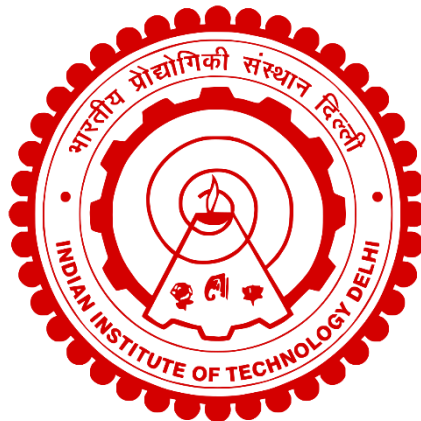


**DEFORMATION AND FRACTURE BEHAVIOUR OF  
ADVANCED ALUMINIUM ALLOY AA7475-T7351 UNDER  
EXTREME THERMO-MECHANICAL LOADING**

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by

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**Department of Applied Mechanics**

*Submitted*

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**June 2023**

*Dedicated to*  
*Parents and Teachers*

# CERTIFICATE

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This is to certify that the thesis entitled “*Deformation and Fracture Behaviour of Advanced Aluminium Alloy AA7475-T7351 under extreme Thermo-Mechanical Loading*” is being submitted by **Mr. Purnashis Chakraborty** to the Indian Institute of Technology Delhi for the award of the degree of *Doctor of Philosophy* in 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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**Purnashis Chakraborty**

# ABSTRACT

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There exists an ever-increasing demand for the lightweight materials, capable of meeting rigorous demands of new technologies. In this regard, the advanced aluminium alloys present a favourable solution. They have good strength and aesthetic appearance, lower density, higher resistance to corrosion, good machinability and integrity at a wide range of temperatures. The high-strength aluminium alloys have potential application in the lightweight structural panels of aircraft, spacecraft, defence, automobiles and other high-performance application areas.

The transportation and defence-related structural components may be exposed to extreme loading conditions, such as impact, shock, blast or collision and undergo severe plastic deformation and fracture. The performance of structures depends on the mechanical behaviour of its material, which changes with the strain rate and temperature. At high loading rates, the stress wave propagation phenomenon is more prominent and special experimental techniques are required to achieve the dynamic stress equilibrium and acquire the constitutive behaviour of the material. Similarly, the resistance (toughness) of the material to fracture initiation/propagation also changes with the loading rates and temperatures. The failure mechanism of structural panels of body armour or sheltering structures also depends on the velocity of the projectile. Hence, the thermal softening and strain rate (loading rate) sensitivity of the constitutive behaviour, fracture toughness and impact resistance of aluminium alloys needs to be understood for the design of important *lightweight structures*.

The present thesis considers one zinc-based precipitation-hardened aluminium alloy (AA7475-T7351) with relatively higher strength at extremely low (cryogenic) and elevated temperatures. The Zwick/Roell Z50 Universal Testing Machine is used to investigate the mechanical behaviour of aluminium AA7475-T7351 under low rates of

tensile and compressive strains. The tensile and compressive Split Hopkinson pressure bar setups (SHTB and SHPB) are used to investigate the response of the material at high strain rates. An extensive experimental investigation has been conducted to estimate the tension-compression asymmetry and anisotropic behaviour of thin AA7475-T7351 panels at different temperatures and different rates of loading.

The experimental study on AA7475-T7351 is extended to examine the fracture initiation and propagation behaviour of the material at different loading rates and temperatures. The crack mouth opening displacements (CMOD) are estimated from the three-point bend experiments under Zwick/Roell-50 and MTS-250 machines for quasi-static and lower loading rates, respectively. The modified Hopkinson pressure bar setup is used to estimate the stress intensity factor (SIF) of the three-point bend specimens at higher rates of loading. The initiation and propagation fracture toughness of AA7475-T7351 aluminium alloy along the rolling (L-T) and transverse (T-L) directions are studied through a series of experiments. Further, a single-stage gas gun is used to investigate the dynamic response of aluminium AA7475-T7351 panels under non-deformable blunt and hemispherical-nosed projectiles in the velocity range of 120-250 *m/s*. In all the experiments, the digital image correlation technique is used to obtain the full field deformation profile of the specimens under dynamic loading conditions.

The designers need to depend on the numerical simulation of structural components, as the experimental testing of actual structures may not be feasible. Hence, an accurate constitutive model to represent the deformation and fracture behaviour of the material is extremely important. The results of tension, compression and fracture experiments are used to study the applicability of existing material models. Thereafter, the Johnson-Cook constitutive and failure model (with evaluated material constants for AA7475-T7351) is used for the three-dimensional finite element simulation of representative problems. A satisfactory agreement between the experimental and numerical results is observed in the thesis.

## सार

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नई प्रौद्योगिकियों की कठोर मांगों को पूरा करने में सक्षम हल्की सामग्रियों की मांग लगातार बढ़ रही है। इस संबंध में, उन्नत एल्यूमीनियम मिश्र धातुएँ एक अनुकूल समाधान प्रस्तुत करती हैं। उनके पास अच्छी ताकत और सौंदर्य उपस्थिति, कम घनत्व, संक्षारण के लिए उच्च प्रतिरोध, तापमान की एक विस्तृत श्रृंखला पर अच्छी मशीनेबिलिटी और अखंडता है। उच्च शक्ति वाले एल्यूमीनियम मिश्र धातुओं का विमान, अंतरिक्ष यान, रक्षा, ऑटोमोबाइल और अन्य उच्च-प्रदर्शन अनुप्रयोग क्षेत्रों के हल्के संरचनात्मक पैनलों में संभावित अनुप्रयोग है।

