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ARTICLE

Mechanical Properties and Planar Anisotropy of TC1 Titanium Alloy Sheet

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Abstract: This paper investigated the main mechanical properties of TC1 titanium alloy sheets with different thicknesses, and a useful function that can describe the mechanical properties reasonably was used. Moreover, planar anisotropies of above TC1 titanium alloy sheets were studied by Barlat'89 and Yld2000-2d yield functions. The influence of *M* value was analyzed on describing ability for distribution characteristics of material yield stress and anisotropic coefficient, and their performances were compared on the titanium alloy sheets.

Key words: TC1; mechanical properties; yield function

Titanium and its alloys are widely used in aerospace, biomedical, defense and energy industry due to their high strength-mass ratio, corrosion resistance, biocompatibility and heat resistance[1]. Particularly, in the application of aeronautics and astronautics, mass reduction can enhance aircraft performances, and reduce manufacturing cost[2].

Owing to the inherent crystallographic texture and rolling process, TC1 titanium alloy sheet exhibits strong planar plastic anisotropy[3]. Therefore, research on the mechanical properties in a certain direction is not enough to describe the material properties clearly.

When studying the mechanical properties, especially for strong plastic anisotropy, many anisotropic yield functions such as Hill (1948), Hill (1979), Barlat and Lian (1989), Barlat et al. (2003), Plunkett et el. (2008)[4-8] have been developed so far.

One objective of the paper is to select a function model which can predict the mechanical properties of the TC1 titanium alloy in any direction reasonably. Another one is to evaluate the performance of two widely used anisotropic yield functions, Barlat'89 and Yld2000-2d, in describing the plastic planar anisotropy of the TC1 titanium alloy sheets.

The exponent *M* in Barlat'89/Yld2000-2d yield function is related to crystallographic structure of the material, whose value is 8 for face-centered cubic (fcc) materials and 6 for body-centered cubic (bcc) materials. For (hexagonal close packed) HCP metal, such as TC1, the value of *M* is unknown. In the present paper, a reasonable value of exponent *M*, which can describe plastic anisotropy more accurately, will be discussed by calculation, analysis, and experimental data.

1 Experiment

Up to now, extensive experimental observations have demonstrated that the mechanical properties of Ti titanium alloy sheet represent a strong plastic anisotropy[9]. In this paper, TC1 titanium alloy sheet with three different thicknesses were selected, and its components are listed in Table 1.

The dimensions of the specimen for tensile tests are shown in Fig.1. Specimens with thickness 0.6 and 0.8 mm were extracted at 5 different angles with intervals of 22.5 °, 0 ° (rolling direction), 22.5 °, 45 °(diagonal direction), 67.5 ° and 90 °(transverse direction).

A universal testing machine was used to measure the yield stress $\sigma_{0.2}$, the ultimate tensile strength σ_b, the uniform tensile strain ε_u, the percentage area reduction Φ_f, and the anisotropic index $r_{p\max}$ ($r=\varepsilon_b/\varepsilon_t$) under the maximum

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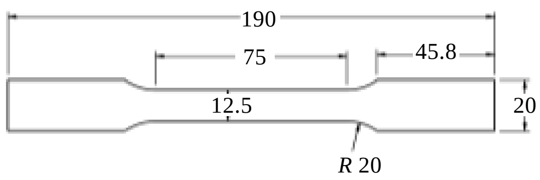

Fig.1 Schematic of the specimen geometry

load. Table 2~Table 4 list material properties obtained by above experiments.

Based on Table 2, for the TC1 titanium alloy sheet of 0.6 mm and 0.8 mm thickness, the highest value of σ_b is in the rolling direction, the second in the transverse direction, and the lowest in the diagonal direction. According to the difference between the rolling and transverse direction, the lowest value should exist in a direction, which is greater than 45 °.

However, there is a different result for the 2.0 mm thickness. The value of σ_b along the transverse direction is the highest, the second is in the rolling, and the lowest is in the diagonal direction.

