DAMAGE MECHANICS BASED APPROACH IN FAILURE PREDICTION OF DRAW FORMING PROCESSES

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

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

JULY 2017

DEDICATION

To my beloved parents and family

ACKNOWLEDGEMENT

Praise to the Almighty.

First and foremost, thanks to Allah s.w.t for the continuous blessing and for giving me the strength and chances in completing this thesis. I would like to express my heartfelt appreciation to my respectful supervisor, Prof. Dr. Mohd. Nasir Tamin for his invaluable advice and supervision throughout this research.

Grateful acknowledgement is also made for financial support by the Ministry of Higher Education (MOHE) Malaysia and Universiti Teknikal Malaysia Melaka. This project is funded by the Ministry of Science, Technology and Innovation (MOSTI) Malaysia and Universiti Teknologi Malaysia through Grant No. TF0608C073-3H010 and RUG-00G42, respectively.

Apart from this, I am thankful to Computational Solid Mechanics Laboratory (CSMLab) members who have shared valuable information, knowledge and thought with me generously. It helps me to solve a lot of problems and difficulties. Their constructive ideas and opinions are also making this research a success indirectly.

Finally yet importantly, further gratitude is forwarded to my beloved family members and friends for their continuous supports and encouragements throughout these years.

ABSTRACT

In a cup draw forming operation, the desired shape results from the material hardening process under controlled plastic deformation and the springback phenomena. In this study, a mechanics-of-deformation approach is developed based on damage variables and large plastic deformation. The approach is then employed to estimate the onset of the material damage event and the location of fracture based on the mechanics response of the metal blank. Draw forming behavior of low carbon steel is examined as a case study. The loading rate is conducted at a slow loading response of the steels in the large deformation of the draw forming processes. Axisymmetric and 3D solid models are developed for finite element (FE) simulations to gain insight into the evolution of internal states and damage in the steel blanks during the draw forming process. In the FE simulation, Johnson-Cook constitutive model with isotropic hardening rule is employed. The Rice-Tracey ductile damage criterion is employed to indicate damage initiation event along with a linear energy-displacement relation for damage evolution rule. Results show that while the applied loading (tool displacement) is quasi-static corresponding to the strain rate of 0.001 sec^{-1}, the maximum plastic strain rate at fracture could reach 100 times greater at the critical material flow region. Failure of the deforming steel blank is localized with excessive plastic deformation. While the onset of damage can be efficiently predicted using the axisymmetric FE model with damage-based model, the subsequent damage evolution of the localized ductile failure requires a 3D continuum FE model. The predicted tool load-displacement response is employed in validating the FE model. Effects of drawing parameters including drawing speed, blank holder force and die clearance on the resulting deformation of the drawn cup-shape part are established. Based on the response of the mechanics-of-deformation, the established failure prediction approach is proven more accurate and reliable.

ABSTRAK

Di dalam operasi pembentukan cawan, bentuk yang diinginkan terhasil daripada proses pengerasan bahan di bawah fenomena tindakan ubah bentuk plastik dan anjalan. Di dalam kajian ini, kaedah mekanik ubah bentuk dibangunkan berdasarkan pemboleh ubah kerosakan dan ubah bentuk besar plastik. Kaedah ini kemudiannya diguna pakai bagi menganggarkan permulaan kejadian kerosakan bahan serta lokasi retakan berdasarkan tindak balas mekanik kepingan logam kosong. Sifat pembentukan keluli berkarbon rendah adalah dikaji sebagai satu kajian kes. Muatan ke besi dikenakan pada kadar tindak balas perlahan mengakibatkan perubahan besar dalam proses penghasilan pembentukan. Model asimetrik dan model pepejal 3D dibangunkan untuk simulasi unsur terhingga bagi mendapatkan pemahaman evolusi keadaan dalaman dan kerosakan logam kosong semasa proses pembentukan tarikan. Di dalam simulasi unsur terhingga, model menjuzuk Johnson-Cook bersama dengan peraturan pengerasan isotrop adalah diguna pakai. Kriteria kerosakan mulur Rice-Tracey digunakan bagi menunjukkan kejadian permulaan kerosakan berserta hubungan linear tenaga dan sesaran untuk peraturan evolusi kerosakan. Hasil menunjukkan walaupun laju alat yang dikenakan adalah pada kuasi-statik menurut kadar terikan $0.001 saat^{-1}$, kadar terikan retakan plastik tertinggi boleh mencecah 100 kali ganda di kawasan genting pengaliran bahan. Kerosakan oleh perubahan logam kosong disetempatkan dengan lebihan ubah bentuk plastik. Sementara itu permulaan kerosakan boleh di jangka dengan berkesan menggunakan model simulasi unsur terhingga asimetrik menggunakan model berasaskan model kerosakan, evolusi kerosakan seterusnya adalah kerosakan mulur setempat memerlukan model unsur terhingga 3D. Jangkaan respon beban kepada sesaran digunakan bagi mengesahkan model simulasi unsur terhingga. Kesan parameter penarikan termasuk kelajuan penarikan, daya pemegang logam kosong dan kelegaan acuan tekan pada hasil ubah bentuk oleh tertarik berbentuk cawan adalah tertubuh. Berdasarkan respon mekanik ubah bentuk, pendekatan jangkaan kerosakan tertubuh dibuktikan lebih tepat dan yakin.

