Yield Loci of TRIP590 Advanced High Strength Steel Based on Biaxial Loading Test

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(Received 19 April 2018; revised 30 September 2018; accepted 4 July 2019)

Abstract: The main purpose of the paper is to obtain the experimental yield loci of TRIP590 advanced high strength steel, and to compare it with the theoretical loci in order to obtain the best yield criterion for this material. First, the biaxial loading tests under different loading paths in the method of load control are carried out. Then, the experimental yield loci of different deformation stages are obtained. Finally, the experimental yield loci are compared with the theoretical loci of Mises criterion and Hill48 criterion, the parameters of which are calculated based on the *r*-value and the yield stress method, respectively. The results show that the accuracy of the theoretical yield loci of Hill48 based on the yield stress is higher than that of Mises criterion and Hill 48 criterion based on *r*-value method.

Key words: TRIP590 advanced high strength steel; yield locus; yield criterion

CLC number: TG142.1 **Document code**: A **Article ID**: 1005-1120(2019)04-0686-07

0 Introduction

In recent years, the sheet metal forming technology has been very important in the automotive, aerospace and other industrial production and processing areas. As a new material in sheet metal forming, the transformation-induced plasticity (TRIP) steel is mainly used on automobile baffles, classic components and door impact beams. However, the related theory of forming and application is not mature enough, which seriously restricts the application of TRIP steel sheet in sheet metal forming. After the TRIP steel is rolled into sheet metal, the sheet material will show anisotropy due to the production and processing. Anisotropy makes the sheet possess different mechanical properties in different directions. Therefore, it affects the initial yield and subsequent yield of the sheet, which will affect the calculation of the stress-strain relationship in sheet metal forming. If the yield loci of the sheet material can be determined, the corresponding yield criterion can be determined. Combined with a certain intensity law, the corresponding constitutive relation can be deduced according to the Drucker formula, so that the stress-strain behavior of the sheet in the deformation can be predicted[1-3].

Scholars at home and abroad have conducted many studies on the yield criterion of anisotropy. The earliest research on the yield behavior of anisotropic sheet began with R. Hill's Hill48 anisotropic yield criterion proposed in 1948, followed by yield rules such as Hill90, Hosford and Barlat89[4-5]. In China, Wang et al.[6] studied the variation of yield loci under the condition of axisymmetric plane stress and further quantitatively analyzed the variation rule of the yield track of the thin cylinder under the steady state forming process. Tan et al.[7] studied the yield loci of orthotropic materials, on the basis of the original parametric equation, and the Hill criterion of plane stress state is further studied. These new yield criteria improve the theoretical description of the yield behavior of anisotropic sheets, but some

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How to cite this article: GUAN Yanzhi, LI Jiaxin, WANG Haibo, et al. Yield Loci of TRIP590 Advanced High Strength Steel Based on Biaxial Loading Test[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2019,36(4): 686-692.
http://dx.doi.org/10.16356/j.1005-1120.2019.04.016

of the outstanding problems that follow are the scope and application of these yield rules. The team of Prof. Wan from Beihang University[1-3,8-9] took the lead in the development of two-way loading test machine and related experimental research, and carried out a series of theoretical and experimental studies on yield criteria.

In this paper, on the cross-shaped biaxial tensile test system, the bipolar tensile test under different loading paths is carried out on the TRIP590 steel plate using a slit-shaped cross-shaped test piece[8]. In this way, the experimental yield trajectory under tensile loading is determined, and the experimental yield trajectory is compared with the most commonly used theoretical yield criterion (Mises yield criterion and Hill48 yield criterion) in the current industry, to determine the most suitable yield criterion for TRIP590 advanced high strength steel.

1 Determination of Parameters of Hill48 Yield Function

Hill48 yield criterion function is shown as

$$F(\sigma_{yy}-\sigma_{zz})^2+G(\sigma_{zz}-\sigma_{xx})^2+H(\sigma_{xx}-\sigma_{yy})^2+ 2L\sigma^2_{yz}+2M\sigma^2_{zx}+2N\sigma^2_{xy}=\bar{\sigma}^2 \tag{1}$$

where x, y and z are orthodontic principal axes; F, G, H, L, M and N are mutually independent anisotropic characteristic parameters, which are determined by experiments according to different materials; and $\bar{\sigma}$ is the equivalent stresses. When $3F=3G=3H=L=M=N$, Eq. (1) becomes the Mises yield criterion for describing isotropic materials.

