

EXPERIMENTAL AND NUMERICAL INVESTIGATION ON DYNAMIC FRACTURE OF ALUMINIUM ALLOYS

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EXPERIMENTAL AND NUMERICAL INVESTIGATION ON DYNAMIC FRACTURE OF ALUMINIUM ALLOYS

by

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Submitted

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



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Dedicated to

My father Late **Shree Kedar Nath Singh**

CERTIFICATE

This is to certify that the thesis entitled, **“EXPERIMENTAL AND NUMERICAL INVESTIGATION ON DYNAMIC FRACTURE OF ALUMINIUM ALLOYS”** submitted by **Mr. Sanjay Kumar** for the award of degree of **Doctor of Philosophy** to the **Indian Institute of Technology, Delhi** is a record of bonafide research work carried out by him under my guidance and supervision.

Mr. Sanjay Kumar has fulfilled all the prescribed requirements and the thesis is, in my opinion, worthy of consideration for the degree of Doctor of Philosophy in accordance with the regulations of the Institute. The contents of 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

Materials having high strength/weight as well as stiffness/weight ratio are preferably used as conventional materials in the aerospace and automotive industry with the aim of reducing the weight of structures. Among nonferrous metals aluminum alloys are lightweight metallic materials having high strength to weight ratio and are hence used for crashworthy applications. The structure made from aluminium alloys may be subjected to different loading conditions such as tensile, compressive, and flexural during service. The stress-strain behavior of materials at high strain rates under dynamic loading is significantly different from that observed under quasi-static conditions. It is seen that some materials exhibit positive strain rate sensitivity, whereas some materials show negative strain rate sensitivity and some poor strain rate sensitivity.

The aim of the present study is to investigate the material behavior of AA7075-T651 and AA6063-T6 at quasi-static and dynamic conditions. The aluminium alloy AA7075-T651 was characterized to study the plastic flow and failure of the material. Tensile tests were carried out on AA7075-T651 and AA6063-T6 at different strain rates, stress triaxiality, and temperatures. Quasi-static tests at low strain rate were performed on a standard universal testing machine (UTM), while a split Hopkinson pressure bar (SHPB) was used to conduct high strain rate tests. The quasi-static tests at different temperatures and at reference strain rate ($10^{-3}/s$) were also conducted on a special UTM having a heating system. From the above experiments, a force-displacement curve was obtained, and it was converted to a true stress-strain curve.

The results obtained from the above experiments were used to calibrate the material parameters of the Johnson-Cook (J-C) model, which relates flow stress with effective plastic strain, strain rate, and temperature of the material. Johnson-Cook failure

model, which relates the failure strain with stress triaxiality, strain rate, and temperatures of material, was also calibrated.

The three-point bend tests at different strain rates were conducted on AA7075-T651 and AA6063-T6 to obtain fracture initiation toughness at different strain rates. Three-point bend specimens used in the experiments were machined according to the ASTM-E399 standard. The experimental setup used in this study was a modified Hopkinson pressure bar (MHPB) conjugation with digital image correlation (DIC). It was observed that the dynamic fracture toughness increased with loading rates. Stress intensity factor (SIF) was evaluated using an established load point displacement (LPD) technique and crack mouth opening displacement (CMOD) method, whereas the time of initiation of fracture was obtained using a stereo-configuration of high-speed cameras. The fractography was also performed on the fractured surfaces of the specimen. Trans granular facets, small and large dimples were seen on micrographs, which illustrated the reasons for the increase in fracture toughness with loading rates. In addition to observation of fractography, three-dimensional, and two-dimensional surface profiles were drawn, which showed the relation of undulation with fracture toughness.

In this study, quasi-static and dynamic three-point bend experiments were also performed to investigate the effect of high loading rates on the crack mouth opening displacement (CMOD) and fracture behavior of the Aluminum 6063-T6 alloy. A 3D Digital Image Correlation (DIC) was utilized for measuring the CMOD experiments. Quasi-static three-point bend experiments were performed using UTM and a high-resolution stereo camera system for low loading rates. For the dynamic three-point bend experiment, a Modified Hopkinson pressure bar setup, two high-speed digital cameras, and a dedicated data acquisition system were utilized in measuring load point data and

the full field displacement profile. It was found that the dynamic fracture toughness values were significantly higher as compared to static fracture toughness.

