

ADHESIVE BONDING OF COMPOSITE MATERIALS FOR ARMOR APPLICATIONS

AISHA AHMED



**DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2024**

© Indian Institute of Technology Delhi, New Delhi, 2024

ADHESIVE BONDING OF COMPOSITE MATERIALS FOR ARMOR APPLICATIONS

by

AISHA AHMED

Department of Mechanical Engineering

Submitted

in fulfilment of the requirements of the degree of

Doctor of Philosophy



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2024

Certificate

This is to certify that the thesis entitled “**Adhesive Bonding of Composite Materials for Armor Applications**” being submitted by **Ms. Aisha Ahmed** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** in Mechanical Engineering is a bonafide record of original research work carried out by her under my supervision in conformity with rules and regulations of the institute. The thesis work in my opinion has reached the requisite standard for the degree of Doctor of Philosophy. The results contained in this thesis have not been submitted, in part or in full, to any other University or Institute for the award of any degree or diploma.

Date:

Place: New Delhi, India

Dr. Naresh Bhatnagar

Professor

Department of Mechanical Engineering

Indian Institute of Technology Delhi

New Delhi – 110016, India

Acknowledgements

‘*All praise be to Allah*’ for bestowing countless blessings and above all the intellectual ability to understand Him, His creation and to grow for the betterment of my own, society and the whole mankind.

I would like to express my profound gratitude to Professor Naresh Bhatnagar, my dedicated supervisor, for his unwavering guidance, boundless wisdom and unrelenting support throughout the entire journey of my PhD. His mentorship has been invaluable and his commitment to excellence has been a constant source of inspiration. His dedication to the pursuit of knowledge and his genuine passion for research and development have left an indelible mark on my academic and personal development.

I would also like to extend my appreciation to the entire academic community at *IIT Delhi*, where I have had the privilege of engaging with brilliant minds, attending thought-provoking lectures and learning with fellow students in a positive and proactive environment. I owe heartfelt thanks to my Student Research Committee members Prof. P.V. Rao, Prof. Puneet Mahajan and Prof. D. K. Dubey for their kind support and valuable feedback on the regularly held progress seminars.

I am deeply grateful to my fellow colleagues Dr. Kartikeya, Dr. Alok, Dr. Prajesh, Makhan, Khushiram, Dhruv, Mohit Aggarwal and Mohit who have provided constant support, both academically and emotionally. My heartfelt thanks go out to my seniors and mentors Dr. Hemant Chouhan, Dr. Vedpal Arya, Dr. Pankaj Chauhan, Dr. Pooja Bhati and Dr. Neelanchali Asija for their encouragement, counselling and motivations. The hours-long brainstorming discussions in the lab on a cup of tea with them was a great problem-solving technique.

I would like to thank entire team of *Production Engineering Lab* and *Personal Body Armor Lab*, Mr. Tulsi Ram, Mr. Anil Kumar, Mr. Vijay Tiwari, Mr. Prithvi Raj Vyas, Mr. Anil Kumar Yadav and Mr. Sachin, for always extending a helping hand in the hour of need.

I am fortunate to have amazing friends who have stood by me throughout this demanding journey. My heartfelt thanks go to Sufia, Firdos, Uzma, Rumysa, Najia and Ieeba for their unwavering encouragement and companionship during highs and lows of research.

The greatest source of strength is my family, my father Ikramuddin is the centre pole of my marquee, he has instilled moral values in me and showed by living an example how to remain steadfast in the most desperate circumstances. From my mother I have learned empathy towards people around. My brother Yasir has made me learn how to persevere during the hardships.

Seemingly, Ph.D. looks like scientific research, but I feel a research scholar's learnings are beyond a scientific finding. I should say how we acknowledge our limitations, shortcomings, failures and then how we drive out new findings with patience and perseverance, is actually a priceless achievement. I desperately want to acknowledge my weaknesses, which have evolved me. Also, I am thankful to all those who have corrected me in those tender moments.

