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Numerical simulation and experimental verification of springback on magnesium alloy “v” roll bending using the optimized Hill’ 48 yield criterion

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Abstract: The bending springback of magnesium alloys is difficult to predict accurately in numerical simulations because of its anisotropic characteristics. The springback of magnesium alloys in v-shaped roll bending was analyzed more accurately using the error optimization function in Matlab to optimize the anisotropic potential values required for the Hill’48 yield criterion in ABAQUS. The optimized Hill’48 yield criterion model was used to numerically simulate the springback of magnesium alloy v-shaped roll bending. The simulation results were compared with the experimental results. The error between the springback change ratio obtained using the optimized Hill’48 yield criterion and experimentally formed parts was within 2%. Overall, the optimized Hill’48 yield criterion model can improve the springback prediction accuracy of magnesium alloy v-shaped roll forming.

Keywords: Magnesium alloy, Roll bending, Springback, Matlab, Anisotropic potential values

1 Introduction

Magnesium alloys are materials with low density, high specific strength, high vibration resistance, and good heat dissipation that are widely used in automobile bodies[1-2]. Roll forming has broad application prospects as an energy-efficient metal forming technology and is one of the most applied processing methods for mass production[3]. The roll-forming process will be an effective way for the mass production of magnesium alloy structural parts in the future because of the characteristics of magnesium alloys and mature processing technology. As an unavoidable defect in the roll-forming technology, the impact of springback on the forming profile of the final plate cannot be ignored[4]. Therefore, the accurate prediction of the roll-forming springback of the magnesium alloy material and controlling the amount of springback has become a new problem in manufacturing complex structural parts made from magnesium alloys.

In recent years, the springback of profile bending have been investigated. Gattmah et al[5] used a three-dimensional explicit/dynamic finite element model to analyze the bending process of V-shaped sheets. The effects of the punching radius and plate thickness on the springback and residual strain behavior were predicted. Results showed that the

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springback decreased as the punching radius decreased and plate thickness increased. Furthermore, the residual strain on the tensile side was greater than that on the compressive side.Sen[6] explored the forming properties of CP800 plates under v-bending conditions by combining experiments with finite element analysis. The springback amount under different bending angles was obtained. Nie et al[7] used a combination of experiments and finite element simulations to study the springback of titanium alloy after the unloading of “v” hot bending. Ning et al[8] examined the diversity of microstructure, springback, and texture of AZ31B magnesium alloy sheet at room temperature under continuous bending at three loading rates. Results showed that the springback was minimized at a bending rate of 100 mm/min. Furthermore, the experimental process was simulated accurately using finite element software.

The numerical simulation technique is widely used in practical engineering applications because it can accurately predict the final geometrical characteristics, mechanical properties, and defects generated during molding[9], which is crucial for subsequent experimental studies. The yield function model greatly influences the results of finite element analysis, especially for sheets with unique behavior. Many studies have been conducted on the yield function model to achieve finite element simulation analysis closer to the material behavior. Moreover, new yield function models have been proposed[10]. The von Mises criterion describes the yield behavior for isotropic materials. However, it requires some additional parameters for anisotropic materials, for which the Hill yield criterion was proposed in 1948[11]. In many finite element analysis softwares, such as ABAQUS, the Hill 48 yield criterion is used for anisotropic materials[12]. Wang et al[13] obtained the mechanical properties and various anisotropic parameters of Al–Mg–Li alloys through uniaxial and biaxial tensile tests and ultimate strain tests. They predicted the forming limit curves of the plates by combining the modified M–K model with the Yld2000-2d yield criterion, which was verified experimentally. Yan et al[14] proposed an inverse parametric method to determine the Hill’48 yield criterion parameters based on plane strain tensile experiments combined with finite element simulation analysis. Results showed that the Hill’48 yield criterion predictions using the obtained parameters were superior to those obtained via the von Mises criterion. Trieu et al[15] investigated the effect of Hill’48S, Hill’48R, and von Mises yield criteria on various anisotropic behaviors and fracture prediction of SECC steels. The results showed that the fracture predictions obtained via Hill’ 48R yield criterion were closer to the experimental results. Furthermore, the importance of each potential anisotropic value *r* was mentioned and future research should be conducted in this area.

