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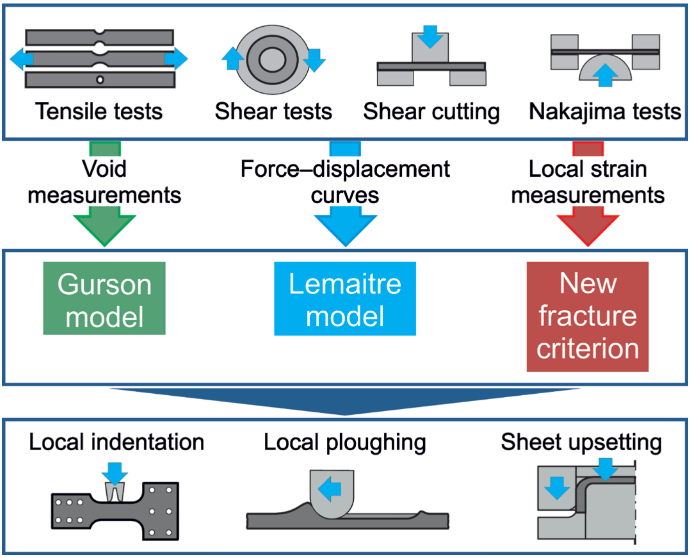
Kerim Işık

Modelling and characterization of damage and fracture in sheet-bulk metal forming



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“Simplicity is the ultimate sophistication.”

Leonardo da Vinci

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Abstract

Sheet-bulk metal forming differs from the conventional sheet forming processes, in the application of the bulk forming operations on the sheet material. Although the initial workpiece is a sheet blank, the occurrence of the three-dimensional stress/strain states requires a revise of the basic assumptions and available material models for the conventional sheet forming processes. Independent from the forming operation (sheet or bulk forming), the reduction in the load carrying capacity of a material and the driving reasons of the final fracture are associated with the void mechanisms. Predictive models aim either only identification of the onset of fracture or damage (void) evolution till final fracture and onset of fracture together.

In this study, necessary material characterization techniques for the available damage models are developed to predict damage and fracture during sheet-bulk forming processes. The applicability of the models for these forming processes is evaluated. Two mainstream continuum damage models, namely Gurson's porous plasticity and Lemaitre's continuum damage model, are investigated. A direct material characterization methodology for Gurson model and an inverse parameter identification methodology for Lemaitre model are introduced. The characterization tests are enriched by adding the shear cutting test to identify through-thickness shear behavior and shear related model parameters.

A new fracture criterion, which is originated from the experimental observations related to normal and shear fracture, is introduced. This criterion includes the stress state dependent measures of the continuum models, which depend on stress triaxiality and Lode angle parameter. A simplified structure of this criterion allows a rapid characterization methodology for the material parameters.

The models' predictive performances are compared for three sheet-bulk forming processes, namely local indentation, local ploughing and sheet upsetting. The results show the impact of the modelling capability for the void decrease under compressive stress states on the prediction performance. The predictions with Gurson model, which provides the void content reduction under compression, are closer to the experimental observations compared to the other models. The newly introduced fracture criterion provides fair results considering the reduced effort for the parameter identification.

Zusammenfassung

Die Blechmassivumformung unterscheidet sich durch die Anwendung von Massivumformprozessen auf Blechwerkstoffe von der klassischen Blechumformung. Obwohl das anfängliche Werkstück ein Blech ist, erfordert das Auftreten dreidimensionaler Spannungs- und Dehnungszustände eine Überprüfung der Materialmodelle und Grundannahmen von Blechumformprozessen. Unabhängig vom Umformvorgang (Blech- oder Massivumformung) sind die Abnahme der Tragfähigkeit eines Werkstoffs und die Ursache des endgültigen Bruchs mit den Poren-Mechanismen (Bildung, Wachstum und Zusammenschließen der Poren) verbunden. Die numerischen Vorhersagemodelle zielen bislang entweder nur auf die Ermittlung der Rissinitiierung oder auf die Poren- bzw. Schädigungsentwicklung bis zum Bruch sowie den Beginn des Risses ab.