Aisha

Abstract

The joining of the two-constituent armor material is as crucial as their ballistic property itself since neither of the two ballistic materials can defeat hardened core projectiles individually at an optimum weight and thickness of an armor panel. A perfectly bonded metal or ceramic to the composite laminate can defeat one or two hits of hardened steel core (HSC) projectiles, but the same configuration might not be a right solution in the multi-hit scenario. This research work has been focused on the development of armor panels resisting multiple shots of HSC projectiles in order to counter threat level V of BIS Standard IS17051:2018 or equivalent NIJ standard 0101.07 (2023), and also to investigate the relationship between the interfacial shear properties of the bonding adhesive and the ballistic performance of the bonded armor materials. All possible adhesives were characterised to better understand the applicability for bonding armor materials particularly with ultra-high molecular weight polyethylene (UHMWPE) composite laminate. A fixture was fabricated and modified to evaluate the interfacial shear strength (IFSS) of the adhesive bonded dissimilar substrates, as per standard ASTM D4501. The modified fixture was validated by comparing shear strength values obtained experimentally with the shear values obtained in a single lap joint geometry (ASTM D 1002) on similar substrates of aluminium and steel. Interfacial shear tests were performed using fixture to optimize the thickness of resin adhesive bonding boron carbide (B_4C) to steel substrates. The IFSS values were evaluated and compared for the selected adhesives bonding different armor material combinations such as B_4C /steel, B_4C /UHMWPE laminae and Steel/UHMWPE laminae. UHMWPE fibers are non-polar in nature hence UHMWPE laminae was subjected to plasma treatment for incorporation of reactive sites on the surface of laminae which was to be bonded to B_4C tiles to enhance adhesion of the substrates. IFSS test of the treated laminae bonded with B_4C showed good improvement in shear strength. The test panels were fabricated with different adhesives using B_4C /UHMWPE substrate configuration and subjected to high velocity impact tests in a single-stage gas gun. Shear strength of the adhesive bonded steel and UHMWPE-fiber laminate were also determined to understand correlation of the shear strength and its ballistic performance.

सारांश

दो-घटक कवच सामग्री का जुड़ना उनकी प्राक्षेपिकी विशेषताओं जितना ही महत्वपूर्ण है क्योंकि दोनों में से कोई भी प्राक्षेपिकी सामग्री कवच पैनल के इष्टतम वजन और मोटाई पर व्यक्तिगत रूप से कठोर कोर प्रक्षेप्य (प्रोजेक्टाइल) को हरा नहीं सकती है। मिश्रित लैमिनेट से पूरी तरह बंधी धातु या सिरेमिक कठोर स्टील कोर (एचएससी) प्रक्षेप्य के एक या दो आघात को हरा सकती है, लेकिन एकाधिक- आघात परिदृश्य में समान विन्यास एक सही समाधान नहीं हो सकता है। यह शोध कार्य बीआईएस मानक IS17051:2018 या समकक्ष एनआईजे मानक 0101.07 (2023) के खतरे के स्तर वी का मुकाबला करने के लिए एचएससी प्रोजेक्टाइल के कई शॉट्स का विरोध करने वाले कवच पैनलों के विकास पर केंद्रित है, और इंटरफेशियल कतरनी के बीच संबंधों की जांच करने के लिए भी। बंधन चिपकने वाले गुण और बंधी कवच सामग्री का प्राक्षेपिकी प्रदर्शन। सभी संभावित चिपकने वाले विशेष रूप से अल्ट्रा-उच्च आणविक भार पॉलीथीन (यूएचएमडब्ल्यूपीई) मिश्रित टुकड़े टुकड़े के साथ कवच सामग्री को जोड़ने के लिए प्रयोज्यता को बेहतर ढंग से समझने के लिए विशेषता रखते थे। मानक एएसटीएम डी4501 के अनुसार, चिपकने वाले बंधुआ असमान सबस्ट्रेट्स की इंटरफेशियल कतरनी ताकत (आईएफएसएस) का मूल्यांकन करने के लिए एक स्थिरता का निर्माण और संशोधन किया गया था। एल्यूमीनियम और स्टील के समान सबस्ट्रेट्स पर एकल लैप संयुक्त ज्यामिति (एएसटीएम डी 1002) में प्राप्त कतरनी मूल्यों के साथ प्रयोगात्मक रूप से प्राप्त कतरनी ताकत मूल्यों की तुलना करके संशोधित स्थिरता को मान्य किया गया था। स्टील सबस्ट्रेट्स के लिए राल चिपकने वाली बॉन्डिंग बोरान कार्बाइड (बी₄सी) की मोटाई को अनुकूलित करने के लिए फिक्स्चर का उपयोग करके इंटरफेशियल कतरनी परीक्षण किए गए थे। आईएफएसएस मूल्यों का मूल्यांकन किया गया और बी₄सी/स्टील, बी₄सी/UHMWPE लैमिनाई और स्टील/UHMWPE लैमिनाई जैसे विभिन्न कवच सामग्री संयोजनों को जोड़ने वाले चयनित चिपकने वाले पदार्थों के लिए तुलना की गई। UHMWPE फाइबर प्रकृति में गैर-ध्रुवीय होते हैं इसलिए UHMWPE लैमिनाई को लैमिनाई की सतह पर प्रतिक्रियाशील साइटों को शामिल करने के लिए प्लाज्मा उपचार के अधीन किया गया था जिसे सबस्ट्रेट के आसंजन को बढ़ाने के लिए बी₄सी टाइल्स से जोड़ा जाना था। बी₄सी से जुड़े उपचारित लैमिनाई के आईएफएसएस परीक्षण ने कतरनी ताकत में अच्छा सुधार दिखाया। परीक्षण पैनलों को बी₄सी/UHMWPE सबस्ट्रेट विन्यास का उपयोग

