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On the fracture prediction of 304L stainless steel sheets utilizing different hardening models

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Abstract: Fracture prediction is one of the challenging problems in sheet metals. Forming limit curves at fracture (FLCF), as a tool to determine fracture in sheet metal processes, are obtained through the use of numerical analyses. As one of the approaches, the ductile fracture criteria (DFCs) represent the fracture initiation of the sheets formed by different loading histories. In this study, the effects of three different hardening models on different DFCs to predict the fracture for stainless steel 304L have been investigated. The results show that most of DFCs work better in the region $\varepsilon_2 < 0$ especially with the kinematic hardening model. However, for the region $\varepsilon_2 > 0$ where the stretching conditions are dominant, none of them could precisely estimate the fracture initiation.

1. Introduction

Forming limit curves (FLCs) which were first drawn experimentally in 1960s have been used as an effective tool to analyze the behavior of the sheet metal for years. It is reported by many researchers that the strain paths can produce considerable variations in the forming limits [1-2]. Ductile fracture criterion as one of the less dependent methods to strain-path, has been employed extensively in the recent years to draw the forming limit curves at fracture (FLCF). But there are many parameters affecting the efficiency of the DFCs and Dizaji et al [3] show that the hardening rule is one of those factors.

In this study, the effects of three hardening models; namely, isotropic, kinematic and combined hardening were investigated for different ductile fracture criteria. For this purpose, ductile fracture criteria proposed by Freudenthal [4], Cockroft and Latham [5], Oh et al. [6], Ayada et al. [7] and Brozzo et al. [8] have been used. Zeigler-Prager [9] equation and the Chaboche-Zeigler formulation with five constants [10] have been utilized in the kinematic hardening and the combined hardening models, respectively. All of the criteria and models were implemented to a commercial FE software using user subroutines [11]. The FEM results have been compared with experimental data for Nakazima tests to recognize the DFC and the corresponding hardening model which predict the fracture better in stainless steel material SS304L. Also a deep drawing process with square blank was utilized to compare the DFCs predictions.

2. Experimental tests and Numerical models

The explicit solver of the commercial finite element code ABAQUS has been used in all numerical analyses of the deformation processes. All tools were assumed as rigid and the mesh for the sheets were created by using an 8-node linear brick, reduced integration elements. The friction coefficients, based on Coulomb law, have been taken as 0.05 for lubricated interfaces and 0.13 for dry interfaces in the simulations. The penalty contact algorithm has been utilized to model the interaction between the surfaces. To have a quasi-static conditions in the dynamic explicit solutions, the kinetic energy is kept less than 10 percent of the total internal energy [11].

The properties of the stainless steel SS304L that were obtained by employing uniaxial tensile test (UTT) and are presented in table 1. To calculate the combined hardening constants, the half cycle data shown in table 1 were used as input for the numerical analyses. Then, with some numerical manipulation, the required material constants were found as shown in table 2.

Table 1. Material properties of SS304L steel.

Parameter	$E\ (GPa)$	ν	$\sigma_Y^0\ (MPa)$	r	$K\ (MPa)$	n
Value	194	325	339	1.0125	1196	0.32

Table 2. The parameters of Chaboche-Zeigler combined hardening model.

Parameter	γ	C	σ_Y^0	b	Q
Value	1732.6	120.7	339	5.32	347.54

3. Results and Discussion

The required constants for each empirically formulated phenomenological uncoupled DFCs used in this study, are shown in table 3 for different hardening rules.

Table 3. Criteria constants for SS304L material.

Constants	$C_{Freu.}$	$C_{Cock.}$	$C_{Broz.}$	C_{Oh}	C_{Ayada}
Isotropic Hardening	922.5	989.5	0.996	0.985	0.371
Kinematic Hardening	843	872	0.901	0.855	0.313
Combined Hardening	903.4	995.6	1.02	1.007	0.392

To evaluate the reliability of each implemented DFC on the sheet forming process the Nakazima tests were carried out using the SS304L stainless steel. The comparison of the strain values obtained by the simulations for different DFCs with the experimental results are presented in figures 1-3.

It is observed that the FLCF curves of all ductile fracture criteria are almost linear lines with a negative slope predicting the fracture better when $\varepsilon_2 < 0$; while for the region $\varepsilon_2 > 0$, all of the criteria have inaccurate estimations except for the certain deformation states. In the region $\varepsilon_2 < 0.1$, FLCF curves obtained by DFCs of Ayada et al. and Brozzo et al. are closer together and have better predictions among all DFCs for all hardening models. In this region, the best results are obtained by the DFC of Ayada et al. for kinematic hardening rule and DFC of Brozzo et al. for isotropic and combined hardening rules. The better results of Ayada et al. and Brozzo et al. can be attributed to the consideration of both mean stress and equivalent plastic strain simultaneously in their formulations [2]. For the region $\varepsilon_2 > 0.1$ the predictions of all DFCs with all hardening models deviate from the experimental results. However, the predictions of Freudenthal, Cockroft and Latham, and Oh et al. are better for equi-biaxial conditions especially with isotropic hardening rule. Fracture initiation in square cup drawing, as a process which has complicated deformation history, was also predicted by various DFCs together with the three hardening models. For this purpose, 1 mm thick, 80×80 mm blanks made of SS304L steel were drawn by using an 40×40 mm punch as shown in figure 4.

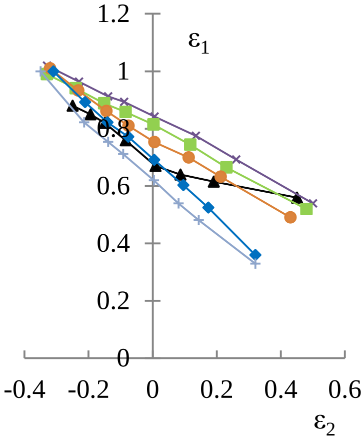

Figure 1. Nakazima test results rule using piecewise isotropic hardening model.

