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Notch strength and stress concentration sensitivity of alloy 2090 with various cerium contents

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The tensile strength of notch specimens has been investigated for alloy 2090 sheets with various Ce contents. The notch strength (σ_N) has been quantitatively analyzed. By comparison with Ce-free alloy, σ_N of Ce-containing alloy sheets exhibits an insignificantly change. The statistical estimation shows that σ_N evaluated from the theoretical expression is in better agreement with the test data. Accordingly, the strength of notched specimens can be conveniently predicted by means of the conventional tensile properties of smooth specimens. The notch insensitivity factor (K_N) has been derived for the alloy 2090 sheets with various Ce contents. K_N can be applied to assess the stress concentration sensitivity to structural notches in practical structures by comparison with the theoretical stress concentration factor (K_t). Increasing in Ce content in the alloy 2090 sheets can slightly enhances K_N or reduces the stress concentration sensitivity. However, Ce microalloying can not still essentially decrease the stress concentration sensitivity of the alloy 2090 sheets because the ductility can not be improved to a greater degree only by adding Ce element. Therefore, high stress concentration sensitivity may be a potential obstruction to the practical application of high-strength Al-Li based alloys in primary aircraft structures containing structural notches.

1. Introduction

A structural element of always contains geometrical discontinuities such as fastener holes, fillets and grooves, which are collectively known as *stress raisers*, or *notches*. Stress concentration usually occurs at notch root where crack initiates under monotonic tension or cyclic loading. Notch strength is a governing factor for the safety of notch elements before crack initiation at notch root while fracture toughness is a governing factor for that after crack initiation at notch root. Therefore, as a parameter of quality control, notch strength or stress concentration sensitivity usually plays an important role in metallic structural materials [1].

Al-Li based alloys have the prospect of applications in aircraft structures to save weight because of their lower density and higher elasticity modulus [2–5]. However, there is still a primary obstruction to widespread application of these alloys in that the present generation of Al-Li based alloys still has some unsatisfactory sides in engineering properties such as ductility and fracture toughness [6–12]. Therefore, there must be a high stress concentration sensitivity in Al-Li based alloys, especially in high-strength Al-Li based alloys because of their poor ductility. When the alloys are utilized to make an aircraft structure, it is possible to readily produce cracks at geometric discontinuities and consequently to cause quickly tearing failure under the flight condition of variable-amplitude load or overload. However, the importance of notch strength or stress concentration behavior for Al-Li based alloys is not still understood sufficiently.

Moreover, microalloying methods can significantly improve the mechanical properties of Al-Li based alloys [13–16]. Some rare earth elements can be utilized as the beneficial alloying additions. They can improve the ductility, fracture toughness and fatigue strength [17–23]. Since rare earth elements in Al-Li based alloys can modify the mechanical properties, the stress concentration characteristics must also change with the changes of the mechanical properties. Therefore, it is also necessary to understand the changes of stress concentration sensitivity and notch strength when Al-Li based alloys are modified by rare earth microalloying.

The objectives of this research are to characterize the notch strength and the stress concentration sensitivity for alloy 2090 contained with different Ce contents, and to give the theoretical expressions for predicting the level of notch strength and evaluating the degree of stress concentration sensitivity.

2. Experimental procedures
2.1. Test materials
The materials used in the investigation were prepared in our laboratory by the processes of melting in a vacuum induction furnace, casting into ingots in argon shield, forging at 488°C into slabs and rolling first at 480°C and then at 300°C into 2.0 mm sheets.

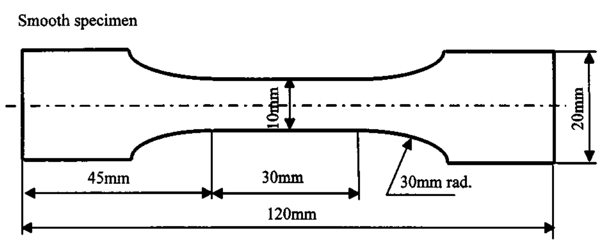
The chemical compositions of the test materials are given in Table I. The contents of basic constituents such as Li, Cu and Zr are generally within the range of nominal composition of alloy 2090, which is a typical high-strength Al-Li based alloy. In addition, a various amount of Ce was added in some test materials, which were denoted as alloys A7, A8 and A9, respectively. Correspondingly, A6 is Ce-free alloy. The test alloy sheets were solution heat treated at 540°C, water quenched, stretched about 6 pct and aged for 18 h at 165°C.

