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Evaluation of Ductile Damage Criteria in Warm and Hot Forming Processes

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ABSTRACT

Ductile fracture process usually occurs due to the accumulation, growth, and combination of defects or cracks of material and is called ductile damage. Failure in materials can be predicted, using damage mechanics and damage criteria. On the other hand, most of the materials depended on the manufacturing process, are formed in warm or hot conditions so that; the temperature affects on the probable damage initiation. In this study first, a number of conventional hot forming processes of aluminum alloys such as forming process by tail gas, hydroforming, and blank forming with punch are simulated by finite element method and employing different damage criteria, and damage initiation in them is predicted. Then, the obtained numerical results are compared with the experimental results achieved from empirical experiments and validated. Finally, the damage criteria are classified based on the accuracy of the predicted results and the most appropriate criteria for predicting the damage in hot forming processes are introduced. It is concluded that Brozzo and Ayada damage criteria are the most proper criteria for predicting the damage initiation in the hot forming processes.

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1. INTRODUCTION

Aluminum-magnesium alloys are widely applied in the automobile, marine, and aerospace industries [1-4]. Although these alloys have many advantages, but their ductility at ambient temperature is very limited and they are formed by super-hot forming methods.

Material, forming process, and also possible damage are the factors which depend on temperature of the material and the process. Therefore, predicting the damage of the processes leads to producing high quality parts.

Naka and Yoshida studied the formability of 5083 aluminum alloy during the deep drawing process in a wide range of strain rates and different temperatures [5]. Hydroformability of aluminum tubes between room temperature to 300 °C was investigated by Lee et al. [6]. Besides, Yuan et al. analyzed the effect of temperature on the mechanical properties of aluminum tubes in tube hydroforming [7]. Free bulging test of aluminum alloy tubes at high temperature was empirically and numerically conducted by Kim et al. [8]. Moreover, Kulas et al. experimentally determined the forming limit diagram (FLD) of 5083 aluminum sheet in warm condition [9]. Study of aluminum tubes formability in hydroforming process was performed by Moslemi Naeini et al. [10]. Also, Wang et al. examined the formability and the failure of an aluminum alloy in the hot forming process [11]. Finally, applying the gas bulging forming process, FLD of 5083 aluminum sheet at a temperature of 500 °C was taken into account by Tagata et al. [12].

Due to the importance of simulation and preventing a lot of experiments to reach safe and sound products, research in this field is necessary and important. In this study first, geometry of some hot forming processes is made by the SolidWorks software and imported to the DEFORM-3D software. After assigning the mechanical and thermal properties, forming processes are simulated by employing different damage criteria and numerical results are obtained. Then, the numerical results are compared with experimental tests and validated. At the end, the most appropriate criteria for predicting the damage in hot forming processes are determined.

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2. DAMAGE CRITERIA

Recently, different criteria have been proposed for predicting the damage of materials which predict the damage phenomenon based on the related theory:

2. 1. McClintock (MC) Criterion It is clearly observed that fracture of ductile solids occur because of the large growth and coalescence of microscopic voids. This dependency guided McClintock to assume that fracture criterion can be written as [13]:

$$D=\int_0^{\bar{\varepsilon}_f}\left\{\begin{array}{l}\dfrac{\sqrt{3}}{2(n-1)}\sinh\left\{\dfrac{\sqrt{3}(1-n)}{2}\,\dfrac{(\sigma_a+\sigma_b)}{\bar{\sigma}}\right\}+\\ \dfrac{3}{4}\dfrac{(\sigma_a+\sigma_b)}{\bar{\sigma}}\end{array}\right\}d\bar{\varepsilon}_{pl} \qquad (1)$$

σ_a and σ_b are the principal stresses in the directions of the greatest and smallest void deformation, and $\bar{\varepsilon}_f$ is effective strain at failure moment. Also, $\bar{\sigma}$ and $\bar{\varepsilon}_{pl}$ are the effective stress and effective plastic strain, respectively. Symbol *n* represents the gradient of stress-strain logarithmic curve of the material. Moreover, *D* is damage variable which varies from zero (undamaged material) to one (fully ruptured material).