Further, the finite element simulation was carried out for three-point bend tests, which were conducted at different loading rates using a three-dimensional solid model. The plastic and failure properties for numerical simulation were substituted from Johnson-Cook constitutive and failure models obtained from experimental results. The results obtained using simulation were found to be in fine agreement with experimental results for AA7075-T651.

सार

संरचनाओं के वजन को कम करने के उद्देश्य से एयरोस्पेस और ऑटोमोटिव उद्योग में उच्च शक्ति/वजन के साथ-साथ कठोरता/वजन अनुपात वाली पदार्थ को पारंपरिक पदार्थ के रूप में उपयोग किया जाता है। अलौह धातुओं में एल्युमीनियम मिश्र धातु हल्के वजन के अनुपात में उच्च शक्ति वाले धातु के पदार्थ होते हैं और इसलिए इनका उपयोग दुर्घटनाग्रस्त अनुप्रयोगों के लिए किया जाता है। एल्युमीनियम मिश्र धातुओं से बनी संरचना सेवा के दौरान विभिन्न लोडिंग स्थितियों जैसे तन्यता, संपीडित और फ्लेक्सुरल के अधीन हो सकती है। गतिशील लोडिंग के तहत उच्च तनाव दरों पर सामग्री का तनाव-तनाव व्यवहार अर्ध-स्थिर परिस्थितियों में देखे गए से काफी अलग है। यह देखा गया है कि कुछ पदार्थ सकारात्मक तनाव दर संवेदनशीलता प्रदर्शित करती हैं, जबकि कुछ पदार्थ नकारात्मक तनाव दर संवेदनशीलता और कुछ खराब तनाव दर संवेदनशीलता दिखाती हैं।

वर्तमान अध्ययन का उद्देश्य अर्ध-स्थिर और गतिशील स्थितियों में AA7075-T651 और AA6063-T6 के पदार्थ व्यवहार की जांच करना है। एल्युमीनियम मिश्र धातु AA7075-T651 को प्लास्टिक के प्रवाह और पदार्थ की विफलता का अध्ययन करने की विशेषता थी। AA7075-T651 और AA6063-T6 पर विभिन्न तनाव दरों, तनाव त्रिअक्षीयता और तापमान पर तन्यता परीक्षण किए गए। कम स्ट्रेन दर पर अर्ध-स्थिर परीक्षण एक मानक यूनिवर्सल टेस्टिंग मशीन (UTM) पर किए गए थे, जबकि स्प्लिट हॉपकिंसन प्रेशर बार (SHPB) का उपयोग उच्च स्ट्रेन रेट टेस्ट करने के लिए किया गया था। विभिन्न तापमानों पर और संदर्भ तनाव दर (10-3/s) पर अर्ध-स्थिर परीक्षण भी एक विशेष UTM पर एक हीटिंग सिस्टम पर आयोजित किए गए थे। उपरोक्त प्रयोगों से, एक बल-विस्थापन वक्र प्राप्त किया गया था, और इसे एक वास्तविक प्रतिबल-विकृति वक्र में बदल दिया गया था।

उपरोक्त प्रयोगों से प्राप्त परिणामों का उपयोग जॉनसन-कुक (जे-सी) मॉडल के भौतिक मानकों को जांचने के लिए किया गया था, जो प्रभावी प्लास्टिक तनाव, तनाव दर और पदार्थ के तापमान के साथ प्रवाह तनाव से संबंधित है। जॉनसन-कुक विफलता मॉडल, जो तनाव त्रिअक्षीयता, तनाव दर और पदार्थ के तापमान के साथ विफलता तनाव से संबंधित है, को भी कैलिब्रेट किया गया था।