For the value of ε_u, the range of the present paper is bigger than other experimental material values, and the reason may be the influence of the experimental error.

In Table 4, one can draw a conclusion that for the TC1 titanium alloy sheet of 0.6 and 0.8 mm in thickness, the value of Φ_f increases as the angle between the tensile direction and rolling direction increases. For the thickness of 2.0 mm, the value of Φ_f along the rolling direction is the smallest.

Table 1 Chemical composition of TC1 alloy sheet (wt%)

Thickness/mm	C	Mn	Si	Fe	Al	N	H	O	Ti
0.6	0.09	1.54	0.09	0.055	1.75	0.025	0.0084	0.12	Balance
0.8	<0.047	1.51	0.10	0.03	1.66	0.017	0.0044	0.103	Balance
2.0	0.07	1.37	0.03	0.07	1.43	0.027	0.0105		Balance

Table 2 Values of σ_b in uniaxial experiments

Loading dir.	Thickness /mm	Range /MPa	Average /MPa
Rolling direction	0.6	729~733	731
Diagonal direction	0.6	696~700	697
Transverse direction	0.6	711~718	714
Rolling direction	0.8	710	710
Diagonal direction	0.8	672~680	675
Transverse direction	0.8	685~687	686
Rolling direction	2.0	823~827	825
Diagonal direction	2.0	795~805	800
Transverse direction	2.0	854~871	863

Table 3 Values of ε_u in uniaxial experiments

Loading dir.	Thickness /mm	Range /%	Average /%
Rolling direction	0.6	10.8~11.8	11.3
Diagonal direction	0.6	8.8~10.0	9.3
Transverse direction	0.6	7.3~9.4	8.1
Rolling direction	0.8	13.0~14.0	13.5
Diagonal direction	0.8	9.8~10.3	10.07
Transverse direction	0.8	7.2~7.6	7.4
Rolling direction	2.0	9.3~9.4	9.3
Diagonal direction	2.0	5.0~7.3	5.8
Transverse direction	2.0	4.0	4.0

Table 4 Values of Φ_f in uniaxial experiments

Loading dir.	Thickness /mm	Range /%	Average /%
Rolling direction	0.6	43.9~44.8	44.2
Diagonal direction	0.6	47.2~49.1	48.3
Transverse direction	0.6	51.9~53.4	52.4
Rolling direction	0.8	43.6~45.3	44.2
Diagonal direction	0.8	47.47~47.54	47.5
Transverse direction	0.8	51.0~53.0	52.0
Rolling direction	2.0	37.5~37.9	37.7
Diagonal direction	2.0	50.3	50.3
Transverse direction	2.0	42.9~48.0	45.6

2 A Useful Function Model

On the above analysis related to the material properties along three directions, a useful function model was used to describe the mechanical properties in any direction.

According to experimental phenomenon of the deep drawing for TC1 cylindrical parts, the deformation has a symmetric feature in the rolling and transverse directions. In other words, the mechanical properties along the rolling direction and the transverse direction have extreme values. Meanwhile, for the anisotropy materials, it's enough to represent material properties of any direction just in one quadrant. Therefore, the distribution of the mechanical properties should be a function of $\cos 2n\theta$, where θ is the angle between a certain direction and the rolling direction, and n is a positive integer.

In addition, as mentioned before, many kinds of properties have a maximum or minimum value in a certain direction that is larger or smaller than 45 °. It means that the mechanical property has another extreme value between 0 °~90 °.