करके विभिन्न चिपकने वाले पदार्थों के साथ निर्मित किया गया था और एकल-चरण गैस गन में उच्च वेग प्रभाव परीक्षणों के अधीन किया गया था। चिपकने वाली बंधुआ स्टील और UHMWPE-फाइबर लेमिनेट की कतरनी ताकत को कतरनी ताकत और उसके बैलिस्टिक प्रदर्शन के सहसंबंध को समझने के लिए भी निर्धारित किया गया था।

Table of Contents

<i>Certificate</i>	i
<i>Acknowledgements</i>	ii
<i>Abstract</i>	iv
<i>List of Figures</i>	xii
<i>Acronyms</i>	xvii
Chapter 1. Introduction	1
1.1 Preamble.....	1
1.2 Ballistic Threat Standards	2
1.3 Body Armor	4
1.3.1 Armor Performance.....	5
1.3.2 Need for Adhesive Bonding in Body Armors.....	5
1.3.3 Construction of a Body Armor.....	7
1.4 Adhesion.....	13
1.4.1 Theories of Adhesion	13
1.4.2 Factors Affecting Adhesion	15
1.4.3 Mechanism of Bond Failure.....	17
1.5 Motivation.....	18
1.6 Outline of the thesis	18
Chapter 2. Literature Review	20
2.1 Preamble.....	20
2.2 Adhesion.....	20
2.2.1 Fundamental and Practical	20
2.2.2 Properties of Adhesives	21
2.2.3 Bonding Dissimilar Substrates.....	25
2.2.4 Numerical Modelling of Adhesive Joints	26
2.3 Adhesives in Armors.....	27
2.3.1 Types of Adhesives.....	27

2.3.2	Confinement of Ceramic	28
2.3.3	Ballistics Tests	30
2.4	Surface Treatment of Substrates	32
2.4.1	Ceramic	32
2.4.2	UHMWPE Laminate	33
2.5	Conclusion from the Literature	36
2.6	Research Gaps	38
2.7	Objectives	39
Chapter 3.	Materials & Methods	40
3.1	Preamble.....	40
3.2	Materials	40
3.2.1	Boron Carbide Tiles	40
3.2.2	High Hardness Metal Sheet.....	41
3.2.3	UHMWPE Composite Laminate	42
3.2.4	Adhesives	44
3.3	Manufacturing Techniques	47
3.3.1	Compression Moulding	47
3.3.2	Autoclave Moulding	48
3.3.3	Abrasive Water Jet	52
3.4	Characterisations Techniques	53
3.4.1	Atomic Force Microscopy (AFM)	53
3.4.2	Differential Scanning Calorimetry (DSC)	53
3.4.3	Fourier Transform Infrared Spectroscopy (FTIR)	54
3.4.4	X-Ray Photoelectron Spectroscopy (XPS)	55
3.4.5	Surface Wettability	56
3.5	Mechanical Testing.....	58
3.5.1	Universal Testing Machine (UTM).....	58
3.5.2	Single Stage Gas-gun	59
Chapter 4.	Surface Preparation and Characterisation of Substrates and Adhesives.....	62

