DETERMINATION OF THE CRITICAL EFFECTIVE STRAIN OF AA1050-O ALLOY TO PREDICT NECKING UNDER COLD PLASTIC DEFORMATION

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The aim of this paper is to determine the strain hardening limit of aluminium alloy AA1050-O using the critical effective strain value as determined by the ductile fracture criterion proposed by Cockroft-Latham. A numerical simulation of the Erichsen cupping test using the Cockroft-Latham ductile fracture criterion was performed to predict the onset of necking. To verify the prediction of necking, an experimental procedure involving Erichsen necking tests until predicted necking, annealing, and subsequent Erichsen necking tests until sample destruction was performed. The simulation results predicted that necking would occur at a critical effective strain of 0.37, which corresponds to a critical Cockroft-Latham damage parameter of 0.53. By combining numerical simulations of the cold plastic deformation process with the experimental procedure and using the Cockroft-Latham ductile fracture criterion, the critical effective strain value of AA1050-O alloy can be determined.

KEYWORDS

hardening, annealing, ductile fracture, necking, cold plastic deformation

1 INTRODUCTION

The ability of materials to undergo plastic deformation is a critical aspect of metal forming, especially in the cold state. The manufacture of parts using cold forming technology often requires the design of numerous operations involving significant levels of deformation. In many cases, prior plastic deformation in the cold forming process results in hardening of the metal, which can lead to failure in subsequent forming operations. As a result, an intermediate heat treatment operation, usually annealing, must be used to restore plasticity and heal defects in the deformed metal [Kolmogorov 1977], [Bogatov 1984]. Therefore, determining the critical value of the cold deformation level at which a heat treatment operation must be applied and assessing the extent of plasticity recovery by heat treatment is a fundamental task. Kolmogorov V. L. addressed this task and developed a model aimed at quantifying the extent of defect healing due to heat treatment performed after cold plastic deformation [Bogatov 1984], [Kolmogorov 1995-1998]. Specifically, to assess the susceptibility to ductile fracture in materials undergoing cold plastic deformation, Kolmogorov V. L. introduced the cumulative damage model defined by the following formula:

$$D_K = \frac{\Lambda}{\Lambda_f\left(k,\mu_\sigma\right)} \tag{1}$$

where:

$\Lambda = \sqrt{3}\varepsilon_i$	- the degree of shear deformation,
ε_i	- the effective strain,
$k = \dfrac{\sigma_m\sqrt{3}}{\sigma_i}$	- the stress state index,
σ_m	- mean stress,
σ_i	- effective stress,
μ_σ	- the Lode-Nadai parameter,
$\Lambda_f\left(k,\mu_\sigma\right)$	- the degree of shear deformation at the moment of initial fracture.

This concept is commonly referred to as the ductility model of metal. When

$$D_K = 1,$$

the metal is destroyed, if

$$D_K = 0,$$

it corresponds to the undamaged material, and when

$$0 < D_K < 1,$$

the metal undergoes cold plastic deformation but has not reached the point of destruction. An experimental scheme is proposed which includes the following steps [Kolmogorov 1995], [Kolmogorov 1998]:

- Initially, the metal specimen is cold plastic deformed to a certain degree of deformation corresponding to a specified damage value D_{K1}
- Heat treatment of the deformed sample is carried out to restore plasticity and heal defects, then the total accumulated damage is reduced by ΔD_K.
- Cold plastic deformation of the specimen is carried out until destruction is achieved. This second plastic deformation process leads to an increase in the total accumulated damage by D_{K2}, and the total damage of the experimental process reaches a value of 1.