TABLE OF CONTENTS

CHAPTER	TITLE		PAGE
	DECLARATION		ii
	DEDICATION		iii
	ACKNOWLEDGEMENT		iv
	ABSTRACT		v
	ABSTRAK		vi
	TABLE OF CONTENTS		vii
	LIST OF TABLES		x
	LIST OF FIGURES		xi
	LIST OF ABBREVIATIONS		xvi
	LIST OF SYMBOLS		xvii
1	**INTRODUCTION**		**1**
	1.1	Background of the Study	1
	1.2	Statement of the Research Problem	3
	1.3	Research Objectives	3
	1.4	Scope of the Study	4
	1.5	Significance of Study	4
	1.6	Thesis Layout	5
2	**LITERATURE REVIEW**		**7**
	2.1	Introduction	7
	2.2	Trends in Sheet Metal Forming Processes	7
		Automotive Steel Sheets	9
	2.3	Formability in Draw Forming Processes	10
		Forming Limit Diagram	11
	2.4	Mechanics of Large Plastic Deformation	19

	2.5	Strain Rate Dependent Models	26
		Johnson-Cook Model	27
	2.6	Continuum Damage Mechanics	28
		Damage Initiation Criterion	34
		Damage Evolution Equation	36
	2.7	Mechanisms of Failure	38
	2.8	FE Simulation of Sheet Metal Forming Processes	42
	2.9	Summary of Literature Review	49
3	**RESEARCH METHODOLOGY**		**52**
	3.1	Introduction.	52
	3.2	Research Framework	57
	3.3	Demonstrator Material.	57
		Material Properties	57
		Properties and the Constitutive Model	59
		Material Damage Model	62
	3.4	Experimental Procedure.	64
		Erichsen Cup Forming Machine	64
	3.5	Finite Element Simulation of the Draw Forming Process	66
		FE Circular Cup Draw Forming Model.	68
		Mesh Convergence Study	72
		Model Validation	74
	3.6	Concluding Remarks	76
4	**DEFORMATION AND FAILURE PROCESSES IN DRAW FORMING OF A CIRCULAR CUP**		**77**
	4.1	Introduction	77
	4.2	Mechanics Deformation	78
	4.3	Effects of Blank Holder Force and Die Clearance Setting on Deformation Processes	80
	4.4	Evolution of Plastic Instability.	84
	4.5	Fracture Location and Failure Mechanism	86

	4.6	Summary	88
5	**SIMPLIFIED OF FE SIMULATION OF THE DRAW FORMING PROCESS**		**89**
	5.1	Introduction	89
	5.2	Characteristic of Stress and Strain Fields	89
	5.3	Evolution of Plastic Instability	94
	5.4	Failure Mechanics	98
	5.7	Summary	98
6	**FULL THREE DIMENSIONAL FE SIMULATION OF THE DRAW FORMING PROCESS**		**100**
	6.1	Introduction	100
	6.2	Fracture Location	100
	6.3	Failure Mechanics	101
	6.4	Damage Initiation	103
	6.5	Damage Evolution	104
	6.6	Stress and Strain Behavior	106
	6.7	Characterization of Localized Thinning	107
	6.8	Fracture Propagation Path	109
	6.9	Summary	110
8	**CONCLUSIONS & RECOMMENDATIONS**		**112**
	7.1	Conclusions	112
	7.2	Recommendations	113
REFERENCES			**114**
Appendices A - B			126-127