2. 2. Cockcroft & Latham (CL) Criterion Cockcroft and Latham suggested an alternative fracture criterion based on a critical value of the tensile strain energy per unit volume [14]:

$$D=\int_0^{\bar{\varepsilon}_f}\sigma_1\,d\bar{\varepsilon}_{pl} \qquad (2)$$

in which, σ_1 is the largest tension principal stress.

2. 3. Normalized Cockcroft & Latham (NCL) Criterion Oh et al. modified the CL damage model, using the dimensionless maximum principal stress [15]:

$$D=\int_0^{\bar{\varepsilon}_f}\frac{\sigma_1}{\bar{\sigma}}\,d\bar{\varepsilon}_{pl} \qquad (3)$$

2. 4. Rice & Tracy (RT) Criterion Rice and Tracy established a variational principle to characterize the flow field in an elastically rigid and incompressible plastic material containing an internal void or voids via the next equation [16]:

$$D=\int_0^{\bar{\varepsilon}_f}e^{\left[\frac{A\sigma_m}{\bar{\sigma}}\right]}d\bar{\varepsilon}_{pl} \qquad (4)$$

where, σ_m is hydrostatic stress and *A* is a material constant to be estimated by experiments, that in the simulations is usually considered equal to main model value of 1.5 [17].

2. 5. Freudenthal Criterion Freudenthal assumed that the onset and growth of cracks under the influence of a critical amount of plastic work is per volume unit based on effects of the effective stress on damage [18]:

$$D=\int_0^{\bar{\varepsilon}_f}\bar{\sigma}\,d\bar{\varepsilon}_{pl} \qquad (5)$$

2. 6. Brozzo Criterion Explicit dependency of both the largest (tension) principal stress σ_1 and the hydrostatic stress σ_m, was proposed by Brozzo et al. [19]:

$$D=\int_0^{\bar{\varepsilon}_f}\frac{2\sigma_1}{3(\sigma_1-\sigma_m)}\,d\bar{\varepsilon}_{pl} \qquad (6)$$

2. 7. Maximum Effective Stress (MES) Criterion This criterion predicts the damage by comparing the maximum effective stress and tensile yield strength:

$$D=\frac{\bar{\sigma}_{\max}}{\bar{\sigma}_{ult}} \qquad (7)$$

$\bar{\sigma}_{\max}$ and $\bar{\sigma}_{ult}$ respectively are the maximum effective stress and the ultimate tensile strength.

2. 8. Ayada Criterion Ayada et al. introduced another criterion as [20]:

$$D=\int_0^{\bar{\varepsilon}_f}\frac{\sigma_m}{\bar{\sigma}}\,d\bar{\varepsilon}_{pl} \qquad (8)$$

In the above criteria, damage variable, *D* is considered to be zero at the start of loading. Through the loading, this variable grows and when reaches to 1, complete failure of the material happens. However, in the numerical simulations for increasing the safety factor and margin, critical damage magnitude which is less than 1, is usually used. This value is experimentally determined to be 0.7 for aluminum material [21].

3. NUMERICAL SIMLATIONS

In this section, a number of high temperature forming processes are simulated and the numerical results are compared with the practical tests. For this aim, geometries are created by the SolidWorks software and imported to the DEFORM-3D software. Due to the symmetry and according to the geometry, a quarter or half of the model is simulated. Additionally, tools (die, punch, and holder) are defined as rigid parts. Simulations are carried out by applying mechanical and thermal properties, and boundary conditions, in accordance with the empirical tests.