Thus, the healing of defects resulting from the initial cold plastic deformation is determined by equation:

$$\Delta D_K = D_{K1} + D_{K2} - 1 \tag{2}$$

Kolmogorov V.L. et al. performed a series of experiments to identify the ductility model

$$\Lambda_f(k,\mu_\sigma)$$

and the annealing-restored plasticity model ΔD_K for low carbon steel CT3 and austenitic steel 12X18H10T [Kolmogorov 1977], [Kolmogorov 1995-1998]. The results obtained are quite similar for both types of steel. Specifically, at the first cold plastic deformation, if the first damage D_{K1} is less than the critical value

$$D_{K*} = 0.2 \div 0.3,$$

the annealing process almost completely restores the plasticity of the metal, i.e.,

$$\Delta D_K = D_{K1}.$$

If the first damage D_{K1} exceeds the critical value

$$D_{K**} = 0.6 \div 0.7,$$

the annealing process restores plasticity only slightly, ΔD_K gradually decreasing to *0* as the first damage approaches 1. If

$$D_{K*} < D_{K1} < D_{K**},$$

the annealing process does not restore the plasticity of the material completely. Thus, according to Kolmogorov's model, for steel CT3 and 12X18H10T, cold plastic deformation processes carried out until the cumulative damage reaches a critical value

$$D_{K**} = 0.6 \div 0.7$$

requires a heat treatment operation to restore ductility. Although the damage accumulation model proposed by Kolmogorov V.L. is very suitable for failure prediction and damage level assessment in metal forming, several problems remain in determining the parameters of the ductility model $\Lambda_f(k,\mu_\sigma)$. This is due to the requirement for numerous experiments and accurate measurements [Kolmogorov 1970-1977], [Bogatov 1984]. In addition, the specific determination of the two critical damage values, D_{K*} and D_{K**}, has not yet been established. In addition, insufficient attention has been paid to materials other than steel, such as non-ferrous metals and alloys.

Meanwhile, a number of other ductile fracture criteria are commonly used to predict failure in metal forming, including [Freudenthal 1950], [Cockroft-Latham 1968], normalized Cockroft-Latham [Oh 1979], [Oyane 1980] and others. These ductile fracture criteria are usually formulated as integral functions, dependent on stress and effective strain:

$$C = \int_0^{\bar{\varepsilon}_f} f(\sigma)\, d\bar{\varepsilon} \tag{3}$$

where:

$f(\sigma)$	- the stress dependent function,
$\bar{\varepsilon}$	- effective plastic strain,
ε_f	- effective strain at the moment of fracture,
C	- the critical damage value to the criterion (considered a material constant).

Among these ductile fracture criteria, the Cockroft-Latham criterion is commonly used in predicting metal forming damage due to its convenience and simplicity in determining its critical value [Cockroft-Latham 1968], [Myint 2017], [Schowtjak 2017], [Takada 2015], [Stefanik 2011], [Bjorklund 2013], [Hoan 2024]. It is expressed according by the formula:

$$C_{CL} = \int_0^{\varepsilon_f} \sigma_1\, d\bar{\varepsilon} \tag{4}$$

where:

C_{CL}	- critical damage of the Cockroft-Latham criterion (MJ/m^3),
σ_1	- maximum principal stress (MPa),
$\bar{\varepsilon}$	- the effective strain,
ε_f	- fracture strain (calculated from the initial and final surfaces on the neck).

This criterion implies that ductile fracture depends on both shear stress, which induces plastic deformation and work hardening, and tensile stress. In addition, fracture depends on both the imposed stresses and the developed strain [Cockroft-Latham 1968].

O. Björklund et al. expressed the maximum principal stress σ_1 as a function of hydrostatic pressure, the second invariant of stress deviation and the Lode angle in addition to the effective plastic strain. The critical damage values for the high-strength steel Docol 600DP and the ultra-high-strength steel Docol 1200M were determined and calibrated by experiments and numerical simulations, including simple in-plane shear and plane strain tests. The results of the evaluation of Nakajima tests demonstrated that the Cockroft-Latham criterion predicts tensile fracture with high accuracy [Bjorklund 2013]. The material constant C_{CL} is often determined by combining a cold plastic deformation experiment, which involves determining the moment of failure, with a numerical simulation that extends to that moment of failure using the Cockroft-Latham ductile fracture criterion. The critical value C_{CL} is then determined as the maximum damage value obtained in the simulation. The location of the finite element in the numerical simulation corresponding to the maximum damage value indicates where the failure is predicted to occur. This method of determining the critical damage value is now widely used [Myint 2017], [Hoan 2024], [Zhag 2016], [Pater 2019]. According to the Cockroft-Latham, the level of damage development during cold plastic deformation is controlled by the accumulated damage parameter, which can be represented as [Takada 2015], [Hoan 2024], [Takuda 1999], [Jeysingh 2008], [Park 2020]:

$$D_{CL} = \frac{1}{C_{CL}} \int_0^{\bar{\varepsilon}} \sigma_1\, d\bar{\varepsilon} \tag{5}$$

where D_{CL} - the Cockroft-Latham damage parameter, with no units. In the course of cold plastic deformation until failure occurs, the value D_{CL} gradually increases from 0 to 1.