Consequently, the easiest function, describing the distribution of mechanical properties, should be expressed as follows:

$$A = A_{cp} + A_2 \cos 2\theta + A_4 \cos 4\theta \quad (1)$$

Where A is some kind of mechanical property, such as σ_b, $\sigma_{0.2}$, Φ_f. A_{cp} is the average value of this property. A_2, A_4 are two coefficients calculated by the experimental data in the rolling, transverse and diagonal directions. Taking a derivative of Eq. (1) with respect to θ, the result is shown in Eq.(2):

$$dA/d\theta = -2A_2\sin 2\theta - 4A_4\sin 4\theta = -2(A_2 + 4A_4\cos 2\theta)\sin 2\theta \quad (2)$$

We can get $dA/d\theta=0$, when θ=0, π/2, π, 3π/2, 2π. This satisfies the condition that the mechanical properties have extreme values in rolling and transverse directions. Furthermore, if α also satisfies the above condition, we obtain Eq.(3)

$$\cos 2\theta|_{\theta=\alpha} = \cos 2\alpha = -A_2/4A_4 \quad (3)$$

Where α represents a direction between 0 °~90 °and $dA/d\theta$ is equal to 0. Therefore, as long as $A_4 \neq 0$, there must exists another extreme point in a direction between 0 °to 90 °. The maximum or minimum value is shown in Eq.(4):

$$A_{max} \text{ or } A_{min} = A_{cp} - A_4(1 + 2\cos^2 2\alpha) \quad (4)$$

The A_{cp}, A_2 and A_4 are given by Eq.(5):

$$A_{cp} = (A_{0°} + 2A_{45°} + A_{90°})/4 \quad (5a)$$

$$A_2 = (A_{0°} - A_{90°})/2 \quad (5b)$$

$$A_4 = (A_{0°} + A_{90°} - 2A_{45°})/4 \quad (5c)$$

In this paper, $A_{0°}$, $A_{45°}$ and $A_{90°}$ represent the mechanical properties in three different directions, respectively.

The effectiveness of the trigonometric function mentioned above has been demonstrated in related Ref.[9].

3 Performance of Two Yield Functions

All parameters of these yield functions, Barlat’89 and Yld2000-2d, are obtained from the *r* values and the values of yield stress in three directions. These values with three different thicknesses are listed in Table 5~Table 7.

3.1 Fundamental review on anisotropic yield functions

For describing the plastic anisotropy of TC1 titanium alloy sheet, it is essential to select a suitable yield criterion. Two widely used anisotropic yield functions, Barlat'89 and Yld2000-2d, were chosen to investigate the planar anisotropy of TC1. The first yield function needs a small number of experimental data required for calibration. The second one requires more material data to identify the anisotropy coefficients and thus it is more flexible than the first one.

Barlat et al. have made a significant contribution to anisotropic yield criteria such as Barlat’89 and Yld2000-2d. Because its expression format is simple and its anisotropy parameter can be obtained easily, Barlat’89 yield criterion is used widely for anisotropic material in numerical simulation. In plane stress condition, Barlat’89 is expressed as in Eq.(6)

$$f = a|K_1 + K_2|^M + a|K_1 - K_2|^M + c|2K_2|^M = 2\bar{\sigma}^M \quad (6a)$$

with

$$K_2 = \sqrt{\left(\frac{\sigma_{xx} - h\sigma_{yy}}{2}\right)^2 + p^2\sigma_{xy}^2} \qquad K_1 = \frac{\sigma_{xx} + h\sigma_{yy}}{2} \quad (6b)$$

Where *a*, *c*, *h*, and *p* are material constants. The exponent *M* is typically chosen based on the crystal plasticity calculations of Logan and Hosford[10]. Following their recommendation for crystallographic structure material, the values of *M* is 8 for body-centered cubic (bcc) and 6 for face-centered cubic (fcc) materials[11]. For hcp metal, such as TC1, the value of *M* is unknown. It is recommended for 8~12 by Guo et al[12].