For the sheet, the forming process is often in a plane stress state, i.e. σ_{zz}, σ_{zx} and σ_{yz} are zero. And x, y and z are anisotropic principal axes, then Eq.(1) is

$$f=(G+H)\sigma^2_{xx}-2H\sigma_{xx}\sigma_{yy}+ (H+F)\sigma^2_{yy}+2N\sigma^2_{xy}=\bar{\sigma}^2 \tag{2}$$

If the material is in the principal stress state, when the principal axis of the stress state coincides with the anisotropy major axis, σ_{zz}, σ_{zx}, σ_{yz} and σ_{xy} are zero, and Eq.(1) is simplified to

$$F(\sigma_2-\sigma_3)^2+G(\sigma_3-\sigma_1)^2+H(\sigma_1-\sigma_2)^2=\bar{\sigma}^2 \tag{3}$$

The corresponding plane stress state expression is

$$(G+H)\sigma_1{}^2-2H\sigma_1\sigma_2+(H+F)\sigma_2{}^2=\bar{\sigma}^2 \tag{4}$$

1.1 Solution of parameters based on yield stress

According to the anisotropic Hill48 yield criterion expression (Eq. (2)) under plane stress state, the x and y directions are assumed to be the rolling direction and the vertical rolling direction, respectively.

The rolling direction is taken as the reference direction, that is, the yield stress σ_0 in the rolling direction is taken as the reference stress, so that

$$\sigma_{xx}=\sigma_0=\bar{\sigma} \tag{5}$$

From Eq.(2), we may have

$$G+H=1 \tag{6}$$

Assume that the uniaxial tensile yield stress in the vertical rolling direction is σ_{90}, at this time, $\sigma_{xx}=\sigma_{xy}=0$, according to Eq.(2) and Eq.(5), we have

$$H+F=\frac{\sigma^2{}_0}{\sigma^2{}_{90}} \tag{7}$$

Assume the double tensile yield stress be σ_b, in this case, $\sigma_{xx}=\sigma_{yy}=\sigma_b$, $\sigma_{xy}=0$, by combining Eqs.(2) and (5), we have

$$G+F=\frac{\sigma_0^2}{\sigma_b^2} \tag{8}$$

The uniaxial tensile yield stress in the direction of 45° with the rolling direction is σ_{45}. According to the knowledge of material mechanics, the uniaxial tensile stress in the 45° direction can be converted into bidirectional isotropic and shear stress, so

$$\sigma_{xx}=\sigma_{yy}=\sigma_{xy}=\frac{\sigma_{45}}{2} \tag{9}$$

According to Eqs.(2), (5) and (9), we have

$$G+F+2N=\frac{4\bar{\sigma}^2}{\sigma_{45}{}^2} \tag{10}$$

Available from Eqs. (6)—(8) and (10), we have

$$F=\frac{1}{2}\left[\left(\frac{\sigma_0}{\sigma_{90}}\right)^2-1+\left(\frac{\sigma_0}{\sigma_b}\right)^2\right] \tag{11}$$

$$G=\frac{1}{2}\left[1-\left(\frac{\sigma_0}{\sigma_{90}}\right)^2+\left(\frac{\sigma_0}{\sigma_b}\right)^2\right] \tag{12}$$

$$H=\frac{1}{2}\left[1+\left(\frac{\sigma_0}{\sigma_{90}}\right)^2-\left(\frac{\sigma_0}{\sigma_b}\right)^2\right] \tag{13}$$

$$N=\frac{1}{2}\left[\left(\frac{2\sigma_0}{\sigma_{45}}\right)^2-\left(\frac{\sigma_0}{\sigma_b}\right)^2\right] \tag{14}$$

1.2 Solution of parameters based on *r* value

The r value during uniaxial stretching characterizes the deformation anisotropy of the sheet. Assumed that the anisotropy indices measured by uniaxial stretching along the reference direction (rolling direction), the vertical rolling direction and the 45° direction are r_0, r_{90} and r_{45}, respectively. According to the definition of the anisotropy index, we have

$$r_0=\frac{\varepsilon_{yy}}{\varepsilon_{zz}} \tag{15}$$

where ε_{yy} and ε_{zz} are plastic strains in the width direction and the thickness direction, respectively, when uniaxially stretched in the rolling direction.

