्यास, जो विशेषकर लोड वहन करने वाले अनुप्रयोगों में कार्बन फाइबर पॉलिमर कम्पोज़िट्स (CFPCs) की संरचनात्मक अखंडता और यांत्रिक प्रदर्शन को प्रभावित करती हैं।

इन सीमाओं को दूर करने हेतु, यह शोध कार्य एक नवीन अल्ट्रासोनिक-सहायता प्राप्त थ्री-डी प्रिंटिंग (UA-3DP) तकनीक के विकास और समग्र मूल्यांकन को प्रस्तुत करता है, जिसे विशेष रूप से CFPCs के लिए डिज़ाइन किया गया है। इस तकनीक का प्रमुख उद्देश्य एक ऐसा अल्ट्रासोनिक प्रणाली विकसित करना था जिसे FDM प्लेटफ़ॉर्म में एकीकृत किया जा सके, और जो नियंत्रित ढंग से X-दिशा (डिपॉज़िशन पथ के समानांतर) और Z-दिशा (बिल्ड प्लेट के लंबवत) में कंपन प्रदान कर सके। अल्ट्रासोनिक ऊर्जा के इस रणनीतिक समावेशन का उद्देश्य फाइबर-मैट्रिक्स इंटरफेस को बेहतर बनाना, आणविक गतिशीलता को बढ़ाना, फाइबर के बेहतर वितरण को प्रोत्साहित करना, और परत दर परत अधिक प्रभावी बॉन्डिंग प्राप्त करना था।

अनुसंधान की अगली अवस्था में, इनफिल घनता (ID), वॉल लेयर (WL) और लेयर हाइट (LH) जैसे बेसलाइन FDM मापदंडों का पूर्ण फैक्ट्रियल डिज़ाइन और ANOVA-आधारित सांख्यिकीय विश्लेषण के माध्यम से अनुकूलन किया गया। यह एक ठोस संदर्भ बिंदु प्रदान करता है जिससे अल्ट्रासोनिक प्रक्रिया

मापदंडों — जैसे कि कंपन आवृत्ति (37.5 kHz और 42.5 kHz), पावर रेशियो (0% से 100%) और कंपन की दिशा — के यांत्रिक और संरचनात्मक गुणों पर प्रभावों का अध्ययन किया जा सके।

विस्तृत प्रयोगों से यह ज्ञात हुआ कि X-दिशा में 42.5 kHz आवृत्ति और 100% पावर रेशियो पर अल्ट्रासोनिक सहायता के साथ बनाए गए नमूनों में सबसे अधिक यांत्रिक सुधार देखने को मिले। तुलना में, पारंपरिक FDM से बने नमूनों की तुलना में तनाव शक्ति में 52.30%, प्रभाव शक्ति में 50.66%, और वक्र शक्ति में 53.35% की वृद्धि दर्ज की गई। ये सुधार बढ़ी हुई इंटरलेयर चैन एंटेगलमेंट, अधिक समान फाइबर वितरण, कम वॉयड घनत्व, और बेहतर इंटरफेसल फ्यूजन जैसे संयोजित प्रभावों के कारण प्राप्त हुए। स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी (SEM) द्वारा सूक्ष्मसंरचनात्मक विश्लेषण और कम्प्यूटेड टोमोग्राफी (CT) के माध्यम से गैर-विनाशकारी संरचनात्मक परीक्षणों से यह पुष्टि हुई कि अल्ट्रासोनिक सहायता प्राप्त प्रिंटों में अधिक घनत्व, बेहतर एकरूपता और कम दोष पाए गए। हालाँकि Z-दिशा में कंपन से भी निचली परतों में सुधार हुआ, लेकिन ऊँचाई के साथ ऊर्जा की क्षीणता के कारण इसका प्रभाव सीमित रहा।

इस प्रक्रिया की वास्तविक व्यावहारिकता को परखने के लिए, ऑटोमोटिव पावर विंडो मोटर्स में प्रयुक्त हेलिकल गियर्स के 3D प्रिंटिंग पर एक केस स्टडी की गई। अल्ट्रासोनिक सहायता से बने गियर्स को ब्रेकिंग टॉर्क परीक्षणों के माध्यम से परखा गया, जिसमें पारंपरिक गियर्स की तुलना में अधिक बल वहन करने की क्षमता प्रदर्शित हुई। विशेष रूप से X-दिशा में अल्ट्रासोनिक सहायता प्राप्त गियर्स ने 45.4 Nm का ब्रेकिंग टॉर्क दिखाया, जबकि पारंपरिक गियर्स ने केवल 31.0 Nm, जो कि 46.1% अधिक वक्र तनाव प्रतिरोध है। यह प्रदर्शन कम्प्रेसन-मोल्डेड व्यावसायिक गियर्स के स्तर के समीप था, जिससे UA-3DP की उपयोगिता और औद्योगिक संभावनाओं की पुष्टि होती है।