Yld2000-2d yield function is expressed as in Eq.(7), where recommended values of the exponent *M* is 8 for face-centered cubic (fcc) materials and 6 for body -centered cubic (bcc) materials.

$$\phi = |X_1' - X_2'|^M + |2X_2'' + X_1''|^M + |2X_1'' + X_2''|^M = 2\bar{\sigma}^M \quad (7)$$

where, X_j'' and X_k'' are the principle values of X' and X'' defined as

$$X' = C's = C'T\sigma = L'\sigma \quad (7a)$$

$$X'' = C''s = C''T\sigma = L''\sigma$$

With

$$\begin{bmatrix} L'_{11} \\ L'_{12} \\ L'_{21} \\ L'_{22} \\ L'_{66} \end{bmatrix} = \begin{bmatrix} 2/3 & 0 & 0 \\ -1/3 & 0 & 0 \\ 0 & -1/3 & 0 \\ 0 & 2/3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_7 \end{bmatrix} \quad \begin{bmatrix} L''_{11} \\ L''_{12} \\ L''_{21} \\ L''_{22} \\ L''_{66} \end{bmatrix} = \frac{1}{9} \begin{bmatrix} -2 & 2 & 8 & -2 & 0 \\ 1 & -4 & -4 & 4 & 0 \\ 4 & -4 & -4 & 1 & 0 \\ -2 & 8 & 2 & -2 & 0 \\ 0 & 0 & 0 & 0 & 9 \end{bmatrix} \begin{bmatrix} \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \\ \alpha_8 \end{bmatrix} \quad (7b)$$

This yield criterion is isotropic if the anisotropy coefficient α_i (for *i* from 1 to 8) decreases to 1. Uniaxial tension tests along the rolling, diagonal and transversal direction provide six input data points (σ_0 , σ_{45}, σ_{90}, r_0 ,

Table 5 Experimental values of material parameters for TC1 titanium alloy sheet of 0.6 mm thickness

	r_0	r_{45}	r_{90}	σ_0/MPa	σ_{45}/MPa	σ_{90}/MPa
Numerical range	2.05~1.37	2.95~3.56	3.00~3.20	512~514	507~507.5	562~588
Average	2.21	3.26	3.10	513	507	575

Table 6 Experimental values of material parameters for TC1 titanium alloy sheet of 0.8 mm thickness

	r_0	r_{45}	r_{90}	σ_0/MPa	σ_{45}/MPa	σ_{90}/MPa
Numerical range	2.05~2.24	3.96~4.07	3.20~3.28	553~565	531~538	555
Average	2.16	4.0	3.24	559	534	555

Table 7 Experimental values of material parameters for TC1 titanium alloy sheet of 2.0 mm thickness

	r_0	r_{45}	r_{90}	σ_0/MPa	σ_{45}/MPa	σ_{90}/MPa
Numerical range	0.73~0.78	2.05~2.1	2.0~2.05	625~644	650~676	677~685
Average	0.75	2.1	2.05	635	663	681

Table 8 Anisotropic coefficients for Barlat'89 yield function

Thickness/mm	a	h	p (M=8)	p (M=10)	p (M=12)
0.6	0.5570	0.9542	1.0264	1.0282	1.0298
0.8	0.5546	0.9458	1.0635	1.0668	1.0696
2.0	0.9266	0.7985	0.9889	0.9918	0.9940

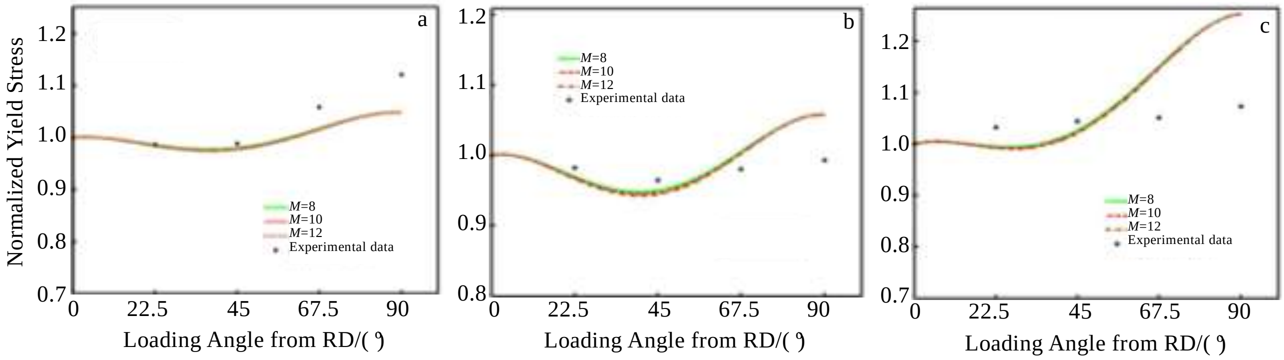

Fig.2 Comparison of experimental and predicted yield stress distribution: (a) 0.6 mm, (b) 0.8 mm, and (c) 2.0 mm