अलग-अलग स्ट्रेन दरों पर ग्री-पॉइंट बेंड परीक्षण AA7075-T651 और AA6063-T6 पर आयोजित किए गए ताकि विभिन्न स्ट्रेन दरों पर फ्रैक्चर प्रवर्तन दृढ़ता प्राप्त की जा सके। प्रयोगों में प्रयुक्त तीन-बिंदु मोड़ नमूनों को ASTM-E399 मानक के अनुसार मशीनीकृत किया गया था। इस अध्ययन में प्रयुक्त प्रायोगिक सेटअप डिजिटल छवि सहसंबंध (डीआईसी) के साथ एक संशोधित हॉपकिंसन प्रेशर बार (एमएचपीबी) संयुग्मन था। यह देखा गया कि लोडिंग दरों के साथ गतिशील फ्रैक्चर दृढ़ता में वृद्धि हुई। तनाव तीव्रता कारक (एसआईएफ) का मूल्यांकन एक स्थापित लोड पॉइंट विस्थापन (एलपीडी) तकनीक और फ्रैक माउथ ओपनिंग विस्थापन (सीएमओडी) विधि का उपयोग करके किया गया था, जबकि फ्रैक्चर की शुरुआत का समय हाई-स्पीड कैमरों के स्टीरियो-कॉन्फिगरेशन का उपयोग करके प्राप्त किया गया था। नमूने की खंडित सतहों पर भी फ्रैक्चरोग्राफी की गई थी। ट्रांस ग्रेन्युलर पहलू, छोटे और बड़े डिम्पल माइक्रोग्राफ पर देखे गए, जो लोडिंग दरों के साथ फ्रैक्चर की कठोरता में वृद्धि के कारणों को दर्शाते हैं। फ्रैक्चरोग्राफी के अवलोकन के अलावा, त्रि-आयामी और दो-आयामी सतह प्रोफाइल तैयार किए गए थे, जो फ्रैक्चर दृढ़ता के साथ तरंगण के संबंध को दर्शाता है।

इस अध्ययन में, फ्रैक माउथ ओपनिंग विस्थापन (CMOD) पर उच्च लोडिंग दरों के प्रभाव और एल्युमीनियम 6063-T6 मिश्र धातु के फ्रैक्चर व्यवहार की जांच के लिए अर्ध-स्थैतिक और गतिशील तीन-बिंदु मोड़ प्रयोग भी किए गए थे। CMOD प्रयोगों को मापने के लिए एक 3D डिजिटल छवि सहसंबंध (DIC) का उपयोग किया गया था। यूटीएम और कम लोडिंग दरों के लिए एक

उच्च-रिज़ॉल्यूशन स्टीरियो कैमरा सिस्टम का उपयोग करके अर्ध-स्थैतिक तीन-बिंदु मोड़ प्रयोग किए गए थे। गतिशील तीन-बिंदु मोड़ प्रयोग के लिए, एक संशोधित हॉपकिंसन दबाव बार सेटअप, दो उच्च गति वाले डिजिटल कैमरे और एक समर्पित डेटा अधिग्रहण प्रणाली का उपयोग लोड बिंदु डेटा और पूर्ण क्षेत्र विस्थापन प्रोफाइल को मापने में किया गया था। यह पाया गया कि स्थिर फ्रैक्चर दृढ़ता की तुलना में गतिशील फ्रैक्चर दृढ़ता मूल्य काफी अधिक थे।

इसके अलावा, तीन-बिंदु मोड़ परीक्षणों के लिए परिमित अव्यव अनुकरण किया गया था, जो तीन-आयामी ठोस मॉडल का उपयोग करके विभिन्न लोडिंग दरों पर आयोजित किया गया था। संख्यात्मक अनुकरण के लिए प्लास्टिक और विफलता गुणों को प्रयोगात्मक परिणामों से प्राप्त जॉनसन-कुक के गठन और विफलता मॉडल से प्रतिस्थापित किया गया था। सिमुलेशन का उपयोग करके प्राप्त परिणाम AA7075-T651 के प्रयोगात्मक परिणामों के साथ ठीक समझौते में पाए गए।

