



Faculty of Mechanical Engineering

**VIBRATION ANALYSIS OF FUSED DEPOSITION
MODELING PRINTED LATTICE STRUCTURES
CELLULAR MATERIAL**

Muhamad Syafwan bin Azmi

Master of Science in Mechanical Engineering

2019

**VIBRATION ANALYSIS OF FUSED DEPOSITION MODELING PRINTED
LATTICE STRUCTURES CELLULAR MATERIAL**

MUHAMAD SYAFWAN BIN AZMI

**A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
in Mechanical Engineering**

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

DECLARATION

I declare that this thesis entitled “ Vibration Analysis of Fused Deposition Modeling Printed Lattice Structures Cellular Material ” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name : Muhamad Syafwan bin Azmi

Date :

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature :

Supervisor Name : Dr. Rainah binti Ismail

Date :

DEDICATION

“To my beloved mother and father”

ABSTRACT

This research presents a vibration analysis on the lattice structure material fabricated by utilizing fused deposition modeling (FDM) additive manufacturing (AM) for application as load-bearing lightweight body part in automated device. The work has been motivated by the need to explore the dynamic behaviour of the lattice structure material so that the real behaviour of the system, performance, suitability and limitations can be understood and which at the end can provide better safety of the structure in the real dynamic applications. This work has undertaken on clarifying issues related to weight and built quality of the manufactured lattice structure material samples prior to vibration testing. The four proposed topological designs namely simple cubic (SC), face centred cubic (FCC), body centred cubic (BCC) and body centred cubic with reinforced z pillars (BCC_z) are evaluated based on these two criteria which are from manufacturability and weight practicality. Based on the selection process, it is found that the BCC topological design of the lattice structure is more acceptable and henceforth used to represent the vibrational response study of the lattice structure cellular material with different strut diameter sizes. The results show that the natural frequency of the lattice structure material can be greatly affected by the strut diameter sizes due to increase in stiffness as the strut diameter increases. In addition, the mathematical equation is also derived to calculate the total area moments of inertia of the lattice structure model and the validity of this developed model is shown through comparison of the results with experimental work of the three-point bending test. From the calculation of total area moment of inertia, it is found that the lattice structure model with the highest strut diameter size yield highest value of total area moment of inertia. The results show a good agreement between the theoretical model and experimental work. The investigation on various effects of damage existence including damage locations and damage extents to the natural frequency values of the lattice structure material are also examined. The damage in the lattice structure is represented by a damage parameter η which indicates the ratio of missing unit cells to the total unit cells of the intact lattice structure. It is found that the natural frequency values decrease with the increase of damage parameter η from ratio of 0.00 to 0.50. Meanwhile, the natural frequency values increase as the damage location became farthest from the clamped edge. This indicates that the effect of damage on the natural frequency values become smaller as the damage zone moves from the clamped edge boundary condition to the free end. This research provides a good information on the influence of the strut diameter design parameter as well as the effects of damage existence to the natural frequency values of the lattice structure material and it can be seen that the results could constitute a useful information for subsequent investigation into the development of the lattice structure in order to fulfil the demand on the lightweight and cost reduction of materials.

