Equivalence between Localization Criteria and Fracture Criteria as Forming Limit in Failure Evaluation for 7xxx Series Aluminum Alloy Sheets

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Abstract. The equivalence between the localization criteria and the fracture criteria was validated as a forming limit for the proper prediction of failure induced by severe strain localization in the two-step hybrid forming process of 7xxx series aluminum alloy sheets at the elevated temperature. In the previous researches, an extensive and systematic method combined with sophisticated material characterization had been revisited as the localization criterion to estimate the onset of the failure without any fracture criteria. As for the fracture criteria, a deformation path and effective strain-rate sensitive fracture criterion was utilized. In the event of failure occurrence with abrupt strain localization, which has been traditionally known as the localization criteria dominant case, the fracture criteria can replace the localization criteria as a forming limit.

1. Introduction

As an indicator of the deformation limit of material without failure, the forming limit diagram (FLD) has been extensively utilized in automobile and aerospace industry. The previous studies showed that FLD is a combination of fracture criteria as material properties and localization criteria as the consequence of the mathematics derived from constitutive equations in boundary value problem [1, 2]. The fracture criteria which define the occurrence of fracture have been investigated by many researchers [3-6]. The localization criteria, meanwhile, are widely utilized for the practical reason. It has been studied that the sophisticated material characterization considering hardening deterioration and the strain-rate sensitivity is crucial for the accurate prediction of failure phenomenon induced by strain localization without fracture criteria [2, 7-9].

In this study, the equivalence of the fracture criteria and the localization criteria was validated in the two-step hybrid forming process of 7xxx series aluminum alloy sheets at elevated temperature. An isotropic hardening law composed of the work hardening, the hardening deterioration, and the strain-rate sensitivity coupled with the isotropic yield stress function and the associated flow rule was used. Due to the importance of the strain-rate sensitivity, a simple strain-rate sensitive fracture criterion restrictively depending on deformation path was developed and exploited as a mean of fracture prediction. The previous prediction by localization criterion was revisited and compared with the results of the prediction by a fracture criterion validating the equivalence between the fracture criteria and the localization criteria in the research.
2. Material Characterization
The 7075 aluminum alloy sheets (Al-Zn-Mg-Cu) in peak age temper T6 with 2.0mm were utilized. In order to obtain the elastic properties and plastic properties at 400°C and 470°C, the impulse excitation of vibration and uniaxial tensile test were performed. The detail experiment description and results are referred in the previous study [10]. An extensive and systematic method in the previous researches to foresee the initiation of failure with strain localization as the application of the localization criterion can be summarized: 1) The sophisticated material characterization considering the hardening deterioration and strain-rate sensitivity is crucial as the first step. 2) The critical element and the neighboring elements are selected by comparing the ratio of the critical element to the neighboring elements. 3) The localization criterion can determine the onset of failure induced by strain localization when local strain increment of the critical element reaches critical value (ten times) which means the critical element deforms faster than those of surrounding elements in the equation (2.1). In order to minimize mesh size effect, the number of elements was selected based on the 3mm emulating grid size if it is done experimentally to average out the mean of strain increment of the surrounding elements.

\[
\frac{d\bar{\varepsilon}_{cr}}{d\bar{\varepsilon}_{avg}} \geq 10
\]  

where \(d\bar{\varepsilon}_{cr}\) is the strain increment of the critical element which experiences maximum effective strain and \(d\bar{\varepsilon}_{avg}\) is the average value of the strain increment of neighboring elements which has 3mm distance from the critical element emulating grid size if it is done experimentally. The uniaxial tensile test was characterized by the multiplicative hardening law following:

\[
\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}, \dot{\varepsilon}) = \left\{ K + C(1 - e^{-p\dot{\varepsilon}}) \right\} \left\{ \bar{w} + (1 - \bar{w}) \exp(-s\bar{\varepsilon}) \right\} \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_A} \right)^m(e^{\bar{\varepsilon}d_e} - 1) \]  

