ADHESIVE BONDING OF COMPOSITE MATERIALS FOR ARMOR APPLICATIONS

AISHA AHMED

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

AISHA AHMED

Department of Mechanical Engineering

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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

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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 विशेषताओ 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 सब्सट्रेट्स की इंटरफेशियल कतरनी ताकत (आईएफएसएस) का मूल्यांकन करने के लिए एक स्थिरता का निर्माण और संशोधन किया गया था। एल्यूमीनियम और स्टील के समान सब्सट्रेट्स 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 सब्सट्रेट्स के लिए राल चिपकने वाली बॉन्डिंग बोरान कार्बाइड (बी$_4$सी) की मोटाई को अनुकूलित करने के लिए फिक्स्चर का उपयोग करके इंटरफेशियल कतरनी परीक्षण किए गए थे। आईएफएसएस मूल्यों का मूल्यांकन किया गया और बी$_4$सी/स्टील, बी$_4$सी/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 सब्सट्रेट के आसंजन को बढ़ाने के लिए बी$_4$सी टाइल्स से जोड़ा जाना था। बी$_4$सी से जुड़े उपचारित लैमिनाई के आईएफएसएस परीक्षण ने कतरनी ताकत में अच्छा सुधार दिखाया। परीक्षण पैनलों को बी$_4$सी/UHMWPE सब्सट्रेट 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।

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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_4C	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