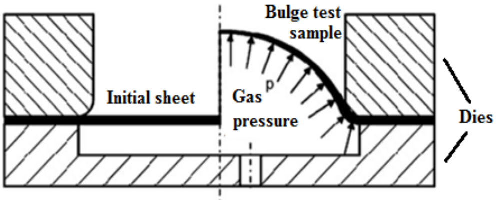


Figure 1. Schematic of bulging test [12]

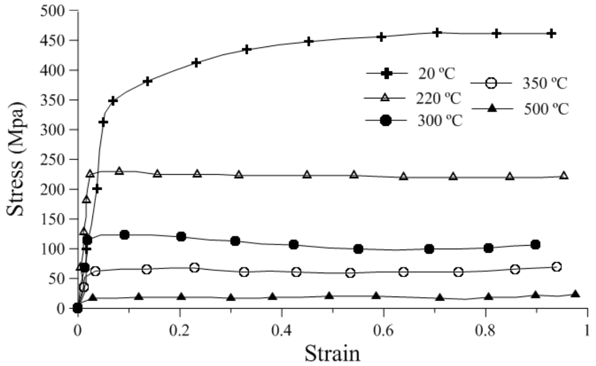


Figure 2. Stress-strain diagrams of 5083 aluminum at various temperatures [22]

TABLE 1. Mechanical and thermal properties of 5083 aluminum [23]

Properties	Value
Elasticity modulus (GPa)	70.3
Poisson's ratio	0.33
Thermal expansion coefficient (1/°C)	0.000026
Heat transfer coefficient (W/(m°C))	117
Heat capacity (J/(kg°C)	900

TABLE 2. Mechanical and thermal properties of 1050 aluminum [10]

Properties	Value
Elasticity modulus (GPa)	75
Poisson's ratio	0.3
Thermal expansion coefficient (1/°C)	0.000024
Heat transfer coefficient (W/(m°C))	220
Heat capacity (J/(kg°C)	904

3. 1. Bulging Test

Tagata et al. practically conducted hot gas bulging tests [12]. In this process, aluminum sheet is fully taken by the dies and the process is done. Figure 1 explicitly shows a schematic of the process [12].

In this study, the process of bulging test on 5083 aluminum sheet with a thickness of 1 mm at a temperature of 500 °C is considered and simulated. The simulations are repeated by four elliptical dies with diameter ratios of 1:1, 10:7, 10:6, and 10:4. The main circle diameter and the opening radius are 100 and 5 mm, respectively. Table 1 indicates the mechanical and thermal properties of the material [23]. Besides, Figure 2 denotes the stress-strain diagram of 5083 aluminum at various temperatures [22]. Utilizing the element deletion technique, numerical results and damage zones are achieved. Figure 3 reveals comparison between the predicted results based on the damage criteria and the results of practical experiments [12].

The comparison between the practical and numerical results represents that the Brozzo criterion has a more accurate prediction of damage and correctly predicts the location of damage. Other criteria predict no damage or definitely estimate a large zone of fracture. According to Ayada, NCL, and MES criteria, no failure is observed and RT, Freudenthal, CL, and MC criteria predict more damage in the workpiece.

3. 2. Hydroforming Test

The hydroforming process is applied in different industries such as aerospace, automotive, and military industries [24]. Naeini et al. empirically carried out the tube hydroforming tests [10]. Figure 4 displays a schematic of the tube hydroforming process [10].

In this research, the onset of damage in the tube hydroforming process as a one-side bulge and free bulging is investigated. The tube is made of 1050 aluminum with initial thickness of 1 mm, diameter of 24 mm at a temperature of 200 °C, and without axial feeding. Figure 5 and Table 2 indicate the die geometry, the mechanical and thermal properties of 1050 Aluminum [10], respectively. The stress-strain diagram of 1050 aluminum at different temperatures and the fluid pressure effect, required for the process are revealed in Figures 6 and 7 [10].

