BALLISTIC IMPACT BEHAVIOUR OF ALUMINIUM ALLOY AA2014-T652 SUBJECTED TO RIGID AND DEFORMABLE PROJECTILES

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by

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CERTIFICATE

This is to certify that the thesis entitled **"Ballistic Impact Behaviour of Aluminium Alloy AA2014-T652 Subjected to Rigid and Deformable Projectiles"** being submitted by **Mr. Prince Sharma** to the **Indian Institute of Technology Delhi,** for the award of the degree of Doctor of Philosophy in Applied Mechanics Department is a record of original, bonafide research work carried out by him under our supervision and guidance. The thesis work, in our opinion, has reached the requisite standard fulfilling the requirements 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.

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Abstract

The tremendous increase in demand for light weight armour systems has inspired the development of novel armour designs using optimal combination of high strength metals, polymers, composites and ceramics. Aluminium alloys have emerged as a strong candidate material for defence, aerospace and automobile applications due to their low density, high strength and high corrosion resistance. But their impact behaviour needs to be fully understood in order to utilize their potential for such critical applications

The dynamic behaviour of high strength aluminum alloys during ballistic impact is a complex phenomenon due to the presence of, large deformations, high strain rates, elevated temperatures and propagation of elastic, plastic and shock waves. The failure of target may occur due to a combination of various perforation mechanisms depending upon the material properties, impact velocity, projectile shape and size, target thickness etc. An in-depth understanding of the dynamic behaviour of impacting materials is thus of paramount importance in designing materials and structures for defence applications.

The present study is aimed at investigating the ballistic impact response behaviour of aluminium alloy AA2014-T652, which is one of the strongest available aluminium alloys, against rigid and deformable projectiles. Hardened steel spheres were used as rigid projectiles while soft iron spheres were used as deformable projectiles. An integrated approach encompassing dynamic material characterization, constitutive and failure modeling, ballistic impact tests, analytical analysis and numerical simulations has been employed to gain more insight about the material behaviour.

A comprehensive material characterization program was executed to study the plastic flow and failure of the material. Tensile tests were carried out on target and projectile materials at different stress triaxialities, strain rates and temperatures. Hardened steel projectiles were considered rigid and no material tests were conducted for steel. Low and medium strain rate tests

were conducted on a standard universal testing machine (UTM) while high strain rate tests were conducted using split hopkinson pressure bar (SHPB). High temperature tests were conducted using a special UTM having provision for in-situ heating of the specimen. True stress – true strain curves were generated using the measured force-displacement data from UTM and SHPB. Fracture strain values of the materials were calculated by measuring the reduction in area of fractured specimens.

The experimental information from stress-strain curves were used to calibrate the material parameters of Johnson-Cook constitutive model, which relates the flow stress of the material to effective plastic strain, strain rate and temperature. Fracture strain values were used to calibrate the material parameters of Johnson-Cook failure model, which relates the fracture strain of a material to stress triaxiality, strain rate and temperatures.

Ballistic impact tests were conducted using a smooth bore propellant gun of 30 mm bore diameter. 15 mm thick target plates were impacted by 10 mm diameter steel and iron spheres. Impact velocities were varied by changing the amount of propellant in the cartridge to achieve complete perforation of the target. Impact phenomenon was captured with a high speed video camera to measure the impact velocity and residual velocity of the projectiles. Ballistic limit velocity was calculated by using energy based analytical methods. An analysis of crater dimensions in the targets was carried out in order to identify various perforation mechanisms responsible for target failure.

Finite element analyses of all the impact experiments were carried out using a two dimensional axisymmetric model. Ballistic impact velocities were overestimated and all the perforation mechanisms were not captured in numerical results using Johnson-Cook constitutive and failure model. Limitations of Johnson-Cook failure were analyzed and numerical simulations were repeated using hydrostatic tensile stress failure model. A non-linear equation of state was also introduced in the model for more accurate calculations of hydrostatic stress. These modifications resulted in an excellent correlation between experimental and numerical results.