According to the assumption that the plastic deformation volume is constant, there is

$$\sigma_{yy}=\sigma_{xy}=0 \tag{16}$$

Available from Eqs.(15) and (16), we have

$$r_0=\frac{\varepsilon_{yy}}{-(\varepsilon_{xx}+\varepsilon_{yy})} \tag{17}$$

According to Drucker

$$\mathrm{d}\varepsilon_{xx}=\mathrm{d}\lambda\frac{\partial f}{\partial\sigma_{xx}} \tag{18}$$

$$\mathrm{d}\varepsilon_{xx}=\mathrm{d}\lambda\frac{\partial f}{\partial\sigma_{xx}} \tag{19}$$

$$\mathrm{d}\gamma_{xy}=\mathrm{d}\lambda\frac{\partial f}{\partial\sigma_{xy}} \tag{20}$$

The uniaxial stretching process is proportional loading, so that

$$\frac{\mathrm{d}\varepsilon_{xx}}{\mathrm{d}\varepsilon_{yy}}=\frac{\varepsilon_{xx}}{\varepsilon_{yy}} \tag{21}$$

Uniaxial stretching in rolling direction means $\sigma_{yy}=\sigma_{xy}=0$.

Available from Eqs.(2) and (17)—(21), we have

$$r_0=\frac{H}{G} \tag{22}$$

Similarly available

$$r_{90}=\frac{\varepsilon_{xx}}{-(\varepsilon_{xx}+\varepsilon_{yy})}=\frac{H}{F} \tag{23}$$

According to the knowledge of material mechanics, the uniaxial tension in the 45° direction can be decomposed into two-way isotropic and shear forces, and the stress relationship is shown in Eq.(9). According to the anisotropy index definition, the anisotropy index when uniaxial tensile test is carried out in the 45° direction is

$$r_{45}=\frac{\varepsilon_{135}}{\varepsilon_{zz}} \tag{24}$$

According to the assumption that the plastic deformation volume is constant, we have

$$\varepsilon_{45}+\varepsilon_{135}+\varepsilon_{zz}=0 \tag{25}$$

So that

$$r_{45}=\frac{\varepsilon_{135}}{\varepsilon_{zz}}=\frac{\varepsilon_{135}}{-(\varepsilon_{45}+\varepsilon_{135})} \tag{26}$$

According to the strain Mohr circle rule

$$\varepsilon_{135}=\frac{1}{2}(\varepsilon_{xx}+\varepsilon_{yy}-\gamma_{xy}) \tag{27}$$

$$\varepsilon_{45}=\frac{1}{2}(\varepsilon_{xx}+\varepsilon_{yy}+\gamma_{xy}) \tag{28}$$

Available from Eqs.(26)—(28), we have

$$r_{45}=\frac{\varepsilon_{xx}+\varepsilon_{yy}-\gamma_{xy}}{-2(\varepsilon_{xx}+\varepsilon_{yy})} \tag{29}$$

It is also available from Drucker (Eqs.(18)—(20) and (21)), i.e.

$$r_{45}=\frac{F+G-2N}{-2(G+F)} \tag{30}$$

Available from Eqs.(6), (22), (23), and (30), we have

$$F=\frac{r_0}{(1+r_0)r_{90}} \tag{31}$$

$$G=\frac{1}{1+r_0} \tag{32}$$

$$H=\frac{r_0}{1+r_0} \tag{33}$$

$$N=\frac{(1+2r_{45})(r_0+r_{90})}{2(1+r_0)r_{90}} \tag{34}$$

2 Experiment Materials and Methods

2.1 Materials

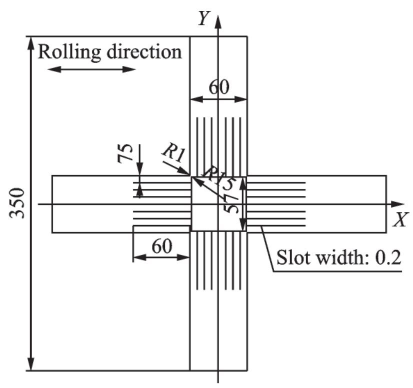
TRIP590 steel is adopted in the experiment. The chemical composition is shown in Table 1.