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Three different deformation theories	20
2.2	Typical strain rates for various engineering problem	26
3.1	Chemical composition of low carbon steel sheet (wt. %)	58
3.2	Tensile properties at different strain rates	60
3.3	Elastic property and material density of LCS	60
3.4	Materials parameters used for J-C model	61
3.5	Combinations of process parameters for drawing cases examined	65
5.1	Interrupted sample test at various draw forming depth	94

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Cross sectional view of typical cup draw forming process	2
2.1	Trends of new material debut in every five years	8
2.2	Relationship between ductility and tensile strength of various steel sheets	9
2.3	Relationship between stress vs. percent elongation for various steel grades and their applications in auto-body structure	10
2.4	Forming limit diagram	12
2.5	Schematic representation of the strain path followed before and after necking	14
2.6	An example of FFL on FLD plot	14
2.7	M-K with the thickness imperfection method	16
2.8	Deformation regimes in cup draw forming operation	22
2.9	Diffused and localized necking phenomenon in thin sheet specimen	25
2.10	Large plastic deformation covering elastic deformation, yielding, onset of diffused necking, onset of local necking and fracture	25
2.11	Analysis domains for solid mechanics	29
2.12	Mechanical representation of damage	30
2.13	Deformation and damage concept for mechanical equivalence of damage at mesoscale	32

2.14	The concept for continuum damage mechanics	34
2.15	Relationship between the equivalent strain with the stress triaxiality	35
2.16	Damage evolution paths	37
2.17	Mechanism of failure	39
2.18	Damage process in different length scale	40
2.19	Nucleation, growth and coalescence of micro-voids	41
2.20	Ductile failure behavior corresponding to the true stress strain	42
2.21	A quarter of deformable blank illustrating the fracture in FLD post-processor	45
2.22	Simulation results at different drawn depth with different stiffness degradation value compare to the experimental test	46
2.23	Simulation results prior to fracture at different drawn depth with different stiffness degradation	47
2.24	Illustration of fracture in experiment and FE simulation corresponding to the FLD result and the load-displacement curve	48
2.25	Comparison between implicit and explicit integration domain	49
3.1	Overall research methodology flow-chart	53
3.2	Overall research methodology	54
3.3	Microstructure of as received cold rolled 0.034C steel sheet (a) surface and (b) across thickness	59
3.4	True stress-plastic strain curves at different strain rate	60
3.5	Measured (solid lines) and predicted (dashed lines) true stress-plastic strain curves of 0.034C cold-drawn steel sheet at different strain rates	62
3.6	Damage initiation parameter for ductile failure	63

3.7	Erichsen Cup Forming Machine	65
3.8	Flow-chart of FE model setup with the preparation and model sensitivity analysis	67
3.9	Physical model of circular cup shape part	68
3.10	Schematic sectional view of forming tool design set-up for draw forming of cup-shape parts	69
3.11	Boundary conditions of the draw forming process	70
3.12	(a) Top view of meshed steel blank (b) compression and elongation region demonstrated in three-dimensional one over eight-size cup	71
3.13	Sectional view of 3D draw forming model with boundary condition	72
3.14	Mesh sensitivity analysis for selected region in the deformable blank	73
3.15	Mesh sensitivity study conducted at the onset of fracture	74
3.16	Comparison between measured and calculated tool force-displacement curve using axisymmetric model	75
3.17	Comparison between measured and calculated tool force-displacement curve using 3D model	75
4.1	Punch force-displacement curve illustrating the three stages of the steel blank deformation throughout the drawing process	80
4.2	Variation of punch force with BHF and DC setting for sheet metal drawing of cup shape parts	81
4.3	Variations of maximum drawing depth, d_{max} and limit (non-damage) drawing depth, d_L for sheet metal drawing of cup-shape parts.	82
4.4	Punch force-displacement curves at various DC settings for drawing case with BHF of 70 kN.	83
4.5	Distance of fracture location at various DC setting at 70 kN of BHF.	84