In this context, the present study proposes a method to optimize the Hill’48 yield criterion parameters for improving the prediction accuracy of numerical simulation of the roll-bending process while reducing the number of basic experiments to obtain more accurate Hill’48 yield criterion parameters. The error optimization function was introduced, and the optimal anisotropic potential values were obtained via iterative optimization using Matlab. A finite element model was established based on the optimized Hill’48 yield criterion for the “v” roll bending of magnesium alloy plates. The results of the numerical simulation were experimentally verified. This study provides a basis for further research on the Hill’48 yield criterion.

2 Materials and experimental methods

2.1 Materials

The research material used in this study was AZ31B magnesium alloy. Table 1 lists the chemical composition of the alloy. It exhibits superior mechanical properties compared with steel and is mainly used in aerospace, automotive industry, communications, weapons, and other fields.

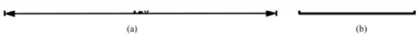

Fig. 1 Uniaxial tensile test specimens

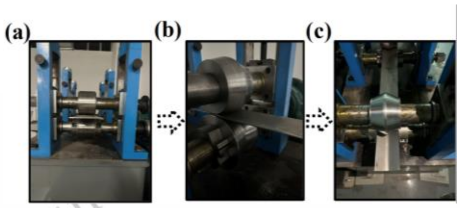

Fig. 2 "v" roll forming experiment device

2.2 Uniaxial tensile test

The magnesium alloy tensile experiments were conducted using an electronic universal tensile testing machine for uniaxial tensile. According to the test requirements, uniaxial tensile specimens of AZ31B magnesium alloy were prepared along the rolling direction, at 45° to the rolling direction, and perpendicular to the rolling direction. Fig. 1 shows the tensile specimens in each direction and their dimensions.

2.3 Roll-bending experiment

The size of the magnesium alloy sheet used in the V-shaped roll-bending experiment was 700 ×78 ×2 mm. The forming angle of the three passes was 0°–15°–25°, and the roll gap was 2, 2.2, and 2.5 mm, respectively. The distance between machine frames was 480 mm. Fig. 2 shows the roll-bending experimental equipment.

3 Numerical simulation of "v" roll bending

In ABAQUS finite element simulation software, the Mises criterion is used widely by researchers[16]. However, for HCP magnesium alloy with anisotropy, the embedded von Mises yield criterion in the software cannot accurately describe the bending behavior of magnesium alloy sheets[17]. Regarding the anisotropic characteristics of magnesium alloy, researchers have proposed various anisotropic yield criteria, such as CaBa2004 yield criterion, CPB06 yield criterion, and Hill yield criterion. This study focuses on the Hill yield criterion.

Table 1 Chemical composition of AZ31B magnesium alloy (%)

AL	Si	Ca	Zn	Mn	Fe	Cu	Ni	Mg
3.2	0.08	0.04	1.4	0.7	0.03	0.01	0.001	Bal.

3.1 Method for solving anisotropic parameters of the Hill' 48 yield criterion

The thickness anisotropy coefficient r expresses the deformation anisotropy characteristics of magnesium alloy sheets. It reflects the difference between the plastic deformation along the width and thickness directions under the tensile test, which can be calculated using Eq. (1).

$$r = \frac{\varepsilon_\omega}{\varepsilon_t} \tag{1}$$

where $\varepsilon_\omega = \ln b/b_0$ is the strain in the width direction and $\varepsilon_t = \ln t/t_0$ is the strain in the thickness direction.

For each anisotropic material, r values along the rolling direction, at 45° to the rolling direction, and perpendicular to the rolling direction were obtained by solving Eq. (1), and the three obtained values were substituted into Eqs. (2), (3), (4), and (5) to obtain the anisotropic parameters of the Hill'48 yield criterion[18].

$$F = \frac{r_0}{(1+r_0)r_{90}} \tag{2}$$

$$G = \frac{1}{1+r_0} \tag{3}$$

$$H = \frac{r_0}{1+r_0} \tag{4}$$

$$N=\frac{(1+2r_{45})(r_0+r_{90})}{2(1+r_0)r_{90}} \tag{5}$$

where r_0 , r_{45} , and r_{90} are thick anisotropy coefficients under uniaxial tensile test along rolling, at 45° to the rolling direction, and perpendicular to the rolling direction.