Table 1 Chemical components of TRIP590 steel (mass fraction) %

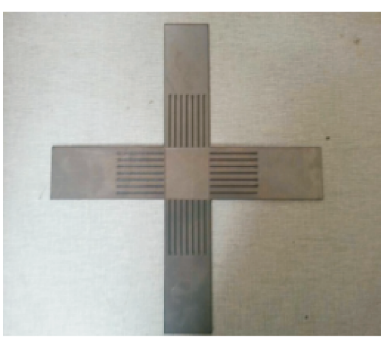
Steel No.	C	Si	Mn	S	P
TRIP590	0.1—0.14	0.4—0.6	1.5—1.8	0.01	0.05

2.2 Experimental method

The experimental device used to stretch the standard cross-shaped specimen is a biaxial loading test system controlled by servomotor, which is developed in North China University of Technology. The shape of the specimen is shown in Fig.1. Two extensometers with the gauge length of 50 mm are adopted. The extensometers are fixed on both sides of the specimen center, respectively. So the deformations along the two directions during biaxial tension can be measured simultaneously.



(a) Dimensions of cruciform specimen after optimized



(b) Picture of cruciform specimen

Fig.1 Shape of the cruciform specimen

3 Experimental Process and Results

The uniaxial tensile tests are carried out on the TRIP590 high-strength steel specimens in different directions: Rolling direction, perpendicular to the rolling direction and rolling direction at 45°. The cross-shaped specimens' biaxial tensile tests under different loading ratios are controlled by the load control mode. The two-extensometer signals in the X and Y directions need to be calibrated before testing to get data that are more accurate. The experimental equipment is shown in Fig.2.

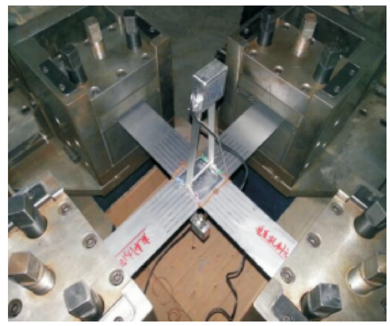
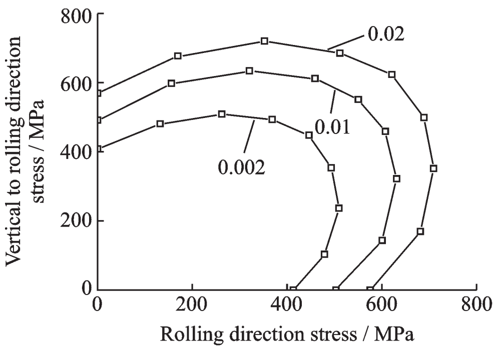


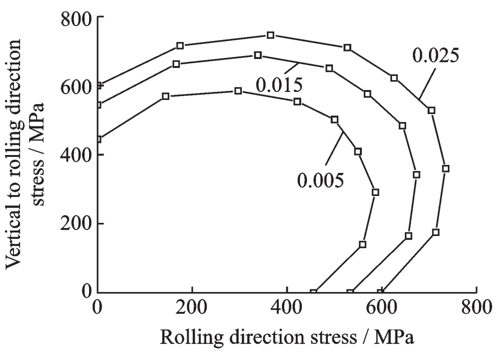
Fig.2 Establishment of the biaxial tensile test system

According to the data processing program in the biaxial tensile testing machine independently developed by North China University of Technology, the real stress-strain curve of biaxial tensile test under different loading paths can be obtained. Then the curve is calculated to obtain the plastic work of the uniaxial tensile stress-strain curve at certain equivalent strain. According to the principle that the sum of the plastic work done in two directions of the stress-strain curves under different ratios equals to the plastic work under the same equivalent strain, that is, the principle of the same plastic work per unit volume, the corresponding stress point can be obtained, which is the yield point on the plastic work contour line.