At present, the Cockroft-Latham ductile fracture criterion is mainly used to predict failure in metal forming processes [Takuda 1999], [Bjorklund 2013], [Hoan 2024], i.e.

$$D_{CL} = 1.$$

However, as Kolmogorov V.L. stated earlier, there is a critical value of the Cockroft-Latham damage parameter, referred to as D_{CL**}, before the metal is destroyed. If the cold plastic deformation process is carried out with the value of the damage parameter exceeding this critical value, the plasticity restored by the heat treatment operation will be almost negligible.

Tran Duc Hoan et al. set the critical value of the Cockroft-Latham damage criterion for aluminium alloy AA1050-O to C_{CL}=61,49 MJ/m^3 and predicted the value of the Cockroft-Latham damage parameter at which neck may be formed. However, this has not yet been analysed in detail or evaluated experimentally [16]. Therefore, in this study, the Cockroft-Latham damage parameter was analysed and evaluated to predict necking by numerical simulation of the Erichsen cupping test using the Cockroft-Latham ductile fracture criterion. An experimental procedure similar to the approach used by Kolmogorov V.L. was carried out, involving the performance of the Erichsen cupping tests until the predicted necking occurs, followed by annealing and subsequent Erichsen cupping tests until the specimen is destroyed. The results of the experimental procedure confirmed the damage prediction and determined the critical value of the Cockroft-Latham damage parameter D_{CL**} for aluminium alloy AA1050-O. This methodology facilitates the determination of the corresponding critical effective strain for AA1050-O alloy during the cold forming process.

1 METHODS

The Erichsen cupping test is commonly used to assess the formability of plate materials. In this test, the sample is clamped firmly between the blank holder and the die while a 20 mm diameter hemispherical punch moves at a constant speed and deforms the sample. After the sample has started to be destroyed, the punch stops and returns to its initial position. The indentation depth in the sample serves as a characteristic value for the formability of the sheet material, often referred to as the Erichsen Index (EI). In this study, a set of Erichsen indentation test tools was used to conduct the experiments. These tests were conducted at the Metal Forming Laboratory at Le Quy Don Technical University using the Erichsen testing machine model 111. Commercial AA1050-O alloy sheets with a diameter of 90 mm and a thickness of 2.0 mm were used for the samples. Five AA1050-O aluminium alloy sheet samples were tested under the condition that the speed of the hemispherical punch was 4 mm/s. The EI values obtained were 10.5 mm, 10.4 mm, 10.4 mm, 10.4 mm and 10.8 mm, resulting in an average EI value of 10.5 mm. A numerical simulation of the Erichsen cupping test process was performed using the Cockroft-Latham criterion combined with experience to determine critical value of the Cockroft-Latham damage parameter D_{CL**} and the EI_{neck} neck appearance moment for the AA1050-O aluminium sheet. The numerical simulation model was performed based on the finite element method using Deform 2D software with the geometric model illustrated in Figure 1. In this simulation, a material model according to Swift's law

$$\sigma = K\left(\varepsilon_0 + \varepsilon\right)^n$$

where: K=132 Mpa, $\varepsilon_0 = 0{,}0005$ and n=0,285 was used [22].