3.2 Solving method of anisotropic potential values for the Hill' 48 yield criterion

In ABAQUS, the anisotropic parameters of the Hill'48 yield function under plane stress state can be defined using the following expression.

$$F=\frac{1}{2}\left(\frac{1}{R_{22}^2}+\frac{1}{R_{33}^2}-\frac{1}{R_{11}^2}\right) \tag{6}$$

$$G=\frac{1}{2}\left(\frac{1}{R_{33}^2}+\frac{1}{R_{11}^2}-\frac{1}{R_{22}^2}\right) \tag{7}$$

$$H=\frac{1}{2}\left(\frac{1}{R_{11}^2}+\frac{1}{R_{22}^2}-\frac{1}{R_{33}^2}\right) \tag{8}$$

$$N=\frac{3}{2R_{12}^2} \tag{9}$$

where F , G , H , and N are the anisotropy parameters and R_{11} , R_{22} , R_{33} , and R_{12} are the anisotropic potential values.

3.3 Optimization of anisotropic potential values for the Hill' 48 yield criterion

Generally, tthe anisotropic potential parameters of the Hill'48 yield criterion require multiple experiments to obtain more precise results, and these experiments generally take a significant amount of time. Considering the constraints of experimental conditions and time, this paper proposes an optimization method for the anisotropic potential parameters of the Hill'48 yield criterion in order to improve the accuracy of simulation results.

The theoretical value of the ratio of yield stress in each direction to the yield stress in the rolling direction of the material was introduced to optimize the anisotropic potential values, which could be obtained using the following equation:

$$R^m(\theta)=\frac{1}{\sqrt{(F+H)\sin^4\theta+(G+H)\cos^4\theta+2(N-H)\sin^2\theta\,\mathrm{c}}} \tag{10}$$

where F , G , H and N are anisotropic parameters, and θ represents three directions, i.e., 0°, 45°, and 90°.

In this study, the theoretical value of the ratio of yield stress in each direction to the yield stress in the rolling direction was obtained using Eq. (10), which tends to have an error with the experimental value. The error optimization function expression was established to minimize the error, as shown in Eq. (11). Using Matlab to write the error optimization function expression, four anisotropic parameters were iterated continuously within the range of 0.25–2 until the error between R^m and R^t reached the minimum, thereby obtaining the optimal anisotropic parameters.

The error optimization function is expressed as:

$$y(F,G,H,N)=(R_0^m-R_0^t)^2+(R_{45}^m-R_{45}^t)^2+(R_{90}^m-R_{} \tag{11}$$

where F , G , H , and N are the anisotropy parameters; R^m is the theoretical value of ratio of yield stress; and R^t is the experimental value of ratio of yield stress.

The optimal anisotropic parameters derived from the continuous iteration were substituted into Eqs. (6), (7), (8), and (9) to calculate the optimized anisotropic potential values of the Hill'48 yield criterion. Table 2 lists the results, providing a basis for accurate simulation analysis.

Table 2 Data of various potential values of anisotropy

R11	R22	R33	R12	R13	R23
1.3056	1.4142	1.3056	2.4495	1	1

3.4 Establishment of the roll-bending simulation model

3.4.1 Material model

The dimensions of the magnesium alloy sheet for V-shaped roll bending were 700×78×2 mm, and the material parameters were obtained by uniaxial tensile test.

3.4.2 Geometric model

The forming angle of each pass was 0°, 15°, and 25°. The size of the roll gap for each pass was 2, 2.2, and 2.5 mm, respectively. Fig. 3 shows the assembly diagram of the three passes roll bending forming model. The rolls were set as discrete rigid bodies when importing components because only the sheet and not the deformation of the rolls was being analyzed.

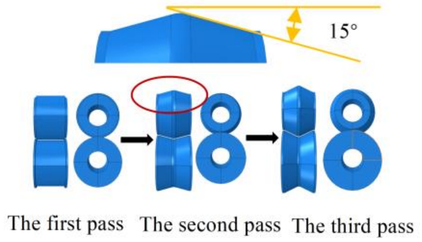

Fig. 3 Geometric modeling of "v" roll forming

3.4.3 Setting boundary conditions

In the simulation process of roll bending, the corresponding boundary conditions should be given to replace the roll speed in the experiment. The roll angular velocity was required in ABAQUS simulation software. The angular velocity calculation formula was as follows:

$$\omega = 2\pi \frac{L}{RT} \tag{12}$$

where L was the forming path of sheet metal, which refers to two machine frame spacings and sheet length. R, T, and ω are the radius of the roll, the theoretical time of the roll-bending analysis step, and the angular speed of the forming roll, respectively. In this study, L = 2000 mm and T = 1.

The calculation of roll angular velocity should follow the right-hand principle, i.e., the upper and lower roll angular velocity were positive and negative, respectively. Table 3 lists the radius and angular velocity of each roll in the model.