सारांश

हल्के वजन की कवच प्रणाली की मांग में जबरदस्त वृद्धि ने सम्मिश्रित पदार्थ से बने कवच डिजाइन के विकास को प्रेरित किया है। एल्यूमीनियम अपने कम घनत्व, उच्च सामर्थ्य तथा उच्च जंग निरोधक क्षमता के कारण रक्षा, एयरोस्पेस और ऑटोमोबाइल अनुप्रयोगों के लिए एक मजबूत उम्मीदवार के रूप में उभरा है। प्राक्षेपीय समाघात के समय उत्पन्न विशाल विकार, उच्च विकृति दर तथा उच्च तापमान के कारण एल्युमीनियम धातु का व्यवहार बहुत जटिल प्रक्रिया हो जाता है। इसलिए रक्षा अनुसन्धान जैसे महत्वपूर्ण अनुप्रयोगों के लिए एल्युमीनियम के संघात व्यवहार को व्यापक तरीके से समझने की जरूरत है।

वर्तमान अध्ययन की जांच का उद्देश्य एल्युमीनियम २०१४-टी ६५२, जोकि सबसे मज़बूत एल्युमीनियम मिश्रधातुयों में से एक है, के संघात व्यवहार का अन्वेषण करना है। दो तरह के प्रक्षेप्य इस अध्ययन में प्रयोग किये हैं। स्टील के गोलों को अनम्य प्रक्षेप्य के रूप में तथा शुद्ध लोहे के गोलों को मुलायम गोलों के रूप में प्रयोग किया गया था। वर्तमान अध्ययन में यांत्रिकी परिक्षण, पदार्थ प्रतिरूपण, प्राक्षेपिक परिक्षण, सैद्धांतिक विश्लेषण तथा अभिकलन अनुकरण का समन्वित प्रयोग किया गया है, तांकि पदार्थ के संघात व्यवहार का सम्पूर्ण ज्ञान प्राप्त किया जा सके।

एक विस्तृत यांत्रिकी परिक्षण कार्यक्रम संचालित किया गया था, जिसमे पदार्थों के प्रत्यास्थ, नम्य तथा विघात व्यवहार का निरक्षण किया गया। विभिन्न विकृति दरों, प्रतिबल त्रिअक्षितायों तथा तापमानों पर तन्यता परीक्षण किते गए। प्रक्षेपीय परीक्षणों में स्टील के प्रक्षेप्यों में किसी विकार की अनुपस्थिति के कारन उन्हें अनम्य मान लिया गया तथा इसलिए स्टील पर यांत्रिकी परिक्षण नहीं किये गए। एल्युमीनियम २०१४-टी ६५२ तथा शुद्ध लोहे पर मंद तथा उच्च विकृति दर परिक्षण किये गए जिसके लिए सार्वलौकिक परिक्षण यन्त्र तथा स्प्लिट होप्किंसन बार का प्रयोग किया गया। उच्च तापमान पर परिक्षण करने के लिए विशेष सार्वभौमिक परिक्षण यन्त्र का उपयोग किया गया जिसमे प्रतिरूप को गर्म करने की व्यवस्था थी। तन्यता यांत्रिक परीक्षणों से प्राप्त जानकारी से जॉनसन-कुक पदार्थ प्रतिमान के अचर मापदंडों का परिकलन किया गया। जॉनसन-कुक प्रतिमान पदार्थ के प्रतिबल को विकार, विकृति, विकृति दर तथा तापमान के साथ संबंधित करता है।

प्राक्षेपीय परीक्षणों के लिए ४० मिलीमीटर व्यास वाली गन का प्रयोग किया गया । १५ मिलीमीटर मोटी एल्युमीनियम के लक्ष्य पर १० मिलीमीटर व्यास वाले स्टील और शुभ लोहे के गोले दागे गए। संघात घटना को उच्च गति वाले कैमरे से अभिलेखित किया गया तांकि प्रक्षेप्यों की संघात गति मापी जा सके। लक्ष्यों में हुए छिद्रों का गहरायी से अध्ययन किया गया तांकि वेध की विभिन्न क्रियाविधियों की पहचान की जा सके।

सभी प्रक्षेपिकीय परीक्षणों का सीमित तत्त्व विश्लेषण किया गया, जिसके लिए द्विआकारीय प्रतिमान का उपयोग किया गया । जिन अभिकलित अनुकरणों में जॉनसन-कुक विघात प्रतिमान का प्रयोग किया था, उनमे प्रक्षेपिकीय सीमा वेग परीक्षणों की तुलना में अधिक पाया गया। जॉनसन-कुक विघात प्रतिमान की समस्याओं का अध्ययन करने के पश्चात जलस्थैतिक प्रतिबल प्रतिमान का उपयोग करते हुए दोबारा अभिकलित अनुकरणो की पुनरावृत्ति की गयी। एक गैर रेखीय स्थिति समीकरण को भी सीमित तत्त्व विश्लेषण में सम्मिलित किया गया ताकि जलस्थैतिक प्रतिबल का यथार्थ आंकलन किया जा सके। इन परिवर्तनो से परीक्षणात्मक तथा अभिकलनात्मक परिणामो में अति-उत्कृष्ट समकक्षता पायी गयी

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