4.1	Preamble.....	62
4.2	Surface Preparation of Substrates	62
4.2.1	Steel.....	64
4.2.2	Boron Carbide.....	65
4.2.3	UHMWPE Composite Laminate	67
4.3	Surface Energy and Wettability of Substrates	68
4.4	Thermal Characterization of Adhesives	71
4.5	FTIR Spectroscopy of Adhesive Films	72
4.6	Conclusion.....	75
Chapter 5.	Shear Strength Test for Adhesively Bonded Interfaces of Dissimilar Substrates...	76
5.1	Preamble.....	76
5.2	Interfacial Lap Shear.....	76
5.2.1	Block Shear Test.....	78
5.2.2	Fabrication of Shear Fixture	79
5.2.3	Limitations of Existing Designs.....	80
5.2.4	Modification in the Fixture Design	83
5.2.5	Validation of Improvised Design.....	85
5.3	IFSS Test using Improved Fixture.....	87
5.3.1	Specimen Fabrication.....	88
5.3.2	Mounting of Specimen in Fixture	90
5.3.3	IFSS Test with B ₄ C/steel.....	92
5.3.4	IFSS Test with B ₄ C/UHMWPE Lamina	96
5.3.5	IFSS Test: Steel/UHMWPE Lamina.....	101
5.4	Conclusion.....	105
Chapter 6.	Surface Treatment of UHMWPE Laminae	107
6.1	Preamble.....	107
6.2	UHMWPE Substrates	107
6.3	Plasma Treatment.....	108

6.3.1	Surface Treatment using Hot Plasma Jet	108
6.3.2	Surface Treatment using Cold Plasma	110
6.4	Characterization of Treated UHMWPE Laminae.....	111
6.4.1	Wettability.....	111
6.4.2	SEM Images.....	113
6.4.3	Atomic Force Microscopy	114
6.4.4	Interfacial Shear Test	116
6.4.5	XPS	119
6.5	Conclusion.....	122
Chapter 7. Adhesive Joining of B₄C/UHMWPE Composite Armor and High Velocity Testing at Gas-Gun		123
7.1	Preamble.....	123
7.2	Adhesive Bonded B ₄ C/UHMWPE Composite Armor.....	123
7.3	Fabrication of B ₄ C/UHMWPE Laminate Armor Panel.....	124
7.3.1	Surface Preparation of Armor Materials	125
7.3.2	Autoclave Moulding	126
7.4	Ballistic Test at Single Stage Gas Gun	130
7.4.1	Trial with a Single B ₄ C Tile Bonded to UHMWPE.....	131
7.4.2	Trial with No Cladding	131
7.4.3	Ballistic Impact Tests on Armor Test Panels.....	132
7.4.4	Crack Propagation Analysis.....	137
7.4.5	Mode of Failure of Bonding Adhesive.....	139
7.4.6	Erosion of Core of Projectile	139
7.5	Conclusion.....	140
Chapter 8. Conclusion and Future Scope		142
8.1	Summary.....	142
8.2	Major Contributions.....	142
8.2.1	Development of Shear Characterisation Tools for Interfacial Adhesion	142

8.2.2 Comparison of Hot Plasma Jet and Cold Plasma for Surface Treatment of UHMWPE Lamina	143
8.2.3 Fabrication of Test Panel	143
8.2.4 Ballistic Test of Adhesive Bonded Armor Panels.....	143
8.3 Future Directions	144
8.3.1 Analysis of Adhesive Materials Properties	144
8.3.2 Shear Analysis at Elevated Temperature	144
8.3.3 Numerical Modelling	144
Bibliography	145
Publications	155
Biodata of Author	157