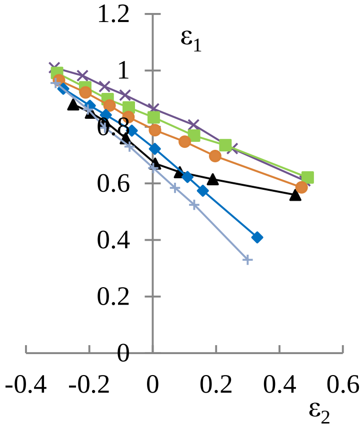

Figure 2. Nakazima test results using Zeigler-Prager kinematic hardening model.

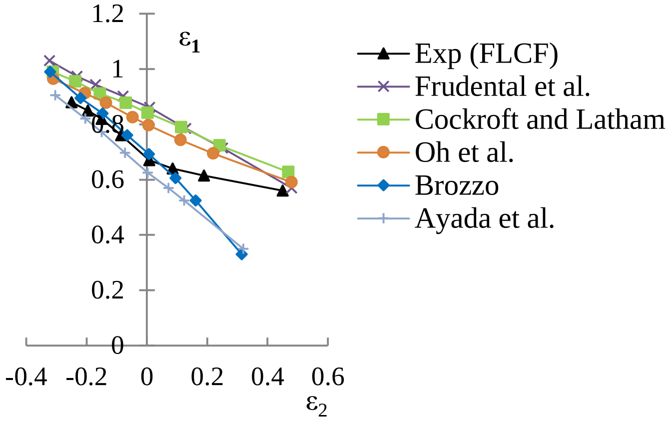

Figure 3. Nakazima test results for combined hardening that uses Chaboche- Zeigler equation.

In figure 5, each point in the diagram stands for the major and minor principal strains in the critical element of the mesh in which the fracture is initiated by using specific DFC and hardening model. The deformation histories of the points have not been shown to avoid confusedly diagram.

It is observed by figure 5 that fracture initiation is better predicted by the DFC of Oh et al. with isotropic hardening between all DFCs. Also the DFCs of Cockroft and Latham with isotropic hardening and DFC of Brozzo et al. with kinematic hardening rule are the other DFCs which have closer estimations. These results can also be remarked based on the figures 1-3 in the region that fracture has been initiated ($0.2 < \varepsilon_2 < 0.3$).

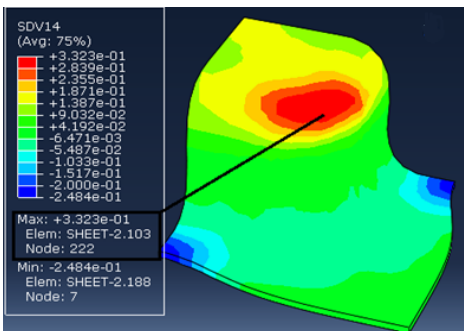

Figure 4. Distribution of the variable SDV14 indicating the element where fracture has occurred at 21.3 mm of cup height using DFC of Ayada et al. with kinematic hardening model.

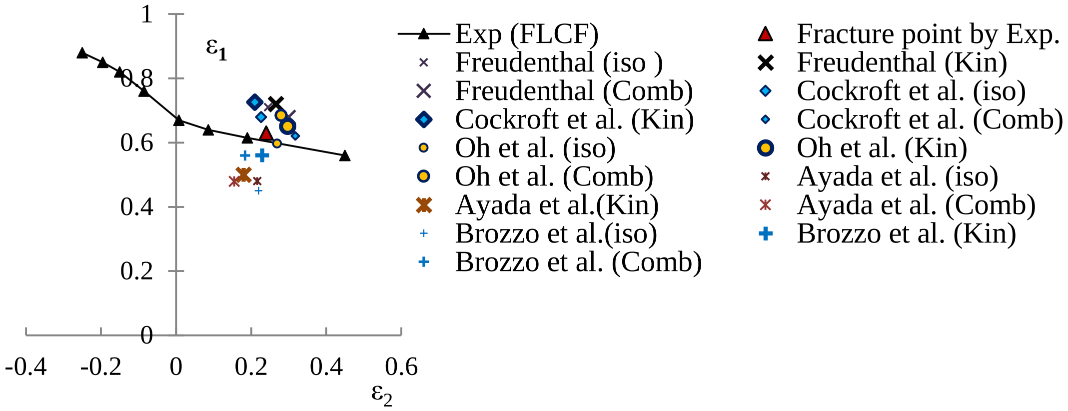

Figure 5. Comparison of different DFCs results for square cup drawing.

4. Conclusions

The effects of hardening rules on the reliability and applicability of different ductile fracture criteria were studied and it is shown that they have significant influences in the forming of SS304L sheets.

1. The best predictions were obtained by DFCs of Ayada et al. and Brozzo et al. when $\varepsilon_2 < 0$ especially with kinematic and combined hardening models, respectively.
2. For $\varepsilon_2 > 0$, although DCF of Oh et al. gives better predicitions, none of the DFCs are accurate enough. Especially DFCs of Ayada et al. and Brozzo et al. should be used cautiously with stretching dominant deformations.
3. The DFCs of Oh et al. and Cockroft and Latham with isotropic hardening rule and DFC of Brozzo et al. with kinematic hardening rule have shown the better fracture predictions between all DFCs in square cup drawing as expected from the Nakazima test results.

5. Acknowledgements

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