TABLE OF CONTENTS

Certificate	i
Acknowledgments	ii
Abstract	iv
सारा	vii
Table of Contents	ix
List of Figures	xiv
List of Tables	xxi
CHAPTER 1 Introduction	1-4
CHAPTER 2 Literature review	5-35
2.1 Introduction	5
2.2 Mechanical Behaviour of Aluminium Alloys	6
2.2.1 High Strain Rate Mechanical Behaviour	10
2.2.2 Thermally Activated Dislocation Motion	11
2.2.3 Inertia Effects	12
2.2.4 Strain Rate Sensitivity of Aluminium Alloys at a High Loading Rate	14
2.2.5 Fracture Properties of Aluminium Alloys at a High Loading Rate	16
2.3 Quasi-Static test	21
2.4 Split Hopkinson Tension Bar	23
2.4.1 Expression of Stress and Strain in Pressure Bars due to Impact loading	24
2.5 Constitutive Equations	27
2.5.1 Johnson-Cook Material Model	28
2.5.2 Cowper-Symonds Material Model	29
2.5.3 Zerilli-Armstrong Material Model	29

2.5.4	Steinberg-Guinan Material Model	30
2.6	Johnson and Cook Cumulative Damage Model	30
2.7	The Existing gaps in knowledge	32
2.8	The Scope of the Present Investigation	34
CHAPTER 3 Calibration of Johnson-Cook material and Failure Models for Aluminium alloys		36-89
3.1	Method for Calibration of the Johnson-Cook Constitutive model	36
3.1.1	Method to Determine Parameter A	37
3.1.2	Method to Determine Strain Hardening Parameters B and n	37
3.1.3	Method to Determine Strain Rate Sensitivity Parameter C	38
3.1.4	Method to Determine Thermal Softening Parameter m	39
3.2	Method to Calibrate the Johnson-Cook Failure Model	40
3.2.1	Method to Determine Johnson-Cook Failure Model Parameters D1, D2 and D3	40
3.2.2	Method to Determine Johnson Cook Strain Rate Parameter D4	44
3.2.3	Method to Determine Johnson Cook Thermal Parameter D5	44
3.3	Materials and Methods	45
3.3.1	Materials used	45
3.3.2	Experimental Details	46
3.3.3	Experimental Details for Tensile SHPB	49
3.3.4	Plan for Experiments	51
3.4	Material Characterisation and Calibration of AA7075-T651	56
3.4.1	Calibration for Johnson-Cook Constitutive Model of AA7075-T651	56
3.4.2	Calibration for Johnson-Cook Failure Model for AA7075-T651	63
3.5	Material Characterisation and Calibration for AA6063-T6	70

3.5.1	Calibration for Johnson-Cook Constitutive Model of AA6063-T6	70
3.5.2	Calibration for Johnson-Cook Failure Model for AA6063-T6	82
3.6	Summary	88
CHAPTER 4 Evaluation of Dynamic Initiation Fracture Parameters for AA7075-T651 using MHPB and DIC		90-124
4.1	Introduction	90
4.2	Experimental Procedure	94
4.2.1	Experiment	94
4.2.2	Specimen Details	97
4.3	Theoretical Background	98
4.3.1	Dynamic Initiation Fracture Toughness (K _{1d})	98
4.3.2	DIC Theory	99
4.4	Results and Discussions	101
4.4.1	Fractography	115
	4.4.1.1 Digital Microscopy and Scanning Electron Microscopy	116
4.4.2	Three-Dimensional Profiles of Fractured Surfaces	121
4.5	Crack Propagation History	122
4.6	Summary	123
CHAPTER 5 Fracture Parameters and Failure Visualization of AA6063-T6 under Different Loading Rates		125-135
5.1	Introduction	125
5.2	Material and specimen Preparation	127