\(\bar{\sigma}, \bar{\varepsilon}, \) and \(\dot{\varepsilon}\) are the effective stress and effective strain, and effective strain-rate, respectively. \(K, C,\) and \(p\) are the Voce type based hardening function parameters. \(\bar{w}, r,\) and \(s\) are the Avrami type hardening deterioration function parameters. \(m\) is the power-law type strain-rate sensitive function parameter. As for the strain-rate sensitivity, the piece-wised in tens, power-law strain-rate sensitive functions are interpolated in strain-rate range between \(\dot{\varepsilon}_B\) and \(\dot{\varepsilon}_A\). The obtained basic material properties and the hardening parameters are arranged in Table 1 and Table 2, respectively.

![Figure 1](image-url)  
Figure 1. The engineering stress and engineering strain curves of experiment with the simulation.
results at 400°C and 470°C. 0.35 was utilized as Poisson's ratio. The parameters of the multiplicative hardening law were calibrated by numerical inverse characterization spontaneously considering the localization criterion under uniaxial tensile test. The engineering stress and engineering strain curves of the experiment performed at 400°C and 470°C were compared with the simulation results as shown in the Figure 1. The x-marks were obtained from the localization criterion in the equation (2.1).

### Table 1. Experimental condition and material properties of AA7075-T6 sheets at 400°C and 470°C.

| Temp. (°C) | Crosshead speed (mm/s) | E (GPa) | Yield Strength (MPa) | UTS (MPa) | Elongation |
|------------|------------------------|---------|---------------------|-----------|------------|
| 400        | 0.02                   | 51.82   | 39.95               | 40.40     | 0.02       |
|            | 0.2                    |         | 49.00               | 52.52     | 0.02       |
|            | 2.0                    |         | 70.05               | 76.58     | 0.02       |
| 470        | 0.02                   | 47.45   | 22.84               | 25.03     | 0.02       |
|            | 0.2                    |         | 31.17               | 34.70     | 0.02       |
|            | 2.0                    |         | 44.56               | 49.79     | 0.02       |

### Table 2. The hardening parameters of the multiplicative hardening law.

| Temp. (°C) | Rate (/s) | K (MPa) | C (MPa) | p | w | s | r |
|------------|-----------|---------|---------|---|---|---|---|
| 400        | 0.001     | 36.15   | 5.53    | 145.02 | 0.35 | 1.50 | 3.30 |
| 0.01       | 51.48     | 3.47    | 98.41   | 0.35 | 0.40 | 10.00 |
| 0.1        | 73.68     | 5.40    | 122.81  | 0.30 | 0.11 | 9.80 |
| 0.001      | 22.92     | 2.46    | 195.69  | 0.20 | 9.00 | 6.20 |
| 0.01       | 32.35     | 3.41    | 127.90  | 0.20 | 0.50 | 15.30 |
| 0.1        | 44.99     | 5.74    | 171.46  | 0.25 | 0.02 | 15.50 |

3. Fracture Criteria

A simple strain-rate sensitive fracture criterion restrictively depending on deformation path was developed and exploited in the research. A damage parameter( $\omega$ ) of fracture criteria was defined under the uniform stress triaxiality and effective strain-rate condition:

$$\omega = \int d\omega = \int \frac{d\varepsilon}{\varepsilon_{ef}(\eta, \varepsilon)}$$