4.6	Progressive thickness variation across necking band, shown at selected draw forming depth, case A11.	85
4.7	Evolution of necking during sheet metal drawing process for drawing case A11.	86
4.8	Fracture locations.	87
4.9	Fractured section of drawn cup for drawing case A11. Inset figure shows enlargement of the selected ductile failure area	87
4.10	Characteristic of fractured surface at different BHF loading	88
5.1	(a) Equivalent stress at draw forming depth of 10.7 mm (b) residual stress, (c) residual strain	90
5.2	Plastic strain rate measured at various locations	91
5.3	Calculated strain rates at various location	93
5.4	Evolution of necking during the sheet metal drawing process	95
5.5	Thinning section along the blank profile	96
5.6	The stress-strain behavior-along the profile	97
5.7	Comparison between FE and experimental test with illustration of ductile failure.	98
6.1	Comparison between the simulated FE and observed fracture location in the draw forming test	101
6.2	Comparison between FE and experimental draw forming test	102
6.3	An element is separated from the cup sidewall at the onset of fracture	103
6.4	Comparison between localized damage initiation variable and the global load-displacement response of the draw forming test	104
6.5	Degradation of critical element until it is separated	105
6.6	Characteristic of stress and strain evolution throughout the draw forming process	106

6.7	Simulation results at several drawn depths of the interrupted draw forming	107
6.8	Comparison between FE simulations and experimental test of thru-thickness evolution	108
6.9	Sectional view of fracture propagation from outer to inner fiber at various draw forming depths	109
6.10	Crack propagation of fracture in biaxial direction of fiber at different draw forming depth	110

LIST OF ABBREVIATIONS

AHSS	-	Advance High Strength Steel
BHF	-	Blank Holder Force
CAE	-	Computer Aided Engineering
CDM	-	Continuum Damage Mechanics
Cof	-	Coefficient of friction
C-S	-	Cowper- Symonds
DC	-	Die Clearance
DIC	-	Digital Image Correlation
FE	-	Finite Element
FFL	-	Fracture Forming Limit
FLC	-	Forming Limit Curve
FLD	-	Forming Limit Diagram
FLDF	-	Forming Limit Diagram at Fracture
FLDN	-	Forming Limit Diagram at Necking
GTN	-	Gurson–Tvergaard–Needleman
HER	-	Hole Expansion Ratio
J-C	-	Johnson-Cook
LCS	-	Low Carbon Steel
LDH	-	Limiting Dome Height
LDR	-	Limiting Drawing Ratio
R-K	-	Rusineck-Klapeczko
RVE	-	Representative Volume Element
SEM	-	Scanning Electron Microscope
TM	-	Tanimura-Mimura
Z-A	-	Zerilli-Armstrong

LIST OF SYMBOLS

A	-	Area
$A^{'}$	-	Johnson-Cook material constant
a	-	Material damage initiation parameters
$B^{'}$	-	Johnson-Cook strain hardening coefficient
$C^{'}$	-	Johnson-Cook strain rate sensitivity
c	-	Material damage initiation parameters
D	-	Damage variable
$\dot{D}$	-	Material constant
d	-	Drawing depth
d_i	-	Damage initiated
d_L	-	Drawing limit
d_{max}	-	Maximum drawing depth
dA	-	Change of area
dF	-	Change of loading force
$d\sigma$	-	Change of stress
$d\varepsilon$	-	Change of strain
E	-	Young's modulus
E_o	-	Young's modulus of the material in the initial undamaged state
E_D	-	Damaged state after loading
F	-	Force
F_{max}	-	Maximum force
F_L	-	Limit punch force
G_f	-	Fracture energy
L	-	Characteristic length of the element
m	-	Johnson-Cook temperature sensitivity

n	-	Johnson-Cook strain hardening
T^*	-	Johnson-Cook homologous temperature
T_{melt}	-	Melting temperature
T_{room}	-	Room temperature
t	-	Thickness
t_{blank}	-	Thickness of the blank
$\bar{u}^{pl}$	-	Equivalent plastic displacement
$\bar{u}_f^{pl}$	-	Equivalent plastic displacement at failure (damage evolution)
ν	-	Poisson's ratio
ω_D	-	Internal state variable
ΔA	-	Apparent area (undamaged surface)
$\Delta \tilde{A}$	-	Changes the effective area
ΔA_{void}	-	Area with micro-voids
ΔF	-	External loading force
$\bar{\sigma}$	-	Equivalent stress
$\tilde{\sigma}$	-	Effective stress
σ_m	-	Mean stress
σ_y	-	Yield stress
σ_{yo}	-	Value of yield stress when damage criterion is met
ε	-	Strain
$\dot{\varepsilon}$	-	Strain rate
$\dot{\varepsilon}^*$	-	Johnson-Cook dimensionless strain rate
$\dot{\varepsilon_0}$	-	Johnson-Cook nominal strain rate
ε_D^{pl}	-	Effective plastic strain at the damage initiation
$\bar{\varepsilon}^{pl}$	-	Equivalent plastic strain
$\bar{\varepsilon}_0^{pl}$	-	Effective plastic strain at the damage initiation
$\bar{\varepsilon}_f^{pl}$	-	Effective plastic strain at fracture
$\bar{\varepsilon}_D^{p}$	-	Plastic strain rate at the onset of damage