5.3	Experimental Procedure	128
5.3.1	Quasi-Static Test	128
5.3.2	Dynamic Test	129
5.3.2.1	Dynamic Stress Intensity Factor (DSIF)	129
5.4	Results and Discussion	130
5.4.1	Quasi-Static Results	130
5.4.2	Dynamic Experimental Results	131
5.5	Summary	135
CHAPTER 6 Finite Element Simulation of Three-Point Bend Test for Aluminium Alloy AA7075-T651 in Dynamic Condition		136-153
6.1	Introduction	136
6.2	Formulation of equations used for Finite Element Methods	137
6.3	Different Modules used for Finite Element Simulation	138
6.3.1	Part Module	139
6.3.2	Property Module	139
6.3.3	Assembly Module	140
6.3.4	Step Module	141
6.3.5	Interaction Module	141
6.3.6	Load Module	142
6.3.7	Mesh Module	142
6.3.8	Job Module	143
6.3.9	Visualization Module	144
6.4	Results and Discussion	144
6.4.1	Load Point Displacement along the Longitudinal Direction of Incident Bar	144

6.4.2	Crack Mouth Opening Displacement of specimen	148
6.4.3	Plasticity properties and Failure Criteria	150
6.5	Mesh Sensitivity Analysis for FEA Simulation	151
6.6	Summary of Observations	153
CHAPTER 7 Conclusions and Scope of Future Work		154-158
7.1	Uniaxial Tensile Behaviour	154
7.1.1	Aluminium Alloy AA7075-T651	154
7.1.2	Aluminium Alloy AA6063-T6	155
7.2	Quasi-static and Dynamic Fracture Behaviour	155
7.2.1	Aluminium Alloy AA7075-T651	155
7.2.2	Aluminium Alloy AA6063-T6	156
7.3	Finite Element Analysis	157
7.4	Future Scope of Research	157
References		159-169
Appendix-1		170-174
Appendix-II		175-186
Appendix-III		187-188
Appendix-IV		189-197
List of Publications		198-200
Brief Bio-Data of the Author		201

LIST OF FIGURES

Figure Number	Caption	Page Number
Fig 2.1	Lower yield stress as a function of strain rates for En3BSteel	11
Fig 2.2	Compressed specimen with input bar	13
Fig 2.3	Inertial stress- logarithmic strain rate for copper specimen with 3.8mm diameter and 2.3 mm thickness	13
Fig 2.4	Schematic of a tensile split Hopkinson pressure bar	23
Fig 2.5	Dynamic equilibrium of element ABCD	25
Fig 3.1	Notched specimen (a) Geometry (b) Triaxial stress distribution in notch	41
Fig 3.2	Zwick Z250UTM	49
Fig 3.3	Experimental set up of a tensile split Hopkinson pressure bar	50
Fig 3.4	Tensile test specimen diagram for UTM (a) Actual (b) Drawing (AA7075-T651)	53
Fig 3.5	Tensile test specimen diagram for SHPB(a) Actual (b) Drawing (AA7075-T651)	53
Fig 3.6	Notched specimen (Notch Radius 1mm) for UTM (a) Actual (b) Drawing (AA7075-T651)	54
Fig 3.7	Notched specimen (Notch Radius 2 mm) for UTM (a) Actual (b) Drawing (AA7075-T651)	54
Fig 3.8	Notched specimen (Notch Radius 3mm) for UTM (a) Actual (b) Drawing (AA7075-T651)	55
Fig 3.9	Notched specimen (Notch Radius 4mm) for UTM (a) Actual (b) Drawing (AA7075-T651)	55
Fig 3.10	Engineering and True stress-strain curve for AA7075-T651	56
Fig 3.11	True stress-strain curve for AA7075-T651 at strain rate 10^{-4}s^{-1} (25°C temp)	57
Fig 3.12	True stress-strain curve for AA7075-T651 at strain rate 10^{-3}s^{-1} (25°C temp)	58

