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Investigation on the Effect of Different Constitutive Models on the Forming Limit of the Sheet under Nonlinear Strain Path

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ABSTRACT: Forming limit diagrams are a criterion to predict the necking for constructing an optimal design in metal products. In this paper, the Marciniak-Kuczynski instability theory is used to determine the forming limits of the AA6111-T43 sheet. Also, Hill 48, Gotoh, and Yld2000-2d yield criteria are investigated to describe the yield behavior of the alloy, and their coefficients are computed based on the results obtained from uniaxial and bulge tests. Finally, forming limit diagrams are plotted by employing different yield functions and appropriate hardening models. The comparison between theoretical and experimental results indicated that the limit strains obtained by the Yld2000-2d criterion and Swift model are in better agreement with experimental data than others. Since in complex forming processes, the strain path is rarely linear, the investigation of the forming limit diagram by considering the nonlinear strain path is important. In multi-stage forming processes, while the limit strains are significantly path dependent, the forming limit stress diagram is less dependent on the loading path. However the sensitivity of the forming limit stresses to the path is lower than limit strains, the limit stresses in large pre-strain are not completely loading path independent. The sensitivity of the limit stresses to strain path in addition to the magnitude of the pre-strain, also depends on the used hardening model and yield function that are examined in detail in this study.

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1- Introduction

Since in complex metal forming processes, considering the linear loading condition is not a correct assumption, a lot of research is done to investigate the effect of the strain path on Forming Limits Diagram (FLD). Graf and Hosford [1] investigated the effect of nonlinear strain paths on the forming limits of aluminum alloys, and they announced that the change of the strain path has a great effect on the specimen's formability. Yoshida et al. [2] proposed the Forming Limit Stress Diagram (FLSD) as a valuable criterion because of the path-independence of the limit stresses in metal forming processes. Although later, Yoshida and Kuwabara [3] indicated that the limit stresses are not completely path independent, and the path dependence of FLSD is affected by the hardening behavior of the material. Nurcheshmeh and Green [4] investigated the path dependency of the Forming Limit Stress Diagram (FLSD) for various combined loading history and it was observed that for a range of pre-strain values, the FLSD remain constant along different paths. Wang et al. [5] determined the forming limits of the AA5754-O by applying the Yld2000-2d yield criterion in non-linear loading path processes and they discussed the path-dependence of the limit stress diagrams. Sojodi et al. [6] by applying the modified Kim-Tuan hardening model, investigated the influence of the compressive normal stress on the path dependence of FLSD. Also, they examined the effect of the pre-strain magnitudes on the sensitivity of FLD to compressive normal stress.

In this paper, the influences of the loading path on forming limit diagrams are studied and the path dependence of FLD and FLSD are analyzed in detail. In the end, the sensitivity of the FLSD to the magnitude of the pre-strain for different constitutive models is discussed and the critical effective strain values that specified the path dependence of FLSD are determined.

2- Marciniak-Kuczynski Model

This method is based on the existence of the initial imperfection that is characterized by the reduction of thickness in a part of the sheet. The initial thickness imperfection is defined as:

$$f_0 = \frac{t_0^b}{t_0^a} \tag{1}$$

Where t_0^a and t_0^b are the initial thickness in the safe

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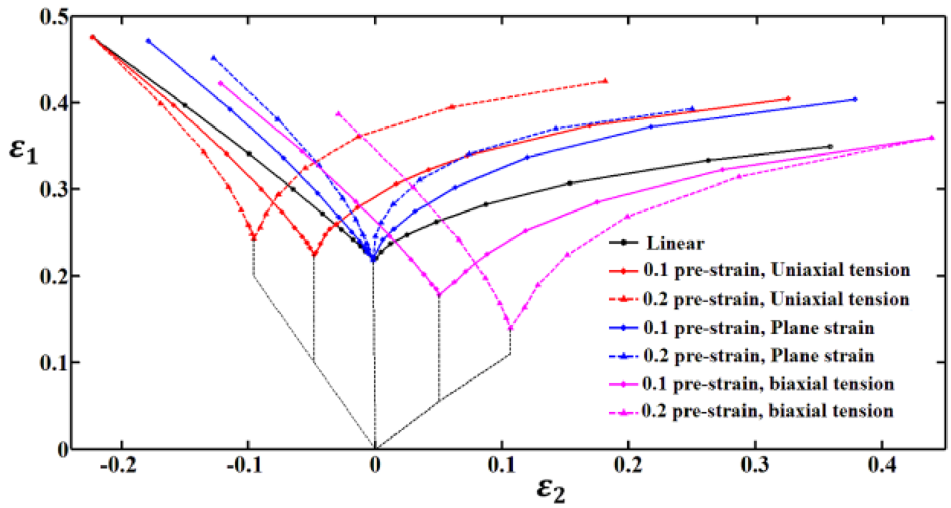


Fig. 1. The FLCs based on different pre-strains along a different direction

and defect region, respectively. In the M-K approach, the equivalent strain increment $d\bar{\varepsilon}$ with a specific stress ratio $(\alpha = \sigma_2 / \sigma_1)$ was applied to the safe region and then the other strain and stress component values in this area were computed by using the flow rule, hardening equation, and yield function The unknown parameters in the groove zone were calculated according to three major assumptions including compatibility condition, geometrical imperfection, and force equilibrium that are expressed as:

$$d\varepsilon_{tt}^{a} = d\varepsilon_{tt}^{b} \tag{2}$$

$$\begin{cases} \sigma_{nn}^{a} t^{a} = \sigma_{nn}^{b} t^{b} \\ \sigma_{nt}^{a} t^{a} = \sigma_{nt}^{b} t^{b} \end{cases} \Rightarrow \begin{cases} \sigma_{nn}^{b} = \sigma_{nn}^{a} / f \\ \sigma_{nt}^{b} = \sigma_{nt}^{a} / f \end{cases} \tag{3}$$

The Numerical Newton-Raphson method is used to solve the nonlinear set of equations, and the unknown stress and strain components in the defect region are obtained when the effective strain increment in the groove reaches ten times greater than the perfect area. This numerical procedure in each stress ratio is repeated for different groove directions to determine minimum limit strains [4].