2.2. Notched specimens and tension test
Both the smooth and double-edge-notched specimens (Fig. 1) were cut in transverse orientation (normal to rolled direction) for all test alloy sheets and in longitudinal orientation (parallel to rolled direction) for the alloy sheets A6 and A8. The values of K_t for the notched specimens which had different notch root radii and depths were determined as 2.0, 3.0, 4.0 and 8.0, respectively [24]. For the smooth specimens, $K_t = 1.0$.

Tension test was carried out at ambient temperature and in laboratory air. The strain rate of the specimens

TABLE I Chemical compositions (wt. pct) of the test alloy sheets

Alloy	Li	Cu	Zr	Ce	Fe	Si	Al
A6	2.39	2.52	0.11	—	0.055	0.022	Balance
A7	2.21	2.56	0.09	0.13	0.034	0.019	Balance
A8	2.25	2.34	0.10	0.21	0.050	0.022	Balance
A9	2.29	2.34	0.08	0.31	0.060	0.010	Balance



Notched specimens:

K_t	2.0	3.0	4.0	8.0
D (mm)	11	13	22	20.8
r (mm)	1.2	0.6	0.43	0.1

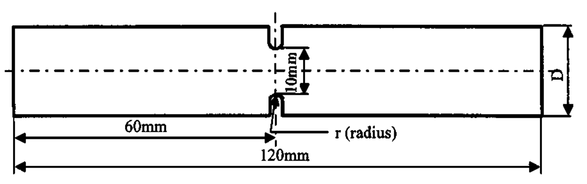


Figure 1 Dimensions of the tensile specimens used in the investigation.

was selected as 0.0048 s^{-1}. The load and displacement were recorded autographically.

3. Notch strength and its theoretical prediction
Fig. 2 shows the test results of notch strength under different values of K_t for each test material. Moreover, the predicted results of notch strength and notch insensitivity factor, which will be discussed in what follows, are also given in Fig. 2. With the increase of stress concentration level, the notch strength sharply decreases for all the test materials when K_t is greater than 2.0. With the change of Ce content, notch strength exhibits a little variation under the same value of K_t, whether the notched direction is in transverse orientation or longitudinal orientation. Therefore, it can be roughly agreed that Ce modification produces an insignificant effect on notch strength.

In order to predict notch strength conveniently by the aid of conventional tension test of smooth specimens, Zheng [1] presented a theoretical expression based on an assumption that crack initiation at notch root occurs due to the fracture of a hypothetical material element (more details in Ref. [1]):

$$\sigma_N = \frac{\alpha\sqrt{E\sigma_f\varepsilon_f}}{K_t} \tag{1}$$

where α is a constant depending on practical stress state at notch root, $\alpha = 1.0$ for plane stress state and $\alpha = 0.64$ for plane strain state; α_f is the fracture strength, ε_f the fracture ductility and E the Young's modulus.

According to the load-displacement plots recorded in the tension test (Fig. 3), it may be seen that the specimens exhibit a rather small stretch elongation because high-strength Al- Li based alloys commonly have lower ductility than conventional aluminum based alloys. In addition, the yield phenomenon, necking and shear lip can hardly be observed on the macroscopic features of the fractography (Fig. 4). The results indicate that the specimens were subjected predominantly to a uniform plastic elongation before failure. Because the fracture process of the specimens were accompanied by an ignorable local lateral contraction at crack tip, we can roughly consider that the specimen sections experienced the practical strain nearly under plane strain state, although the thickness of the test alloy sheets is possibly insufficient to conduct the standard-sized fracturing measure about plane strain fracture toughness K_{Ic}. Therefore, in the investigation, α in Equation 1 may be taken as 0.64.