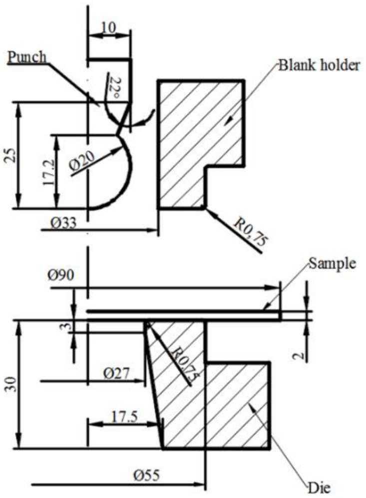


Figure 1. Numerical simulation model for Erichsen test

In the simulation, the components of the moulding, including the blank holder, punch, and die, were considered as rigid bodies. The simulation conditions were set to replicate the conditions the Erichsen cupping test and included specific values: a punch speed of 4.0 mm/s and a blank holder force of 10000 kN. In addition, the coefficient of friction between the sample and the tools was set at 0.12 and a total of 7200 finite elements were used for the sample. The simulation was terminated when the indentation depth of the sample reached an average EI value of 10.5mm, which is consistent with the experimental findings. The results of the numerical simulation are analysed to predict the formation of necks and to evaluate the evolution of the Cockroft-Latham damage parameter during the testing process.

2 SIMULATIONS

The results of the numerical simulation of the Erichsen cupping test process at an indentation depth of 10.5 mm using the Cockroft-Latham ductile fracture criterion are shown in Figure 3. The failure location was predicted at point P1, where the Cockroft-Latham critical damage value of C_{CL} = 61.49 MJ/m^3. Based on these simulation results, plots were constructed showing the Cockroft-Latham damage parameter and the effective strain at point P1, as a function of the indentation depth (EI) during plastic deformation of the sample until failure, as shown in Figure 4.

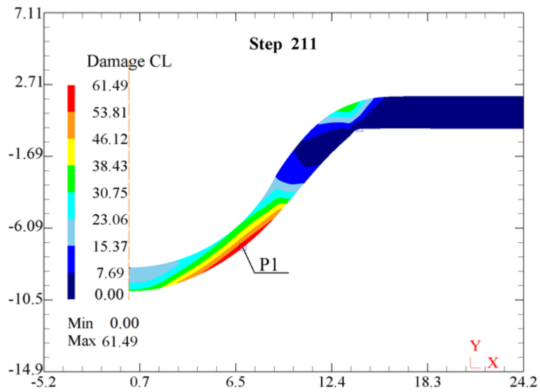


Figure 2. Prediction of failure of AA1050-O alloy using Cockroft-Latham criterion

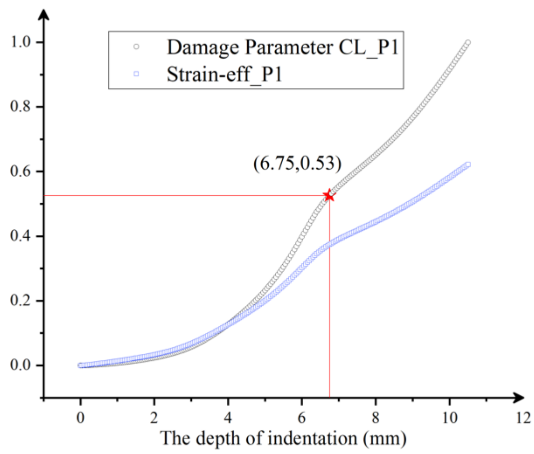


Figure 3. Dependency graph of the Cockroft-Latham damage parameter and the effective strain at point P1 on the depth of indentation

It can be observed that the value of the Cockroft-Latham damage parameter gradually increased from 0 to 1 with increasing impression depth from 0 to 10.5 mm. From the marked point on the graph corresponding to 0.53, the Cockroft-Latham damage parameter displayed a more rapid increase towards 1. At this marked point, an indentation depth of 6.75 mm was measured, indicating the onset of indentation. A value of 0.53 may represent the critical value $D_{CL^{**}}$ for the Cockroft-Latham damage parameter. In addition, the effective strain showed a similar trend. The effective strain increased during plastic deformation of the sample until failure. Simultaneously, the Cockroft-Latham damage parameter, which characterizes the progress of the ductile fracture process, increased at a higher rate.