ABSTRAK

Kajian ini membentangkan analisa getaran terhadap bahan berstruktur kekisi dibuat dengan pembuatan secara tambahan fused deposition modeling (FDM) untuk aplikasi bahagian badan menahan beban ringan pada peranti automatik. Kerja ini termotivasi oleh keperluan untuk meneroka tingkah laku dinamik bahan berstruktur kekisi agar tingkah laku sebenar sistem, prestasi, kesesuaian dan batasan difahami dan akhirnya memberikan keselamatan struktur lebih baik dalam aplikasi dinamik sebenar. Kerja ini juga melaksanakan penjelasan isu berkaitan berat dan kualiti pembinaan bahan berstruktur kekisi sebelum ujian getaran. Keempat rekabentuk topologi dicadangkan iaitu simple cubic (SC), face centred cubic (FCC), body centred cubic (BCC) dan body centred cubic dengan tiang z (BCCz) dinilai berdasarkan dua kriteria iaitu keterbuatan dan kepraktikan berat. Melalui proses pemilihan, didapati rekabentuk topologi BCC lebih baik dan digunakan mewakili kajian respon getaran bahan berstruktur kekisi dengan saiz garis pusat tiang berbeza. Hasil kajian menunjukkan frekuensi semulajadi bahan berstruktur kekisi amat dipengaruhi saiz garis pusat tiang kerana peningkatan kekakuan apabila saiz garis pusat tiang meningkat. Selain itu, persamaan matematik diperolehi untuk mengira jumlah kawasan momen inersia model bahan berstruktur kekisi dan kesahihan model diperolehi ini dibuktikan dengan perbandingan hasil kajian dengan eksperimen lenturan tiga titik. Dari pengiraan jumlah kawasan momen inersia, didapati model bahan berstruktur kekisi dengan saiz garis pusat tiang tertinggi menghasilkan nilai jumlah kawasan momen inersia tertinggi. Hasil ini menunjukkan persetujuan baik antara model teori dan kerja eksperimen. Kajian terhadap pelbagai kesan kerosakan termasuk lokasi dan keterukan kerosakan terhadap nilai frekuensi semulajadi bahan berstruktur kekisi juga dilaksanakan. Kerosakan bahan berstruktur kekisi diwakili parameter kerosakan η yang menunjukkan nisbah sel unit yang hilang berbanding sel unit struktur sempurna. Didapati nilai frekuensi semulajadi menurun dengan peningkatan parameter kerosakan η dari 0.00 hingga 0.50. Selain itu, nilai frekuensi semulajadi meningkat apabila lokasi kerosakan lebih jauh dari sisi dikapit. Ini menunjukkan kesan kerosakan terhadap frekuensi semulajadi bar bahan selular berstruktur kekisi menjadi lebih kecil apabila zon kerosakan bergerak dari sisi dikapit ke arah sisi bebas. Kajian ini memberikan maklumat baik mengenai pengaruh parameter rekabentuk saiz garis pusat tiang serta kesan kerosakan kepada nilai frekuensi semulajadi bahan berstruktur kekisi dan ianya boleh dilihat bahawa hasil kajian membentuk maklumat berguna untuk siasatan seterusnya ke atas pembangunan bahan struktur berbentuk kekisi dalam memenuhi permintaan untuk bahan ringan dan pengurangan kos bahan.

ACKNOWLEDGEMENTS

Verily, With Hardship Comes Ease (Surah al-Sharh,94).

In the name of Allah, the Most Gracious and the Most Merciful. May his peace and blessings be upon the one after whom there is no other prophet.

First and foremost, I express my profound gratitude to my supervisor, Dr. Rainah Ismail and co-supervisor, Dr Rafidah Hasan of Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka (UTeM) for their constant encouragements, outstanding guidance and understandings towards completing this study. Their supports undoubtedly helped me become the better version of myself then I was before going through this challenging journey.

In addition, my sincere gratitude goes to Mr. Johardi Johar from the Vibro Acoustic laboratory of Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka (UTeM) for his assistances in technical supports during experiment, suggestions and advices regarding the apparatus and facility for this study.

Very special thanks to the Ministry of Education of Malaysia and Universiti Teknikal Malaysia Melaka (UTeM) for opportunity as well as financial support through research grant FRGS/1/2016/TK03/FKM-CARE/F00316.

To all my colleagues, thank you for being extremely supportive friends through the ups and downs I faced to finish this study. Your presence has made my years here more colorful in many special ways.

Last but not least, with all my heart, I am forever and extremely grateful to my amazing parents, the greatest treasures and gifts in my life for their continuous prayers, never ending loves, sacrifices and moral supports to help me cross the finish line.

