IMPULSIVE SHEET METAL FORMING BASED ON STANDOFF CHARGE FOR CONICAL GEOMETRY

ROOZBEH ALIPOUR

A thesis submitted in fulfilment of the requirements for award of the degree of Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

JULY 2017
To

My beloved queen and princess: PEGAH and RONIKA.

I will forever be beholden to your infinite patience, understanding and inspiration
ACKNOWLEDGEMENT

I would like to express my profound gratitude to my supervisors; Professor Dr. Izman Sudin and Professor Dr. Nasir Tamin for invaluable guidance and supervision. I owe my gratitude to Dr. Zaini Ahmad for his fantastic ideas.

Special thanks go to my darling parents for giving me moral and cheering support and care throughout my study in UTM.

Last but not least, I would like to thank all my friends who have contributed to the success of this research in one way or another.
ABSTRACT

Recently, explosive forming has gained much attention from researchers to overcome problems of conventional methods in manufacturing complex geometries such as cone. Despite these developments, analytical studies especially on cone with sharp apex angle are rarely reported. Past analytical studies in explosive forming on cone ignored the effects of friction between the blank and the die, redundant work in the work sheet blank and strain rate on blank material behaviour. Likewise, in finite element (FE) method, Arbitrary Lagrangian Eulerian (ALE) approach, most frequently method in the past is very time consuming and costly especially for large number of simulation tests. An alternative to ALE, Coupled Acoustic-Structural Analysis (CASA) approach has been seen gradually applied to model damage on the marine structure subjected to under water explosion but reports on its applications in modelling of explosive forming is somehow very limited. Moreover, in the past reported works, estimation of explosive mass, deformation history and damage accumulation models were analysed independently which creates difficulties to predict all aspects of the blank behaviour simultaneously. An integrated model that addresses these three issues concurrently is however, not available. The main aim of this research is to establish a satisfactory explosive mass estimation equation for modelling cone forming behaviours under integrated conditions with reasonable number of trials, i.e. simulation and experimental. Analytical model based on the impulse method was adopted to estimate the explosive mass by considering the effects of deformation efficiency and strain rate during cone forming process. This was done prior to establishment of FE model. ABAQUS software was used to develop a FE model based on CASA approach. Both models were validated via a series of experimental tests. Three different circular blank materials were tested, i.e. AISI 1006, Cu-ETP and Al 6061 O subjected to C4 explosive forming under water. Four geometrical parameters were varied in the experiments. They were blank diameter (100 and 110mm), blank thickness (0.8, 1 and 1.2 mm), standoff distance (130, 150 and 170 mm) and half apex angle of cone (45 and 60 degree). Height of deformed cone was measured after each test and these results was used an indicator for the right explosive mass determination. An analytical equation was established by taking into consideration the effects of strain rate, friction and redundant work during forming process. Verification via experimental tests showed that the error of explosive mass required for forming all blank materials into a complete cone is about 20% ± 2.91. The developed FE model was also able to predict concurrently the deformation history, thickness distribution and damage accumulation in a good agreement with experiments. In conclusion, this study provides very encouraging evidences that both impulse method and CASA approach can be used together for predicting material behaviours during explosive forming process.
ABSTRAK

Baru baru ini, pembentukan letupan telah mendapat perhatian meluas daripada penyelidik untuk mengatasi masalah kaedah konvensional untuk menghasilkan komponen bergeometri rumit seperti kon. Disebabkan perkembangan ini, kajian beranalitikal khususnya ke atas kon dengansudut puncak tajam jarang dilaporkan. Kajian analitikal yang lalu dalam pembentukan letupan pada kon mengabaikan kesan geseran antara plat kosong dan dai, kerja lebihan dalam kepingan plat kosong dan kadar terikan ke atas kelakuan bahan plat kosong. Begitu juga, dalam kaedah unsur terhingga (FE), pendekatan Sebarangan Lagrangian Eulerian (ALE) kaedah yang sering digunakan dalam kajian lepas mengambil masa yang panjang dan kos yang besar terutama sekali untuk cubaan simulasi yang banyak. Sebagai alternatif kepada ALE, pendekatan Analisis Gabungan Akustik Struktur (CASA) telah dilihat beransur-ansur digunakan untuk memodelkan kerosakan pada struktur marin yang dikenakan letupan bawah air, tetapi, laporan mengenai aplikasi ini dalam pemodelan pembentukan letupan didapati sangat terhad. Selain itu, dalam kerja-kerja yang lepas juga, anggaran jisim bahan letupan, sejarah ubah bentuk dan model pengumpulan kerosakan telah dianalisis secara bersamaan yang mana mewujudkan kesukaran untuk meramal semua aspek tingkah laku plat kosong secara serentak. Satu model yang bersepadu untuk menangani tiga ini secara serentak masih belum ada. Tujuan utama kajian ini adalah untuk menghasilkan satu persamaan anggaran jisim bahan letupan yang memuaskan bagi pemodelan kelakuan pembentukan kon di bawah keadaan bersepadu dengan bilangan ujian yang munasabah, iaitu secara simulasi dan juga eksperimen. Model beranalisis berdasarkan kepada kaedah dedenyut telah diguna-pakai untuk menganggar jisim bahan letupan dengan mengambil kira kesan kecekapan ubah bentuk dan kadar terikan semasa proses pembentukan kon. Ini dilakukan sebelum penghasilan model FE. Perisian ABAQUS telah digunakan untuk membangunkan model FE berdasarkan kepada pendekatan CASA. Kedua-dua model telah disahkan melalui satu siri ujian eksperimen. Tiga bahan plat kosong bulat yang berbeza telah diuji, iaitu AISI 1006, Cu-ETP dan Al 6061-O tertakluk kepada pembentukan C-4 di dalam air. Empat parameter bergeometri telah diubah dalam eksperimen. Mereka adalah diameter plat kosong (100 dan 110 mm), ketebalan plat kosong (0.8, 1 dan 1.2 mm), jarak tempuh (130, 150 dan 170 mm) dan separuh sudut puncak kon (45 dan 60 darjah). Ketinggian kon yang terubah bentuk diukur selepas setiap percubaan dan keputusan ini telah digunakan sebagai petunjuk bagi penentuan jisim letupan yang betul. Persamaan analisis yang terhasil mengambil kira kesan kadar terikan, geseran dan kerja lebihan semasa proses pembentukan. Pengesahan melalui ujian eksperimen menunjukkan bahawa ralat jisim bahan letupan yang-diperlukan untuk membentuk semua bahan plat kosong menjadi kon lengkap adalah kira kira 20% ± 2.91. Model FE yang dibangunkan juga dapat meramal secara serentak sejarah ubah bentuk, taburan ketebalan dan pengumpulan kerosakan yang mana keputusannya sepadan dengan eksperimen. Kesimulannya, kajian ini menyediakan bukti-bukti yang amat menggalakkan bahawa kedua-dua kaedah dedenyut dan pendekatan CASA boleh digunakan secara bersama untuk meramal tingkah laku bahan semasa proses pembentukan letupan.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECLARATION</td>
<td>ii</td>
<td></td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iii</td>
<td></td>
</tr>
<tr>
<td>ACKNOWLEDGEMENT</td>
<td>iv</td>
<td></td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>vi</td>
<td></td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
<td></td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xii</td>
<td></td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xiii</td>
<td></td>
</tr>
<tr>
<td>LIST OF SYMBOLES</td>
<td>xix</td>
<td></td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xxii</td>
<td></td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>xxiii</td>
<td></td>
</tr>
</tbody>
</table>