In the experiment, the plastic strain stages are adopted as 0.002, 0.005, 0.01, 0.015, 0.02, and 0.025, as indicated by the arrow in Fig.3. As can be seen from Fig.3, with the equal biaxial tensile point as the boundary, the upper and lower parts of the experimental yield loci are asymmetric, which is due to the anisotropy of TRIP590 high strength steel. In general, the intervals of each curve are not the same, and the interval during uniaxial tensile test is the smallest. As the point on the yield loci is closer to the biaxial tensile point, the interval is larger, which means that as the equivalent plastic strain increases, the yield loci continues to expand outward. The degree of strengthening is minimal in uniaxial stretching. As the point on the yield loci is closer to the biaxial tensile point, the degree of strengthening is also increasing.



(a) Yield loci under the plastic strain of 0.002, 0.01, 0.02

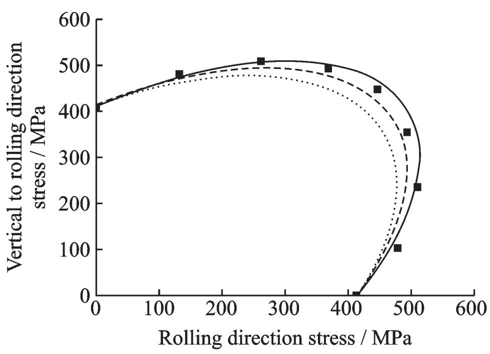


(b) Yield loci under the plastic strain of 0.005, 0.015 and 0.025

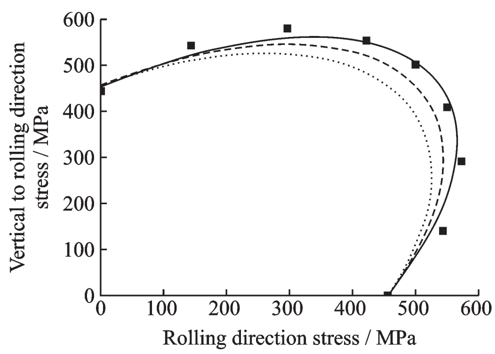
Fig.3 Yield loci under different plastic strain

This paper compares and analyzes the experimental yield loci of TRIP590 material and the theoretical loci based on the Mises yield criterion and Hill48 yield criterion (based on yield strength and r-value). Among them, in Hill48 yield criterion, there are two commonly used methods. One is the use of sheet thickness directional anisotropy index r-value to calculate the Hill48 yield criterion parameters. The other is the use of the rolling direction, perpendicular to the rolling direction, 45° direction yield strength, and yield strength under biaxial tensile test to calculate the parameters of the Hill48 yield criterion[9]. Fig. 4 shows a comparison of the theoretical and experimental yield locus.

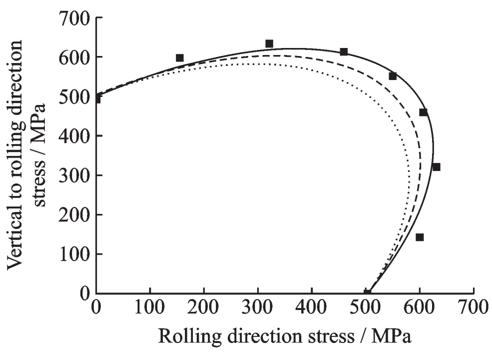
From the comparison of Fig. 4, the yield loci based on the Hill48 yield criterion calculated with the yield strength has a higher fit accuracy to the experimental yield loci than the yield loci of the Hill48 yield criterion calculated with the r-value and the yield loci based on Mises yield criterion. With the equivalent biaxial tensile line as the boundary, the lower half of the yield loci based on Hill48 yield criterion calculated with yield strength is more in conformity with the experimental yield loci than the upper half, the theoretical yield loci and experimental