List of Figures

<i>Figure 1.1 Important events in the modern history of armor materials [3].</i>	<i>1</i>
<i>Figure 1.2 Kinetic Energy of the different ammunitions; (Right) A complete ammunition.</i>	<i>4</i>
<i>Figure 1.3 A typical body armor covering torso (front and back), throat, sides, and groin.</i>	<i>4</i>
<i>Figure 1.4 Fracture cracks and conoid formation on impacted bare Alumina [13].</i>	<i>6</i>
<i>Figure 1.5 Stress reverberations at the point of impact (R^* and T^* stands for reflected and transmitted stress wave, respectively).</i>	<i>7</i>
<i>Figure 1.6 Shape of the indentations caused by (a) Vickers, (b) Knoop and (c) Brinell hardness tester.</i>	<i>9</i>
<i>Figure 1.7 Different shape and size of alumina tiles to contain the cracks generated upon impact [19].</i>	<i>10</i>
<i>Figure 1.8 Single lap-joint test performance showing adhesive chemical classifications for qualifying ballistic test [26].</i>	<i>12</i>
<i>Figure 1.9 Cracks generated on the front face of alumina after projectile penetration, typical samples are (a) Alumina only, (b) Alumina weakly bonded to carbon fiber composite (C-PET) backing and (c) Alumina strongly bonded to C-PET backing [27].</i>	<i>12</i>
<i>Figure 1.10 A typical adhesive bond.</i>	<i>13</i>
<i>Figure 1.11 Different physical interactions and chemical bonds explaining adhesion mechanisms [28].</i>	<i>14</i>
<i>Figure 1.12 (a) Good and (b) poor wetting by an adhesive spreading across a surface.</i>	<i>16</i>
<i>Figure 1.13 Different failure modes of adhesive bond</i>	<i>17</i>
<i>Figure 3.1 The B_4C tile used and its dimension.</i>	<i>41</i>
<i>Figure 3.2 Line roughness of the B_4C tile measured using optical profilometry.</i>	<i>41</i>
<i>Figure 3.3 SEM micrograph of 0/90 laying configuration of UHMWPE fibers in laminae.</i>	<i>43</i>
<i>Figure 3.4 (a) 2-part epoxy adhesive cans, (b) 2-part polyurethane adhesive cartridge, (c) static mixer and (d) Dispensing gun mounted with adhesive cartridge.</i>	<i>46</i>
<i>Figure 3.5 Compression moulding machine and its different components.</i>	<i>47</i>
<i>Figure 3.6 A sketch of compression moulding process to fabricate UHMWPE hard armor panel (PE HAP).</i>	<i>48</i>
<i>Figure 3.7 Autoclave Moulding machine installed in Personal body armor lab at IIT Delhi.</i>	<i>49</i>
<i>Figure 3.8 Dimension of the pressure vessel (left); Image of the actual autoclave chamber from inside (right).</i>	<i>50</i>
<i>Figure 3.9 Vacuum bagged product placed inside the autoclave chamber.</i>	<i>51</i>
<i>Figure 3.10 Waterjet cut samples of UHMWPE composite (left) and steel (right).</i>	<i>52</i>
<i>Figure 3.11 Simultaneous Thermal Analyser (STA) used for thermal analysis in the study.</i>	<i>53</i>
<i>Figure 3.12 (a) Working principle of FTIR spectroscopy, (b) FTIR instrument (Thermo Nicolet IS-50) in ATR mode.</i>	<i>55</i>
<i>Figure 3.13 Principle of X-ray Photoelectron Spectroscopy: Typical Photoelectric process</i>	<i>55</i>
<i>Figure 3.14 Different levels of spreading of a liquid droplet.</i>	<i>56</i>
<i>Figure 3.15 Instron's Universal testing system employed to evaluate mechanical properties in the study.</i>	<i>59</i>
<i>Figure 3.16 Simplified schematic of the single stage Gas-gun.</i>	<i>60</i>
<i>Figure 3.17 Single Stage Gas-gun employed for the high-velocity impact tests.</i>	<i>60</i>

Figure 4.1 Microscopic images of steel after every step of surface preparation, a) grounded, b) polished and c) sandblasted.	64
Figure 4.2 Energy Dispersive X-ray spectrum of steel substrate demonstrating energies corresponding to the elements present.	65
Figure 4.3 SEM images of (a) acetone washed and dried, (b) uncleaned B ₄ C tile with loose particles.	66
Figure 4.4 EDX spectrum and elemental mapping corresponding to B ₄ C substrate.	66
Figure 4.5 Scanning Electron Microscopic (SEM) image of UHMWPE fiber based prepreg.	67
Figure 4.6 Contact angle measured with two solvents to measure surface energy of substrates using OWRK method; a) UHMWPE ply, b) B ₄ C, c) Steel and d) Aluminium substrates.	69
Figure 4.7 DSC thermograms to understand curing and melting temperature profiles for a) thermosetting resin and b) thermoplastic film adhesives, respectively.	71
Figure 4.8 FTIR spectrum of Adhesive films, a) FPE1, FPE2 and FPE3 (PE side), stacked in a single graph, and b) zoomed absorbance spectrum of FPE2 adhesive film.	73
Figure 4.9 FTIR spectrum of Bilayer adhesive film (FPE3) from both sides, polyethylene (PE) and thermoplastic polyurethane (TPU).	74
Figure 5.1 Shearing of bonded materials.	76
Figure 5.2 a) non-uniform adhesive shearing and b) rotation of the substrates caused due to eccentric load path in SLJ [116].	77
Figure 5.3 Stress distribution in SLJ consisting, a) similar, and b) dissimilar adherends [116].	78
Figure 5.4 Difference in specimen configuration for, a) SLJ and b) block shear fixture.	79
Figure 5.5 Model design of the block shear fixture as per standard.	80
Figure 5.6 Substrate failure caused due to misalignment in the fixture.	81
Figure 5.7 In-house designed and fabricated fixture, after rectifying failures due to misalignment, shear failure of bolts and dowel pins connecting adaptor.	81
Figure 5.8 Interlaminar shear failure of the laminate before shearing of the adhesive bond.	82
Figure 5.9 Commercially available designs of block shear fixture with design flaws [120], [121].	83
Figure 5.10 Modifications in the design of block shear fixture.	84
Figure 5.11 A picture of block shear fixture with improved design.	84
Figure 5.12 Validation of the fixture performing shear tests using similar substrates.	86
Figure 5.13 Comparison of single lap shear (SLS) strength and block shear (BS) strength values for, (a) Epoxy bonded mild steel (MS/MS) and aluminium (Al/Al) substrates experimentally assessed using a modified fixture, whereas (b) Three different epoxy adhesives bonding glass/epoxy FRP substrate tested using older fixture. (Refer Redmann et al. 2021, pp. 11 [126])	87
Figure 5.14 Block shear test setup gripped in jaws of the universal testing machine.	88
Figure 5.15 Block shear specimen to evaluate IFSS of adhesive bond between (a) B ₄ C/UHMWPE laminae and (b) B ₄ C/steel.	89
Figure 5.16 Stepwise illustrations to mount the specimen in the newly designed fixture.	92
Figure 5.17 Interfacial shear strength of adhesives bonding B ₄ C and steel using, a) AEPX1 (thermoset epoxy), b) APU (thermoset polyurethane) at different adhesive thicknesses.	93