A relationship between the Cockroft-Latham damage parameter and the effective strain was found as shown in Figure 5. The third-order polynomial function describing this dependence was determined using the formula:

$$D_{CL} = 0.75249\bar{\varepsilon} + 2.27122\bar{\varepsilon}^2 - 1.47849\bar{\varepsilon}^3 \quad (6)$$

Of particular importance was the point at which the Cockroft-Latham damage parameter reached a critical value of 0.53, which coincides with an effective strain value of 0.37. Moreover, equation (6) facilitated the determination of the value of the Cockroft-Latham damage parameter when the effective strain was known. Furthermore, it allowed to predict the evolution of during cold plastic deformation of AA1050 aluminium alloy.

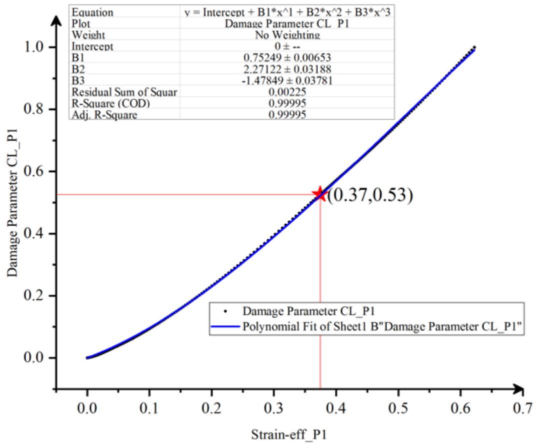


Figure 4. Dependency graph of the Cockroft-Latham damage parameter on the effective strain at point P1

The predicted position of the neck, determined by the Cockroft-Latham criterion, was characterized by a maximum value of instantaneous damage, corresponding to a indentation depth of 6.75 mm, as shown in Figure 6. The predicted H_{neck} distance was 4.82 mm. It is noteworthy that the most significant thinning of material thickness occurs at this position, corresponding to section A in Figure 6 with a thickness value of 1.57 mm. Further tests will play a key role in clarifying the expected position of the neck, evaluating the degree of plasticity recovery by annealing and finally determining the critical value of the Cockroft-Latham damage parameter for AA1050-O aluminium alloy.

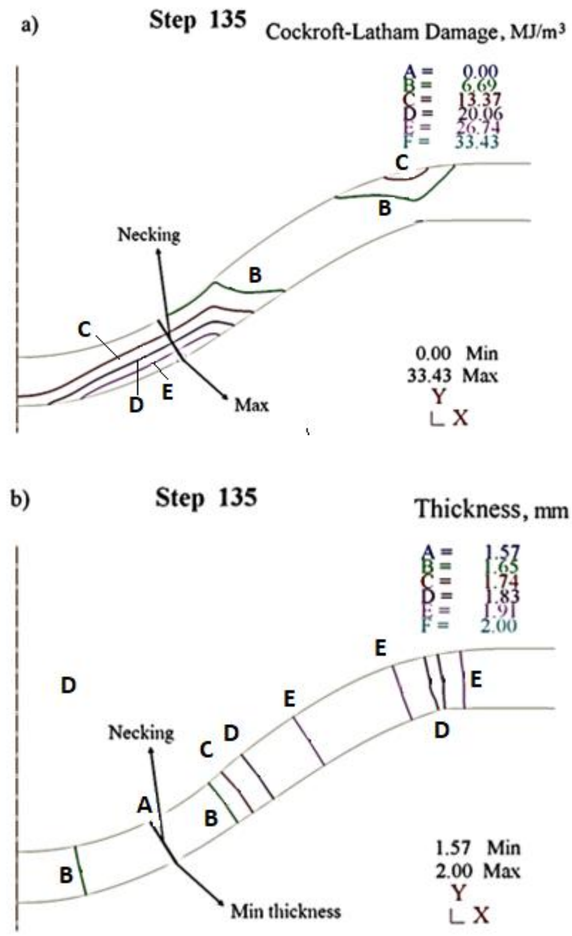


Figure 5. Predicted location of necking according to Cockroft-Latham criterion

3 EXPERIMENTAL

An experimental procedure was performed involving cold plastic deformation of the samples (step 1), annealing (step 2), and plastic deformation until sample was destroyed (step 3). In step 1, the Erichsen cupping tests were performed until the predicted EI_{neck} point. Subsequently, the thickness distribution of the deformed samples from step 1 were examined to determine the thinnest position corresponding to the necking location. At the same time, in step 2, annealing of the samples from step 1 was performed using Nabertherm LH 120/13 Chamber Furnaces to restore plasticity and heal defects caused by previous cold plastic deformation. Finally, in step 3, the annealed samples were subjected to the Erichsen cupping test until destruction. After this experimental procedure, the final samples exhibited an indentation depth value, referred to as EI_{crack}. By comparing this value with the initial average EI value of 10.5 mm measured during the Erichsen cupping tests, the degree of plasticity recovery by annealing and the critical value of the Cockroft-Latham damage parameter were evaluated.