परिवहन और रक्षा-संबंधित संरचनात्मक घटक अत्यधिक लोडिंग स्थितियों, जैसे प्रभाव, झटका, विस्फोट या टकराव के संपर्क में आ सकते हैं और गंभीर प्लास्टिक विरूपण और फ्रैक्चर से गुजर सकते हैं। संरचनाओं का प्रदर्शन उसकी सामग्री के यांत्रिक व्यवहार पर निर्भर करता है, जो तनाव दर और तापमान के साथ बदलता है। उच्च लोडिंग दरों पर, तनाव तरंग प्रसार घटना अधिक प्रमुख है और गतिशील तनाव संतुलन प्राप्त करने और सामग्री के संवैधानिक व्यवहार को प्राप्त करने के लिए विशेष प्रयोगात्मक तकनीकों की आवश्यकता होती है। इसी प्रकार, फ्रैक्चर आरंभ/प्रसार के लिए सामग्री का प्रतिरोध (कठोरता) भी लोडिंग दर और तापमान के साथ बदलता है। बॉडी कवच या आश्रय संरचनाओं के संरचनात्मक पैनलों की विफलता तंत्र भी प्रक्षेप्य के वेग पर निर्भर करता है। इसलिए, महत्वपूर्ण हल्के संरचनाओं के डिजाइन के लिए एल्यूमीनियम मिश्र धातुओं की थर्मल नरमी और तनाव दर (लोडिंग दर) संरचनात्मक व्यवहार की संवेदनशीलता, फ्रैक्चर कठोरता और प्रभाव प्रतिरोध को समझने की आवश्यकता है।

वर्तमान थीसिस अत्यंत कम (क्रायोजेनिक) और ऊंचे तापमान पर अपेक्षाकृत उच्च शक्ति वाले एक जस्ता-आधारित वर्षा-कठोर एल्यूमीनियम मिश्र धातु (AA7475-T7351) पर विचार करती है। Zwick/Roell Z50 यूनिवर्सल टेस्टिंग मशीन का उपयोग तन्यता और संपीड़न तनाव की कम दरों के तहत एल्यूमीनियम AA7475-T7351 के यांत्रिक व्यवहार की जांच करने के लिए किया जाता है। उच्च तनाव दर पर सामग्री की प्रतिक्रिया की जांच करने के लिए तन्य और संपीड़ित स्लिट हॉपकिंसन दबाव बार सेटअप

(एसएचटीबी और एसएचपीबी) का उपयोग किया जाता है। विभिन्न तापमानों और लोडिंग की विभिन्न दरों पर पतले AA7475-T7351 पैनलों के तनाव-संपीड़न विषमता और अनिसोट्रोपिक व्यवहार का अनुमान लगाने के लिए एक व्यापक प्रयोगात्मक जांच की गई है।

AA7475-T7351 पर प्रायोगिक अध्ययन को विभिन्न लोडिंग दरों और तापमानों पर सामग्री के फ्रैक्चर आरंभ और प्रसार व्यवहार की जांच करने के लिए विस्तारित किया गया है। क्रैक माउथ ओपनिंग विस्थापन (सीएमओडी) का अनुमान क्रमशः अर्ध-स्थैतिक और कम लोडिंग दरों के लिए ज्विक/रोएल-50 और एमटीएस-250 मशीनों के तहत तीन-बिंदु मोड़ प्रयोगों से लगाया जाता है। संशोधित हॉपकिंसन प्रेशर बार सेटअप का उपयोग लोडिंग की उच्च दरों पर तीन-बिंदु मोड़ नमूनों के तनाव तीव्रता कारक (एसआईएफ) का अनुमान लगाने के लिए किया जाता है। रोलिंग (एल-टी) और अनुप्रस्थ (टी-एल) दिशाओं के साथ एए7475-टी7351 एल्यूमीनियम मिश्र धातु की शुरुआत और प्रसार फ्रैक्चर कठोरता का प्रयोगों की एक श्रृंखला के माध्यम से अध्ययन किया जाता है। इसके अलावा, 120-250 मीटर/सेकेंड की वेग सीमा में गैर-विकृत कुंद और अर्धगोलाकार-नाक वाले प्रोजेक्टाइल के तहत एल्यूमीनियम एए7475-टी7351 पैनलों की गतिशील प्रतिक्रिया की जांच करने के लिए एकल-चरण गैस गन का उपयोग किया जाता है। सभी प्रयोगों में, गतिशील लोडिंग स्थितियों के तहत नमूनों की पूर्ण क्षेत्र विरूपण प्रोफाइल प्राप्त करने के लिए डिजिटल छवि सहसंबंध तकनीक का उपयोग किया जाता है।

डिजाइनों को संरचनात्मक घटकों के संख्यात्मक सिमुलेशन पर निर्भर रहने की आवश्यकता है, क्योंकि वास्तविक संरचनाओं का प्रयोगात्मक परीक्षण संभव नहीं हो सकता है। इसलिए, सामग्री के विरूपण और फ्रैक्चर व्यवहार का प्रतिनिधित्व करने के लिए एक सटीक संवैधानिक मॉडल बेहद महत्वपूर्ण है। मौजूदा सामग्री मॉडल की प्रयोज्यता का अध्ययन करने के लिए तनाव, संपीड़न और फ्रैक्चर प्रयोगों के परिणामों का उपयोग किया जाता है। इसके बाद, जॉनसन-कुक संवैधानिक और विफलता मॉडल (AA7475-T7351 के लिए मूल्यांकित सामग्री स्थिरांक के साथ) का उपयोग प्रतिनिधि समस्याओं के त्रि-आयामी परिमित तत्व सिमुलेशन के लिए किया जाता है। थीसिस में प्रयोगात्मक और संख्यात्मक परिणामों के बीच एक संतोषजनक समझौता देखा गया है।

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