## 1 INTRODUCTION

1.1 Background of Research 1

1.2 Problem Statement 5

1.3 Objectives of Research 6

1.4 Scopes of research 7

1.5 Significance of Research 8

1.6 Organization of Thesis 8

## 2 LITERATURE REVIEW

2.1 Introduction 10

2.2 Low Rate Forming Process of Sheet Metal 11

   2.2.1 Deep Drawing Process 12
3 RESEARCH METHODOLOGY

3.1 Introduction 65

3.2 Open Die Explosive Forming Concept and Common Terminologies 66

3.3 Procedure of Developing Analytical Model 67

3.4 Procedure of Developing FE Model 68

3.4.1 Model Description: Geometry, Elements and boundary conditions 70

3.4.2 Convergence Evaluation 74

3.4.3 Materials Model 75

3.4.4 Modeling of the UNDEX Shock pressure 77

3.4.5 Equation of State 80

3.4.6 Simulation Procedure 80

3.5 Experimental Procedure 81

3.5.1 Blank Materials 81

3.5.2 Explosive Material 83

3.5.3 Experimental Set-up of Explosive Forming Process 84

3.5.3.1 Explosive Die Design and Analysis 84

3.5.3.2 Explosion Container 86

3.5.4 Field Experiment Trials 88

3.5.5 Experimental Plan 90

3.6 Measurement Equipments 91

3.7 Summary 91

4 DEVELOPMENT OF ANALYTICAL MODEL: RESULTS AND DISCUSSION 92

4.1 Introduction 92

4.2 Establishment of Analytical Equation for Estimating Explosive Mass 93

4.2.1 Determination of UNDEX Impulse 93
4.2.2 Determination of Forming Strain Energy
   4.2.2.1 Effect of Strain Rate
   4.2.2.2 Effects of Friction and Redundant Work
4.2.3 Evaluation of Required Impulse for Cone forming
4.2.4 Estimation of Explosive mass

4.3 Validation of Analytical Equation
   4.3.1 Analytical and Experimental Results of Explosive Mass
   4.3.2 Error of Analytical Results

4.4 Effects of Deformation Efficiency and Strain Rate Variations

4.5 Robustness Verification of MVMEs for $R_r$ at Different Standoffs

4.6 Summary

5 FINITE ELEMENT SIMULATION: RESULTS AND DISCUSSION

5.1 Introduction

5.2 FE Prediction of Explosive Mass to Complete the Cone Profile

5.3 Deformation Profile and History
   5.3.1 Deformation Modes
   5.3.2 History of Profile Accomplishment

5.4 Wall Thickness Distribution

5.5 Damage Accumulation
   5.5.1 Safe Formed Part
   5.5.2 Unsafe Formed Part

5.6 Summary
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1 Introduction 150
6.2 Conclusions 150
6.3 Recommendation for Future Studies 152