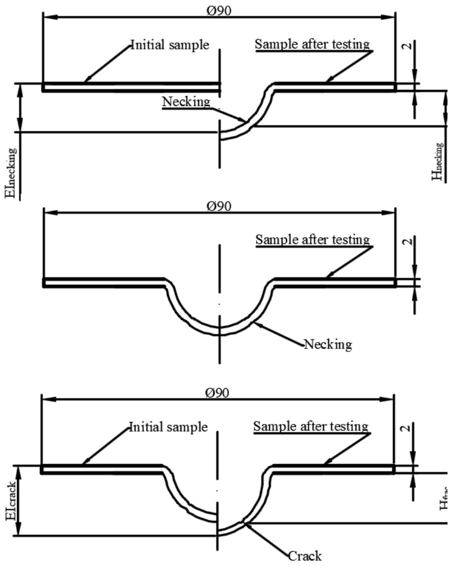


Figure 6. The experimental procedure

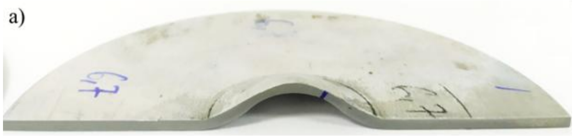
The experimental procedure is described in Figure 2. In step 1, Erichsen cupping tests were performed on four samples of the above dimensions, achieving the predicted throat depth from the simulation results. The tests were performed at a punch travel speed of 4.0 mm/s. Two of the samples from step 1 were cut in half to investigate the minimum thickness. For aluminium alloy AA1050, annealing to restore plasticity was performed at 350 °C with a holding time of 60 min [23]. Then the remaining two samples were annealed. In the third step, Erichsen flask tests were performed on the annealed samples at the same punch movement speed as in the first step until destruction occurred.

The results of the experimental procedure demonstrate that the prediction of necking by numerical simulation was confirmed. The value of the Cockroft-Latham damage parameter corresponding to the critical effective deformation was identified as the critical limit that requires heat treatment to be performed in order to allow plastic deformation in subsequent operations.

3.1 Results of the experiment

The Erichsen cupping tests were run until the indentation depth reached EI1 = 6.7 mm and EI2 = 6.8 mm, exactly matching the indentation depth predicted by simulation, EI_{neck} = 6.75 mm. The position of the neck was determined by the minimum thickness along the cross-sectional axis of symmetry shown in Figure 7. For the EI1 = 6.7 mm sample, a neck position with $H1_{neck}$ = 4.76 mm was found, which corresponds to a thickness of 1.53 mm. For sample EI2 = 6.8 mm, the neck position is found at $H2_{neck}$ = 4.84 mm, which corresponds to a thickness of 1.50 mm. Taking the experimental results as average values obtained: $H_{expneck}$ = 4.85 mm; thinnest thickness is 1,515 mm. This result is in considerable agreement with the prediction based on the Cockroft-Latham criterion in Figure 6.

a)



b)

Figure 7. Necking position for samples with depth of indentation EI1 =6.7mm(a) and EI2=6.8mm (b)

Two samples, designated EI1 and EI2, were annealed and then Erichsen cupping tests were continued until the sample failed. The corresponding EI_{crack} values were $EI1_{crack}$ = 10.83 mm and $EI2_{crack}$ = 10.60 mm, as shown in Figure 8.