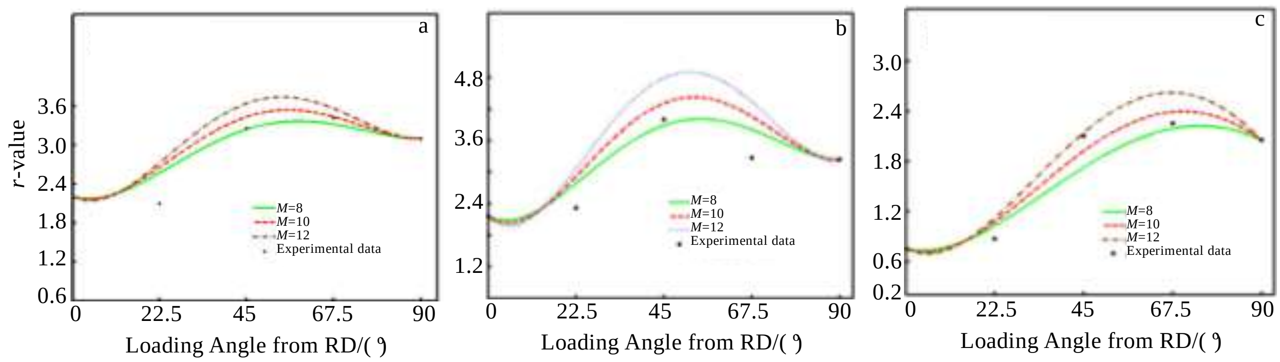

Fig.3 Comparison of experimental and predicted r values distribution: (a) 0.6 mm, (b) 0.8 mm, and (c) 2.0 mm

r_{45} and r_{90}) to determine the coefficients of the Yld2000-2d yield function. The ratio of the bi-axial yield stress to yield stress in rolling direction, σ_b/σ_0, is additionally required to calibrate the Yld2000-2d yield function [7]. However, in this paper, considering the limitation of experimental condition, the value of σ_b was estimated on the average of σ_0 and σ_{90}. In this way, only seven coefficients are needed to account for the seven input data mentioned above. The eighth coefficient was identified using the practical assumption, $L''_{12}=L''_{21}$ following Yoon et al[13].

3.2 Evaluation of different exponent *M* in Barlat'89 yield function

For Barlat'89 yield function, the parameter p varies with the change of M. As the method mentioned in Section 3.1, using r values along $0^\circ, 45^\circ, 90^\circ$, the material coefficients for TC1 sheet sample are listed in Table 8.

Fig.2 shows the predictions of the yield stress distribution. No matter which value of M is chosen, their performances to describe the plastic anisotropy of the target materials are the same. The comparisons of the r value distribution are plotted in Fig.3 for 0.6 mm, 0.8 mm and 2.0 mm. It is noted that the Barlat'89 yield model with M= 8 shows better agreements with experiments than the other two exponents.

In conclusion, the result from Barlat'89 criterion with M=8 exhibits much better agreement with experiments than other two M values. But the r values and the yield stress distribution can't be more accurately described. Therefore, Yld2000-2d yield function also needs to be chosen to evaluate its performance to describe the plastic anisotropy of this material.

3.3 Evaluation of different exponent *M* in Yld2000-2d yield function

As mentioned in Section 3.1. Yld2000-2d yield function requires more material data to identify the anisotropy coefficients.