REFERENCES 153

Appendices A-E 179-206
### LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Specification of sheet metal specimens in FE model</td>
<td>75</td>
</tr>
<tr>
<td>3.2</td>
<td>Constants of JC model for specimens’ material</td>
<td>76</td>
</tr>
<tr>
<td>3.3</td>
<td>Damage constants for Specimens’ material</td>
<td>77</td>
</tr>
<tr>
<td>3.4</td>
<td>Explosive-dependent constants for C4 shockwave simulation</td>
<td>79</td>
</tr>
<tr>
<td>3.5</td>
<td>Mechanical properties of blank materials</td>
<td>83</td>
</tr>
<tr>
<td>3.6</td>
<td>Experimental plan and codes</td>
<td>90</td>
</tr>
<tr>
<td>4.1</td>
<td>REF for explosive materials</td>
<td>105</td>
</tr>
<tr>
<td>4.2</td>
<td>Analytical and experimental results of explosive mass</td>
<td>107</td>
</tr>
<tr>
<td>4.3</td>
<td>REPs of analytical estimated explosive mass in comparison with the experimental results</td>
<td>111</td>
</tr>
<tr>
<td>4.4</td>
<td>Initial estimation, modified estimation and MVME for $R_c$</td>
<td>116</td>
</tr>
<tr>
<td>4.5</td>
<td>Verification tests at different standoffs for MVMEs of $R_c$: Analytical and experimental results of explosive mass</td>
<td>118</td>
</tr>
<tr>
<td>4.6</td>
<td>REPs of analytical estimated explosive mass in comparison with verification test results using MVME of $R_c$</td>
<td>119</td>
</tr>
<tr>
<td>5.1</td>
<td>FE and experimental results of explosive mass</td>
<td>122</td>
</tr>
<tr>
<td>5.2</td>
<td>REPs of analytical and FE estimated explosive mass in comparison with the experimental results</td>
<td>125</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Categories of metal forming processes</td>
<td>11</td>
</tr>
<tr>
<td>2.2</td>
<td>The steps of deep drawing process of a blind cylinder</td>
<td>12</td>
</tr>
<tr>
<td>2.3</td>
<td>Schematic of setup for stamping a “U” shape bracket (Pereira et al., 2013)</td>
<td>13</td>
</tr>
<tr>
<td>2.4</td>
<td>Diagram of rubber-pad forming operation to produce bipolar plate (Gume, 2012)</td>
<td>14</td>
</tr>
<tr>
<td>2.5</td>
<td>The schematic of metal spinning process</td>
<td>15</td>
</tr>
<tr>
<td>2.6</td>
<td>Schematic of the steps in hydroforming process</td>
<td>16</td>
</tr>
<tr>
<td>2.7</td>
<td>Effect of loading rate on flow stress and elongation of low-carbon steel (Emmens, 2011)</td>
<td>18</td>
</tr>
<tr>
<td>2.8</td>
<td>Schematic of EMF process (Mynors et al., 2002)</td>
<td>19</td>
</tr>
<tr>
<td>2.9</td>
<td>The schematic of EHF configuration (Golovashchenko et al., 2013)</td>
<td>20</td>
</tr>
<tr>
<td>2.10</td>
<td>Fabrication of pre-structured in non die explosive forming (Tiesheng, et al., 1992)</td>
<td>22</td>
</tr>
<tr>
<td>2.11</td>
<td>Non die explosive forming process (Mehrasa, et al., 2012)</td>
<td>22</td>
</tr>
<tr>
<td>2.12</td>
<td>A vessel made by non die explosive forming (Tiesheng, et al., 1992)</td>
<td>23</td>
</tr>
<tr>
<td>2.13</td>
<td>Equivalent strains for four, five and six pre-conical structures (Zhang, et al., 1999)</td>
<td>24</td>
</tr>
<tr>
<td>2.14</td>
<td>Arrangement of a setup for explosive free forming (Iyama et al., 2004)</td>
<td>25</td>
</tr>
<tr>
<td>2.15</td>
<td>Experimental setup in Wierzbicki and Nurick research (Wierzbicki and Nurick, 1996)</td>
<td>26</td>
</tr>
</tbody>
</table>
2.16 Schematic of experimental set-up and a formed-cladded
(Raghukandan, et al., 1992) 28
2.17 Wavy interface between two blanks. Zoom in: X 400
(Raghu kandan, et. al, 1998) 29
2.18 Schematic diagram of FDEXF arrangement (Mynors and
Zhang, 2002) 30
2.19 Schematic diagram of MDEXF arrangement (Mynors and
Zhang, 2002) 31
2.20 Schematic of this experimental setup for explosive forming
using detonation of gases mixture 33
2.21 Enhancement of wrinkling with an increase in the radius
ratio (Kowsarinia, et al., 2012) 34
2.22 Explosive forming of square cups using lead plug
(Wijayathunga and Webb, 2006) 35
2.23 Process set configuration in (Jabalamelian et al., 2012) 36
2.24 Distribution of thickness strain in (Jabalamelian et al.,
2012) 36
2.25 Explosive formed part (a) Experimental (b) FE
(Jabalamelian et al., 2012) 37
2.26 Probable area for wrinkling or failure in conventional deep
drawing 40
2.27 Wrinkling phenomena in the flange area of a conical part
(Kawka, et al., 2001). 40
2.28 The differences between primary set-up (a) and maximum
drawing ratio (Thiruvaru dchelvan and Tan, 1991) and
secondary set-up (b) (Thiruvaru dchelvan and Gan, 2004)
42
2.29 Microstructure of cone profile (Thiruvaru dchelvan and Tan,
2004) 42
2.30 (a) Necking and (b) bursting in cone forming (Gorji, et al.,
2011) 43
2.31 Wrinkles in explosive formed metal cone (Darvizeh et al.,
2009) 46
2.32 Experimental deformation history of cone forming by (Ashani et al., 2008) 47
2.33 Explosive formed steel cone with equation 2.6 (Javabvar et al., 2012) 48
2.34 FE model for cone explosive forming in (Emami and Nia, 2010) 48
2.35 Flow chart of the numerical procedure in (Izman et al., 2015) 49
2.36 Visualization of UNDEX bubble: the primary and secondary shockwaves (Han, et al., 2016) 51
