Error Analysis of FLC Experimental Data at Warm/Hot Stamping Conditions

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Abstract: Forming limit curves (FLCs) are commonly used for evaluating the formability of sheet metals. However, it is difficult to obtain the FLCs with desirable accuracy by experiments due to that the friction effects are non-negligible under warm/hot stamping conditions. To investigate the experimental errors, experiments for obtaining the FLCs of the AA5754 are conducted at 250° C. Then, FE models are created and validated on the basis of experimental results. A number of FE simulations are carried out for FLC test-pieces and punches with different geometry configurations and varying friction coefficients between the test-piece and the punch. The errors for all the test conditions are predicted and analyzed. Particular attention of error analysis is paid to two special cases, namely, the biaxial FLC test and the uniaxial FLC test. The failure location and the variation of the error with respect to the friction coefficient are studied as well. The results obtained from the FLC tests and the above analyses show that, for the biaxial tension state, the friction coefficient should be controlled within 0.15 to avoid significant shifting of the necking location away from the center of the punch; for the uniaxial tension state, the friction coefficient should be controlled within 0.1 to guarantee the validity of the data collected from FLC tests. The conclusions summarized are beneficial for obtaining accurate FLCs under warm/hot stamping conditions.

Keywords: forming limit curve (FLC), error analysis, warm/hot stamping, finite element analysis

1 Introduction

In recent years, there has been a significant increase in the use of aluminum alloys in the automotive industry. This can be attributed to their excellent properties, such as high strength/weight ratio, good corrosion resistance, and favorable weldability\(^{[1-2]}\). It is however obvious that the poor formability of aluminum alloys at room temperature substantially limits their usage in the automotive industry. One practical solution to this problem is logically the use of the warm/hot stamping process, which can considerably improve the formability of aluminum alloys\(^{[3-9]}\).

The forming limit curve (FLC), first presented by KEELER and BACKOFEN\(^{[10]}\), is widely used in sheet metal forming for determining the likely occurrence of failure\(^{[11]}\). It plays a safety-judging role in sheet metal formability simulation\(^{[12]}\). Specifically, any strain state falls into the area that is encompassed by the FLC is safe; otherwise, failure should occur. Therefore, the accuracy of formability simulation of a stamping process by using finite element method (FEM) depends on that of the FLC used\(^{[13]}\).

To obtain an accurate FLC for sheet metal forming at room temperature, tests should be carried out under six different strain states (see Fig. 1) according to the ISO standards\(^{[14-15]}\). As can be seen from the figure, the strain paths are linear, meaning that the corresponding loading states maintain the same from the start to the end\(^{[16]}\). Also, the determined linear strain paths of a general FLC range from the uniaxial tension strain state (path 1: \(\varepsilon_2/\varepsilon_1 = -0.5\)), to the biaxial tension strain state (path 6: \(\varepsilon_2/\varepsilon_1 = 1.0\)).

Fig. 1. Strain states of a typical FLC


The feasibility of two commonly used tests, namely, the Marciniak test and the Nakajima test, for the determination
of the FLCs has been analyzed during past decades. RAGHAVAN\cite{17} reported that in-plane (the Marciniak test) forming limits are slightly lower than out-of-plane (the Nakajima test) forming limits near plane strain. BOISSIÈRE R, et al\cite{18}, suggested that the Nakajima test can obtain a complete FLC with limited number of tests at any chosen scale staying within the non-influential range of grain size and defect dimensions. Based on their study, it can be concluded that the Nakajima test is better choice for the determination the FLCs.

Many researches have also been carried to investigate the factors affecting the FLCs at room temperature. BRESSAN\cite{19} suggested that the FLCs are affected by the thickness of the test-piece, and thicker sheets have higher limit strains. BLECK, et al\cite{20}, suggested that the FLCs are also affected by factors such as yield tensile strength, the strain hardening and the strain-rate sensitivity. MARCINIAK, et al\cite{21}, conducted both experimental and theoretical research to study the influence of plastic property on the FLCs. Their research revealed that the FLCs are also affected by the uniformity of material orientations, specifically, the FLC in the rolling direction is significantly different from that in the transverse direction, and the limit strains are somewhat higher in rolling direction.

The key factor of obtaining accurate results from Marciniak FLC tests is to keep the friction coefficient as close as possible to zero. As regards cold FLC tests, seven layers of lubricants are applied to ensure that the friction coefficient is close to zero\cite{11} so that the errors can be minimized. However, for warm/hot FLC tests, the lubrication method is not suitable since the polymer-type lubricant layers cannot be used at high temperatures; and the friction is normally much higher than that in cold FLC tests. On the basis of the above facts, significant research was carried out by HSU, et al\cite{13}, suggesting that a test-piece tends to fail at the contact area between the punch and the unsupported region away from the center of the test-piece, due to the friction in the Nakajima test. Nevertheless, they have not proposed a suitable friction coefficient range to achieve a desirable failure location for the accurate FLC experiments. Although they emphasized that the Nakajima test is complicated by the effect of friction, the relation between the friction and the errors of FLC experiments was not studied properly. Therefore, the main aim of this paper is to quantify the effect of friction on the errors of FLC data through carrying out numerical simulations.

In this paper, the warm/hot FLC experimental procedure is introduced; and experimental results for AA5754 at warm/hot stamping condition with temperature of 250°C are presented and analyzed, based on which, the FLC errors, particularly for uniaxial tension and biaxial tension conditions are identified. This leads to the main aim of the research. Then FE models, calibrated from the experimental results, are created for the investigation of the errors at different test conditions. The simulation results on errors are presented and analyzed. Finally, conclusions are given at the end of the paper.

2 Experiments

2.1 Material and geometry of test-pieces

Test-pieces used in this research were made of the commercial alloy AA5754, which offers good corrosion resistance, weldability and formability. The chemical compositions of the AA5754 are given in Table 1.

| Table 1. Chemical compositions of AA5754 (wt. %)\cite{11} |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Si              | Fe              | Mn              | Mg              | Al              |
| 0.4             | 0.4             | 0.5             | 2.6–3.2         | Bal.            |

Based on the ISO standards\cite{15}, the Nakajima type forming method was selected to determine FLC at various warm/hot stamping conditions. Fig. 2 shows the tools used for Nakajima tests. The blanker holder has a circular draw bead with a diameter of 104 mm. As is clear from Fig. 3, the test-piece is a circular blank with a waist (W) in the middle forming by two parallel edges; the rolling direction of the material is parallel to the waist axis for the aluminum alloy in accordance with the ISO standards\cite{15}.

![Fig. 2. Forming tools for Nakajima tests](image_url)

![Fig. 3. Waisted test-piece geometry for Nakajima type test for AA5754](image_url)

According to the ISO standards\cite{15}, the FLC can be derived by considering six strain states as depicted in Fig. 1. Test-pieces with different widths of the waist (W), listed in