Table 3 Roll radius and angular velocity

Roll	Roll radius/mm	Angular velocity(rad/s)
A0	63	199.36
A1	64.2	212.92
A2	64.8	223.26
B0	65	-193.23
B1	63.8	-182.02
B2	63.2	-175.06

3.4.4 Meshing

Due to the influence of longitudinal stress on the solid element during the simulation of roll bending, it can be easily distorted. Hence, the mesh type of the roll was a discrete rigid body element. The magnesium alloy sheet, S4R, was adopted as a solid shell unit[19]. The mesh was refined in the bending angle part of the roll to ensure convergence; the thinning mesh can effectively solve the influence of the hourglass phenomenon. The total number of elements was 12,250. Fig. 4 shows the overall mesh division and an enlarged view of the meshing of the upper roll in the second pass.

3.5 Analysis methods

Considering the computational efficiency and accurate calculation results, the dynamic explicit algorithm was first used to simulate the sheet-forming process. Then, using this result file as the basis, the static implicit algorithm was employed to simulate the sheet springback.

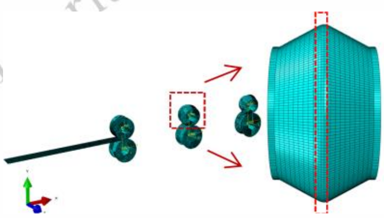

Fig. 4 Grid division diagram

4 Result analysis

4.1 Sheet tensile test results

The tensile test was performed on magnesium alloy sheet to obtain engineering stress and strain. Fig. 5 shows the engineering stress and engineering strain curve of the alloy.

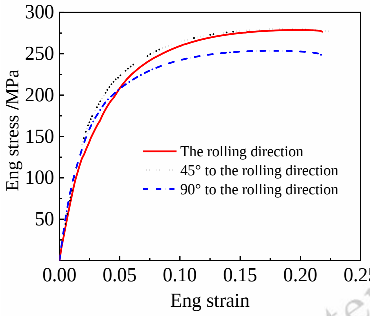

Fig. 5 Engineering stress– strain curve

4.2 Analysis of the springback results

4.2.1 Springback analysis of the FEM

In the forming region, the edge and middle sections in the forming region of the magnesium alloy sheet are forced to move toward the centerline of the rolls under the action of the upper and lower rolls. Bounded by the neutral layer of the sheet, the inner and outer sides are the compression and tensile regions, respectively. During the roll-bending forming process of the magnesium alloy sheet, the bending part is divided as tensile plastic deformation, compressive plastic deformation, and elastic deformation, of which the elastic deformation region is the main cause of springback, as shown in Fig. 6.

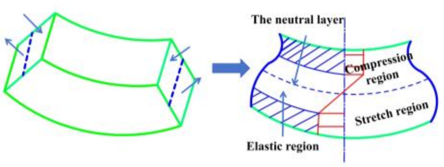

Fig. 6 Deformation state of the corners

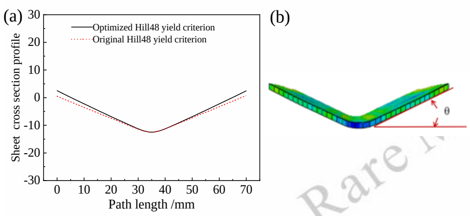

Fig. 7 “v”-shaped sheet profile cross section

Fig. 7(a) compares finite element simulation results obtained using the optimized and original Hill’48 yield criterion models. The sheet cross-section profile with the optimized Hill’48 yield criterion under the optimization of each anisotropic potential value has been changed in forming angle with that of the original Hill’48 yield criterion, so the springback situation is different. A larger forming angle indicates a smaller springback[20]. The forming angle (Fig. 7(b)) was measured using the ABAQUS “Measurement Angle Module.” The final bottom-line-forming angle of the sheet cross-section profile using the optimized Hill’48 yield criterion model was 23.7°, and the springback angle was 1.3°. Although the bottom-line-forming angle was 21.7° under the original Hill’48 yield criterion, the springback angle was 3.3°. Hence, the sheet springback obtained using the original Hill’48 yield criterion model is larger than that obtained using the optimized Hill’48 yield criterion model.