TABLE OF CONTENTS

	PAGE
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF APPENDICES	xi
LIST OF SYMBOLS	xii
LIST OF ABBREVIATIONS	xv
LIST OF PUBLICATIONS	xvii
LIST OF AWARDS	xix
CHAPTER	
1. INTRODUCTION	1
1.1 Motivation and problem statement	1
1.2 Research objectives	5
1.3 Research scopes	5
1.4 Thesis outline	6
2. LITERATURE REVIEW	8
2.1 Introduction	8
2.2 Cellular structures materials	9
2.3 Lattice structures cellular material manufacturing techniques	16
2.3.1 Conventional manufacturing techniques	16
2.3.2 Additive manufacturing techniques	23
2.4 Static analysis of the lattice structures cellular material	30
2.4.1 Compression analysis	31
2.4.2 Impact analysis	33
2.4.3 Bending analysis	35
2.5 Dynamic analysis of the lattice structures cellular material	36
2.5.1 Introduction to dynamic analysis	36
2.5.2 Damage detection methods in structure	39
2.5.3 Vibration based damage detection method	41
2.5.4 Vibration analysis on the lattice structures cellular material	44
2.5.5 Vibration analysis on other type of structure	47
2.6 Transverse vibration analysis of Euler-Bernoulli for cantilever beam	50
2.7 Summary	52

3. METHODOLOGY	55
3.1 Introduction	55
3.2 Sample preparation	57
3.2.1 Topological design	57
3.2.2 Sample's topological design selection	62
3.2.3 Lattice structures cellular material bar samples	63
3.2.3.1 Effect of the strut diameter size design parameter	64
3.2.3.2 Effect of damage extents	66
3.2.3.3 Effect of damage locations	68
3.3 Vibration test	69
3.4 Operating deflection shape (ODS)	72
3.5 Theoretical mathematical modelling to calculate total area moment of inertia	72
3.6 Bending test	80
3.7 Summary	82
4. RESULT AND DISCUSSION	83
4.1 Introduction	83
4.2 Sample preparation	84
4.2.1 Manufacturability observation	84
4.2.2 Weight practicality analysis	89
4.2.3 Topological design selection summary	91
4.3 Vibration analysis	93
4.3.1 Effect of the strut diameter size design parameter	93
4.3.1.1 Vibration characteristics characterization	93
4.3.1.2 Bending stiffness characterization analysis	101
4.3.2 Comparative assessment between analytical and experimental natural frequency results	103
4.3.3 Factors which influence changes in the total area moment of inertia mathematical modelling	106
4.3.3.1 Strut diameter design parameter	106
4.3.3.2 Unit cell size design parameter	107
4.3.4 Effect of damage extents	108
4.3.5 Effect of damage locations	111
4.4 Summary	115
5. CONCLUSION AND RECOMMENDATIONS	117
5.1 Conclusions	117
5.2 Thesis contribution	120
5.3 Recommendations for future works	121
REFERENCES	122
APPENDICES	134

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Summary of materials, advantages, disadvantages and the typical applications between additive manufacturing techniques	28
2.2	Transfer functions used in vibration measurement (Irvine, 2000; Inman and Singh, 2014)	39
3.1	Topological design illustrations and lattice design details	59
3.2	List of FDM parameters for the lattice structures cellular material bar sample fabrication	65
3.3	List of vibration test equipment	70
4.1	Topological designs weight practicality analysis	90
4.2	Topological design selection summary	92
4.3	Vibration test results, mass, calculated mass and calculated area moments of inertia of the lattice structures cellular material bar samples	96
4.4	Three-point bending test results	102
4.5	Comparative assessment between the analytical and experimental results	104
4.6	Natural frequency values for the first two vibration modes of the artificially damaged lattice structures cellular material bar samples with different damage extents	110
4.7	Natural frequency values for the first two vibration modes of artificially damaged lattice structures cellular material bar samples with different damage locations	113

LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Strength versus density for various materials (Budynas et al., 2011)	2
2.1	Classification of cellular materials, adapted from (Rehme, 2010)	10
2.2	Illustration of the honeycomb with different topologies (Wadley, 2006)	11
2.3	Open-cell alporas foam structure b) closed-cell duocel foam structures (Dannemann and Lankford Jr, 2000)	12
2.4	Lattice single unit cell (a) body-centred cube (BCC); (b) body-centred cube with vertical struts (BCC _z), (c) gyroid, (d) matrix phase of D-gyroid, (e) face centred cube (FCC), (f) face centred cube with vertical struts (PFCC), (g) Boolean combination of BCC and FCC (F2BCC) (Aremu et al., 2014)	14
2.5	Additively manufactured lattice crushable material to be used within an Earth Return Capsule (ERC) for Mars Sample Return mission (Anonymous, 2016)	15
2.6	Schematic diagram of the (a) hot press mould (b) single truss unit cell mould (Li et al., 2015)	18
2.7	An illustration of the thermal expansion approach process (Yin et al., 2011)	19
2.8	Multifunctional metal textile laminate (Sypeck and Wadley, 2001)	20
2.9	Wire lay-up process using solid or hollow wires (Wadley, 2006)	20
2.10	Hexagonal perforated metal sheet bend and bonded to form the tetrahedral lattice truss core sandwich structure (Wadley, 2006)	21
2.11	Metal expansion technique to fabricate the lattice truss core (Kooistra and Wadley, 2007)	22
2.12	Additive manufacturing general process flow (Anonymous, 2017)	24

2.13	A typical PBF machine set-up (Electron beam is used instead of laser in EBM) (Swift and Booker, 2013)	25
2.14	An illustration of FDM machine set-up (Stansbury and Idacavage, 2016)	26
2.15	An illustration of SLA machine set-up (Swift and Booker, 2013)	27
2.16	General compressive behaviour of cellular structures materials (Rehme, 2010)	32
2.17	An illustration of MSD model of a SDOF system	37
2.18	FRF and bode-plot graphs of a SDOF system with $m=2000$ kg, $k= 45$ kN and $C= 2000$ s·N/m	39
2.19	An illustration of cantilever beam for the Euler-Bernoulli beam theory	50
3.1	Flow of research methodology	56
3.2	CubePro FDM type 3D printer developed by 3D Systems Inc.	61
3.3	CubePro's own software's parameters selection interface	62
3.4	Dino-lite Edge digital microscope	63
3.5	An illustration of tessellated lattice structure cellular material bar	64
3.6	(a) ABS lattice structures cellular material bar sample with 1.4 mm, 1.6 mm and 1.8 mm strut diameter size (top view) (b) commercial real arm (c) solid ABS	65
3.7	<i>SolidWorks</i> ' rendition of damaged regions with different damage extents within the lattice structures cellular material bar samples (top view)	67
3.8	<i>SolidWorks</i> ' rendition of damaged regions with different damage locations within the lattice structures cellular material bar samples (top view)	68
3.9	(a) Actual and (b) schematic experimental set-up for vibration test	70
3.10	Boundary condition, excitation and measurement points location of the lattice structures cellular material bar sample (top view)	71
3.11	Illustration of use of the parallel axis theorem in the 2D xy -plane view with the variables used in I_{xsi} , I_{ysi} , I_{zsi} , I_{xnj} , I_{ynj} and I_{znj}	74
3.12	(a) Isometric view of a lattice structure cellular material cube (b) an xz -plane view cut at the nodes and (c) an xz -plane view at the joints	74

3.13	An illustration of xy -plane axes rotation with respect to the unit cell's origin	74
3.14	Illustration for the calculation of the moments of inertia for a strut showing (a) an illustration of x_s , y_s and z_s , and (b) an illustration of θ and θ_{xy}	75
3.15	(a) First ellipse (b) second ellipse (c) square and (d) merged node illustrations	78
3.16	(a) Schematic diagram and (b) actual experimental set-up for the three-point bending test	81
4.1	Manufacturability observation results for BCC topological design (front view)	84
4.2	Manufacturability observation results for FCC topological design (front view)	85
4.3	Manufacturability observation results for BCC _z topological design (front view)	85
4.4	Manufacturability observation results for SC topological design (front view)	86
4.5	An illustration of overhangs situation (Odom, J., 2017)	87
4.6	An illustration of FCC lattice structure cellular material (front view)	88
4.7	An illustration of cut up of (a) BCC _z and (b) SC lattice structure cellular material	88
4.8	An illustration of failed formation of the Z pillars that lead to more severe overhangs	89
4.9	(a) Accelerance FRF graph and (b) bode plot plot of arbitrarily chosen vibration measurement point	93
4.10	Coherence graph of arbitrarily chosen vibration measurement point	94
4.11	FRF graphs of the lattice structures cellular material bar sample with (a) 1.4 mm (b) 1.6 mm (c) 1.8 mm strut diameter size (d) commercial real arm and (e) solid ABS (measurement point 5)	95
4.12	Natural frequency values for the first two vibration modes of the lattice structures cellular material bar samples, the solid ABS and the commercial real arm	96