Fig 3.13	True stress-strain curve for AA7075-T651 at strain rate 10^{-2} s^{-1} (25 ⁰ C temp)	58
Fig 3.14	True stress-strain curve for AA7075-T651 at strain rate 10^{-1} s^{-1} (25 ⁰ C temp)	59
Fig 3.15	True stress-strain curve for AA7075-T651 at different strain rates (25 ⁰ C temp)	59
Fig 3.16	True stress-strain curve for AA7075-T651 at strain rate 700 s^{-1} (25 ⁰ C temp)	60
Fig 3.17	True stress strain curve for AA7075-T651 at 250C temp (strain rate 10^{-3} s^{-1})	60
Fig 3.18	Determination of yield strength for AA7075-T651	61
Fig 3.19	Determination of strain hardening parameter for AA7075-T651	62
Fig 3.20	Comparison of experimental and J-C model results for AA7075-T651	62
Fig 3.21	Determination of strain rate sensitivity parameter(C) for AA7075-T651	63
Fig 3.22	Notched specimens of different notch radius AA7075-T651	64
Fig 3.23	Notched specimens of different notch radius of AA7075-T651 sprayed with white and black paint	64
Fig 3.24	Digital Image correlation set up with UTM for the tensile test of notched specimen	65
Fig 3.25	Determination of failure parameter D1, D2, and D3 for AA7075-T651	66
Fig 3.26	Fractured Tensile specimen of AA7075-T651 at various stress triaxilities	67
Fig 3.27	(a) The fractured surface of AA7075-T651 at triaxiality 0.6518 (b) Fractured specimen with scale	67
Fig 3.28	(a)The fractured surface of AA7075-T651 at triaxiality 1.2496 (b) Fractured specimen with scale	68
Fig 3.29	Determination of strain rate parameter(D4) for AA7075-T651	69
Fig 3.30	Fractured tensile specimens for AA7075-T651 at different strain rates	69

Fig 3.31	Dimensions used for tensile test specimens of AA6063-T6	71
Fig 3.32	Tensile test specimens of AA6063-T6	72
Fig 3.33	Actual experimental set up of H50KS UTM	72
Fig 3.34	Clamped tensile specimen in a universal testing machine	73
Fig 3.35	Engineering and True stress-strain curve for AA6063-T6	74
Fig 3.36	(a)Engg. stress-strain curve and (b) Yield Stress at strain rate 10^{-4}s^{-1} (25 ⁰ C temp)	74
Fig 3.37	(a)Engg. stress strain curve and (b) Yield Stress at strain rate 10^{-3}s^{-1} (25 ⁰ C temp)	75
Fig 3.38	(a)Engg. stress-strain curve and (b) Yield Stress at strain rate 10^{-2}s^{-1} (25 ⁰ C temp)	76
Fig 3.39	(a)Engg. stress-strain curve and (b) Yield Stress at strain rate 10^{-2}s^{-1} (25 ⁰ C temp)	76
Fig 3.40	Determination of yield strength for AA6063-T at strain rate $10^{-3}/\text{s}$	77
Fig 3.41	Determination of strain hardening parameter for AA6063-T6	78
Fig 3.42	Fractured Tensile specimens at different strain rates	78
Fig 3.43	Dynamic experiment at constant strain rate	79
Fig 3.44	True stress-strain curve for AA6063-T6 at strain rate 410 s-1(25 ⁰ C temp)	80
Fig 3.45	Determination of strain rate sensitivity parameter (C) for AA6063-T6	80
Fig 3.46	Engg. stress-strain curves at various temperatures for AA6063-T6 (strain rates 10^{-3}s^{-1})	81
Fig 3.47	Determination of thermal sensitivity parameter(m)AA6063-T6 (strain rates 10^{-3}s^{-1})	82
Fig 3.48	Notched specimens of 3mm, 2mm, and 1mm radius with their stress triaxilities	83
Fig 3.49	Determination of failure parameter D1, D2, and D3 for AA6063-T6	84
Fig 3.50	Determination of strain rate parameter (D4) for AA6063-T4	85
Fig 3.51	Fractured notched specimens of 3mm, 2mm, and 1mm radius with their stress triaxilities	85