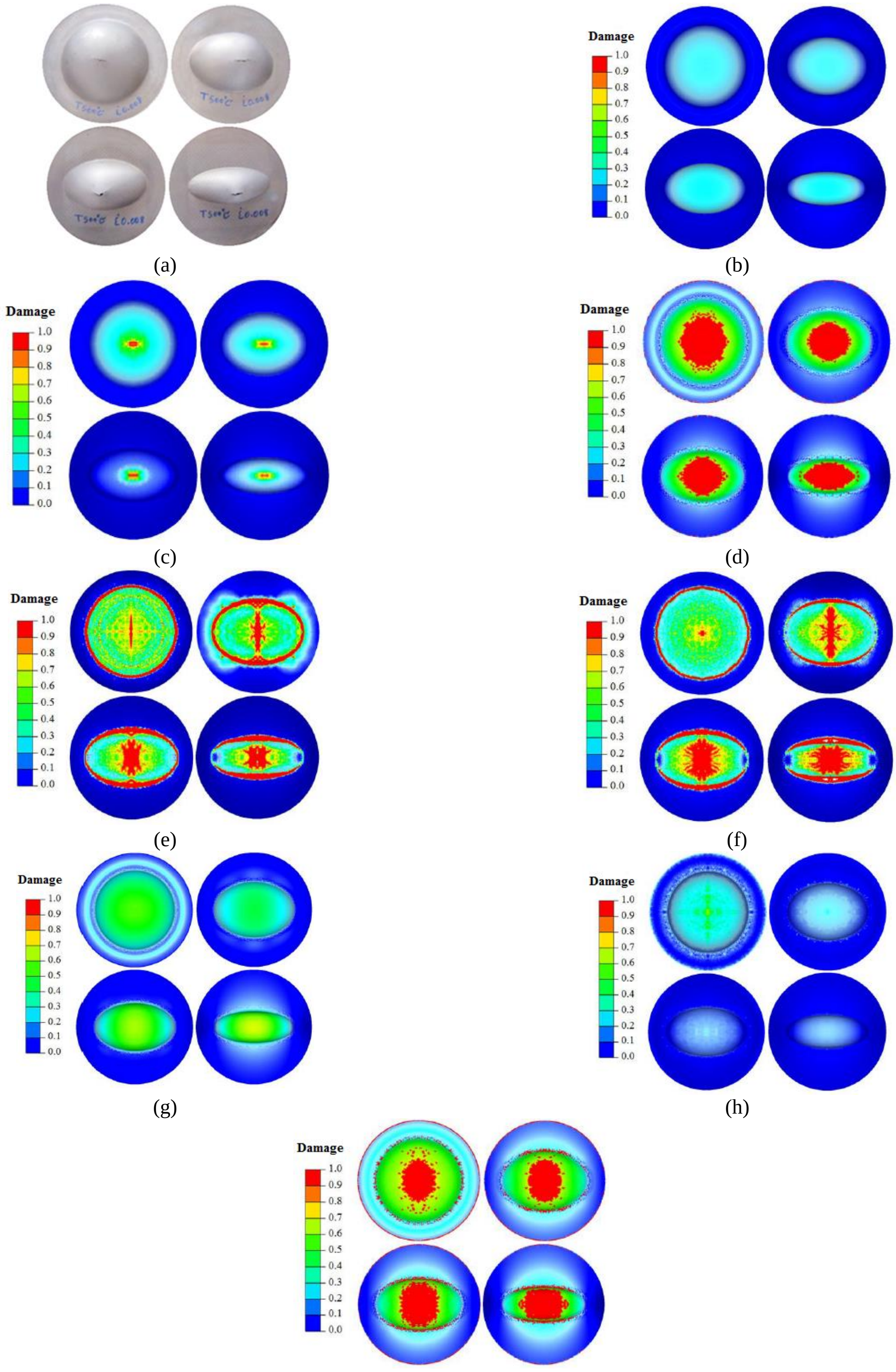
Meanwhile, the friction coefficient between the outer surface of the tube and the inner surface of the die with Coulomb friction law is assumed to be 0.1 [10].

Figure 8 illustrates comparison of the numerical results of damage criteria with the empirical results [10] in two different cases of free and one side bulging.

Comparison of the numerical and practical results approves that the RT and MC criteria have the best prediction of damage. In the other words, in the free bulging test, the criteria predict safe part, while in the one side bulge they predict the failure of the workpiece. Some criteria such as Ayada and NCL predict no damage and other criteria like Brozzo, Freudenthal, CL, and MES estimate damage for both cases.