$\dot{\varepsilon}^{pl}$	-	Equivalent plastic strain during the damage evolution stage
η	-	Stress triaxiality
ρ	-	Material density

LIST OF APPENDICES

APPENDIX.	TITLE	PAGE
A	Mesh quality index for axisymmetric model of deformable blank.	126
B	Mesh quality index for 3D model of deformable blank	127

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Automotive body parts such as front quarter panel, suspension housing and floor panel are produced through numerous metal forming processes. It is a process of governing the formability of material into the desired shape throughout the forming operation without fail [1]. In the classical shop floor approach, the well-known forming limit diagram (FLD) is employed as a tool to predict the material failure in the metal forming operation. It is practiced as an approach to prevent the occurrence of fracture in sheet metal forming production.

In general, metal forming operation is divided into two main distinct processes, which are cutting and shaping. The process of cutting such as blanking is a process of separating the blank. While shaping for instance draw forming is to form the blank into desired parts. As the main shaping metal forming process in the automotive industries, the study of material failure concentrates on the draw forming operation. The typical tool and die movement are described thru the mechanism of the draw forming process. The tool consists of a punch, blank holder and die cavity while steel blank is employed as deformable parts as depicted in Figure 1.1. This monotonic loading process of punch draws the steel blank into the die cavity at a specified drawing depth and loading speed to draw forming shaped parts. The interactions between deformable blank and forming tools induced large plastic deformation until it is properly form into desired shape.

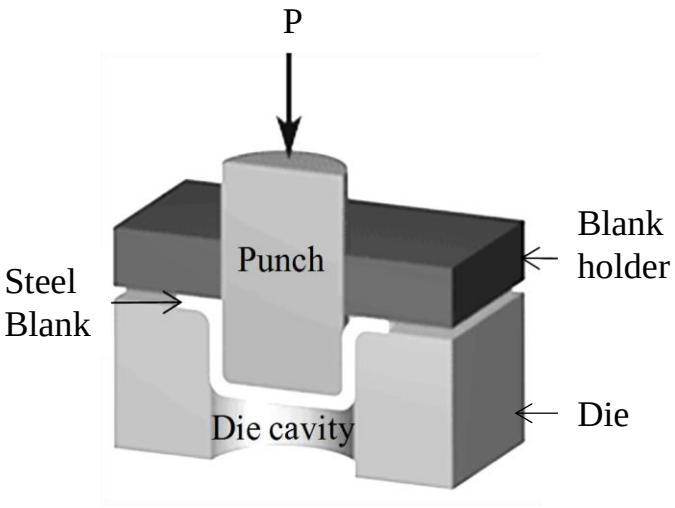

Figure 0.1: Cross sectional view of typical cup draw forming process

During the draw forming operation, steel blank undergoes material hardening process under controlled plastic deformation and springback phenomena. As a result, variation of thickness strain induced by the large plastic deformation is detected in the draw-forming cup. The blank holder force (BHF) induces the compressive stress at the flange region, while the punch tool induces the longitudinal and radial stresses throughout the loading process into the die cavity. These excessive stresses can cause the material failure known as wrinkling and localized necking. Wrinkling at flange is local buckling phenomena that attribute to the excessive compressive stresses [2]. Whereas, localized necking is due to the excessive tensile stresses [3]. The localized necking is usually detected in the sidewall region that can lead to ductile fracture.

As commonly practiced by the shop floor, the popular conventional FLD is defines as a linear strain path dependent criteria [4]. Thus, it is inaccurate for the analysis of complex draw forming processes [5]. The proposed approach is to use the internal states change of steel blank during draw forming processes. It is a mechanics of deformation approach. A process of degradation of material strength properties that initiate and evolve until fracture is dictated [6]. The failure prediction approach is developing based on the Rice-Tracey (R-T) ductile damage criterion to indicate the damage initiation event. While the linear energy-based relation, is used for damage evolution rule. The employ damage variables can estimate the localized deformation and tolerable stretching of material throughout the degradation process of material.