2.37 UNDEX in explosive forming process (Aman and Rui, 2014) 52
2.38 Summarizing the steps of hydrocode modeling (Pierazzo et al., 2000) 56
2.39 Scanning electron microscope photograph of fracture morphology of under different strain rates (Yibo et al., 2013) 60
3.1 Overall research methodology flow chart 66
3.2 Schematic diagram of an open die system used in cone explosive forming 67
3.3 Steps followed in analytical study 68
3.4 Flow chart of FE modeling procedure 69
3.5 A sample of meshed specimen with hexahedral elements 70
3.6 Acoustic transfer medium (water) meshed by tetrahedron elements 71
3.7 Locating the explosive material in FE model 72
3.8 Whole assembled FE model and free surface of water 72
3.9 Boundary conditions for dies 73
3.10 Boundary conditions for explosion container 73
3.11 Configuration of die and sheet inside the acoustic transfer media 74
3.12 The overall view of the experimental procedure 81
3.13 Three different blank materials, i.e. Al, St and Cu used as specimens with different thickness (0.8, 1.0 & 1.2mm) and diameter (100 & 110mm)  
3.14 Stress–strain curves of Al, St and Cu sheet metals  
3.15 C4 explosive and detonator unit  
3.16 (a) 3D sketch of a die with half apex angle 45, (b) Cross section A-A plane of the die  
3.17 Maximum stress location in die during explosive loading  
3.18 Final fabricated die  
3.19 Effect of Container radius on maximum stress created in a 25 mm thick container wall due to blasting of 450 gr TNT at the container center (Semiatin and Committee, 2006)  
3.20 Details of explosion container: (a) container, (b) front view of container (c) locator bolts for fixing dies (d) dies bolted in the container  
3.21 Field experimental set-up  
4.1 Impulse transmitted from the explosive to the circular sheet  
4.2 A schematic for forming a circular sheet metal into a cone  
4.3 Deformation of grid patterns in a specimen: (a) original pattern; (b) after ideal deformation; (c) after inhomogeneous deformation (Hosford, 2010)  
4.4 Analytical and experimental explosive mass for copper samples  
4.5 Analytical and experimental explosive mass for steel samples  
4.6 Analytical and experimental explosive mass for aluminum samples  
4.7 Variations of estimated explosive mass vs. R_r for copper samples  
4.8 Variations of estimated explosive mass vs. R_r for steel samples  
4.9 Variations of estimated explosive mass vs. R_r for aluminum samples
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>FE and experimental explosive mass for copper samples</td>
<td>123</td>
</tr>
<tr>
<td>5.2</td>
<td>FE and experimental explosive mass for steel samples</td>
<td>123</td>
</tr>
<tr>
<td>5.3</td>
<td>FE and experimental explosive mass for aluminum samples</td>
<td>124</td>
</tr>
<tr>
<td>5.4</td>
<td>Experimental and FE deformation modes for copper samples</td>
<td>127</td>
</tr>
<tr>
<td>5.5</td>
<td>Experimental and FE deformation modes for steel samples</td>
<td>127</td>
</tr>
<tr>
<td>5.6</td>
<td>Experimental and FE deformation modes for aluminum samples</td>
<td>128</td>
</tr>
<tr>
<td>5.7</td>
<td>Different steps of forming process for a copper sample with the apex angle of 60: experimental (left) and FE (right)</td>
<td>129</td>
</tr>
<tr>
<td>5.8</td>
<td>Movement of the plastic hinge from surrounding to the center of the smaller base</td>
<td>130</td>
</tr>
<tr>
<td>5.9</td>
<td>Time-displacement for the profile center point of the copper samples during forming</td>
<td>131</td>
</tr>
<tr>
<td>5.10</td>
<td>Time-displacement for the profile center point of the steel samples during forming</td>
<td>131</td>
</tr>
<tr>
<td>5.11</td>
<td>Time-displacement for the profile center point of the aluminum samples during forming</td>
<td>132</td>
</tr>
<tr>
<td>5.12</td>
<td>Internal and kinetic energy histories for copper samples</td>
<td>133</td>
</tr>
<tr>
<td>5.13</td>
<td>Internal and kinetic energy histories for steel samples</td>
<td>134</td>
</tr>
<tr>
<td>5.14</td>
<td>Internal and kinetic energy histories for aluminum samples</td>
<td>134</td>
</tr>
<tr>
<td>5.15</td>
<td>Thickness measurement of the cones wall</td>
<td>136</td>
</tr>
<tr>
<td>5.16</td>
<td>Distribution of wall-thickness for Copper samples</td>
<td>137</td>
</tr>
<tr>
<td>5.17</td>
<td>Distribution of wall-thickness for steel samples</td>
<td>137</td>
</tr>
<tr>
<td>5.18</td>
<td>Distribution of wall-thickness for aluminum samples</td>
<td>138</td>
</tr>
<tr>
<td>5.19</td>
<td>Linear regression of thickness variation for trials with half apex angle 60</td>
<td>139</td>
</tr>
<tr>
<td>5.20</td>
<td>Linear regression of thickness variation for trials with half apex angle 45</td>
<td>140</td>
</tr>
<tr>
<td>5.21</td>
<td>(a) Experimental and; (b) FE predicted damage accumulation in a copper sample with initial thickness of 1 mm and half-apex of 60</td>
<td>142</td>
</tr>
</tbody>
</table>
5.22 History of JCCRT and PEEQ parameters in the most critical element at the apex in a copper sample with initial thickness of 1 mm and half-apex of 60