Fig 3.52	Determination of thermal parameter (D5) for AA6063-T6	86
Fig 3.53	Fractured specimen of AA6063-T6 at various temperatures	86
Fig 3.54	Figure 3.54: Fractured surfaces of specimen of AA6063-T6 at 50°C (b) Fractured specimens with scale	87
Fig 3.55	Figure 3.54: Fractured surfaces of specimen of AA6063-T6 at 200°C (b) Fractured specimens with scale	87
Fig 4.1	Line diagram of the MHPB for the current study	96
Fig 4.2	Actual photograph of the experimental setup (MHPB) for the current study	96
Fig 4.3	Schematic of the Three-point bend specimen used in this study (dimensions in mm)	97
Fig 4.4	Specimen subjected to fatigue loading for inducing natural crack	97
Fig 4.5	L-T Specimen of Al7075-T651	98
Fig 4.6(a)	The representation of the reference subset before deformation	100
Fig 4.6(b)	The representation of the reference subset and deformed subset	100
Fig 4.7	Strain history in the incident bar for 1 bar launch pressure	101
Fig 4.8	Variation of load point displacement (mm) with time (μsec) at different striker velocities	102
Fig 4.9	DIC processed images with LPD at the time ((a) 0 μs , (b) 10 μs , (c) 20 μs , (d) 30 μs , and (e) 40 μs) and impact velocity of 9.90m/s	103
Fig 4.10	DIC processed images with LPD at the time ((a) 0 μs , (b) 10 μs , (c) 20 μs , (d) 30 μs , and (e) 40 μs) and impact velocity of 12.8m/s	104
Fig 4.11	DIC processed images with LPD at the time ((a) 0 μs , (b) 10 μs , (c) 20 μs , and (d) 30 μs) and impact velocity of 14.1m/s	105
Fig 4.12	The experimental value of dynamic stress intensity at projectile velocities (9.9/s, 12.8m/s, and 14.1m/s)	106
Fig 4.13	CMOD, LPD (DIC) vs time at the different impact velocities (9.90m/s, 12.8m/s and 14.1m/s)	107

Fig 4.14	DIC images for crack mouth opening displacement(CMOD) at (0 μ s, 10 μ s, 20 μ s, 30 μ s, and 40 μ s) and the impact velocity of 9.90m/s	109
Fig 4.15	DIC images for crack mouth opening displacement (CMOD) at ((a) 0 μ s, (b) 10 μ s, (c) 20 μ s, (d) 30 μ s, and (e) 40 μ s) and impact velocity 12.8m/s	110
Fig 4.16	DIC images for crack mouth opening displacement(CMOD) at ((a)0 μ s, (b)10 μ s, (c) 20 μ s, and (d) 30 μ s) and the impact velocity of 14.1m/s	111
Fig 4.17	The experimental value of the dynamic stress intensity factor at projectile velocities (9.90m/s, 12.8m/s, and 14.1m/s)	112
Fig 4.18	The micrographs of Al7075-T651 at the impact velocity of 9.90m/s (a) DVM6 Digital microscope 150x (b) Scanning electron magnification 500x and (c) Scanning electron magnification 5000x.	116
Fig 4.19	The micrographs of Al7075-T651 at the impact velocity of 12.8m/s (a) DVM6 Digital microscope 150x (b) Scanning electron magnification 500x and (c) Scanning electron magnification 5000x	117
Fig 4.20	The micrographs of Al7075-T651 at the impact velocity of 14.1 m/s (a) DVM6 Digital microscope 150x (b) Scanning electron magnification 500x and (c) Scanning electron magnification 5000x	119
Fig 4.21	Variation of the mean undulation (mm) along with the distance of the fractured surface from the crack tip (mm)	122
Fig 4.22	Crack propagation velocities at different impact velocities	123
Fig 5.1	Schematic of a 3-point bend specimen	128
Fig 5.2	Quasi-static 3-point bend experimental setup	128
Fig 5.3	Modified Hopkinson pressure bar (MHPB)	129
Fig 5.4	Fractured specimen at a low strain rate	130
Fig 5.5	Applied force variation with crack mouth opening displacement	130
Fig 5.6	Visualization of CMOD at different static load	131