3. 3. Forming by Punch

Wang et al. experimentally investigated sheet forming by punch tests [11]. Figure 9 schematically illustrates the process [5].



(a) (b)

(c) (d)

(e) (f)

(g) (h)

(i)

Figure 3. Results of bulging test: a) experimental test [12], b) Ayada, c) Brozzo, d) RT, e) Freudenthal, f) CL, g) NCL, h) MES, and i) MC

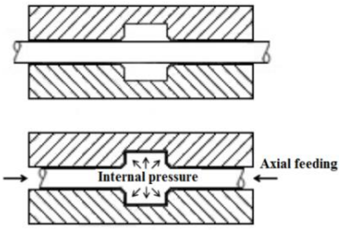


Figure 4. Schematic of tube hydroforming process [10]

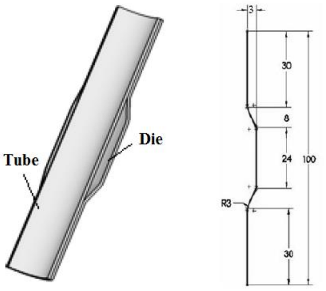


Figure 5. Hydroforming die geometry [10]

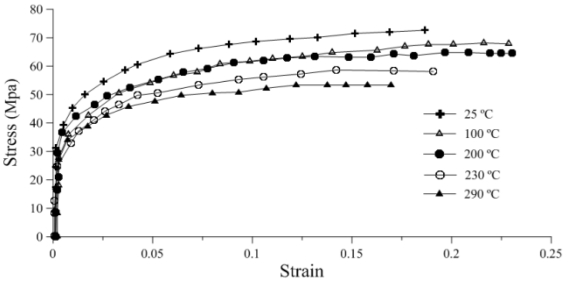


Figure 6. Stress-strain diagrams of 1050 aluminum at different temperatures [10]

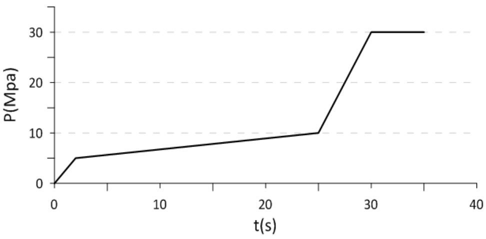


Figure 7. Applied internal pressure in the hydroforming process [10]

TABLE 3. Geometry of the sheet and punch

Title	Dimension
Sheet thickness (mm)	2
Diameter of sheet central hole (mm)	16
Diameter of spherical punch (mm)	80
Displacement of the punch (mm)	26

TABLE 4. Mechanical and thermal properties of 2024 Aluminum [23]

Properties	Value
Elasticity modulus (GPa)	73.1
Poisson's ratio	0.33
Thermal expansion coefficient (1/°C)	0.0000247
Heat transfer coefficient (W/(m°C))	121
Heat capacity (J/(kg°C)	875

TABLE 5. Accuracy summary of damage criteria predictions in hot forming processes