a) EI2=6.8 mm   b) EI1=6.7 mm

Figure 8. Samples after experimental procedure

It was found that the annealing process in the intermediate period restored plasticity insignificantly and healed defects caused by previous plastic deformation. This is evident when comparing the average EI value of 10,5 mm (plastic deformation without annealing) with the samples subjected to cold plastic deformation with intermediate annealing, which showed approximately the same indentation depth values. Specifically, the EI1 sample increased by approximately 3 % and the EI2 sample by approximately 1 % compared to the 10,5 mm value. This finding is consistent with the ductile fracture mechanism of metals under cold plastic deformation as explained by the theory of continuous damage mechanics [Kolmogorov 1977-1998], [Yoon 2005], [Mhedhbi 2017], [Kachanov 1999], [McClintock 1968], [Lemaitre 1968], [Kolmogorov 1996], [Smirnov 2012], [Testa 2017].

Accordingly, the process of ductile fracture of metals occurs in three phases:

Nucleation stage: cavities usually form around the second phase particles or inclusions at the interface between the particles and the matrix. It is assumed that cavities nucleate in a given material either at a critical stress or at a critical strain threshold. Cavity initiation occurs when the plastic strain reaches a critical value, and the rate of cavity formation depends on the equivalent plastic strain.

Growth phase: microvoids grow, gradually enlarge and then merge into macrovoids, with the formation of new microvoids continuing throughout the plastic deformation process. As the deformation progresses, the effect of stress concentration, which influences the formation of voids, increases. The macrovoids reach a stabilisation point after increasing to a certain size, which requires further plastic deformation in order for ductile fracture to occur. The dilation of voids induced by the triaxiality of stresses represents the bulk growth of voids.

The coalescence phase: Cavity growth is followed by cavity coalescence, which is the final phase prior to the initiation of ductile fracture, in which cavity coalescence also manifests itself in two forms: cavity ligament and shear. Analogous to the mechanisms governing cavity growth, the progression of internal neck and shear depends on factors such as triaxiality and shear stress.

Simultaneously with the formation and development of microvoids and macrovoids, the healing process of these defects can take place. Increasing temperature and hydrostatic compressive stress, as well as alternating tensile and compressive strain, stimulate the healing of these defects [Kolmogorov 1977-1998]. This theory is consistent with the findings reported by Kolmogorov V. L., according to whom the initial increased cold plastic deformation, which marks the transition from the nucleation to the growth stage, determines the critical damage value for microvoids, denoted as D_{K*}. Similarly, the transition from the growth to the coalescence stage determines the critical damage value for macrovoids, denoted as D_{K**}.

4 DISCUSION

In this study, the critical value of the Cockroft-Latham damage parameter, D_{CL**} for aluminium alloy AA1050-Owas quantitatively determined through numerical simulation and validated by experimental testing. The simulation of the Erichsen cupping test predicted that necking would occur at an indentation depth of 6.75 mm, corresponding to D_{CL**} = 0.53 and an effective strain of 0.37. These values were confirmed by the experimental procedure, in which the necking positions of samples deformed to EI = 6.7 mm and 6.8 mm showed minimum thicknesses of 1.53 mm and 1.50 mm, respectively-closely matching the simulated value of 1.57 mm.

To verify whether heat treatment could restore ductility beyond this critical deformation, the deformed samples were annealed at 350 °C for 60 minutes and re-tested. The EI values after annealing and reloading (EI_{crack}) were 10.83 mm and 10.60 mm, indicating only marginal increases of ~3% and ~1% relative to the baseline average EI of 10.5 mm. This suggests that once D_{CL**} exceeds ~0.53, the material's capacity to recover plasticity through annealing becomes negligible.

The observed behavior aligns with damage accumulation theory in cold plastic deformation: as deformation progresses and D_{CL**} increases, the nucleation and growth of microvoids become dominant. Once coalescence begins, damage becomes irreversible, and plasticity cannot be effectively restored even after heat treatment. The effective strain of 0.37, determined from simulation and validated experimentally, can therefore be used as a threshold for pre-annealing decisions in forming processes involving AA1050-O.

This study contributes a validated methodology for identifying critical deformation limits in aluminium forming. By integrating simulation with minimal experimental trials, the critical effective strain and damage parameter values can be determined, guiding process design to avoid excessive cold deformation that would render annealing ineffective.