5.23 (a) FE predicted and; (b) experimental damage accumulation in a copper sample with initial thickness of 1 mm and half-apex of 60 subjected to the 10% extra explosive mass

5.24 History of JCCRT and PEEQ parameters in the most critical element at the apex in a copper sample with initial thickness of 1 mm and half-apex of 60 subjected to the 10% extra explosive mass

5.25 (a) Experimental and; (b) FE predicted damage accumulation in a copper sample with initial thickness of 1 mm and half-apex of 45 subjected to the 20% extra explosive mass

5.26 History of JCCRT and PEEQ parameters in the most critical element at the apex in a copper sample with initial thickness of 1 mm and half-apex of 45 subjected to the 20% extra explosive mass

5.27 (a) Experimental and; (b) FE predicted damage accumulation in an aluminum sample with initial thickness of 1.2 mm and half-apex of 45 subjected to the 20% extra explosive mass

5.28 (a) Experimental and; (b) FE predicted damage accumulation in a steel sample with initial thickness of 0.8 mm and half-apex of 45 subjected to the 20% extra explosive mass
LIST OF SYMBOLS

\( \varepsilon_1 \) - Principle strain
\( \varepsilon_2 \) - Principle strain
\( \varepsilon_3 \) - Principle strain
\( A \) - JC model material constant
\( B \) - JC model material constant
\( C \) - JC model material constant
\( c \) - Speed of sound
\( D \) - Diameter of the sheet metal sample
\( D_0 \) - Diameter of the sheet placed on the die cavity
\( D_i \) - JC model material damage constant
\( D_2 \) - JC model material damage constant
\( D_3 \) - JC model material damage constant
\( D_4 \) - JC model material damage constant
\( D_5 \) - JC model material damage constant
\( du \) - Strain energy per volume unit
\( e \) - Specific energy of the explosive material
\( E_i \) - Internal energy
\( E_K \) - Kinetic energy
\( \varepsilon_{pl} \) - Effective plastic strain in JC model
\( E_v \) - Bulk modulus
\( H \) - Depth of dome
\( I_n \) - Total impulse of perpendicular sheet
\( I_{sh} \) - Impulse required for forming
\( I_t \) - Integrated impulse per unit area in a shockwave
\( k \) - Work hardening constants of material
\( k \) - Constant of explosive material
\( k_1 \) - Explosive constant
\( k_2 \) - Explosive constant
\( K_c \) - Adiabatic explosive constant
\( K_N \) - Coefficient pertaining to the material
\( m \) - Sheet metal mass
\( m \) - Thermal softening exponent in JC model
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>Work hardening constants of material</td>
</tr>
<tr>
<td>$n$</td>
<td>Power-law exponent</td>
</tr>
<tr>
<td>$n$</td>
<td>Exponent of strain hardening in JC model</td>
</tr>
<tr>
<td>$P(R,t)$</td>
<td>Pressure profile to bubble motion</td>
</tr>
<tr>
<td>$P(t)$</td>
<td>Pressure history of the shockwave</td>
</tr>
<tr>
<td>$P_g$</td>
<td>Pressure in gas bubble</td>
</tr>
<tr>
<td>$P_m$</td>
<td>Peak pressure of shockwave</td>
</tr>
<tr>
<td>$P_v$</td>
<td>Vapor pressure of water</td>
</tr>
<tr>
<td>$q$</td>
<td>Power-law coefficient</td>
</tr>
<tr>
<td>$R$</td>
<td>Radius of sheet before forming</td>
</tr>
<tr>
<td>$R_t$</td>
<td>Mechanical coefficient of forming process</td>
</tr>
<tr>
<td>$\sigma^*$</td>
<td>Stress-triaxiality factor in JC model</td>
</tr>
<tr>
<td>$S_d$</td>
<td>Standoff distance</td>
</tr>
<tr>
<td>$T$</td>
<td>Experimental temperature in JC model</td>
</tr>
<tr>
<td>$t_0$</td>
<td>Initial thickness of blank</td>
</tr>
<tr>
<td>$T_E$</td>
<td>Energy density due to UNDEX</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Melting temperature in JC model</td>
</tr>
<tr>
<td>$U$</td>
<td>Total strain energy</td>
</tr>
<tr>
<td>$U_D$</td>
<td>Strain energy required for the dome forming</td>
</tr>
<tr>
<td>$U_f$</td>
<td>Friction strain energy</td>
</tr>
<tr>
<td>$U_I$</td>
<td>Ideal strain energy</td>
</tr>
<tr>
<td>$U_r$</td>
<td>Redundant strain Energy</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume of sheet metal</td>
</tr>
<tr>
<td>$v$</td>
<td>Sheet metal speed</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Volume of the explosive before detonation</td>
</tr>
<tr>
<td>$V_g$</td>
<td>Current volume of the gas bubble</td>
</tr>
<tr>
<td>$W$</td>
<td>Explosive mass</td>
</tr>
<tr>
<td>$Y$</td>
<td>Yield strength of material</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>Explosive constant</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>Explosive constant</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Explosive material constant</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Ratio of dynamic to static flow stress</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>Constant ratio of specific heats for the gas</td>
</tr>
<tr>
<td>$\Delta_1$</td>
<td>Explosive constant</td>
</tr>
<tr>
<td>$\Delta_2$</td>
<td>Explosive constant</td>
</tr>
<tr>
<td>$\varepsilon_a$</td>
<td>Circumferential strain</td>
</tr>
<tr>
<td>$\varepsilon_{eff}$</td>
<td>Effective strain</td>
</tr>
<tr>
<td>$\varepsilon_L$</td>
<td>Slant strain</td>
</tr>
<tr>
<td>$\varepsilon_t$</td>
<td>Thickness strain</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>Constant of explosive material</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>$\eta$</td>
<td>deformation efficiency</td>
</tr>
<tr>
<td>$\eta_m$</td>
<td>Efficiency of energy transfer</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Apex angle of die</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Half-apex angle of cone</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Exponential decay time constant</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>Density of the water</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Flow stress</td>
</tr>
<tr>
<td>$\sigma_1$</td>
<td>Principle stress</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>Principle stress</td>
</tr>
<tr>
<td>$\sigma_3$</td>
<td>Principle stress</td>
</tr>
<tr>
<td>$\sigma_{eff}$</td>
<td>Effective stress</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>Dynamic flow stress</td>
</tr>
<tr>
<td>$\sigma_{y0}$</td>
<td>Static Flow stress</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Explosive material constant</td>
</tr>
</tbody>
</table>
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALE</td>
<td>Arbitrary Lagrangian Eulerian</td>
</tr>
<tr>
<td>BHF</td>
<td>Blank holder force</td>
</tr>
<tr>
<td>CASA</td>
<td>Coupled Acoustic-Structural analysis</td>
</tr>
<tr>
<td>CEL</td>
<td>Coupled Eulerian Lagrangian</td>
</tr>
<tr>
<td>EHF</td>
<td>Electro-hydraulic forming</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromagnetic forming</td>
</tr>
<tr>
<td>EOS</td>
<td>Equation of state</td>
</tr>
<tr>
<td>FDEXF</td>
<td>Female die explosive forming</td>
</tr>
<tr>
<td>FE</td>
<td>Finite element</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element method</td>
</tr>
<tr>
<td>HRF</td>
<td>High rate forming</td>
</tr>
<tr>
<td>JC</td>
<td>Johnson-Cook</td>
</tr>
<tr>
<td>JCCRT</td>
<td>JC damage factor</td>
</tr>
<tr>
<td>JWL</td>
<td>Jones-Wilkins-Lee</td>
</tr>
<tr>
<td>MDEXF</td>
<td>Male die explosive forming</td>
</tr>
<tr>
<td>MVME</td>
<td>Mean value for modified estimation</td>
</tr>
<tr>
<td>PEEQ</td>
<td>Plastic equivalent strain</td>
</tr>
<tr>
<td>REF</td>
<td>Relative effectiveness factor</td>
</tr>
<tr>
<td>REP</td>
<td>Relative error percentage</td>
</tr>
<tr>
<td>UNDEX</td>
<td>Underwater explosion</td>
</tr>
</tbody>
</table>
# LIST OF APPENDICES