The same problem occurs in Yld2000-2d yield function, because the parameter α_i is varied with the change of M, which affects the predicted effect. The anisotropy coefficients of the Yld2000-2d yield criterion are tabulated at various exponents *M* in Tables 9~11 for thickness 0.6, 0.8 and 2.0 mm.

As shown in Fig.4 and Fig.5, the value of *M* does not much influence the performance to describe the plastic anisotropy of the target materials. However, it should be noted that the predicted yield stress distribution is less accurate than the other two when *M*=12. So, in the following comparison among different yield criterions, the value of *M* can be determined to be 8.

4 Evaluation of Anisotropic Yield Criteria

Experimental data required for the calculation of the coefficients in different yield functions are summarized in Tables 5~7 for 0.6 mm, 0.8 mm, and 2.0 mm respectively.

The performance of the yield criteria was evaluated by comparison of the yield stress and *r* value with experimental data and the trigonometric function method as Eq.(1). The comparisons of *r* value are illustrated in Fig.6 for 0.6, 0.8, and 2.0 mm. In conclusion, the trigonometric function coincides with the experimental data and two yield criteria. All three predicted methods above do not show a significant difference in the prediction of *r* value, especially using them in 0.6 mm thickness. By contrast, the

Table 9 Anisotropic coefficients for YLD2000-2D yield function when exponent *M* is 8

Thickness/mm	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8
0.6	1.1916	0.7983	1.0362	0.8882	0.9199	1.0045	1.0673	0.8855
0.8	1.0109	1.0991	1.1039	0.9458	0.9761	1.0736	1.1029	0.8244
2.0	0.9756	0.9701	1.0232	0.9129	1.0006	0.9356	0.9988	0.8330

Table 10 Anisotropic coefficients for YLD2000-2D yield function when exponent *M* is 10

Thickness/mm	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8
0.6	1.1719	0.7967	1.0225	0.8928	0.9331	0.9822	1.0550	0.9276
0.8	1.0083	1.0794	1.0807	0.9596	0.9809	1.0593	1.0887	0.8766
2.0	1.0012	0.9417	1.0119	0.9219	0.9963	0.9375	0.9988	0.8586

Table 11 Anisotropic coefficients for YLD2000-2D yield function when exponent *M* is 12

Thickness/mm	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8
0.6	1.1598	0.7951	1.0136	0.8959	0.9413	0.9682	1.0470	0.9549
0.8	1.0062	1.0671	1.0662	0.9682	0.9843	1.0501	1.0796	0.9105
2.0	1.0157	0.9254	1.0057	0.9269	0.9940	0.9386	0.9840	0.8749

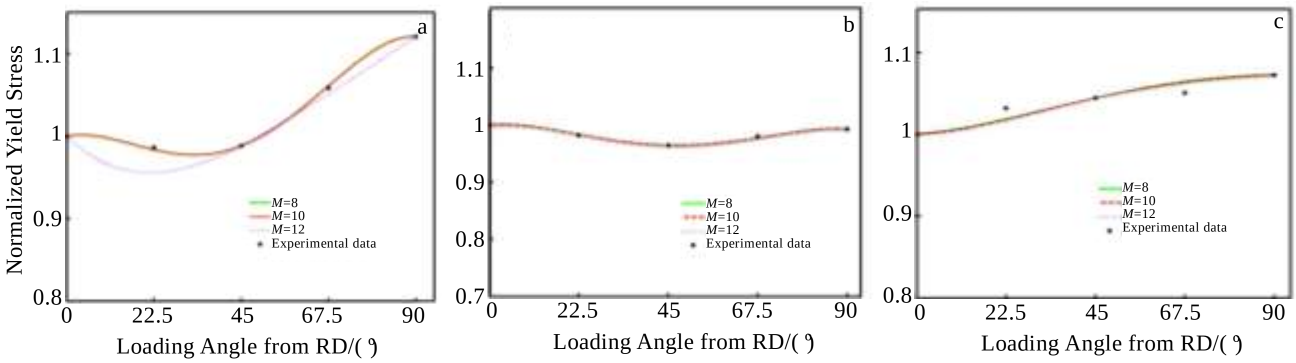

Fig.4 Comparison of experimental and predicted yield stress distribution: (a) 0.6 mm, (b) 0.8 mm, and (c) 2.0 mm