(3.1)
The apparent effective fracture strain, \( \varepsilon_f^*(\eta, \dot{\varepsilon}) \), can be obtained by following relationship:

\[
\varepsilon_f^*(\eta, \dot{\varepsilon}) = \varepsilon_f(\eta, \dot{\varepsilon}) + \left( \int d\varepsilon - \omega \cdot \varepsilon_f(\eta, \dot{\varepsilon}) \right)
\]  \hspace{1cm} (3.2)

where \( \varepsilon_f(\eta, \dot{\varepsilon}) \) is the apparent effective fracture strain and \( \varepsilon_f(\eta, \dot{\varepsilon}) \) is the effective fracture strain at the current state of the deformation and effective strain-rate. The derivation of the equation (3.2) can be referred in a paper [11]. The effective fracture strain dependence deformation path and effective strain-rate sensitive was developed. The deformation accumulation was restrictively selected in positive triaxiality deformation mode preventing unfavorable fracture in the negative triaxiality mode:

\[
\varepsilon_f(\eta, \dot{\varepsilon}) = \begin{cases} 
C_{SNU}^*(\dot{\varepsilon}) = C_{S1} + C_{S2}\ln(\dot{\varepsilon}) & \text{if } \eta \geq 0.0 \\
\infty & \text{if } \eta < 0.0
\end{cases}
\]  \hspace{1cm} (3.3)

As the damage parameter (\( \omega \)) becomes unity, fracture occurs after macro-crack formation which was assumed with the same point predicted by localization criteria in uniaxial tensile test as shown in Figure 1. The engineering strain values of fracture strain were obtained from uniaxial tensile tests along the strain-rates for each temperature and converted into effective fracture strain in Table 3. The characterized parameters of the model, which were piece-wisely calibrated, were summarized in Table 4. It was confirmed that as the damage parameter (\( \omega \)) of the fracture criteria reached unity, the fracture occurred at the exact moment of effective fracture strain in the uniaxial tensile test simulation for each effective strain-rate and temperature as shown in Figure 2.

**Table 3.** The values of the effective fracture strain for 400°C and 470°C

| Strain-rate (/s) | 400°C | 470°C |
|------------------|-------|-------|
| 0.001            | 0.8671| 0.7694|
| 0.01             | 1.0524| 1.1611|
| 0.1              | 1.1718| 1.2236|

**Table 4.** The parameters of the fracture model for 400°C and 470°C for each strain-rate range

| Range of \( \dot{\varepsilon} \) (/s) | 400°C | 470°C |
|-------------------------------------|-------|-------|
| \( \dot{\varepsilon} \leq 0.001 \)  | \( C_{S1} \) | \( C_{S2} \) | \( C_{S1} \) | \( C_{S2} \) |
| 0.01 \( \geq \dot{\varepsilon} \geq 0.001 \) | 1.5504| 0.2490| 1.9445| 0.3917|
| 0.1 \( \geq \dot{\varepsilon} \geq 0.01 \) | 1.2578| 0.1027| 1.2863| 0.0626|
| \( \dot{\varepsilon} \geq 0.1 \)      | 1.1551| 0.0000| 1.2237| 0.0000|
Figure 2. The fracture simulation results in the uniaxial tensile test for each effective strain-rate, 0.1/s, 0.01/s, and 0.001/s, and temperature condition, 400°C and 470°C.

4. Application
The characterized material properties including the fracture criterion were applied to 10 times reduced miniature version shock absorber housing formed by two-step hybrid forming process composed of the draw forming followed by the pneumatic forming process as shown in Figure 3. The simulation results were compared with localization criterion results in application of miniature version shock absorber housing. As shown in equation (2.1), the localization criterion has no parameters and the exactly same procedure was done in the uniaxial tensile test with the same material hardening property. The draw forming and the pneumatic forming were processed at 400°C and 470°C, respectively. The specific conditions of the two-step hybrid forming process were summarized in Table 5.

Figure 3. The schematic view of the two-step hybrid forming process consisting of the 1st step draw
forming and the 2\textsuperscript{nd} step pneumatic forming.

0.76kN and 29.4kN were applied as a holding force for the draw forming and pneumatic forming, respectively. The holding force in pneumatic forming is much higher than those of the draw forming for the prevention of gas leakage. Draw forming process was performed until the depth of 35mm with punch speed of 100mm/min. Argon gas retaining 1.5 MPa was blown to die and maintained more than 2000sec in pneumatic forming process. To minimize the temperature difference between tool and blank for the assumption of isothermal condition for each temperature, enough waiting time was taken before each test was performed. When a thermometer attached on a point of the specimen shows little oscillation, the each process was performed. BN spray was used as a lubricant. The coefficient of friction was determined as 0.3 based on the force and displacement curve during the draw forming.