<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Analysis of a Coupled Acoustic Structure Systems</td>
<td>179</td>
</tr>
<tr>
<td>B</td>
<td>Die Design and Fabrication</td>
<td>189</td>
</tr>
<tr>
<td>C</td>
<td>Equipment And Facilities</td>
<td>199</td>
</tr>
<tr>
<td>D</td>
<td>Statistical Methods</td>
<td>203</td>
</tr>
<tr>
<td>E</td>
<td>List of Publications</td>
<td>205</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Background of Research

Sheet metal forming techniques have been increasingly used to produce the strategic components such as pressure vessels in petroleum industry (Ishikawa et al., 2014), fuel tanks for rockets in military application (Lee et al., 2016), metallic bent tubular parts for aerospace (Yang et al., 2012) and engine cradles in vehicles (Alaswad et al., 2012). Due to improvement in mechanical properties such as strength, possibility of grain orientation and good dimensional accuracy of sheet metal formed parts (Hosford and Caddell, 2011), this method is gaining momentum to be used for producing precise, complex and variety shapes of metal parts. Despite improving mechanical properties, this method is more sustainable than that of any other known conventional machining processes since the amount of wastage materials is far less.

Generally, sheet metal forming can be categorized into low and high rate loading operations (Cristescu, 2007). Low rate forming generally refers to near quasi-static loading where the load is applied gradually to the sheet metal blank such as using press (Choomlucksana et al., 2015), punch (Gutiérrez Reguerras et al., 2014) or oil pressure pump (Paul, 2015). With the increase in sheet metal part size, more costly and bigger exerting load equipment are required. The main drawback of this low rate forming is time consuming with more wastage materials when part
geometry is getting more complex such as in the form of corrugated, deep sharp apex angle cone or complete spherical components (Altan et al., 2012).

High rate forming (HRF) delivers energy over a very short time to the sheet blank (Mamutov et al., 2015). Since this process occurs too rapidly, desired metal for HRF needs to be ductile at high deformation speeds. Due to high impulse delivered to the sheet metal, HRF techniques are occasionally called impulsive sheet metal forming processes. Instead of press, punch or any other physical facilities, the load required for forming is supplied by a source of energy. There are three categories of HRF; electro-hydraulic forming (EHF), electromagnetic forming (EMF) and explosive forming (Mynors et al., 2002). Among these three methods, explosive forming attracts more researchers’ attentions because of low costs and yet able to manufacture huge, precise and complex components (Blazynski, 2012). Some manufacturers choose explosive forming method for various reasons such as (Ghizdavu et al., 2010):