Fig 5.7	Experimental setup(MHPB) with High-speed Cameras	132
Fig 5.8	CMOD versus time at different velocities	133
Fig 5.9	DSIF versus time at different velocities	133
Fig 5.10	Failure visualization of CMOD at the projectile velocity of 14.10m/s	134
Fig 5.11	Failure visualization of CMOD at the projectile velocity of 15.95m/s	134
Fig 6.1	Input parameters and formulation used for numerical simulation	138
Fig 6.2	(a) Three-point Bend Specimen (Deformable) (b) Incident Bar (Deformable)	140
Fig 6.3	Assembly of the Three-point bend test	141
Fig 6.4	Meshed assembly of specimen and incident bar	143
Fig 6.5	Stress wave extracted from the experiment at impact velocity 9.90m/s	145
Fig 6.6	Comparison of experimental and FEM load point displacement(LPD) curves at impact velocity 9.90m/s	146
Fig 6.7	Comparison of experimental and FEM load point displacement(LPD) curves at impact velocity 12.8m/s	146
Fig 6.8	Comparison of experimental and FEM load point displacement(LPD) curves at impact velocity 14.1m/s	147
Fig 6.9	Comparison of load point displacement(LPD) curves at impact velocities 9.90m/s,12.8m/s and 14.1m/s obtained with FEM	148
Fig 6.10	Comparison of experimental and FEM crack mouth opening displacement(CMOD) curves at impact velocity 9.90m/s	148
Fig 6.11	Comparison of experimental and FEM crack mouth opening displacement (CMOD)curves at impact velocity 12.8m/s	149
Fig 6.12	Comparison of experimental and FEM crack mouth opening displacement(CMOD) curves at impact velocity 14.1m/s	149
Fig 6.13	Comparison of crack mouth opening displacement(CMOD) curves at impact velocities 9.90m/s,12.8m/s and 14.1m/s obtained with FEM	150

Fig 6.14	Figure 6.14 (a) Region 1 and 2 Node 29274 , elements 25600 (b) Region 3 Node 29274and 6699 elements.	151
Fig 6.15	Figure 6.15 Load point displacement with time for three different sets of meshes at notch region.	152

LIST OF TABLES

Table Number	Caption	Page Number
Table 2.1	Types of loading and corresponding strain rates	7
Table 2.2	Classification of Aluminium Alloy	9
Table 2.3	Temper designation for aluminium alloys	9
Table 2.4	Johnson-cook constitutive model parameters for various aluminium alloys	32
Table 2.5	Johnson-cook fracture model parameters for various aluminium alloys	34
Table 3.1	Notch dimensions and stress triaxilities	43
Table 3.2	The chemical composition of AL7075-T651(L-T)	45
Table 3.3	Experiments used to determine parameters A, B, C, n and D4	51
Table 3.4	Experiments used to determine parameters D1, D2 and D3	51
Table 3.5	Experiments used to determine parameters m and D5	52
Table 3.6	Johnson-Cook Constitutive model parameters	63
Table 3.7	Johnson-Cook failure model parameter for AA7075-T651	70
Table 3.8	The chemical composition of AA6063-T6	70
Table 3.9	Johnson-Cook Constitutive model parameters for AA6063-T6	82
Table 3.10	Johnson-Cook failure model parameters for AA6063-T6	88
Table 4.1	Chemical composition of aluminum alloy Al7075-T651 (L-T)	97
Table 4.2	Experimental results with the use of LPD obtained from MHPB and DIC	115
Table 4.3	Experimental results with the use of LPD and CMOD obtained from and DIC	115
Table 4.4	Maximum undulation(mm) and its distance from the crack tip	122
Table 5.1	The chemical composition of AA6063-T6	127
Table 5.2	Mechanical properties of Al6063-T6 alloy	127