अंततः, यह शोध दर्शाता है कि डिपॉज़िशन दिशा (X-अक्ष) में अल्ट्रासोनिक कंपन का उपयोग एक निर्णायक प्रक्रिया मापदंड है जो उच्च शक्ति, न्यूनतम दोष और संरचनात्मक समरूपता वाले CFPC

घटकों के निर्माण में सहायक होता है। यह अध्ययन न केवल अल्ट्रासोनिक सहायता प्राप्त 3D प्रिंटिंग की यांत्रिक और संरचनात्मक श्रेष्ठता को सिद्ध करता है, बल्कि इसकी औद्योगिक स्केलेबिलिटी के लिए महत्वपूर्ण प्रक्रिया डिज़ाइन अंतर्दृष्टियाँ भी प्रदान करता है। इसके साथ ही, यह कार्य भविष्य में ऐसे अनुकूली UA-3DP सिस्टम के विकास की नींव रखता है जो ज्यामिति और सामग्री की जटिलताओं के अनुसार अल्ट्रासोनिक मापदंडों को वास्तविक समय में नियंत्रित करने में सक्षम होंगे।

इस शोध में तीव्र प्रोटोटाइपिंग और उत्पादन-स्तर निर्माण के बीच की खाई को पाटते हुए, उन्नत कम्पोज़िट ऐडिटिव मैनुफैक्चरिंग के क्षेत्र में महत्वपूर्ण योगदान दिया गया है, जो भविष्य के संरचनात्मक अनुप्रयोगों के लिए विश्वसनीय और अनुकूलित यांत्रिक गुणों वाले घटकों के निर्माण का मार्ग प्रशस्त करता है।

कीवर्ड्स: अल्ट्रासोनिक-सहायता प्राप्त 3D प्रिंटिंग (UA-3DP), कार्बन फाइबर पॉलिमर कम्पोज़िट्स (CFPCs), फ्यूज्ड डिपॉज़िशन मॉडलिंग (FDM), दिशा-आधारित अल्ट्रासोनिक कंपन, इंटरलेयर बॉन्डिंग, यांत्रिक गुण, SEM, CT इमेजिंग, प्रक्रिया अनुकूलन, कार्यात्मक गियर्स, वक्र तनाव, संरचनात्मक ऐडिटिव मैनुफैक्चरिंग

Contents

Certificate	i
Acknowledgments	ii
Abstract	iv
सारांश	vii
Contents	x
List of Figures	xx
List of Tables	xxvii
Abbreviations	xxviii
Nomenclature	xxx
Chapter 1 : Introduction	1
1.1 Background	2
1.2 Transition to composites due to material limitations	3
1.3 Classification of composite materials	4
1.3.1 Particle reinforced composites	5
1.3.2 Fiber reinforced composites	5
1.3.3 Structural composites	5
1.3.4 Nano composites	6
1.4 Manufacturing techniques for fiber reinforced composites	7

1.4.1	Resin transfer moulding	7
1.4.2	Compression moulding	7
1.4.3	Filament winding	8
1.4.4	Additive manufacturing	8
1.5	Opportunities and challenges in composite 3D printing	9
1.6	Carbon fiber reinforced polymers in additive manufacturing	10
1.7	The role of advanced manufacturing techniques.....	11
1.7.1	Magnetic field assisted additive manufacturing	11
1.7.2	Electric field assisted additive manufacturing	12
1.7.3	Acoustic assisted additive manufacturing.....	12
1.8	Fundamentals of ultrasonic assisted 3D printing	13
1.8.1	Acoustic streaming.....	14
1.8.2	Cavitation.....	14
1.8.3	Localized heating	14
1.9	Research gaps and motivation.....	15
1.10	Organization of the thesis.....	18
Chapter 2 :	Literature Review.....	20
2.1	Introduction	21
2.2	Additive manufacturing of carbon fiber reinforced polymer composites	21
2.3	Ultrasonic assisted 3D printing	25