i. To decrease manufacturing lead times

ii. To enhance material exploitation and prevent waste

iii. To grow the manufacturing competitiveness

iv. To operate with integrity in a high temperature environment

v. To maximize part stiffness while detracting weight

vi. To design by considering aerodynamic efficiency

There have been many studies on explosive forming for shaping various parts into stepped disc (Balasubramaniam et al., 1984), semi-sphere (Fengman et al., 2000) sphere (Tong et al., 2008), cone (Darvizeh et al., 2009), tubular shell (Hadavi et al., 2009) and torispherical head (Jabalamelian and Ali, 2012) shapes. Focuses of these studies were mainly on the development analytical and finite element (FE) models to estimate explosive mass, blank forming mechanism, improve qualitative forming parameters and design an optimum explosive forming facilities (Iyama et al., 2014).
In most explosive forming processes, the analytical methods are generally developed to predict the amount of explosive mass applied to the sheet metal during the underwater explosion (UNDEX) to avoid any damage or rupture (Zhang and Wang, 2015). They used this strategy to estimate the load or energy required for forming process (Schiffer et al., 2015). There are three common categories of approximate analytical methods based on the empirical surveys, i.e. energy, geometrical and impulse methods (Akbari Mousavi et al., 2007). Due to the complexity of energy transfer phenomenon in the UNDEX, many researchers simplify the computation of load required for forming method by ignoring some mechanical and geometrical aspects of material and forming process. For instance, in (Fengman, et al., 2000) study, they used energy method for estimating explosive mass on spherical shape but ignoring the effects of strain rate and strain hardening. Similarly, energy method was employed to predict explosive mass required for cylindrical shell forming nonetheless ignoring the effects of strain rate and redundant work (Hadavi et al., 2012). These simplifications and assumptions have resulted large range of errors in their analysis from 25 to 95%. Therefore, a more accurate analytical model is required to estimate the explosive mass closer to reality.

Due to the inherent complexity of the explosive forming process, especially underwater, FE models have been seen used a lot to simulate various forming aspects such as strain and/or thickness distribution (Wijayathunga et al., 2006), deformation history and mechanism (Ghizdavu et al., 2011), and damage accumulation (Kowsarinia et al., 2012). It is noticed that most of these models were based on Arbitrary Eulerian Lagrangian (ALE) approach (Barras et al., 2012; Ibrahim et al., 2014) and their investigations always considered one forming aspect at a time. An alternative to ALE, Coupled Acoustic Structural Analysis (CASA) approach is another way that can have high precision prediction of the pressure gradient at the explosion shockwave forehead (Peng, 2009; Woyak, 2002). This approach has been reported more on the marine structure damage subjected to UNDEX (Jen, 2009; Wang et al., 2014; Zhang et al., 2015) but reports on its applications in modelling of sheet metal behaviour under explosive loading is somehow very limited (Fathallah et al., 2014).
Forming of cone attracts considerable attentions than other shapes owing to its strategic usage in various applications such as nozzles of compressor in gas turbines (Nkoi et al., 2013), projectiles and warheads (Sen et al., 2013) and aircraft nose (Liu et al., 2014). Sharp cone forming in fact, is one of the sophisticated and difficult areas in sheet metal forming process. In traditional drawing method, failure is very likely to occur in the middle of the blank because of low-contact area of the sheet with a punch especially in the first step of forming (Dhaiban et al., 2014). Besides, since most of the sheet surface in the area between the punch tips and blank holder is given free rein to form, wrinkles may occur on the flange or product wall (Jalil et al., 2016; Shafaat et al., 2011b). Although, conical parts can be produced by the other forming process such as spinning (Sekiguchi et al., 2012), hydroforming (Gorji et al., 2011), or multi-stage deep drawing (Liuru, 2011) but they are limited to open tolerance components due to the difficulties to control wall thickness distribution and height of the cone. In addition, the overall quality of the final product is mostly dependent on the operator's experiences. Therefore, HRF methods are still preferable for manufacture cones due to the increase the formability of metals through the high rate loading phenomenon (Li et al., 2016). Among all three HRF methods, explosive forming has been more used to cone forming due reasons mentioned earlier.

Tardif (1958) was the first person who explored the possibility of manufacture copper cone by using explosive forming process through some experimental trials. Thereafter, Travis and Johnson (1962) implemented a series of experiments on the aluminum and steel sheets to investigate the extensibility of (Tardif, 1958) research for different geometries and materials. These works followed by Nurick et al. (1989) who experimentally studied the deformation mechanism of a fully clamped circular blank subjected to the explosive loading into cone. In a other study, Darvizeh, et al. (2009) investigated wrinkling defect in the cone during explosive forming with and without blank holder. It was realized that an apex angle with less than 30 degree is almost impossible to form a wrinkleless cone in the absence of blank holder. Experimental studies above revealed several unresolved issues such as wrinkle, rupture and uneven wall thickness distribution.
Similar studies but in a theoretical point of view, an investigation was conducted by Ashani and co-workers (Ashani et al., 2008) to determine the maximum midpoint displacement of a fully clamped circular blanks to make a cone. They also ignored the effect of strain hardening in their works and thus the theoretical model was not able to predict the deformation history of cone forming accurately. Liaghat and his research team (Liaghat et al., 2011) conducted numerical studies and verified by experimental on the hoop strain profile of explosive formed cones. Their results demonstrated that the maximum hoop strain occurs in the nose section and thus concluded the rupture in the apex area is obviously expected. An analytical equation was developed by Javabvar et al. (2012) based on energy method to estimate the explosive mass required for forming steel and aluminium circular blanks into the cones. They took into account the effect of reloading phenomenon during forming process but ignored the effect of deformation efficiency and strain rate. Apart from explosive mass estimation, there was also study on the effect of wall thickness variation of an explosive formed copper cone as a warhead (Sen and Aksoy, 2013). This study was mainly utilized ALE approach and the forming aspects were analyzed individually.