Fracture strength and fracture ductility can be related to ultimate tensile strength (σ_b) and percent reduction of area (RA) by [1, 25]

$$\sigma_f = \sigma_b(1 + \mathrm{RA}) \tag{2}$$

$$\varepsilon_f = -\ln(1 - \mathrm{RA}) \tag{3}$$

Since the specimens experienced primarily uniform strain in the tensile process, the volume change of the specimens was limited to the small change. It is

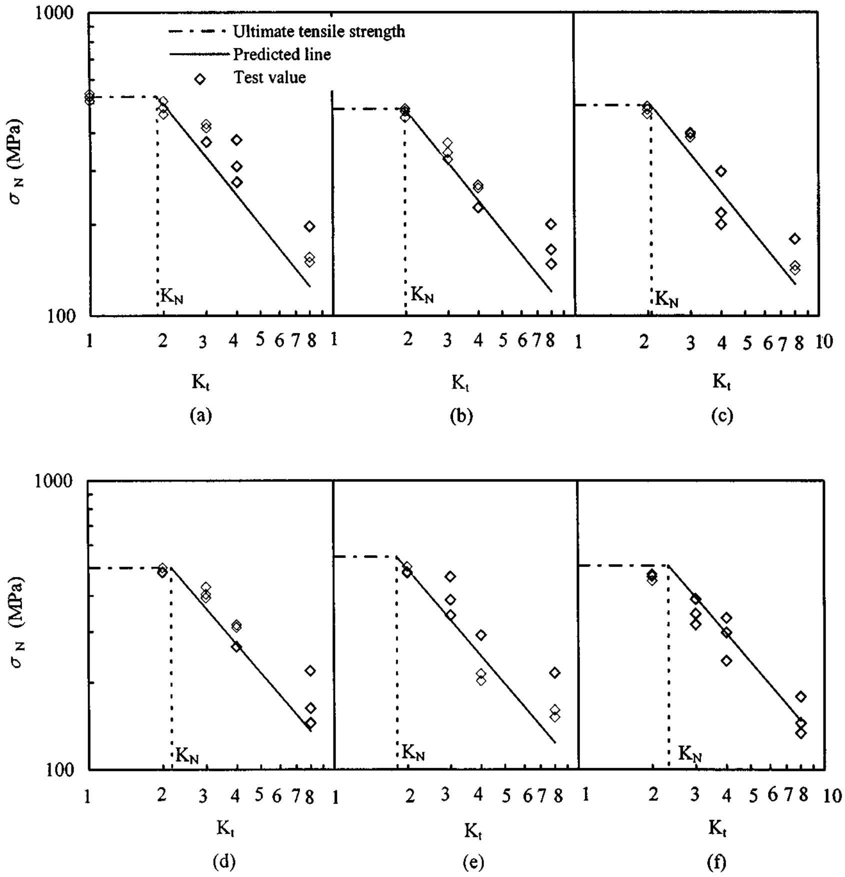


Figure 2 Test values and predicted notch strength for the test alloy sheets: (a) A6, transverse orientation; (b) A7, transverse orientation; (c) A8, transverse orientation; (d) A9, transverse orientation; (e) A6, longitudinal orientation; (f) A8, longitudinal orientation.

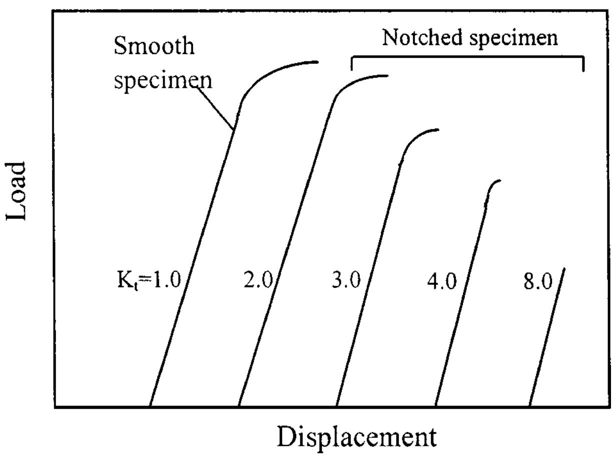


Figure 3 Schematic load-displacement plots for the tensile specimens.