2.4	Challenges in FDM of carbon fiber polymer composites	31
2.4.1	Insufficient interlayer bonding.....	32
2.4.2	Non uniform fiber distribution.....	32
2.4.3	Porosity and voids.....	32
2.4.4	Toolpath and design limitations.....	33
2.4.5	No standardization	33
2.5	Research gaps.....	33
2.5.1	Mapping of research gaps to thesis objectives.....	34
2.6	Proposed research work and objectives	36
Chapter 3 : Development of an Integrated Ultrasonic Assisted 3D Printing.....		37
3.1	Introduction	38
3.2	Objective	38
3.3	Experimental setup and procedure for integrated ultrasonic assisted 3D printing....	39
3.3.1	Overall system architecture.....	39
3.3.2	Build plate design and sensor integration	41
3.3.3	Integration of ultrasonic assistance in the Z-axis direction of the build plate ...	42
3.3.4	CAE dynamic simulation procedure for Z axis ultrasonic assistance build plate	45
3.3.5	Integration of ultrasonic assistance in the X-axis direction of the build plate...	49

3.3.6	CAE dynamic simulation procedure for X Axis ultrasonic assistance build plate	52
3.3.7	Frequency generator and power controller design and development	57
3.3.8	Practical validation using fiber optic displacement sensor	62
3.3.9	Power amplitude response analysis for x and z directional ultrasonic assistance	65
3.4	Preliminary trial results on mechanical performance of ultrasonic assisted 3D printed CFPC specimens	68
Chapter 4 : Optimization of 3D Printing Process to Improve the Mechanical Properties of Carbon Fiber Polymer Composite Parts		71
4.1	Introduction	72
4.2	Experimental methodology	73
4.2.1	Fabrication of specimens using the fused deposition modelling	73
4.2.2	Process parameters.....	75
4.2.3	Central composite design.....	76
4.3	Mechanical and microstructural characterization methods.....	77
4.3.1	Tensile testing	77
4.3.2	Impact testing.....	78
4.3.3	Flexural testing.....	80
4.3.4	Scanning electron microscopy	81
4.3.5	Computed tomography scanning	81

4.4	Design of experiments.....	82
4.5	Statistical modeling of tensile, impact and flexural strength	85
4.5.1	Regression models	85
4.5.2	Model validation using ANOVA.....	86
4.6	Refined statistical models and pooled ANOVA analysis.....	90
4.6.1	Pooled ANOVA analysis	90
4.7	Precision of the predicted models	94
4.7.1	Model verification using confirmation experiments.....	95
4.7.2	Graphical comparison of predicted vs experimental Results.....	95
4.8	Effect of printing process parameters on overall mechanical performance	97
4.9	Effect of printing process parameters on tensile strength	97
4.9.1	Effect of infill density	99
4.9.2	Effect of wall layers	99
4.9.3	Effect of layer height	99
4.9.4	SEM analysis of fracture surfaces.....	99
4.9.5	Interaction effects of printing parameters on tensile strength.....	102
4.10	Effect of printing process parameters on impact strength.....	103
4.10.1	Effect of infill density	104
4.10.2	Effect of wall layers	104
4.10.3	Effect of layer height	104

4.10.4	SEM analysis for impact strength	104
4.10.5	Interaction effects of printing parameters on impact strength	107
4.11	Effect of printing process parameters on flexural strength	108
4.11.1	Effect of infill density	109
4.11.2	Effect of wall layers	109
4.11.3	Effect of layer height	109
4.11.4	CT scan analysis for flexural strength	109
4.11.5	Interaction Effects of printing parameters on flexural strength	111
4.12	Multi response optimization of process parameters	112
4.13	Conclusion.....	113
Chapter 5 :	Effect of Ultrasonic Process Parameters on Mechanical Properties and Fracture Morphology of Carbon Fiber Polymer Composite Parts	114
5.1	Introduction	115
5.2	Significance of CFPC in advanced manufacturing systems	116
5.3	Technical limitations of FDM in printing CFPC	117
5.3.1	Interlayer voids and discontinuities	118
5.3.2	Weak interfacial bonding	118
5.3.3	Fiber misalignment and inhomogeneous reinforcement.....	118
5.3.4	Porosity and microstructural defects.....	118
5.3.5	Anisotropy and directional dependency.....	119