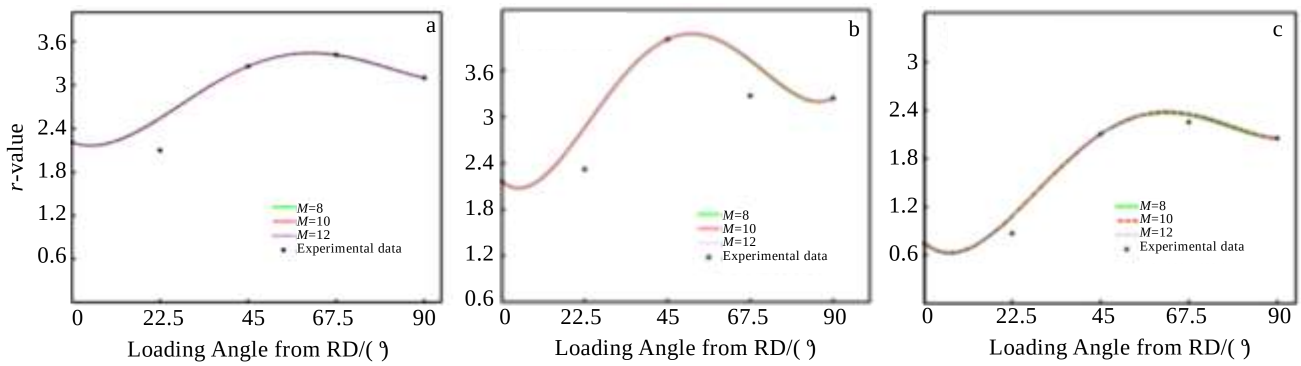

Fig.5 Comparison of experimental and predicted *r* values distribution: (a) 0.6 mm, (b) 0.8 mm, and (c) 2.0 mm

results at 2.0 mm thickness are not so coincident. For the sheet of 0.8 mm thickness, the theoretically calculated planar distributions of the *r* value have a greater deviation with the experimental data. It should be noted that the trigonometric function is simple and easy to predict any mechanical properties. What is more, as shown in Fig. 6, the precision of trigonometric function has a very small difference with Barlat'89 yield criterion for predicting *r* value.

The comparisons of yield stress are illustrated in Fig.7. The distribution calculated with Yld2000-2d, however, displays a strong consistency with the experimental yield stress distribution.

Concerning the TC1 titanium alloy sheet of 0.6 mm and 0.8 mm in thickness, the distribution calculated with Yld2000-2d-2d and trigonometric function displays a strong consistency with the experimental yield stress distribution. About the TC1 titanium alloy sheet of 2.0 mm, results from all yield criteria differ from the experimental value except the Yld2000-2d yield criteria.

This clarifies that the yield criterion based on Yld2000-2d can better describe the plastic anisotropy of the TC1 titanium alloy sheet than other methods despite of its complicated formulation. Therefore, Yld2000-2d yield criterion will be the best method to describe the anisotropic yield locus until now.

