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DAMAGE MECHANICS BASED APPROACH IN FAILURE PREDICTION OF DRAW FORMING PROCESSES

ISMAIL BIN ABU SHAH

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

Faculty of Mechanical Engineering
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JULY 2017

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DEDICATION

To my beloved parents and family

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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 0.001saat^{-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.

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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

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

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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.