5.4	Ultrasonic assisted FDM as a pathway to enhanced composite quality.....	119
5.4.1	Mechanisms of improvement through ultrasonic assistance	119
5.4.2	Influence of ultrasonic parameters on process efficiency	120
5.4.3	Motivation for the investigation.....	121
5.5	Experimental framework for evaluating ultrasonic assisted CFPC printing.....	122
5.5.1	A custom printing system integrated with ultrasonic assistance	122
5.5.2	Material selection and preparation.....	123
5.5.3	Ultrasonic process parameters control methodology	123
5.5.4	Experimental design.....	124
5.5.5	Fabrication process and real-time amplitude calibration	124
5.5.6	Post processing and sample conditioning	124
5.5.7	Mechanical testing of specimens	124
5.5.8	Microstructural and morphological analysis.....	125
5.6	Mechanical performance analysis of ultrasonically printed CFPC.....	125
5.7	Influence of ultrasonic assistance on tensile strength	125
5.7.1	X-axis ultrasonic assistance results.....	127
5.7.2	Z-axis ultrasonic assistance results	128
5.7.3	SEM analysis of fractured tensile specimens.....	129
5.7.4	Overall observations	133
5.8	Influence of ultrasonic assistance on impact strength.....	133

5.8.1	X-axis ultrasonic assistance results.....	135
5.8.2	Z-axis ultrasonic assistance results	136
5.8.3	SEM analysis of fractured impact specimens	137
5.8.4	Overall observations	141
5.9	Influence of ultrasonic assistance on flexural strength	141
5.9.1	X-axis ultrasonic assistance results.....	143
5.9.2	Z-Axis ultrasonic assistance results	144
5.9.3	CT analysis of flexural specimens	145
5.9.4	Overall observations	149
5.10	Summary of mechanical improvements.....	149
5.11	Morphological and structural analysis	151
5.11.1	SEM analysis of tensile fracture surfaces	151
5.11.2	SEM analysis of impact fracture surfaces.....	153
5.11.3	CT analysis of flexural samples.....	155
5.12	Comparative analysis of ultrasonic directions	157
5.12.1	Mechanical property trends by direction	157
5.12.2	SEM based structural comparison	158
5.12.3	CT based structural comparison.....	158
5.12.4	Practical implementation considerations	158
5.12.5	Summary and key observations	159

5.13 Conclusion..... 159

**Chapter 6 : Performance Study of Power Window Motor Helical Gear of Carbon
Fiber Polymer Composite Fabricated by Ultrasonic Assisted 3D Printing
.....161**

6.1 Introduction 162

6.2 Objectives of the case study 163

6.3 Gear design and manufacturing methodology 165

6.3.1 CAD design of the helical gear 165

6.3.2 Material and processing parameters..... 166

6.3.3 Fabrication variants..... 167

6.4 Experimental setup and testing methodology 169

6.4.1 Assembly integration 169

6.4.2 Breaking torque test setup..... 170

6.4.3 Bending stress analysis 171

6.5 Results and observations 171

6.5.1 Comparative analysis of wear and failure modes 171

6.5.2 Comparison of breaking torque in conventional and ultrasonic assisted gears 172

6.5.3 Bending strength improvement in ultrasonic assisted gears 173

6.6 Comparative analysis with compression moulded gears..... 173

6.7 Industrial implications and real world applications 174

6.8	Conclusion.....	175
Chapter 7 : Major Conclusions and Future Scope		176
7.1	Major conclusions	177
7.2	Future scope	179
7.3	Design guidelines and best practices.....	180
7.4	Limitations	180
References		182
List of patents and publication		203
Biodata		205

List of Figures

Figure 1.1 Illustration of fiber and matrix combining to form a composite material	3
Figure 1.2 Comparison of mixture, compound, and composite highlighting fiber–matrix interface using SEM.....	4
Figure 1.3 Classification and types of fiber distribution.....	6
Figure 1.4 Illustration of resin transfer moulding[37]	7
Figure 1.5 Illustration of compression moulding[37]	8
Figure 1.6 Illustration of filament moulding[37].....	8
Figure 1.7 Illustration of additive manufacturing	9
Figure 1.8 Magnetic field assisted additive manufacturing [61, 62]	11
Figure 1.9 Electric field assisted additive manufacturing [65, 67]	12
Figure 1.10 Acoustic or ultrasonic assisted additive manufacturing [69]	13
Figure 2.1 Std specimen for mechanical testing. (a) Tensile specimen. (b) 3-point bending specimen. (c) Details of layer thickness (Lt) and build orientations (Flat and On-edge)[112].	22
Figure 2.2 a) Flat specimens with different fibre volume content. b) On-edge specimens with different fibre volume content[112].....	23
Figure 2.3 a) piezo disc placement over the printing plate. b) Graph surface roughness versus number of piezo [118].....	26
Figure 2.4 Alignment of fibers using ultrasonic actuation and curing of resin[119].....	27
Figure 2.5 Ultrasonic vibrations into Fused Filament Fabrication (FFF)-deposition of thermoplastic polymer. (a) photograph of actual apparatus. (b) Conceptual sketch. [120].....	28