Table 5. The summarized test conditions for the two-step hybrid forming process.

|                  | 1\textsuperscript{st} step draw forming (400°C) | 2\textsuperscript{nd} step pneumatic forming (470°C) |
|------------------|-----------------------------------------------|--------------------------------------------------|
| Blank Holding    | Punch velocity                                | Blank Holding force                              |
| force            | Total drawing depth                           | Applied Pressure                                  |
| 0.76kN           | 100mm/min                                     | 29.4kN                                           |
|                  | 35mm                                          | 1.5 MPa                                          |

![Effective strain](image1.png)

![The value of damage parameter](image2.png)

Figure 4. (a) The effective strain at the moment of the failure with strain localization by the localization criterion (b) The value of damage parameter at the moment of the fracture by the fracture criterion

The results of the characterized fracture criterion were compared with the simulation results predicted by localization criterion and experimental result. The moment of the failure occurrence, the failure location, the final blank shape, and the thickness distribution were compared. The moment of failure was foreseen when the strain increment of the critical element is faster than 10 time than the average of the neighboring elements as the same way in uniaxial tensile test simulation in equation (2.1). The effective strain distribution at the onset of the failure by localization criterion is shown in the Figure 4. The failure location is same with the experimental results. The final blank shape and the thickness distribution along the x and y direction are well matched with the experimental results as shown in Figure 5. As for the fracture criterion, the start of failure was determined when the damage parameter(}
\( \omega \) becomes unity in equation (3.1) as shown in Figure 4. The failure location is same with the those of experimental results and simulation results by the localization criterion. The final blank shape and the thickness distribution were also compared with the experimental results and simulation results by using localization criterion as shown in Figure 5. The results show good agreement with the comparison groups showing equivalence of the localization criterion and the fracture criterion in two-step hybrid forming process at elevated temperature. Furthermore, the most reduced thickness whose original thickness is 2.0mm becomes 0.43mm in experiment compared with 0.54mm, 0.68mm for those predicted by the fracture criterion and the localization criterion. The maximum effective strains of the critical element are 0.939, 1.062 at the onset of failure by the localization criterion and the fracture criterion, respectively. The reason of underestimation predicted by the localization criterion is in the criterion itself. The localization criterion can predict the moment of large deviation of deformation speed for the highest deformed material and the material in surrounding area. The fracture phenomenon occurs after severe localization phenomenon where surrounding material is momentarily frozen showing almost no deformation. This phenomenon also happens for materials which have strain localization dominant failure phenomenon like AZ31, AZ31B, AA7075 at elevated temperature and 340R, DP980 at room temperature, et cetera[2, 7-10].

![Graphs showing comparison between experimental results and simulation results.](image)

**Figure 5.** The final blank shape and the thickness distribution along the x and y direction.

### 5. Summary

The equivalence between the localization criterion and the fracture criterion was confirmed by applying to two-step hybrid forming process at elevated temperature. In the validation, the moment of the failure occurrence, the failure location, the final blank shape, the thickness distribution and the effective strain of the critical element in the two-step hybrid forming process for both criteria were compared with experimental results showing good agreement. For the research, a fracture criterion depending on deformation and strain-rate history was developed. The fracture criterion was characterized based on effective fracture strain obtained from the onset of the failure in the uniaxial tensile test along the different strain-rates and temperatures. As for the comparison, the results of the previous study using an extensive and systematic method to foresee the initiation of failure as the localization criterion was
revisited. As the failure induced by the abrupt strain localization predominates, it was validated that the prediction by the fracture criteria with proper dependent variables is equivalent to those by localization criteria for AA7075 in two-step hybrid forming process at elevated temperature.

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