

IMPULSIVE SHEET METAL FORMING BASED ON STANDOFF
CHARGE FOR CONICAL GEOMETRY

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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 C 4 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 $20\% \pm 2.91$. 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. Disebalik 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 Sebarang 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 berasingan yang mana mewujudkan kesukaran untuk meramal semua aspek tingkah laku plat kosong secara serentak. Satu model yang bersepadu untuk menangani tiga isu 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 mengambilkira 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 letupan 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 berubah 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 $20\% \pm 2.91$. Model FE yang dibangunkan juga dapat meramal secara serentak sejarah ubah bentuk, taburan ketebalan dan pengumpulan kerosakan yang mana keputusannya sepadan dengan eksperimen. Kesimpulannya, 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.

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LIST OF SYMBOLS

ε_1	-	Principle strain
ε_2	-	Principle strain
ε_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_1	-	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
ε_{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

n	-	Work hardening constants of material
n	-	Power-law exponent
n	-	Exponent of strain hardening in JC model
$P(R,t)$	-	Pressure profile to bubble motion
$P(t)$	-	Pressure history of the shockwave
P_g	-	Pressure in gas bubble
P_m	-	Peak pressure of shockwave
P_v	-	Vapor pressure of water
q	-	Power-law coefficient
R	-	Radius of sheet before forming
R_r	-	Mechanical coefficient of forming process
σ^*	-	Stress-triaxiality factor in JC model
S_d	-	Standoff distance
T	-	Experimental temperature in JC model
t_0	-	Initial thickness of blank
T_E	-	Energy density due to UNDEX
T_m	-	Melting temperature in JC model
U	-	Total strain energy
U_D	-	Strain energy required for the dome forming
U_f	-	Friction strain energy
U_I	-	Ideal strain energy
U_r	-	Redundant strain Energy
V	-	Volume of sheet metal
v	-	Sheet metal speed
V_c	-	Volume of the explosive before detonation
V_g	-	Current volume of the gas bubble
W	-	Explosive mass
Y_s	-	Yield strength of material
α_1	-	Explosive constant
α_2	-	Explosive constant
β	-	Explosive material constant
γ	-	Ratio of dynamic to static flow stress
Γ	-	Constant ratio of specific heats for the gas
Δ_1	-	Explosive constant
Δ_2	-	Explosive constant
ε_a	-	Circumferential strain
ε_{eff}	-	Effective strain
ε_L	-	Slant strain
ε_t	-	Thickness strain
ζ	-	Constant of explosive material

η	-	deformation efficiency
η_m	-	Efficiency of energy transfer
θ	-	Apex angle of die
θ	-	Half-apex angle of cone
κ	-	Exponential decay time constant
ρ_w	-	Density of the water
σ	-	Flow stress
σ_1	-	Principle stress
σ_2	-	Principle stress
σ_3	-	Principle stress
σ_{eff}	-	Effective stress
σ_y	-	Dynamic flow stress
σ_{y0}	-	Static Flow stress
φ	-	Explosive material constant

LIST OF ABBREVIATIONS

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

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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 Regueras *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.

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