In dieser Arbeit werden die notwendigen Methoden zur Werkstoffcharakterisierung für bestehende Schädigungsmodelle entwickelt, um Schädigung und Bruch während ausgewählter Blechmassivumformprozesse vorhersagen zu können. Zwei kontinuumsmechanische Schädigungsmodelle, die poröse Plastizität nach Gurson und das kontinuumsmechanische Schädigungsmodell nach Lemaitre, werden untersucht. Die Anwendbarkeit der Modelle wird evaluiert. Eine direkte Methode zur Werkstoffcharakterisierung für das Gurson-Modell und eine inverse Methodik zur Parameteridentifikation für das Lemaitre-Modell werden vorgestellt. Die Charakterisierungsexperimente werden erweitert, indem ein Scherschneidversuch berücksichtigt wird, um das Scherbruchverhalten über die Blechdicke und relevante Modellparameter identifizieren zu können.

Ein neues Bruchkriterium, welches sich sowohl auf Normal- als auch auf Scherbrüche bezieht, wird eingeführt. Dieses Kriterium beinhaltet die spannungszustandsabhängigen Größen der Kontinuumsmodelle, die von der Spannungstriaxialität und dem Lode-Winkel-Parameter abhängen. Eine vereinfachte Formel dieses Kriteriums ermöglicht eine schnelle Methodik zur Ermittlung von Modellparametern.

Die Vorhersageleistungen der Modelle werden für drei Blechmassivumformprozesse verglichen, für lokales Eindrücken, lokales Walzen und für das Blechstauchen. Die Validierungsuntersuchungen zeigen, dass die Berücksichtigung der Abnahme des Porenvolumens unter Druckspannungszuständen für die numerische Vorhersage entscheidend ist. Die Simulationen mit dem Gurson-Modell, welches die Verringerung des Porenvolumens unter Druckspannung ermöglicht, stimmen mit den experimentellen Beobachtungen überein. Das neu eingeführte Bruchkriterium liefert angesichts des reduzierten Aufwands für die Parameteridentifikation zufriedenstellende Ergebnisse.

Content

Symbols and Abbreviations

Symbols (Latin)

Symbol	Unit	Description
A	mm^2	Area
A_D	mm^2	Damaged area
A_T	mm^2	Total area
C_f	-	Generalized fracture threshold
D	-	Damage
D_{cr}	-	Critical damage
$\mathbf{d^p}$	-	Plastic rate of the deformation tensor
e	-	Error
E	MPa	Modulus of elasticity
$\dot{\mathbf{E}}$	-	Total strain rate
f_0	-	Initial void volume fraction
f_c	-	Void volume fraction at the incipient of coalescence
f_f	-	Void volume fraction at the final fracture
$\dot{f}^{g}_{hyd}$	-	Void volume fraction change due to hydrostatic stresses
$\dot{f}^{g}_{shr}$	-	Void volume fraction change due to shear stresses
f_N	-	Void nucleation relevant factor
$\dot{f}^{n}$	-	Void volume fraction change due to nucleation
f_v	-	Void volume fraction
$\dot{f}_v$	-	Void volume fraction change
F	N	Force, load
$\mathbf{F}$	-	Total deformation gradient
FR	-	Fracture risk
h	-	Crack closure parameter (Lemaitre model)
I_1	MPa	First invariant of stress tensor

Symbol	Unit	Description
I_2	MPa^2	Second invariant of stress tensor
I_3	MPa^3	Third invariant of stress tensor
J_1	MPa	First invariant of deviatoric stress tensor
J_2	MPa^2	Second invariant of deviatoric stress tensor
J_3	MPa^3	Third invariant of deviatoric stress tensor
k	MPa	Yield stress at pure shear
K	MPa	Strain hardening coefficient
k_w	-	Material parameter related to the void change under shear
L	-	Lode coefficient
l_h	mm	Inter-hole spacing
n	-	Strain hardening exponent
p	MPa	Pressure
q_1, q_2, q_3	-	Gurson model parameters
r	-	Lankford coefficient
$\bar{r}$	-	Mean value of the Lankford coefficients
r_h	mm	Radius of the hole
S	MPa	Lemaitre model parameter
S_N	-	Standard deviation
$\mathbf{s}$	MPa	Deviatoric stress vector
s_1, s_2, s_3	MPa	Deviatoric stress components
t	mm	Thickness
t_0	mm	Initial sheet thickness
t_f	mm	Sheet thickness at the fracture zone
u	mm	Displacement
v	mm/s	Velocity
V	mm^3	Volume
V_D	mm^3	Damaged (void) volume