Figure 2.6 Hybridization of carbon fiber polymer composites 3D printing and ultrasonic assistance.....	34
Figure 3.1 Conceptual sketch of an ultrasonic assisted 3D printing process for carbon fiber polymer composites	40
Figure 3.2 Build plate (Ultrasonic assistance Z Axis)	44
Figure 3.3 Modal and harmonic analysis for Z Axis ultrasonic assistance build plate	45
Figure 3.4 Modal and harmonic analysis for Z Axis ultrasonic assistance build plate (70mm)	47
Figure 3.5 Modal and harmonic analysis for Z Axis ultrasonic assistance build plate (60mm)	48
Figure 3.6 Build Plate (Ultrasonic Assistance X Axis)	51
Figure 3.7 Modal and harmonic analysis for X Axis ultrasonic assistance build plate	52
Figure 3.8 Modal and harmonic analysis for X Axis ultrasonic assistance build plate (35mm)	55
Figure 3.9 Modal and harmonic analysis for X Axis ultrasonic assistance build plate (27.5mm)	56
Figure 3.10 Novel frequency generator and power controller	59
Figure 3.11 Design of novel frequency generator, power controller	61
Figure 3.12 Illustration the complete experimental configuration.....	62
Figure 3.13 Illustrates complete experimental setup, including all components and sensor ...	63
Figure 3.14 Setup of Philtec fiber-optic sensor for amplitude measurement	65

Figure 3.15 Setup of Philtec fiber-optic sensor for amplitude measurement	66
Figure 3.16 An integrated ultrasonic assisted 3D printing process for carbon fiber polymer composites.....	67
Figure 3.17 Printed samples for preliminary trials	68
Figure 3.18 Effect of ultrasonic assistance on tensile strength, impact strength and flexural strength of 3D printed CFPC's samples.....	69
Figure 4.1 Schematic illustration of 3D printed composite specimen highlighting process parameters: Infill density (ID), wall layers (WL), and layer height (LH)	74
Figure 4.2 Dimensional drawing of ASTM D638 tensile test specimen	78
Figure 4.3 INSTRON 5982 Universal testing machine used for tensile and flexural testing..	78
Figure 4.4 Dimensional drawing of ASTM D256 Impact test specimen	79
Figure 4.5 A) and B) NOTCHVIS Cutter; C) Nikon optical microscope; D) INSTRON 9050 Impact testing machine	79
Figure 4.6 Dimensional drawing of ASTM D790 flexural test specimen	80
Figure 4.7 INSTRON 5982 Universal testing machine used for tensile and flexural testing..	80
Figure 4.8 SEM imaging - Hitachi VP-SEM SU1510 for fracture surface characterization...	81
Figure 4.9 Computed tomography (CT) Nikon XTH225 ST 2X.....	82
Figure 4.10 Comparison between experimental values and predicted values from model for tensile strength corresponding to trials of confirmation experiments.....	96
Figure 4.11 Comparison between experimental values and predicted values from model for impact strength corresponding to trials of confirmation experiments	96

Figure 4.12 Comparison between experimental values and predicted values from model for flexural strength corresponding to trials of confirmation experiments.....	97
Figure 4.13 Main effect plot showing influence of ID, WL, and LH on mean tensile strength	98
Figure 4.14 Pareto chart representing percentage contribution of significant parameters on tensile strength ($\alpha = 0.05$)	98
Figure 4.15 SEM images of fracture surfaces showing improved interlayer fusion and matrix continuity	101
Figure 4.16 3D response surface plot showing the combined effect of infill density and wall layers on tensile strength of CFPC parts.....	102
Figure 4.17 Main effect plot showing influence of ID, WL, and LH on impact strength	103
Figure 4.18 Pareto chart representing percentage contribution of significant parameters on impact strength ($\alpha = 0.05$).....	103
Figure 4.19 SEM fracture surface analysis of impact tested CFPC specimens at different infill densities.....	106
Figure 4.20 3D response surface plot of impact strength as a function of infill density and wall layers	107
Figure 4.21 Main effect plot showing influence of ID, WL, and LH on flexural strength....	108
Figure 4.22 Pareto chart representing percentage contribution of significant parameters on flexural strength ($\alpha = 0.05$)	108
Figure 4.23 CT scan analysis of flexural specimens at varying infill densities.....	110