4.13	Effect of the strut diameter design parameter size of the lattice structure cellular material bar samples on the mass and the calculated total area moment of inertia. The error bar is for the standard deviation	97
4.14	Mode shapes of lattice structure cellular material bars with strut diameter design parameter 1.4 mm, 1.6 mm and 1.8 mm	99
4.15	Illustration of the typical numerical mode shapes of cantilever beam (Sahin and Bayraktar, 2016)	100
4.16	Force-displacement curves for all samples from the three-point bending test	101
4.17	Linear part of the force-displacement curves for all samples from the three-point bending tests	102
4.18	Mode shapes for the first two modes of vibration of cantilever beam	105
4.19	Effect of strut diameter size design parameter to the total area moment of inertia of lattice structure bar	107
4.20	Effect of unit cell size design parameter to the total area moment of inertia of lattice structure bar	107
4.21	FRF graphs of the lattice structures cellular material bar samples with different damage extents (measurement point 5, $\eta = 0.35$ measurement point 6)	109
4.22	Effect of damage extents on the natural frequency values of the lattice structures cellular material bar samples	110
4.23	FRF graphs of the lattice structures cellular material bar samples with different damage locations (measurement point 5)	112
4.24	Graph of natural frequency values against damage location	113

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	CubePro FDM 3D printer technical details	134
B	CubePro FDM 3D printer ABS thermoplastic polymer safety datasheet	139
C	FRF, Bode-plot and Coherence graphs	143

LIST OF SYMBOLS

ω_n	-	Natural Frequency
ω	-	Frequency
x	-	Displacement
\dot{x}	-	Velocity
\ddot{x}	-	Acceleration
F	-	Driven Force
k	-	Stiffness
m	-	Mass
c	-	Damping factor
E	-	Elastic modulus
t	-	Time
L	-	Bar length
A	-	Cross sectional area
$W(x)$	-	Mode shape function
$k_n L$	-	Eigenvalue of vibration mode
L	-	Unit Cell's Length
θ_{xy}	-	Strut to Surface Angle
\emptyset	-	Strut Diameter
η	-	Damage Parameter
Hz	-	Hertz

V_{rms}	-	Root Mean Square Voltage
N	-	Newton
dF	-	Frequency Resolution
$^{\circ}$	-	Degree
ρ	-	Density
I	-	Total Area Moment of Inertia
I_x	-	Total Area Moment of Inertia in x Axis Direction
I_y	-	Total Area Moment of Inertia in y Axis Direction
I_z	-	Total Area Moment of Inertia in z Axis Direction
Σ	-	Summation
N_{strut}	-	Number of Strut
N_{node}	-	Number of Node
i	-	i -th strut
j	-	j -th node
I_{xsi}	-	Area Moments of Inertia of i -th Strut in x Axis Direction
I_{ysi}	-	Area Moments of Inertia of i -th Strut in y Axis Direction
I_{zsi}	-	Area Moments of Inertia of i -th Strut in z Axis Direction
I_{xnj}	-	Area Moments of Inertia of j -th Node in x Axis Direction
I_{ynj}	-	Area Moments of Inertia of j -th Node in y Axis Direction
I_{znj}	-	Area Moments of Inertia of j -th Node in z Axis Direction
x_s	-	Strut distance in x Axis to The Origin
y_s	-	Strut distance in y Axis to The Origin
z_s	-	Strut distance in z Axis to The Origin
x_n	-	Node distance in x Axis to The Origin

y_n	-	Node distance in y Axis to The Origin
z_n	-	Node distance in z Axis to The Origin
θ	-	Angle
l_s	-	Strut's length
d_s	-	Strut's diameter
I'_{xsi}	-	Area Moments of Inertia of The i -th Strut In Horizontal Orientation After Rotation of Axes' Transformation in x Axis Direction With Respect to The Origin
I'_{ysi}	-	Area Moments of Inertia of The i -th Strut In Horizontal Orientation After Rotation of Axes' Transformation in y Axis Direction With Respect to The Origin
I'_{zsi}	-	Area Moments of Inertia of The i -th Strut In Horizontal Orientation After Rotation of Axes' Transformation in z Axis Direction With Respect to The Origin
O	-	Origin
a	-	Radius a
b	-	Radius b