Symbol	Unit	Description
V_T	mm^3	Total volume
w	mm	Width
w_f	mm	Specimen width at the fracture zone
w_0	mm	Initial specimen width
Y_0	MPa	Lemaitre model parameter
x, y, z	-	Coordinates in Cartesian system

Symbols (Greek)

Symbol	Unit	Description
α	-	Material parameter for the related fracture criterion
β	-	Lemaitre model parameter
$\dot{\gamma}$	-	Plastic multiplier
δ	-	Lemaitre model parameter
ε	-	Strain
ε_0	-	Material parameter for Swift hardening rule
ε_N^p	-	Equivalent plastic strain at the incipient nucleation
ε^p	-	Plastic strain
ε_t	-	Thickness strain
ε_w	-	Width strain
η	-	Stress triaxiality
κ	-	Lemaitre model parameter
μ_1, μ_2	-	Lamè's first and second parameters
ν	-	Poisson's ratio
ξ	-	Lode angle parameter
$\boldsymbol{\rho}$	MPa	Hydrostatic stress vector
ρ, s, θ	-	Coordinates in Haigh-Westergaard system
σ	MPa	Stress

Symbol	Unit	Description
$\sigma_1, \sigma_2, \sigma_3$	MPa	Principal stress components
σ_{eq}	MPa	Equivalent stress
σ_f	MPa	Flow stress (instantaneous)
σ_H	MPa	Hydrostatic stress
σ_R	MPa	Rupture stress
σ_{UTS}	MPa	Ultimate tensile strength
σ_y	MPa	Yield strength (initial)
τ	MPa	Shear stress
ϕ	-	Distortion
Φ	-	Dissipation potential
Ψ	-	State potential

Subscript

Index	Description
0	Initial value
1, 2, 3	First, second and third component
At	Atkins
av	average
Ay	Ayada
B	Brozzo
Ch	Christiansen
CL	Cockcroft-Latham
cr	Critical value
D	Damaged
eq	Equivalent
f	Fracture
F	Freudenthal
H	Hydrostatic

Index	**Description**
Hi	Hill
LH	Lou-Huh
mean	Mean value
n	Normal
N	Norris
NF	Normal fracture
Oh	Oh
os	Out-of-plane shear
Oy	Oyane
R	Rupture
RMS	Root mean square
s	Shear
SF	Shear fracture
t	Thickness
T	Total
UTS	Ultimate tensile strength
x, y, z	Components corresponding to the Cartesian coordinates
Y	Yield

Superscript

Index	**Description**
cr	Critical value
d	Damage
Dev	Deviatoric part
e	Elastic
eq	Equivalent
f	Fracture
Hyd	Hydrostatic part
p	Plastic

Index	Description
s	Shear

Operative symbols

Symbol	Description
$d(.)$	Total derivative
$\det(.)$	Determinant of a tensor/matrix
$\ln(.)$	Natural logarithm of a number
$\mathrm{tr}(.)$	Trace of a tensor/matrix
$\partial(.)$	Partial derivative

Abbreviations

Abbreviation	Description
2D	Two-dimensional
3D	Three-dimensional
AHSS	Advanced high strength steel
AISI	American Iron and Steel Institute
ALE	Arbitrary-Lagrangian-Eulerian
ASTM	American Society for Testing and Materials
BH	Bake hardening (steel)
CP	Complex phase (steel)
CT	Computer tomography
DIN	Deutsches Institut für Normung (German Institute for Standardization)
DP	Dual phase (steel)
FB	Ferritic-bainitic (steel)
FE	Finite element
FEM	Finite element modeling
FC	Fracture criterion
FLC	Forming limit curve

Abbreviation	Description
FR	Fracture risk
GEN	Generation
GTN	Gurson-Tvergaard-Needleman
GM	Gurson model
HF	Hot-formed (steel)
HR	Hole radius
HS	High strength
HSLA	High-strength low-alloy (steel)
IF	Interstitial free (steel)
ISO	International Organization for Standardization
LM	Lemaitre model
MS	Martensitic (steel)
NR	Notch radius
PE	Polyethylene
R	Radius
SBMF	Sheet-bulk metal forming
SEM	Scanning electron microscope
SRCL	Synchrotron radiation-computed laminography
SRCT	Synchrotron radiation-computed tomography
TEM	Transmission electron microscopy
TRIP	Transformation induced plasticity (steel)
TWIP	Twinning-induced plasticity (steel)