Figure 5.18 Microscopic images of debonded B ₄ C/Steel shear specimens, a) and c) represents B ₄ C substrates, and b) and d) represents steel substrates bonded with 0.1 mm and 0.3 mm thick AEPX2, respectively.	95
Figure 5.19 Microscopic images of debonded B ₄ C/Steel shear specimens, a) and c) represents B ₄ C substrates, and b) and d) represents steel substrates bonded with 0.1 mm and 0.3 mm thick APU, respectively.	95
Figure 5.20 Interfacial shear strength versus shear strain plots of B ₄ C/UHMWPE specimens bonded using, a) thermoset epoxy (AEPX2), b) thermoset polyurethane (APU), c) PE film (FPE1), d) thick PE film (FPE2), and e) bilayer film (FPE3).....	97
Figure 5.21 Averaged data of the interfacial shear strength of B ₄ C bonded UHMWPE laminae using different adhesives.....	98
Figure 5.22 Type of failure in B ₄ C/UHMWPE block shear tested specimens, bonded using different adhesives; a) FPE1, b) FPE2, c) FPE3, d) AEPX2 and e) APU.	99
Figure 5.23 Microscopic images of B ₄ C/UHMWPE fractured surfaces representing a) B ₄ C and b)UHMWPE substrate bonded using APU, and c) B ₄ C and d)UHMWPE substrate bonded using AEPX2.	100
Figure 5.24 Interfacial shear stress versus shear strain plots of Steel/UHMWPE specimens bonded using, a) thermoset epoxy (AEPX2), b) thermoset polyurethane (APU), c) PE film (FPE1), d) thick PE film (FPE2), and e) bilayer film (FPE3).....	102
Figure 5.25 Type of failure in Steel/UHMWPE block shear tested specimens, bonded using different adhesives; a) APU, b) AEPX2, c) FPE1, d) FPE2 and e) FPE_TPU.	103
Figure 5.26 Microscopic images of steel/UHMWPE fractured surfaces representing a) steel and b)UHMWPE substrate bonded using APU, and c) steel and d) UHMWPE substrate bonded using AEPX2.	103
Figure 6.1 (a) Hot plasma surface treater instrument, (b) Plasma gun mounted on 2-axis CNC machine bed, (c) plasma arc generated through a rotary nozzle head, (d) and (e) Plasma treatment of UHMWPE laminae.	109
Figure 6.2 (a) Cold Plasma instrument and plasma generated inside chamber in, (b) air and (c) Argon environment.	110
Figure 6.3 Static water contact angle formed over (a) untreated UHMWPE surface, (b) treated with CP(3Ar), (c) CP(5Ar), (d) CP(3air) and (e) CP(5air).	112
Figure 6.4 Static water contact angle formed over hot plasma treated UHMWPE surfaces representing, (a) HP(N ₂) for 1, 2 and 3 passes, and (b) HP(He) for 1, 2 and 3 passes.	113
Figure 6.5 Water contact angle measured for UHMWPE laminae undergone different surface treatments.	113
Figure 6.6 SEM images showing microstructure of (a) untreated UHMWPE, and others of treated UHMWPE with (b) HP(He)P3, (c) HP(N ₂)P3, (d) CP(5air), (e) CP(3Ar) and (f) CP(5Ar) at same scale.	114
Figure 6.7 AFM micrographs of UHMWPE laminae which undergoes (a) No treatment (untreated), (b) HP(N ₂)P3, (c) HP(He)P3, (d) CP(5air), (e) CP(3Ar) and (f) CP(5Ar) treatment.	115
Figure 6.8 Line roughness plotted for untreated and plasma treated UHMWPE lamina using AFM images. ...	116
Figure 6.9 (a) UHMWPE/B ₄ C shear specimen bonded using APU, and (b) Interfacial shear strength values for UHMWPE/B ₄ C shear specimens, where UHMWPE treated using hot plasma jet in Helium and nitrogen environment (for n=1,2,3 passes), and cold plasma in air and argon environment, for different durations.	117
Figure 6.10 Types of failure of UHMWPE/B ₄ C shear specimen with no treatment and plasma treatment.	119
Figure 6.11 XPS analysis demonstrating Survey scan for untreated, treated with CP(5air), CP(3Ar) and CP(5Ar) of UHMWPE laminae.	120