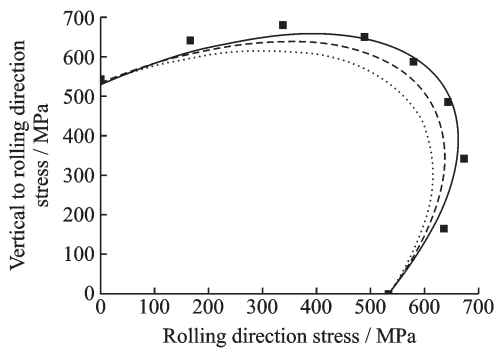
(a) $\bar{\varepsilon}=0.002$



(b) $\bar{\varepsilon}=0.005$



(c) $\bar{\varepsilon}=0.01$



(d) $\bar{\varepsilon}=0.015$

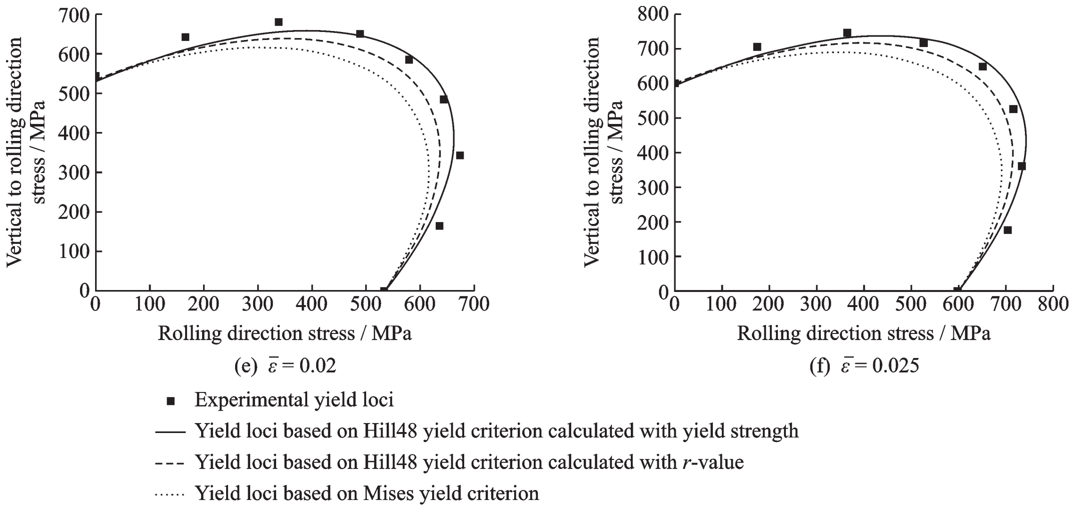


Fig. 4 Comparison between theoretical and experimental yield loci under different plastic strain

yield loci fit the best at the equal biaxial tensile point and its adjacent both sides. The yield loci based on the Hill48 yield criterion (calculated with r-values) fit the experimental yield loci near the upper half of the initial yield loci and the point where the equivalent plastic strain is 0.02. After comparison and analysis, the two yield loci of Hill48 yield criterion calculated with stress method can provide important data support for the forming process design, forming load prediction, and anisotropic behavior prediction of TRIP590 steel plate.

4 Conclusions

(1) From the yield curves of the TRIP590 cross-shaped biaxial tensile test, it can be seen that the experimental yield loci under the different deformation phases of the TRIP590 steel plate are convex. Due to the anisotropy of the material, the yield loci of the TRIP590 plate are not symmetrical. As the amount of deformation increases, the yield loci expand outward.

(2) For the TRIP590 plate, the theoretical yield loci obtained by Hill48 (calculated with yield strength parameters) are in good agreement with the experimental yield loci, followed by Hill48 (calculated with r-values), and the Mises performs the worst .

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Acknowledgements This work was supported in part by the National Natural Science Foundation of China (Nos.

51775004, 51475003), the Beijing Natural Science Foundation (Nos. 3164041, 3152010), and the Beijing Municipal Education Commission Science and Technology Foundation (No. KM201710009005).

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Author contributions Mr. **GUAN Yanzhi** and Prof. **WANG Haibo** designed the study. Mr. **GUAN Yanzhi** completed the experiments and conducted the analysis. Ms. **LI Jiaxin** conducted the data computing and wrote the manuscript. Prof. **WANG Haibo** guided the experiments and the result analyses. Ms. **YAN Yu** contributed to the discussion and the background of this study. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: Zhang Huangqun)