Figure 4.24 Response surface plot showing the effect of infill density and wall layers on flexural strength	111
Figure 5.1 Schematic of ultrasonic vibration assistance applied along the Z-axis	122
Figure 5.2 Schematic of ultrasonic vibration assistance applied along the X-axis.....	123
Figure 5.3 Tensile test specimens fabricated with ultrasonic assistance along the Z-axis and X-axis. Groups XA, XB, ZC and ZD correspond to different ultrasonic process parameter sets for statistical comparison.....	126
Figure 5.4 Effect of ultrasonic assistance on tensile strength along X-axis at varying power ratios and frequency	127
Figure 5.5 Effect of ultrasonic assistance on tensile strength along Z-axis at varying power ratios and frequency	128
Figure 5.6 Fracture morphology comparison for Z-Axis ultrasonic assistance at 42.5 kHz vs 37.5 kHz.....	130
Figure 5.7 Fracture morphology comparison for X-Axis ultrasonic assistance at 42.5 kHz vs 37.5 kHz.....	131
Figure 5.8 Comparative fracture morphology for X-Axis vs Z-Axis ultrasonic assistance at 42.5 kHz.....	132
Figure 5.9 Impact test specimens fabricated with ultrasonic assistance along the Z-axis and X-axis. Groups XA, XB, ZC and ZD correspond to different ultrasonic process parameter sets for statistical comparison.....	134
Figure 5.10 Effect of ultrasonic assistance on impact strength along X-axis at varying power ratios and frequency	135

Figure 5.11 Effect of ultrasonic assistance on impact strength along Z-axis at varying power ratios and frequency.....	136
Figure 5.12 Fracture morphology comparison for Z-Axis ultrasonic assistance at 42.5 kHz vs 37.5 kHz.....	138
Figure 5.13 Fracture morphology comparison for X-Axis ultrasonic assistance at 42.5 kHz vs 37.5 kHz.....	139
Figure 5.14 Comparative fracture morphology for X-Axis vs Z-Axis ultrasonic assistance at 42.5 kHz.....	140
Figure 5.15 Flexural test specimens fabricated with ultrasonic assistance along the Z-axis and X-axis. Groups XA, XB, ZC and ZD correspond to different ultrasonic process parameter sets for statistical comparison.	142
Figure 5.16 Effect of ultrasonic assistance on flexural strength along X-axis at varying power ratios and frequency.....	143
Figure 5.17 Effect of ultrasonic assistance on flexural strength along Z-axis at varying power ratios and frequency.....	144
Figure 5.18 Computed tomography (CT) analysis: Effect of Z-Axis ultrasonic assistance at 42.5 kHz vs 37.5 kHz.....	146
Figure 5.19 Computed tomography (CT) analysis: Effect of X-Axis ultrasonic assistance at 42.5 kHz vs 37.5 kHz.....	147
Figure 5.20 Comparative computed tomography (CT) for X-Axis vs Z-Axis Ultrasonic Assistance at 42.5 kHz.....	148
Figure 5.21 Effect of ultrasonic vibration direction on tensile fracture morphology	151

Figure 5.22 Effect of ultrasonic vibration direction on impact fracture morphology.....	153
Figure 5.23 Effect of ultrasonic vibration direction on flexural fracture computed tomography	155
Figure 6.1 Schematic representation illustrating the hierarchical application of a helical gear within an automotive power window mechanism	162
Figure 6.2 Drawing of the 72-tooth helical gear used in this case study	165
Figure 6.3 Illustrates the final 3D model of the helical gear used in the study	166
Figure 6.4 Illustrates the final printed part of the helical gear.....	168
Figure 6.5 Images of compression moulding (Left) and 3D printed helical gears (Right)...	168
Figure 6.6 Close-up view of the 3D printed helical gear mounted within the motor housing of an automotive power window	169
Figure 6.7 Setup for breaking torque testing of helical gear in power window motor	170
Figure 6.8 Stepwise illustration of experimental setup used to evaluate the breaking torque	171
Figure 6.9 Breaking torque and wear pattern analysis of helical gears without and with ultrasonic assistance.....	172
Figure 6.10 Bending stress performance of helical gears: ultrasonic-assisted 3d printing Vs conventional manufacturing.....	174