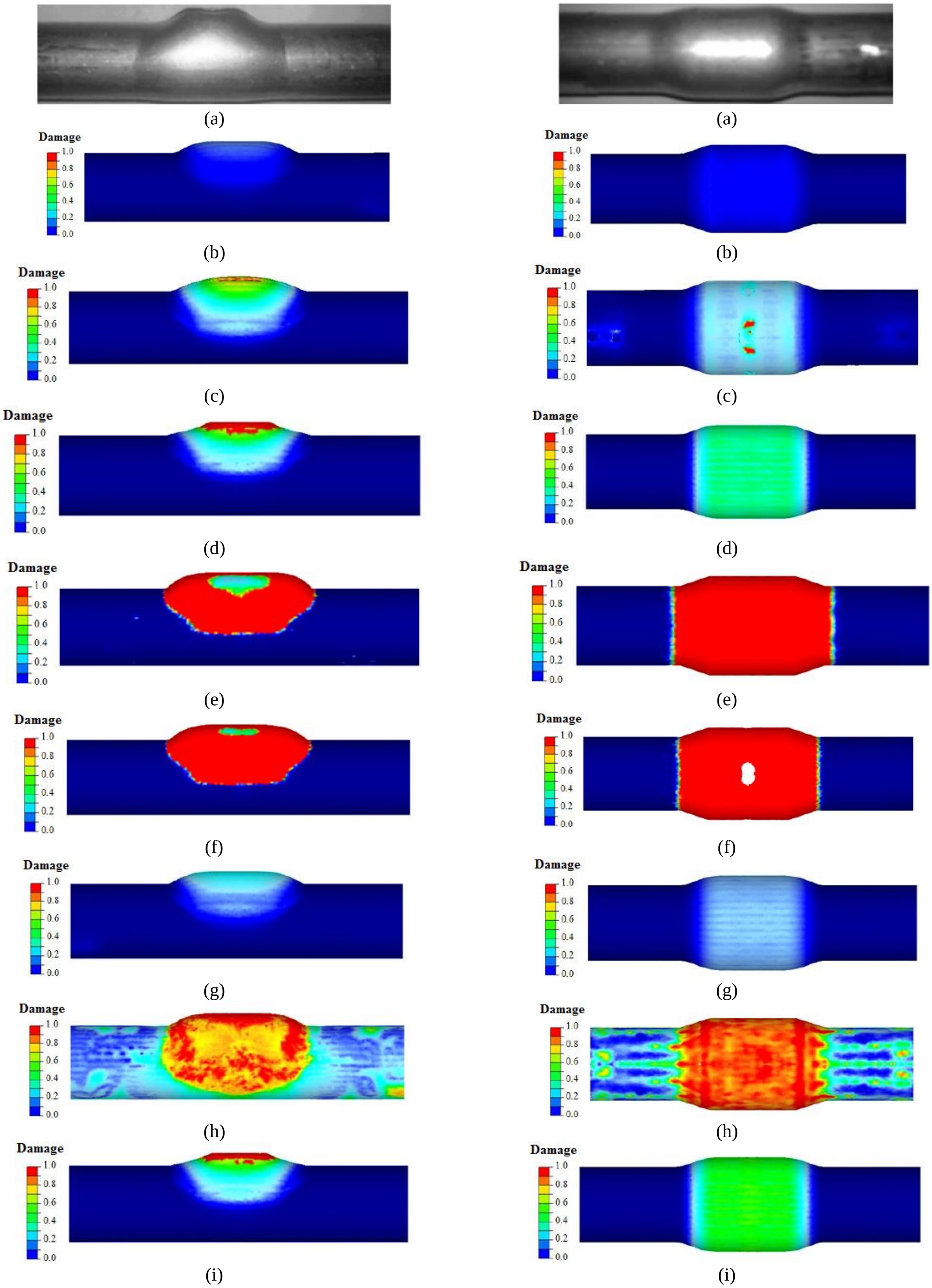
Criterion / Process	Bulging test	Hydroforming		Forming by punch	
	500 °C	Free	1-side	450 °C	493 °C
Ayada		***		***	***
Brozzo	***		***		**
RT	**	***	***		*
Freudenthal	*		*		**
CL	*		*		**
NCL		***			*
MES			*	***	
MC	**	***	***		*

In this section, formability of 2024 aluminum sheet, including a central hole at 450 and 493 °C is studied by a spherical shape punch. Table 3 represents geometry of the sheet and punch, while Table 4 indicates mechanical and thermal properties of the 2024 aluminum [22]. Also, Figure 10 depicts the stress-strain diagram of the material at various temperatures [11].

Speed of the punch is respectively considered to be 170 and 486 mm per second in the first and second case. The sheet is fixed by the holder to be stretched in the process. Furthermore, the friction coefficient between the sheet and other tools (holder and die) is assumed to be 0.2 [25]. Figure 11 compares the results of numerical simulations predicted by damage criteria and the practical results of the tests [11].