1.2 Problem Statement

Conventional sheet forming processes have been used extensively for manufacturing sheet metal parts like cone shapes. It has been reported that these processes face several severe defects such as premature tearing (Jalil, et al., 2016), wrinkling (Zhan et al., 2015) and excessive uneven wall thickness (Sekiguchi and Arai, 2012). Recently, explosive forming method attracts more attentions for manufacture complex sheet metal part geometry. It has been reported that this method able to reduce the earlier common defects in conventional forming processes (Hassannejadasl et al., 2014). However, analytical studies especially on cone with sharp apex angle are rarely reported in the literature. It is observed that past analytical studies in explosive forming especially on cone, they ignored the effects of
friction between the blank and the die, redundant work in the work sheet blank and strain rate on blank material behaviour (Darvizeh, et al., 2009; Javabvar and Habibpour, 2012; Liaghat et al., 2003). Likewise, in FE methods, most of the previous research works on explosive forming were based on ALE approach (Ghizdavu and Pricop, 2011; Iyama, et al., 2014; Jabalamelian and Ali, 2012; Mehrasa et al., 2012) in which, changing the geometry or amount of explosive mass, all Eulerian parts in the model need to be redefined. This has resulted in massive computation time and cost, hence it becomes impractical especially for large number of simulation trials. The latest literature using this approach for modelling cone under explosive forming was reported by (Emami and Alavini, 2010). An alternative to ALE, Coupled Acoustic-Structural Analysis (CASA) approach has been seen gradually applied to model damage on the marine structure subjected to under water explosion (Jen, 2009; Ming et al., 2016; Zhang, et al., 2015; Zong et al., 2013) but reports on its applications in modelling of explosive sheet metal forming is somehow very limited. Damage accumulation of conical cup was studied by El-Mokadem et al., (2009) using CASA. However, this model did not consider the effect of transfer medium-die-sheet interaction. Fathallah and his team used this method to investigate the behaviour of sheet metal under blast loading but it was done on flat shape (Fathallah, et al., 2014). Moreover, in the past reported works on FE, estimation of explosive mass (Liaghat, et al., 2011), deformation history (Darvizeh, et al., 2009; Emami and Nia, 2010) and damage accumulation models (El Mokadem et al., 2009) were analysed independently which creates difficulties to predict all aspects of the blank behaviour simultaneously. In other word, the previous reports of CASA model were restricted to only single aspect of cone behaviour subjected to explosive forming. An integrated CASA model that addresses these three issues concurrently is highly needed, however, not being observed thus far.

1.3 Objectives of Research

The objectives of research were as follows:
i. To establish an equation of explosive mass estimation for forming a metal cone based on impulse method that consider the effects of strain rate, friction and redundant work during forming process.

ii. To develop a FE model based on CASA approach for explosive forming of cones that can predict the deformation history, wall thickness distribution and damage accumulation concurrently.

iii. To validate the analytical and FE results through a series of experiments.

1.4 Scopes of research

The scopes of this study covered the following limits:

i. Three different types of material were used as a blank for explosive forming into cone, i.e. Aluminum (6061-O), Copper (Cu-ET) and steel (AISI 1006).

ii. Explosive material used in the forming process was limited to Composition (C-4) only.

iii. Water was used as the transfer medium during forming process for transmitting the explosion wave to the blank.

iv. Independent geometrical explosive forming variables were limited to die geometry (half apex angles 45, 60 degree), blank diameter (100 and 110 mm) with blank thickness (0.8, 1.0 and 1.2 mm) and standoff (130, 150 and 170 mm).

v. Cone forming dies were made of ASSAB 709 (AISI 4140) material and fabricated in house.

vi. Impulse method was employed through analytical model for estimating the explosive mass.
vii. ABAQUS software V6.12 was used to perform FE simulation of explosive forming process based on Coupled Acoustic Structural Analysis (CASA).

1.5 Significance of Research

Explosive forming offers great advantages over traditional forming processes in many ways such as short processing time within microsecond to milliseconds range, relatively cheap for manufacturing large part at low volume and more suitable in terms of conservation materials. Despite these remarkable benefits, current modeling technique consumes huge researcher’s efforts to remodel the updated parameters on cone forming processes which lead to extremely high computing time. This study employs a combination of analytical and finite element techniques that has great potential to avoid these weaknesses. It is expected that the developed technique can reduce modeling time by more than half of the present methods and thus it will shorten the overall manufacturing lead time. The accuracy of the model produced from the proposed technique is predicted to be improved by at least 80-90% which means less waste on material and energy consumption during actual forming process. This study also contributes to the knowledge enhancement in the understanding of explosive forming process which is rarely reported in the public domain.

1.6 Organization of Thesis

This thesis includes of six chapters. The first chapter is introduction. It overviews the background of HRF in general application, importance of explosive
forming in manufacturing process application of FE modeling to solve complex UNDEX problems, problem statements, research objectives, scope, significance of the research.

The rest of the report is arranged as follows. Chapter 2 is concentrated on the literature reviews. This chapter highlights the background knowledge on the metal forming principles, HRF methods, employment of the explosion wave in sheet metal forming, critical reviews on the metal cone forming methods and FE studies in the explosive forming field. Methodologies used in establishing of the analytical equation to estimate explosive mass for cone forming, development of FE model for cone explosive forming and detail procedure to run experimental trials are described in Chapter 3. Chapter 4 focuses on the analytical study and its results validating by experiments. This chapter provides an estimation of explosive mass which is used as the input by the FE model. Chapter 5 presents FE modelling results which comprise of the investigation of deformation history of cone explosive forming, thickness distribution in cone wall and damage accumulation in the product during the forming process. The results of FE model are validated against the experiments as same as analytical study. Chapter 6 summarizes the conclusions, outlines the significant contributions from the findings and finally suggests recommendation for future works.
REFERENCES