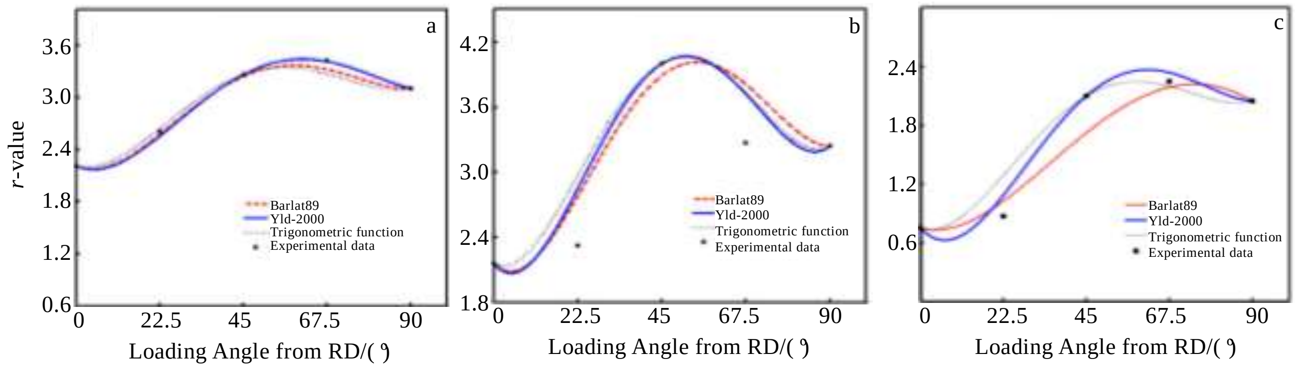

Fig.6 Comparisons of the *r*-value: (a) 0.6 mm, (b) 0.8 mm, and (c) 2.0 mm

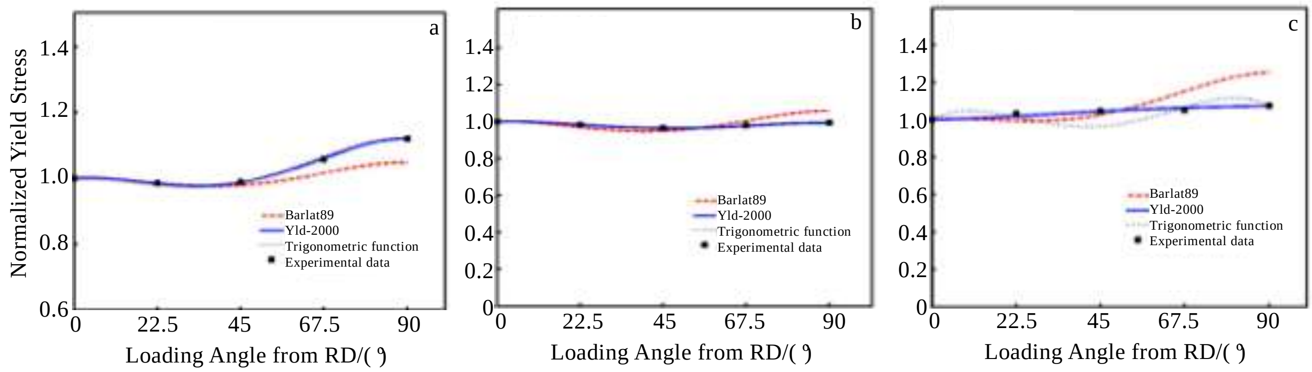

Fig.7 Comparisons of the yield stress distribution: (a) 0.6 mm, (b) 0.8 mm, and (c) 2.0 mm

5 Conclusions

1) A trigonometric function can be used to predict mechanical properties in any direction reasonably.

2) For TC1 titanium alloy sheet, Barlat'89 yield model with $M = 8$ shows better agreements with experiments than the other two exponents. For Yld2000-2d yield model, no matter which value of M is chosen, the performances of M to describe the plastic anisotropy of the target materials are the same.

3) Yld2000-2d yield function can be used to accurately describe the plastic anisotropy of the TC1 titanium alloy sheet.

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TC1 钛合金板的机械性能和面内各向异性

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摘　要：首先全面研究了不同厚度TC1钛合金板料在不同方向的机械性能。在此基础上，介绍了一种能够有效描述不同厚度下的TC1钛合金板料机械性能分布规律的三角函数。此外，重点分析研究了Barlat'89和Yld2000-2d屈服准则中指数*M*对材料屈服应力和厚向异性指数分布规律描述能力的影响，并比较了上述2种屈服准则对不同厚度TC1钛合金板料的适应性。

关键词：TC1; 机械性能; 函数模型

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