List of Tables

Table 2.1 Research on ultrasonic-assisted polymer additive manufacturing.....	29
Table 2.2 Mapping of research gaps to thesis objectives and chapters	35
Table 3.1 Mechanical property enhancement due to ultrasonic assisted 3D Printing	70
Table 4.1 Variable parameters along with selected levels of variable parameters	76
Table 4.2 DOE with input printing parameters and output responses	84
Table 4.3 ANOVA analysis for tensile strength corresponding to equation 4.2	87
Table 4.4 ANOVA analysis for impact strength corresponding to equation 4.3.....	88
Table 4.5 ANOVA analysis for flexural strength corresponding to equation 4.4	89
Table 4.6 Pooled ANOVA analysis for tensile strength corresponding to equation 4.5	91
Table 4.7 Pooled ANOVA analysis for impact strength corresponding to equation 4.6.....	92
Table 4.8 Pooled ANOVA analysis for flexural strength corresponding to equation 4.7	93
Table 4.9 Confirmation experiments for Model Precision	95
Table 4.10 Mechanical performance at optimized process parameters	112
Table 5.1 Improvements with optimized X-axis ultrasonic parameters	149
Table 5.2 Mech. property improvements with ultrasonic assistance (42.5 kHz, X vs Z direction)	157
Table 6.1 Helical gear design specifications.....	166
Table 6.2 Process parameters used for printing of gear worm	167
Table 6.3 Comparison of average breaking torque for different fabrication methods.....	173

Abbreviations

ABS	Acrylonitrile butadiene styrene
AI	Artificial intelligence
AM	Additive manufacturing
ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
CAD	Computer aided design
CAE	Computer aided engineering
CFPCs	Carbon fiber polymer composites
CFRPs	Carbon fiber reinforced polymers
CT	Computed tomography
DMLS	Direct metal laser sintering
DOE	Design of experiments
DOF	Degree of freedom
FDM	Fused deposition modelling
FAAM	Field-assisted additive manufacturing
ID	Infill density
IoT	Internet of things
kHz	Kilohertz
LH	Layer height
Mpa	Megapascal

Nm	Newton meter
PEKK	Polyetherketoneketone
PEEK	Polyether ether ketone
PETG	Polyethylene terephthalate glycol
PLA	Polylactic acid
RTM	Resin transfer moulding
SEM	Scanning electron microscopy
SLA	Stereolithography
SLS	Selective laser sintering
UA-3DP	Ultrasonic-assisted 3D printing
WL	Wall layers

Nomenclature

A	Amplitude of ultrasonic vibration
f	Operating frequency
F	Force
P_{total}	Total electrical power
pF	Static Capacitance
Ω	Resonance impedance
W	Input power
ρ	Density
E	Young's modulus
ν	Poisson's ratio
m	Mass of system
a	Acceleration
k	Stiffness
x	Displacement
p	External load
π	Mathematical constant
fn	Natural frequency
U	Nodal displacement vector
$U1$	Displacement in X-direction
$U2$	Displacement in Y-direction
$U3$	Displacement in Z-direction
ΔVmV	Voltage output from the sensor
Y	Response variables

Z_i	Input coded variables
$\gamma_0, \gamma_i, \gamma_{ii}, \gamma_{ij}$	Regression coefficients (linear, quadratic, interaction)
ε	Random error term
TS	Tensile strength
IS	Impact strength
FS	Flexural strength
$F - value$	Fisher's ratio
$P - value$	Probability value
$\delta(TS), \delta(FS)$	Confidence interval error margin for tensile/flexural strength
$t(\alpha/2, DF)$	t statistic at significance $\alpha/2$ and degrees of freedom
DF	Degrees of freedom
Ve	Error variance
$X - UA$	X-axis ultrasonic
$Z - UA$	Z-axis ultrasonic
σ_t	Bending stress in gear tooth
w_t	Tangential load
Pd	diametral pitch
Y	Lewis form factor
F_t	Tangential force
m	Module
BT	Breaking Torque
I	Current
V	Voltage