4.1 Comparisons with Existing Studies

The critical damage value D_{CL**} ≈ 0.53 and corresponding effective strain ε ≈ 0.37 identified in this study for AA1050-O under biaxial loading conditions are in agreement with damage evolution trends reported in earlier works. For instance, Hoan (2024) determined a critical Cockroft–Latham value C_{CL} = 61.49 MJ/m³ through inverse analysis and numerical simulations for a similar alloy, but did not validate this threshold experimentally or evaluate post-deformation recovery. Likewise, studies such as those by Bjorklund (2013) and Myint (2017) used Nakajima and punching tests to localize fracture initiation in high-strength steels, but did not address the relationship between critical damage and annealing behavior.

Walczuk-Gągała et al. (2020) studied the accumulation of damage in AA1050A using tensile, compression, and rotary compression tests. They reported normalized Cockroft–Latham damage values ranging from 0.384 to 1.368 depending on the stress state. However, their evaluation was based solely on the appearance of fracture, without considering any post-deformation heat treatment. In contrast, our study not only establishes a comparable damage threshold under biaxial stress, but also shows that once this threshold is exceeded, annealing at 350 °C results in minimal recovery in ductility—less than 3% increase in the EI index.

This behaviour is further clarified when compared to the work of Moufida et al. (2017), who investigated cold rolling and annealing of AA1050. Their results showed that samples deformed by 66% thickness reduction ($\bar{\varepsilon}$ ≈ 1.10) regained significant ductility—up to 36% elongation—after annealing at 350 °C for 1 hour. The key distinction lies in the stress state: cold rolling induces compressive stresses in all three principal directions, particularly through the sheet thickness due to roll pressure. This triaxial compressive condition promotes stable plastic flow, delays void nucleation, and enhances the material's ability to recover during post-deformation annealing.

By contrast, the Erichsen cupping test imposes a biaxial tensile stress state at the dome region, which significantly increases local stress triaxiality. This promotes early void nucleation and coalescence, leading to irreversible damage that annealing cannot effectively repair—even at moderate effective strains. Therefore, it is not only the magnitude of strain but also the nature of the stress path that governs the material's capacity for ductility recovery.

Together, these comparisons emphasize that the recovery of ductility in AA1050 is strongly dependent on the prevailing stress state during deformation. The present study contributes a validated framework linking the Cockroft–Latham damage threshold to annealing response, offering practical guidance for safe deformation limits in aluminum sheet forming applications.

5 CONCLUSIONS

The determination of the critical effective strain for AA1050-O alloy in predicting the formation of necks during cold plastic deformation was achieved by numerical simulation of the Erichsen cupping test using the Cockroft-Latham ductile fracture criterion. The simulation accurately predicted the formation of the necks at an indentation depth of 6.75 mm, which allowed a critical Cockroft-Latham damage parameter of 0.53 to be determined, corresponding to a critical effective strain of 0.37.

The experimental procedure consisted of three steps: performing Erichsen cupping tests to indentation depths of EI1 = 6.7 mm and EI2 = 6.8 mm; annealing the samples at 350 ºC for 60 minutes; and performing Erichsen cupping tests until the sample was destroyed. The observed notch positions were consistent with the simulation results, confirming the accuracy of the Cockroft-Latham criterion in predicting neck formation.

The results further showed that when the cold plastic deformation reaches the critical value of effective strain of 0.37 for AA1050-O alloy, the subsequent heat treatment process is hardly able to restore the plasticity and heal the defects caused by the previous plastic deformation. Thus, by combining a limited number of experiments and numerical simulations of the Erichsen cupping test, the critical effective strain value for AA1050-O alloy was effectively determined using the Cockroft-Latham ductile fracture criterion.

In addition, the findings highlight the significant influence of the stress state during deformation. While compressive stress states typically lead to more uniform deformation and enable better recovery after annealing, biaxial tensile stress, such as that present in cupping test -promotes higher stress triaxiality and accelerates irreversible damage.

The proposed approach, combining limited experiments and numerical simulations based on the Cockroft–Latham criterion, offers a practical framework for identifying safe deformation limits in aluminum sheet forming, and supports the optimization of forming processes to avoid premature failure.

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