3- Work-Hardening Models

To investigate the influence of the hardening law on the forming limit diagrams, Swift and voce stress-strain are utilized to describe the mechanical behavior of the AA6111-T43 alloy as [7]:

$$\bar{\sigma} = K\left(\bar{\varepsilon} + \varepsilon_0\right)^n \tag{4}$$

$$\bar{\sigma} = A - Be^{-c\bar{\varepsilon}} \tag{5}$$

4- Yield Functions

Yld2000-2d yield criteria are expressed as:

● Yld200-2d yield criterion[8]:

$$\phi = \phi' + \phi'' = 2\bar{\sigma}^{m} \tag{6}$$

$$\phi'' = \left|2X_2'' + X_1''\right|^{m} + \left|2X_1'' + X_2''\right|^{m} \tag{7}$$

$$\phi'' = \left|2X_2'' + X_1''\right|^{m} + \left|2X_1'' + X_2''\right|^{m} \tag{8}$$

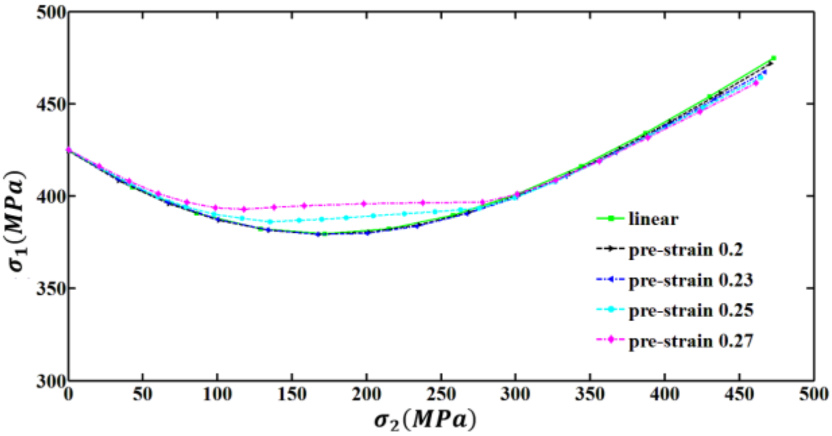
5- Results and Discussion

The M-K criterion code was developed to calculate the theoretical forming limit diagram of AA6111-T43 under combined loading paths. Fig. 1 shows the limit strains obtained under various pre-strains along the uniaxial tension, plane strain, and equi-biaxial tension paths.

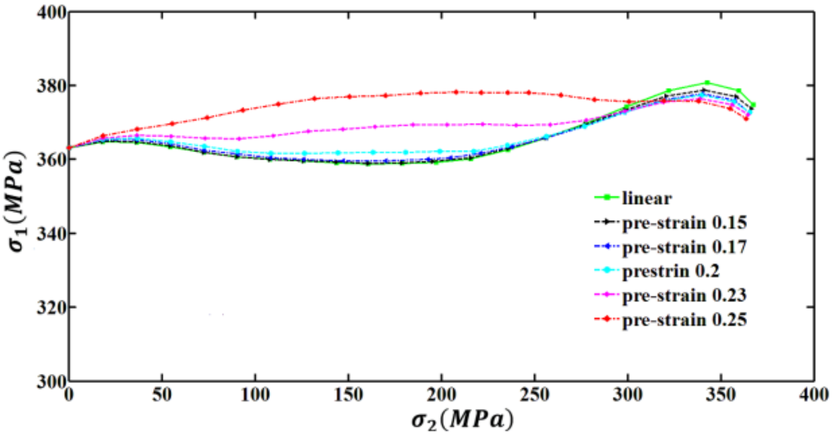
It was seen in Fig. 1 that the strain path dependence of limit strains under bilinear loading paths with higher pre-strains is more obvious. Therefore, the larger the pre-strain causes the more influence on the forming limits.

In the continuation of this section, the sensitivity of the forming limit stress curves to the strain path are examined. Fig. 2 indicated the forming limit stresses for various pre-effective strains in the uniaxial tension direction.

The criterion for this behavior, dependence or independence of FLSD, is the magnitude of pre-effective strain compared to the value of the effective forming limit



(a)



(b)

Fig. 2. FLSDs based on different pre-effective strains by using (a) Swift (b) Voce hardening models

strain in-plane strain state and linear loading condition (effective FLD0). The calculated effective FLD0 for the Swift and Voce hardening laws are 0.237, and 0. 172 respectively. Briefly, if effective pre-strain in the multistep loading path process is less than this critical value, the final limit stresses will coincide with the FLSD in linear condition. But, if the strain path changed after this critical value, the limit stresses will be affected by the pre-strain.

6- Conclusion

The most important consequences of this study are below items:

The FLD in nonlinear strain path processes are significantly dependent on the strain path. Although the sensitivity of forming limits in stress space to loading path are less than limit strains, FLSD is not completely path independent.

The forming limit curves in stress space for the multistep strain path processes will be path-dependent if the pre-strain is more than effective FLD0. Also, the selective constitutive model significantly affects the path dependency of the forming limit stress curve.

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