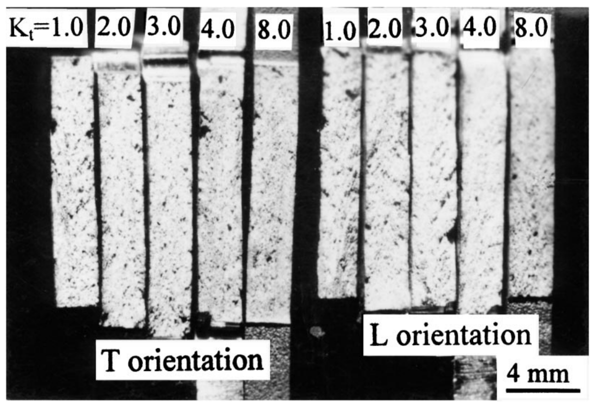


Figure 4 Macroscopic observation of the fractography for the tensile specimens.

therefore reasonable to assume that the specimen volume is constant.

$$A_0 L_0 = AL \tag{4}$$

where A_0 and L_0 are the initial area and length, A and L the final area and length. In Equation 4,

$$A = A_0 - \Delta A = A_0\left(1 - \frac{\Delta A}{A_0}\right) = A_0(1 - \mathrm{RA})$$

$$L = L_0 + \Delta L = L_0\left(1 + \frac{\Delta L}{L_0}\right) = L_0(1 + \delta)$$

where δ is the percent elongation. Substitution of the above into Equation 4 gives

$$\mathrm{RA} = \frac{\delta}{1 + \delta} \tag{5}$$

Substitution of Equation 5 into Equations 2 and 3 gives

$$\sigma_{\mathrm{f}} = \sigma_{\mathrm{b}}\left(1 + \frac{\delta}{1 + \delta}\right) \tag{6}$$

$$\varepsilon_{\mathrm{f}} = \ln(1 + \delta) \tag{7}$$

TABLE II Tensile properties and evaluated values of the test alloy sheets

Alloy	Specimen orientation	σ_b MPa	0.2 YS MPa	δ pct	E GPa	σ_f MPa	ε_f pct	$0.64(E\sigma_f\varepsilon_f)^{1/2}$ MPa
A6	Transverse	526	485	5.46	76.0	555	5.31	956
A7	Transverse	480	433	5.65	76.0	507	5.50	932
A8	Transverse	492	437	6.16	76.0	522	6.00	987
A9	Transverse	500	443	6.85	76.0	534	6.63	1049
A6	Longitudinal	546	505	5.31	76.0	575	5.17	962
A8	Longitudinal	508	452	7.89	76.0	548	7.59	1138

TABLE III Analytical results of the linear correlativity between predicted values and test data for the notch strength of the test alloy sheets

Alloy	Specimen orientation	Correlation coefficient, r	Degree of freedom, $n-2$	Level of significance	t	t_α	Confidence interval
A6	Transverse	−0.703	10	0.05	−3.13	2.23	0.95
A7	Transverse	−0.957	10	0.01	−10.43	3.17	0.99
A8	Transverse	−0.845	10	0.01	−5.01	3.17	0.99
A9	Transverse	−0.923	10	0.01	−7.59	3.17	0.99
A6	Longitudinal	−0.861	10	0.01	−5.35	3.17	0.99
A8	Longitudinal	−0.943	10	0.01	−8.94	3.17	0.99

Substituting Equations 6, 7 and $\alpha = 0.64$ into Equation 1, we can express the notch strength for the test materials by

$$\sigma_N = \frac{0.64\sqrt{E\sigma_b\left(1+\frac{\delta}{1+\delta}\right)\ln(1+\delta)}}{K_t}$$