As comparison of the numerical and practical results confirms, the Ayada criterion is able to correctly predict damage in both cases. Except the MES criterion which predicts a safe and sound workpiece, other criteria estimate the ruptured parts in both cases.

The accuracy of the criteria are summarized in Table 5. The criteria are ranked from one to three stars, based on detection of the location and extensiveness of damage zone. Empty cells denote quite inappropriate prediction of the criterion.



(a) (a)
(b) (b)
(c) (c)
(d) (d)
(e) (e)
(f) (f)
(g) (g)
(h) (h)
(i) (i)

Figure 8. Results of hydroforming test: a) experimental test [10], b) Ayada, c) Brozzo, d) RT, e) Freudenthal, f) CL, g) NCL, h) MES, and i) MC

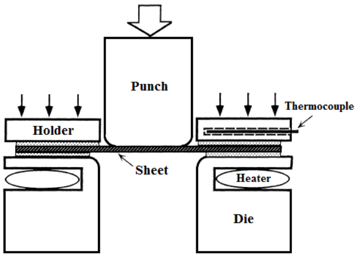


Figure 9. Schematic of forming with punch test at high temperature [5]

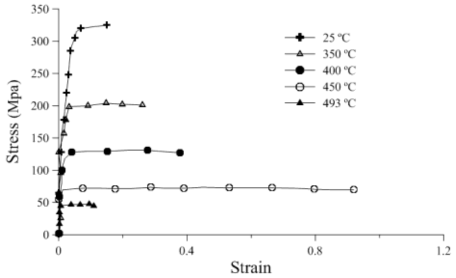


Figure 10. Stress-strain diagrams of 2024 aluminum at various temperatures [11]