<i>Figure 6.12 Deconvoluted C1s peaks for UHMWPE (a) untreated, (b) treated with CP(5air), (c) CP(3Ar) and (d) CP(5Ar).</i>	121
<i>Figure 7.1 (a) Cleaning of B₄C tiles in acetone using ultrasonication bath, and (b) tiles kept on tray inside vacuum oven for drying.</i>	125
<i>Figure 7.2 Kevlar fabric for confinement of B₄C/UHMWPE armor panel.</i>	126
<i>Figure 7.3 Process of vacuum bagging for the autoclave moulding of test panel</i>	128
<i>Figure 7.4 (a) Processing cycles adopted for autoclave moulding process and (b) Actual variation of one of the process parameters during moulding process.</i>	128
<i>Figure 7.5 A schematic of Autoclave moulding process for fabrication of test panel.</i>	129
<i>Figure 7.6 (a) 7.62 x 39 mm HSC projectile (right) and hardened steel core (left), (b) Projectile mounted on sabot and (c) Velocity measurement device.</i>	130
<i>Figure 7.7 First trial: A 100 x 100 mm single square tile bonded to UHMWPE laminate (a) before impact, and (b)after impact.</i>	131
<i>Figure 7.8 Second trial: Test panel fabricated using FPE1 (a) before impact and (b) after impact.</i>	132
<i>Figure 7.9 High velocity impact tested panels fabricated using AEPX2 (top), FPE1 adhesive film (middle) and FPE2 adhesive film (lower).</i>	133
<i>Figure 7.10 Test Panel 4: Front and rear side of the high velocity impact tested panel indicating three stopped shots.</i>	135
<i>Figure 7.11 Test Panel 5: Images of impacted test panel after each impact, bonded using APU, and front and rear face of the impacted panel.</i>	135
<i>Figure 7.12 A closer imaging of tested panel 5 to visualize (a) first and third impact, and (b) second and fourth impact, and intershot distance between them.</i>	136
<i>Figure 7.13 Damages caused to an armor panel upon ballistic impact.</i>	138
<i>Figure 7.14 (a) Sketch of a test panel, and (b), (c) and (d) damage caused to the front face (B₄C tiles) upon ballistic impact at different locations.</i>	138
<i>Figure 7.15 A SEM image of B₄C fragment broken down upon high velocity impact from the panel bonded using (a) APU adhesive and (b)AEPX2 adhesive.</i>	139
<i>Figure 7.16 The length of core of (a) An unimpacted hardened steel core of projectile , (b) A recovered core which perforated a test panel and (c) A recovered core that got stopped by the test panel in a ballistic impact</i>	140