LIST OF ABBREVIATIONS

3D	-	Three Dimensional
ABS	-	Acrylonitrile-Butadiene-Styrene
AM	-	Additive Manufacturing
BCC	-	Body Centred Cube
BCC _z	-	Body Centred Cube with Vertical Struts
CAD	-	Computer Aided Design
CFRP	-	Carbon Fibre Reinforced Polymer
EBM	-	Electron Beam Melting
ERC	-	Earth Return Capsule
ESA	-	European Space Agency
F2BCC	-	Boolean Combination of BCC and FCC
FBCC _z	-	Face and Body Centred Cubic with Z Struts
FCC	-	Face Centred Cube
FCC _z	-	Face Centred Cubic with Z Struts
FDM	-	Fused Deposition Modeling
FEM	-	Finite Element Method
FRF	-	Frequency Response Function
GFRP	-	Glass Fibre Reinforced Polymer
RMS	-	Root Mean Square
NDE	-	Non Destructive Evaluation

NDT	-	Non Destructive Testing
PBF	-	Powder Bed Fusion
PFCC	-	Face Centred Cube with Vertical Struts
PLA	-	Polylactic Acid
SC	-	Simple Cubic
SLA	-	Stereolithography
SLM	-	Selective Laser Melting
SLS	-	Selective Laser Sintering
STL	-	Standard Triangulation Language
TLPDB	-	Transient Liquid Phase Diffusion Bonding

LIST OF PUBLICATIONS

Journal Articles

Azmi, M.S., Hasan, R., Ismail, R., Rosli, N.A. and Alkahari, M.R., 2018. Static and dynamic analysis of FDM printed lattice structures for sustainable lightweight material application. *Progress in Industrial Ecology, an International Journal*, 12(3), pp. 247-259.

Azmi, M.S., Ismail, R., Hasan, R. and Alkahari, M.R., 2018. Vibration Analysis of Fused Deposition Modelling Printed Lattice Structure Bar for Application in Automated Device. *International Journal of Engineering & Technology*, 7 (3.17), pp.21-24.

Proceedings

Mat Tahir, N.A., Azmi, M.S., Abdollah, M.F.B., Ramli, F.R., Amiruddin, H., Tokoroyama, T., and Umehara, N., 2018. Tribological properties of 3D-printed pin with internal structure formation under dry sliding conditions. *Proceedings of Mechanical Engineering Research Day 2018*, pp.260-261.

Azmi, M.S., Ismail, R., Hasan, R., Alkahari, M.R. and Tokoroyama, T., 2017. Vibration analysis of FDM printed lattice structure bar. *Proceedings of SAKURA Symposium on Mechanical Science and Engineering*, pp.33-35.

Azmi, M.S., Ismail, R., Hasan, R. and Alkahari, M.R., 2017. Study on dimensional accuracy of lattice structure bar using FDM additive manufacturing. *Proceedings of Mechanical Engineering Research Day*, pp.397-398.

LIST OF AWARDS

Bronze Award in Universiti Teknikal Malaysia Melaka Exhibition (UTeMEX 2017) for ‘New method to produce optimized ABS polymer lattice structure material manufactured using mid-end additive layer manufacturing’.

Bronze Award in Universiti Teknikal Malaysia Melaka Exhibition (UTeMEX 2017) for ‘A low-cost fire extinguisher using sound wave’.

Silver Award in Mini Universiti Teknikal Malaysia Melaka Exhibition (MiniUTeMEX 2016) for ‘Vibration characteristics for diesel engine oil mixed hexagonal boron nitride (hBN) nanoparticles.’