For simplicity, because the specimens have rather low ductility (see Table II), or $\delta \ll 1$, we can consider $\delta/(1+\delta) \approx \delta$. Thus

$$\sigma_N = \frac{0.64\sqrt{E\sigma_b(1+\delta)\ln(1+\delta)}}{K_t} \tag{8}$$

If the values of σ_b and δ are determined, σ_N can be predicted according to Equation 8 or Equation 1. Table II gives the test data of the smooth specimens and the evaluated values concerned with predicted results of notch strength. The predicted results evaluated according to Equation 8 have been shown in Fig. 2, which should be the straight lines of the ordinate intercept as $0.64\sqrt{E\sigma_f\varepsilon_f}$, and the slope as −1 in double logarithmic coordinate. Since $\sigma_N = \sigma_b$ for the smooth specimens, the values of σ_b should be taken as the upper limits of the applicability of Equation 8, which have been indicated in Fig. 2 by dash-dot lines.

In order to determine the correlativity between predicted notch strength calculated from Equation 8 and the test data, the correlation coefficient, r, between the test data of notch strength and predicted straight line should be evaluated. Therefore, the statistical estimation is performed by using the statistic [26]

$$t = r\sqrt{\frac{n-2}{1-r^2}} \tag{9}$$

where t is the observed value of the random variable T that has a t-distribution with $n-2$ freedom degree and n the number of the test data. The statistical results in the range of K_t from 2.0 to 8.0 are given in Table III.

As may been seen, for the notch strength of all the test materials, there is a significant dependence of the measured data on the predicted lines because the test data under $K_t = 2.0$ to 8.0 agree with Equation 8 to a 99 pct confidence level in all the test alloy sheets when $t < -t_\alpha$ but alloy A6 only in the transverse orientation, where there is agreement to a 95 pct confidence level. In other words, the notch strength for high-strength Al-Li based alloys can be confidently estimated by Equation 8 according to their tensile properties of smooth specimens. Therefore, for the study, the notch strength of the test alloy sheets with various Ce contents can be approximately predicted according to the test results in Table II as follows:

in the transverse orientation,

$$\sigma_N = \frac{(932\text{–}1049)}{K_t}$$

in the longitudinal orientation,

$$\sigma_N = \frac{(962\text{–}1138)}{K_t}$$

4. Stress concentration sensitivity

In engineering applications, it is known that *notch toughness, or notch strength ratio*, defined as σ_N/σ_b is generally to assess the notch sensitivity level under static tensile loading. A material with $\sigma_N/\sigma_b \geq 1$ is not sensitive to the notch; conversely, a material with the ratio $\sigma_N/\sigma_b < 1$ is sensitive to the notch. Based on Equation 1 and the definition of the notch toughness, we have

$$\frac{\sigma_N}{\sigma_b} = \frac{\alpha\sqrt{E\sigma_f\varepsilon_f}}{K_t\sigma_b} \tag{10}$$

If a material is not sensitive to notch, i.e. $\sigma_N/\sigma_b \geq 1$, then

$$K_t \leq \frac{\alpha\sqrt{E\sigma_f\varepsilon_f}}{\sigma_b} \tag{11}$$

At critical, a new materials constant, K_N, may be defined [1]

$$K_N = K_{t(\text{critical})} = \frac{\alpha\sqrt{E\sigma_f\varepsilon_f}}{\sigma_b} \tag{12}$$

where K_N could be called as notch insensitivity factor. Under plane strain state, taking $\alpha = 0.64$ and substituting Equations 6 and 7 into Equation 12, we obtain

$$K_N = \frac{0.64\sqrt{E\sigma_b\left(1 + \frac{\delta}{1+\delta}\right)\ln(1+\delta)}}{\sigma_b}$$

Similarly taking $\delta/(1+\delta) \approx \delta$, we can obtain

$$K_N = \frac{0.64\sqrt{E\sigma_b(1+\delta)\ln(1+\delta)}}{\sigma_b} \tag{13}$$

It may be seen from Equations 11 and 12 that when $K_t \leq K_N$, i.e. $\sigma_N/\sigma_b \geq 1$, the material will not be sensitive to the notch. Conversely, when $K_t > K_N$, i.e. $\sigma_N/\sigma_b < 1$, the material will be sensitive to the notch. If the material is intended to make a practical framework containing a structural notch, it must be noticed that the material may have a high sensitivity to stress concentration at geometric discontinuity. Therefore, an engineering material must have high K_N value to prevent from quickly fracturing caused by stress concentration if the material is intended to make the framework containing structural notches.