List of Tables

<i>Table 1.1: Some of the standards of body armors for different users.</i>	2
<i>Table 1.2: Details of the threat levels mentioned in IS 17051:2018 [5].</i>	3
<i>Table 1.3 Properties of ceramic materials commonly used as strike face in armors [17][2].</i>	8
<i>Table 1.4 Details of physical and chemical interactive forces [29].</i>	15
<i>Table 2.1 Process parameters of different plasma techniques utilised in recent literatures.</i>	35
<i>Table 3.1 Macroscopic Properties of B₄C tiles.</i>	41
<i>Table 3.2 Alloying compositions of HHS Steel.</i>	42
<i>Table 3.3 Properties of 3mm thick 300M steel.</i>	42
<i>Table 3.4 Details of the UHMWPE fabric</i>	43
<i>Table 3.5 Different grades of thermoset resin adhesives selected for the study.</i>	45
<i>Table 3.6 Different grades of the adhesive film selected for the study.</i>	46
<i>Table 3.7 Specifications of the Single stage Gas-gun employed for the study.</i>	61
<i>Table 4.1 Surface tension values of the solvents employed for the contact angle measurement.</i>	70
<i>Table 4.2 Measured contact angle with water, ethylene glycol and ethanol using sessile drop method, and surface energy and its polar and dispersive component calculated for bonding substrates.</i>	70
<i>Table 4.3 Melting and degradation temperature of adhesive films employed in the research work.</i>	72
<i>Table 5.1 Specimen configuration for the fabrication of block shear samples.</i>	86
<i>Table 5.2 Shear strength values obtained using block shear fixture and SLJ.</i>	86
<i>Table 5.3 Processing parameters of Autoclave for curing of adhesives.</i>	89
<i>Table 5.4 Specimen configuration employing different substrates for the IFSS tests.</i>	90
<i>Table 5.5 Average global shear strength or IFSS and elongation percentage values of AEPX1 and APU bonding B₄C/steel specimens at different thicknesses.</i>	94
<i>Table 5.6 Interfacial Shear Strength values obtained for adhesive bonded Steel/UHMWPE and B₄C/UHMWPE substrates using AEPX2, APU, FPE1, FPE2 and FPE3 adhesive systems.</i>	104
<i>Table 6.1 Operating parameters for the treatment of UHMWPE laminae using hot plasma jet.</i>	110
<i>Table 6.2 Operating parameters for the treatment of UHMWPE using cold plasma.</i>	111
<i>Table 6.3 Interfacial Shear Strength values obtained for APU bonded hot and cold plasma treated UHMWPE/B₄C substrates with (IL1 and IL2) and without interlayers.</i>	118
<i>Table 6.4 Atomic percentage of the elements analysed through XPS survey scans and relative concentration of chemical groups in deconvoluted C1s peak.</i>	121
<i>Table 7.1 Details of the armor material and adhesives for the fabrication of armor test panels for multiple ballistic impact test at gas-gun</i>	124
<i>Table 7.2 Processing parameters of autoclave moulding cycle for the fabrication of test armor panels.</i>	130
<i>Table 7.3 Summary of the high velocity impact tests of B₄C/UHMWPE armor panel bonded using different adhesives.</i>	137

Acronyms

HSC	Hardened steel core
UHMWPE	Ultra-high molecular weight polyethylene
FRP	Fiber reinforced polymer composite
CFRP	Carbon fiber reinforced polymer composite
UTM	Universal Testing Machine
ASTM	American Society for Testing and Standards
BIS	Bureau of Indian Standards
NIJ	National Institute of Justice
IFSS	Interfacial shear strength
SLJ	Single lap joint
B ₄ C	Boron carbide
SiC	Silicon carbide
SAP	Soft Armor Panel
HAP	Hard Armor Panel
ICW HAP	In-conjunction with hard armor panel
PE	Polyethylene
API	Armor Piercing Incendiary
KE	Kinetic energy
AD	Areal Density
BHN	Brinell hardness number
KHN	Knoops hardness number
AFM	Atomic force microscopy
DSC	Differential Scanning Calorimetry
FTIR	Fourier Transform Infrared spectroscopy
SEM	Scanning Electron Microscopy
EDX	Energy Dispersive X-Ray Spectroscopy
XPS	X-Ray Photoelectron Spectroscopy
DMA	Dynamic mechanical analysis

RHA	Rolled homogeneous armor steel
HHS	High hardness steel
TPU	Thermoplastic polyurethane
PU	Polyurethane
slm	standard litres per minute
sccm	standard cubic centimetre per minute
Ar	Argon gas
Ra	Average roughness
Rrms	Root mean square roughness
Tg	glass transition temperature
APP	Atmospheric pressure plasma
DBD	Dielectric barrier discharge
C _A	Contact angle