This mechanics of deformation approach is employ as a remedy to the problem in material failure prediction. The mechanics of deformation is a branch of mechanics that examine the behavior of material to the loading. It is an effort of investigating the non-linear response in the material due to the changes in geometry and internal state behavior throughout the draw forming operation.

1.2 Statement of the Research Problem

How could the mechanics of deformation approach employing damage model and finite element (FE) simulation be used to predict material failure process in draw forming operation.

1.3 Objectives

The aim of this study is to develop a damage-based failure prediction approach on the mechanics of materials deformation. Specific objectives are:

1. To establish a validated framework for FE simulation of draw forming processes.
2. To quantify the limitation of axisymmetric FE model for fracture.
3. To determine the effect of damage and its evolution on the material response.

1.4 Scope of Study

The present study covers the following scope of work:

1. Low carbon steel (LCS) is examined as a demonstrator material.
2. Erichsen cup forming machine is used to draw forming LCS into circular cup shape parts.
3. The draw forming test is set at 1 mm/sec slow loading rates with constant BHF to clamp uniformly on the flange part.
4. The FE simulations are carried out at strain rate dependent condition to model the draw forming test.
5. Coulomb friction is applied in every interaction between forming tools and deformable blank throughout the FE simulation.
6. Axisymmetric model with piecewise hardening curve is applied to define the limitation of the geometrical representation of the model when predicting failure.
7. Deformable blank in FE 3D circular cup is modeled using solid elements to determine the thru thickness necking effect.
8. Johnson-Cook (J-C) isotropic hardening parameter incorporated with Rice-Tracey (R-T) ductile damage initiation model and linear energy based model are used to assess hardening and material failure respectively.

1.5 Significance of Study

In predicting material failure, FLD shows some disadvantageous which requires new approach. Compared to the propose approach, its failure prediction quality is considered as inaccurate for the complex analysis of draw forming processes. This is due to its criteria that satisfy only for the linear strain path condition. Furthermore, it is highly depending on the recorded experimental test data with less mechanics based consideration. It is also very time consuming because it requires too

many data to be recorded with too many samples involved. As a result, these works suffered high in cost.

On the other hand, the propose failure prediction approach not only able to predict the onset of failure location accurately. Moreover, it is able to quantify the internal states of material from the process of thru thickness necking throughout the damage evolution until fracture. Therefore, the failure prediction results are more realistic compared to classical shop floor approach.

With the advance in numerical simulation to compute virtually the draw forming processes, the propose approach facilitates the assessment of deformation and failure. It computes the mechanics of deformation throughout the formability of material until the point of separation. Thru the understandings on mechanics of deformation and failure processes, the behavior of tolerable stretching of the material are define explicitly. It gives accurate and realistic physical representation of ductile failure at a localized point in the material.

1.6 Thesis Layout

This thesis consists of seven chapters. In Chapter 1, the background and the necessity of the background of the research are bringing out. The issues of material failure in drawing automotive steel parts are based upon. The objectives, scope and significance of the research are present.

In Chapter 2, reviews are presented on the trends in sheet metal forming processes, automotive steel sheet, formability of draw forming processes, mechanics of large plastic deformation, finite element, strain rate dependent models, continuum damage mechanics, mechanism of failure, FE simulation of sheet metal forming processes and summary of literature review.

In Chapter 3, the research methodology is present. The details of the applied research materials, experimental setup and finite element (FE) simulation models are explained.

In Chapter 4, the assessment of deformation and failure processes in draw forming test are presented and discussed. Mechanics deformation of material formability through the punch-force displacement curve is examined and interpreted. Effects of BHF and DC setting in the process are measured. The interrupted draw forming tests at different displacement depth are conducted. The evolution of plastic instability in the interrupted draw-forming test is characterized. Fracture location and failure mechanism is identified.

In Chapter 5, the application of FE simulation to assess the mechanics deformation is addressed. An axisymmetric FE cup draw-forming model is used to simulate the draw forming processes on LCS at uniform BHF. In modeling the hardening behavior, piecewise plastic strain rate hardening parameter are employed. The evolution of plastic instability in the interrupted draw forming simulation is characterized. The calculated fracture location is compared.

In Chapter 6, the application of FE simulation to assess the damage mechanics is address. Using 3D FE cup model, the damage mechanics are examined by incorporating the J-C strain rate dependent criteria and damage variables until the event of fracture. The calculated localized thinning is characterized and compared. The fracture location in 3D FE cup model is demonstrated.

In Chapter 7, the major conclusions of the research are present. Future works for refining the research are recommend.

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