According to Equations 8 and 13, $K_t = K_N$ when $\sigma_N = \sigma_b$. As a result, the value of K_N for every test alloy should be the value of K_t corresponding to the intersection of σ_b with the predicted line. The K_N values of all test alloys have been indicated in Fig. 2 by vertical dot lines. Certainly, K_N can also be calculated conveniently by Equation 13 according to the test data in Table II.

On the basis of the discussion above, the relationships of Ce content with K_N for the test materials are evaluated and shown in Fig. 5. Increasing in Ce content enhances K_N whether in transverse orientation or longitudinal orientation of the test sheets. This can be attributed to an improvement on the percent elongation by means of Ce microalloying (see Tables I and II).

Usually, the K_t value is approximate to 3.0 if there is a structural notch as a round hole in a large enough panel produce [24, 27]. Therefore, the K_N value for the structural materials intended to make aircraft structures should generally be higher than 3.0 in order to ensure that the crack initiation does not occur at notch root during the flight with possibly overloading status and thus the quick fracture can be prevented. However, the values of K_N for the test materials are only below 2.5 while those of conventional aluminum alloys are

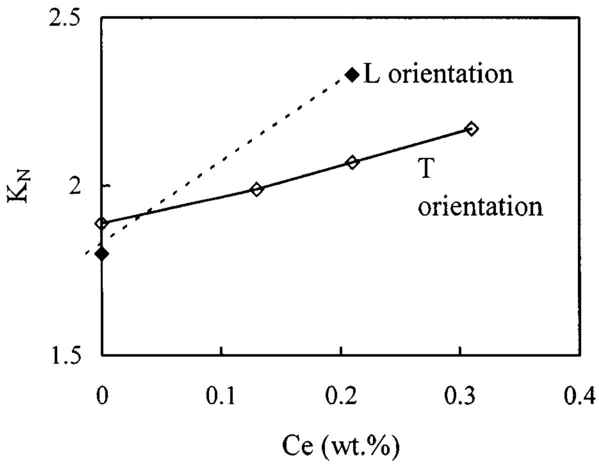


Figure 5 Effect of Ce content on notch insensitivity factor.

over 5.5 [1]. In other words, the high strength alloy 2090 still has poor ductility consequently to result in a high notch sensitivity even though its percent elongation can be improved to a certain degree by adding a minor amount of Ce element. This is still a troublesome problem with possible practical applications of the high-strength Al-Li based alloys in primary aircraft structures.

5. Conclusions

On the basis of the experimental results and analysis, the conclusions can be drawn as follows:

1. Adding Ce element from 0.13 wt. pct to 0.31 wt. pct in the alloy 2090 sheets can reduce the level of stress concentration sensitivity to a certain degree, but produce an insignificant effect on the notch strength.

2. The notch strength of the alloy 2090 sheets with various Ce contents can be expressed or predicted as follows:

$$\sigma_N = \frac{0.64\sqrt{E\sigma_b(1+\delta)\ln(1+\delta)}}{K_t}$$

3. The stress concentration sensitivity of the alloy 2090 sheets with various Ce contents can be quantitatively assessed by the so-called notch insensitivity factor defined as follows:

$$K_N = \frac{0.64\sqrt{E\sigma_b(1+\delta)\ln(1+\delta)}}{\sigma_b}$$

4. Ce modification can not essentially decrease the notch sensitivity of the alloy 2090 sheets although Ce microalloying improves the ductility to a certain degree. Therefore, high level of stress concentration sensitivity may be a noteworthy problem or a potential obstruction to the practical application of high-strength Al-Li based alloys in aircraft frameworks.

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