Joining of Ceramic Matrix Composite Materials for Aerospace Applications

Thesis submitted in partial fulfillment
for the award of degree

Doctor of Philosophy

by

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2023

CERTIFICATE

It is certified that the work contained in the thesis titled "**Joining of Ceramic Matrix Composite Materials for Aerospace Applications**" by "**ANURAG KAMAL**" (Roll No. 21041004) has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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Acknowledgements

I extend my deepest gratitude to my supervisors, ***Dr. Vijay Maruti Shinde and Dr. Anoop Kumar Shukla,*** whose unwavering guidance, insightful feedback, and constant encouragement have been instrumental throughout this doctoral journey. Your expertise and mentorship have shaped my research and personal growth, and I am profoundly grateful for the invaluable lessons learned under your supervision. I would like to honour them with a Sanskrit verse "गुरू ब्रह्मा गुरू विष्णु, गुरु देवो महेश्वरा गुरु साक्षात परब्रह्म, तस्मै श्री गुरुवे नमः". I owe my gratitude to Dr. Shinde, not just for his academic contributions but also for cultivating an atmosphere conducive to personal and professional development. His teachings went beyond the confines of the laboratory, imparting the values of integrity and the significance of being part of a supportive community. I am grateful to Dr. Shukla for instilling essential laboratory knowledge and skills, without which this would not have been possible. His guidance was instrumental in overcoming challenges encountered during experimental works.

Special thanks to my office seniors ***(Shri Buragadda V. Rajasekhar, Dr. Renjith Devasia, Shri Anil Painuly, Dr. Nallaperumal M., and Dr. Manu S.K.)*** and colleagues ***(Shri Shobhit Kumar, Shri Shyin P.P., Shri Sandeep Kumar K.P., and Shri Anjani Kumar Sharma)*** at VSSC/ISRO, whose collaborative spirit and shared knowledge created a stimulating environment for intellectual exchange. Your guidance and camaraderie have been a source of inspiration and motivation. Thanks are also to Analytical Spectroscopy Division (ASD) and Materials Characterisation Division (MCD) for characterisation supports. Sincere thanks extend to Director, VSSC and Chairman, ISRO for providing great supports during this journey. Sincere gratitude to the taxpayers of India, whose contributions provide the fundamental support for this academic pursuit. The financial and administrative support from Vikram Sarabhai Space Centre/Indian Space Research Organisation elevated my aspirations, and I recognize their pivotal role in making this research endeavour possible.

The Department of Chemical Engineering & Technology at the Indian Institute of Technology BHU, Varanasi, deserves recognition for providing a nurturing ecosystem for academic excellence. A special note of appreciation goes to my RPEC members, ***Dr. Arnab Sarkar and Dr. Debdip Bhandary***, for their valuable insights and constructive feedback that enriched the quality of this research. My sincere thanks to ***Shri Aniket Bhiku Jadhav and Shri Anand Gupta*** from IIT (BHU), Varanasi for their invaluable assistance throughout this journey.

I am thankful to my friends (***Shri Vijendra Kumar, Shri Biswa Ranjan Mohanty, and Shri Prasanta Kumar Behera)*** who provided emotional support and shared moments of joy, making the challenges of this academic pursuit more manageable. Your friendship has been a cherished aspect of this academic journey.

To my parents, your unwavering support, sacrifices, and belief in my abilities have been the bedrock of my academic pursuits. Your encouragement has been my driving force, and this achievement is as much yours as it is mine.

Lastly, I extend heartfelt thanks to my wife, for her enduring patience, understanding, and unwavering support. Your love has been my anchor, providing solace and encouragement during the peaks and troughs of this doctoral odyssey.

This accomplishment stands as a collective effort, and I am fortunate to have had such an incredible support system. Thank you all for being an integral part of this significant chapter in my life.

Anurag Kamal

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Chapter 6

Nomenclature

W_a	Work of adhesion
γ_{lv}	liquid-vapour interfacial energy
(s,s)	Solid solution
γ_{sl}	solid-liquid interfacial energy
γ_{sv}	solid-vapour interfacial energy
$\bar{d}_p$	Average particle size
ΔT	Difference in room-to-reaction temperature
$\Delta\alpha$	Difference in CTE
C_0	Constant
CR	Cooling rate
d	Desirability
E	Activation energy of diffusion
E_c	Ceramic Young's modulus
E_m	Metal Young's modulus
E_{mp}	Linear strain hardening coefficient
P_c	Capillary pressure
r	Effective pore radius
R	Universal gas constant
S	Spreading coefficient
T	Temperature
t	time
T_m	Melting temperature
w	Width
w	Weighted factor
β_i, β_{ii}, and	regression coefficients
ΔG	Gibbs free energy
σ	Surface tension
σ_c	Residual stresses
σ_y	Metal yield strength

Greek symbols

α	Hexagonal
β	Cubic
θ	Angle, hexagonal
ε	Error, hexagonal
δ	Orthorhombic
ζ	Orthorhombic

Abbreviations

A4PB	Asymmetric 4-point bending
ABA	Active brazing alloy
ACC	Advanced carbon/carbon
ANOVA	Analysis of variance
BN	Boron nitride

CCD	Central composite design
CFRP	Carbon fibre-reinforced polymers
CMCs	Ceramic matrix composites
CNT	Carbon nanotube
CTE	Coefficient of thermal expansion
CVD	Chemical vapour deposition
CVI	Chemical vapour infiltration
DB	Diffusion bonding
DLO	Double lap offset
DN	Double-notch
DSC	Differential scanning calorimetry
EBSD	Electron backscatter diffraction
EDS	Energy dispersive spectrometer
ESA	European Space Agency
FCC	Face-centred cubic
FE-SEM	field emission scanning electron microscope
HCP	Hexagonal closed packing
HM	High modulus
HS	High strength
HT	High temperature
IPA	Isopropyl alcohol
IRZ	Interfacial reaction zone
LS	Low strength
LSS	Lap shear strength
LST	Low service temperature
MMC	Metallic matrix composites
MMS	Monomethylsilane
MTS	Methyl trichlorosilane
MWCNTs	Multiwall carbon nanotubes
NDT	Non-destructive test
PAN	Polyacrylonitrile
PCS	Polycarbosilane
PDC	Polymer derived ceramics
PIP	Polymer infiltration pyrolysis
PLS	Pressureless-sintered
PSZ	Polysilazane
PyC	Pyrolytic carbon
RB-SiC	Reaction bonded SiC
RLV	Reusable launch vehicles
RMI	Reactive melt infiltration
RSM	Response surface methodology
RT	Room temperature
SEM	Scanning electron microscope
SiCNT	Silicon carbide nanotube
SL	Single lap
SLO	Single lap offset
SPS	Spark plasma sintering
SPS-DB	Spark plasma sintering-diffusion bonding technique
SSTO	Single stage to orbit

TC	Torsion cylinder
THG	Torsion hourglass
TLPB	Transient liquid phase diffusion bonding
TPS	Thermal protection systems
TRS	Thermal residual stress
TS	Torsion square
TSTO	Two stage to orbit
TT	Torsion tube
UAB	Ultrasonic-assisted brazed
UTM	Universal testing machine
V-PMS	Polymethylsilane
XRD	X-Ray diffraction