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Prediction of forming limit curve (FLC) for Al–Li alloy 2198-T3 sheet using different yield functions

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Abstract The Forming Limit Curve (FLC) of the third generation aluminum–lithium (Al–Li) alloy 2198-T3 is measured by conducting a hemispherical dome test with specimens of different widths. The theoretical prediction of the FLC of 2198-T3 is based on the M–K theory utilizing respectively the von Mises, Hill'48, Hosford and Barlat 89 yield functions, and the different predicted curves due to different yield functions are compared with the experimentally measured FLC of 2198-T3. The results show that though there are differences among the four predicted curves, yet they all agree well with the experimentally measured curve. In the area near the planar strain state, the predicted curves and experimentally measured curve are very close. The predicted curve based on the Hosford yield function is more accurate under the tension–compression strain states described in the left part of the FLC, while the accuracy is better for the predicted curve based on Hill'48 yield function under the tension–tension strain states shown in the right part.

1. Introduction

As a new type of aluminum alloy, Al–Li alloy is widely used in the aerospace field because of its low-density, low fatigue crack growth rate, high elastic modulus, high specific strength, high specific stiffness, weldability and other excellent comprehensive performance.[1] Each 1% weight of Li alloyed with Al reduces the density by 3% and increases the Young's modulus by 6% as compared with the pure Al.[2] Using the new Al–Li alloy to replace the conventional high strength aluminum alloy makes it possible for the structure's stiffness to increase by 15%–20% and the structural weight[3] to decrease by 10%–20%.

The course of research and development of the Al–Li alloy can be generally divided into three stages, and corresponding Al–Li alloy products are divided into three generations. The chemical composition of the third generation Al–Li alloy has changed, which enables it to demonstrate significant advantages over the second generation Al–Li alloy and traditional aluminum alloy, such as low-density, high corrosion resistance, high fatigue strength, high tensile strength and high fracture toughness. As a representative of the third generation Al–Li alloy, 2198 Al–Li alloy has been used both in the manufacture of

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first and second overall fuel tank barrels and circular end covers on rocket "Falcon 9" and in the manufacture of aircraft fuselage skin.[4] Therefore, the study of basic material properties of 2198 and other third-generation Al–Li alloys is of great significance.

The forming limit is an important performance indicator and process parameter in the field of sheet metal forming which reflects the largest deformation the sheet can reach before plastic instability occurs in the process. Among a variety of methods for evaluating sheet metal formability, the FLC is of the greatest practical significance and is most widely used. The FLC is a very effective tool to evaluate sheet metal formability and solve sheet metal stamping problems.[5] Usually there are two methods to determine the FLC: theoretical calculation and experiments. The theoretical calculation of the FLC is based on the specific plastic instability theories, including Swift's diffuse instability theory,[6] Hill's localized instability theory,[7] M–K instability theory and Jones–Gilliss (JG) theory,[8] and it uses different yield functions and plastic constitutive equations for theoretical calculation on the forming limit strain. Of these theories, the Swift's diffuse instability theory (valid only when biaxial stress state exits) and Hill's localized instability theory (no strain rate sensitivity is accounted for) have some limitations. The JG theory was originally applied to the tension test of a round bar and then extended to the right-hand side (RHS) and left-hand side (LHS) of the FLD[9] using different yield functions and constitutive laws.[10] In 1967 Marciniak and Kuczynski presented a groove hypothesis from the perspective of material damage, which is the most widely used damage instability theory today, known as the M–K theory.[11]

The FLC of Al–Li alloy 5A90 was extensively studied in literature, including theoretical prediction and parameter influence of FLC based on an M–K model[12] and the constitutive relationship of 5A90 Aluminum–lithium alloy at hot forming temperature.[13] The FLC of 2090, 2091 and 8090 Al–Li alloys were studied in a study on the stamping limit of Al–Li alloy sheets.[14] But the forming limit of 2198-T3 plate has not been reported. In order to characterize the measured FLC, a hemispherical dome test was performed in the present study, and the theoretical FLC of 2198-T3 based on the M–K theory was performed and different yield functions were compared with experimental data. The analysis can be used to prove the validity and accuracy of the theoretical predictions and to establish the theoretical prediction model of FLC for 2198-T3.

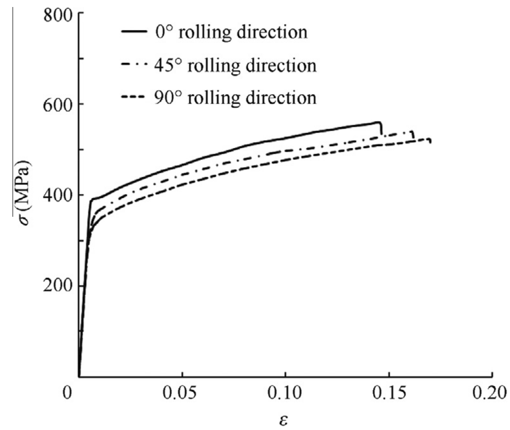

Fig. 1 True stress-true strain curves of 2198-T3.

2. Formability test

2.1. Test material

The test pieces investigated in this work are made of 2198-T3 Al–Li alloy with a 1.5 mm thickness. The sheet was solution treated, quenched and naturally aged to a substantially stable condition (T3 heat treatment).The chemical compositions are shown in Table 1.

2.2. Uniaxial tension test

All tests were carried out at room temperature. The specimens were cut along three different directions (rolling direction, diagonal and transverse direction) from a 2198-T3 sheet. They were selected in an uniaxial tension test according to the standard of GB/T 228-2002 (Metallic materials-Tensile testing at ambient temperature).[15] Three specimens at least were tested for each condition. Scatter is negligible so that only one curve was plotted.[16,17] The true stress–strain curves of the specimens in different directions are shown in Fig. 1.

The basic formability parameters were calculated according to the standards of GB/T 5027-1999 (Metallic materials-Sheet and strip-Determination of plastic strain ratio (*r*-values)) and GB/T 5028-1999 (Metallic materials-Sheet and strip-Determination of strain hardening exponent (*n*-values)). The *K*-value is the hardening coefficient. The *r*-values were thick anisotropy coefficients for a plastic deformation of 10%. See Table 2.

Table 1 Chemical composition of 2198 alloy.

Element	Cu	Li	Zn	Mn	Mg	Zr	Si	Ag	Fe
wt.%	2.9–3.5	0.8–1.1	⩽0.35	⩽0.5	0.25–0.8	0.04–0.18	⩽0.08	0.1–0.5	⩽0.01

Table 2 Basic formability parameters of 2198-T3.

Orientation (°)	Yield stress (MPa)	Ultimate tensile strength (MPa)	Uniform elongation (%)	*K* (MPa)	*n*-value	*r*-value
0	385.0	475.0	14.5	780	0.168	0.951
45	337.5	455.0	15.9	714	0.172	0.779
90	322.5	432.5	17.2	757	0.180	2.073