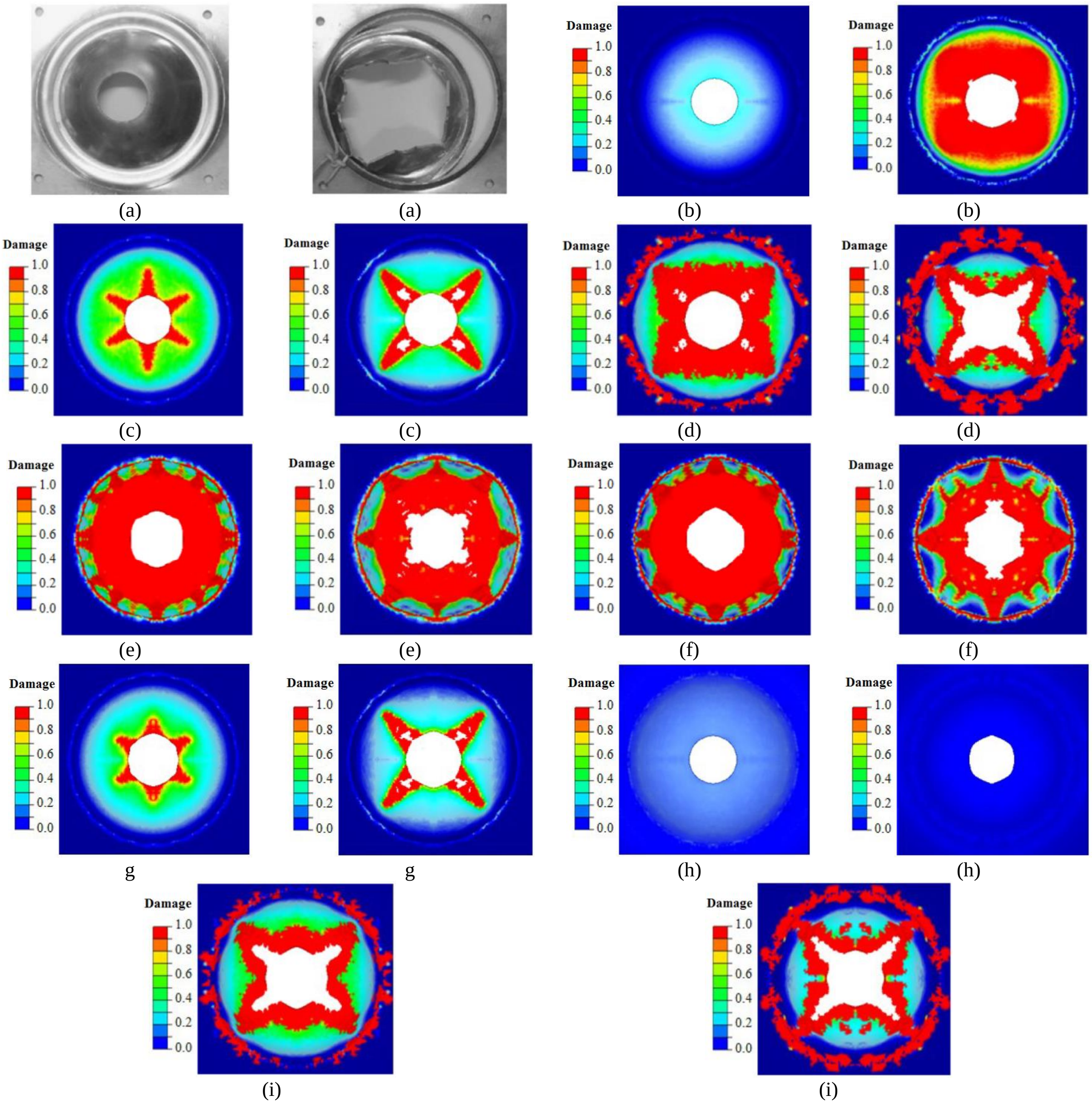


Figure 11. Results of forming by punch: a) experimental test [11], b) Ayada, c) Brozzo, d) RT, e) Freudenthal, f) CL, g) NCL, h) MES, and i) MC

4. CONCLUSIONS

In this research, prediction of damage in hot forming processes was carried out, employing various damage criteria. Comparing the results of numerical simulations with the experimental results in different tests signified that, the Ayada and Brozzo damage criteria have better and more accurate prediction of the damage initiation in hot forming processes. Although, in some of the tests, other criteria like RT and MC have also a good prediction, but, Ayada and Brozzo damage criteria generally show better performance, compared to the other criteria in prediction of damage in various processes.

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چکیده

فرآیند شکست نرم معمولا به‌علت جمع‌شدن، رشد و ترکیب عیوب یا ترک‌های ماده رخ‌داده و آسیب نرم نامیده می‌شود. با استفاده از مکانیک آسیب و معیارهای آسیب می‌توان شکست در مواد را پیش‌بینی نمود. از سوی دیگر بسیاری از مواد بسته به فرآیند ساخت و تولید، در حالت گرم یا داغ شکل‌دهی می‌شوند که در این صورت دما بر بروز آسیب احتمالی تاثیرگذار است. در این تحقیق ابتدا، تعدادی از فرآیندهای متداول شکل‌دهی گرم آلیاژهای آلومینیوم مانند فرآیند شکل‌دهی به‌کمک دمش گاز، هیدروفرمینگ و شکل‌دهی ورق با سنبه به‌روش اجزاءمحدود و به‌کارگیری معیارهای آسیب مختلف، شبیه‌سازی گردیده و بروز آسیب در آن‌ها پیش‌بینی می‌شود. سپس، نتایج عددی به‌دست آمده با نتایج عملی حاصل از آزمایش‌های تجربی مقایسه گردیده و اعتبارسنجی می‌شوند. در نهایت معیارهای آسیب بر اساس دقت نتایج پیش‌بینی شده طبقه‌بندی گردیده و مناسب‌ترین معیارها برای پیش‌بینی آسیب در فرآیندهای شکل‌دهی گرم معرفی می‌شوند. نتیجه‌گیری می‌شود که معیارهای آسیب بروزو و آیادا مناسب‌ترین معیارها برای پیش‌بینی بروز آسیب در فرآیندهای شکل‌دهی گرم می‌باشند.

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