4.2.2 Springback analysis of roll-forming experiment

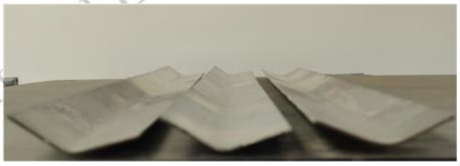

Fig. 8 Magnesium alloy roll-formed parts

Fig. 8 shows the formed parts of the “v” roll-bending experiment. An accurate bottom-forming angle result was obtained using the angle gauge to measure the bottom-line angle of the cross-section profile of formed parts after the roll-forming experiment. The average of the three formed parts was selected as the bottom-line-forming angle under the “v” roll-forming experiment for the magnesium alloy sheet. The final bottom-line-forming angle was 23.2°, and the springback angle was 1.8°.

4.3 Comparative analysis of FEM and roll-forming experiment on springback

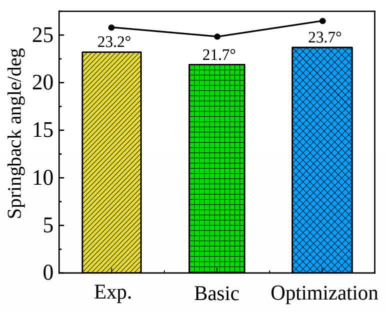

Fig. 9 Comparative analysis of the springback angle

The results obtained using the optimized and original Hill'48 yield criteria were compared with the experimental results (Fig. 9). The springback change ratio was calculated using the following formula to compare the springback in the three cases:

$$\varphi = \frac{\theta_x - \theta_0}{\theta_0} \tag{13}$$

where θ_x are the springback angles obtained from the original Hill'48 yield criterion simulation analysis, the optimized Hill'48 yield criterion simulation analysis, and the roll-bending experiment. θ_0 is the theoretical forming angle of the roller in the third pass, which is equal to 25°. The springback change ratio was obtained using Eq. (13), as shown in Fig. 10:

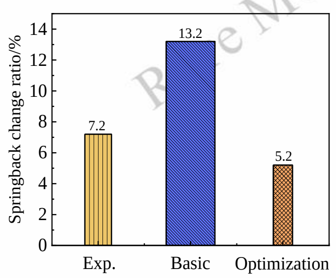

Fig.10 Springback change ratio

The springback change ratio was 5.2% using the optimized Hill'48 yield criterion by optimizing each anisotropic potential value (Fig. 10). However, the springback change ratio of the original Hill'48 yield criterion was 13.2%, and the formed parts of the springback change ratio of the magnesium alloy roll-bending experiment was 7.2%. The error value for the springback change ratio using the optimized Hill'48 yield criterion and the formed parts for the roll-bending experiment was within 2%. Hence, "v" roll-bending numerical simulation analysis on springback using the optimized Hill'48 yield criterion under optimized anisotropic potential values for the magnesium alloy can improve the springback prediction accuracy.

5 Conclusions

1) Matlab software was used to apply the error optimization function for optimizing the anisotropic potential values required in ABAQUS. The "v" roll-bending model under the optimized Hill'48 yield criterion was constructed for the magnesium alloy on the springback.

2) An explicit dynamic algorithm and an implicit static algorithm were used to analyze the "v" roll-bending springback for the magnesium alloy. Based on the optimized Hill' 48 yield criterion, the bottom-line-forming angle of the formed parts was 23.7°. The theoretical forming angle and the springback change ratio were 25° and 5.2%, respectively. In contrast, the bottom-line-forming angle of the numerical simulation using the original Hill' 48 yield criterion and the springback change ratio were 21.7° and 13.7%, respectively.

3) The springback results of the three cases were compared. The error value for the numerical simulation result using the optimized Hill'48 yield criterion and the experiment result was within 2%, confirming the accuracy of the optimized Hill'48 yield criterion model.

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Data Availability: All data used in this work have been properly cited within the article.

Declarations

Ethics approval Not applicable.

Consent to participate The authors declare that all authors have approved the manuscript and agree with its submission to Rare Metal Materials and Engineering.

Consent for publication The authors give permission for the publishing of this article.

Conflict of interest The authors declare no competing interests.

References

1 Kong L F, Huang X Q, Zhou H M et al. Rare Metal Materials And Engineering[J], 2023, 52(10): 3641-3646.

2 Han S L, Li Z Y , Wang Z Y et al. The International Journal of Advanced Manufacturing Technology[J], 2022, 118: 2787－2803.

3 Han F, Liu J Y, Ai Z Q et al. Journal of Plasticity Engineering[J], 2010, 17(5): 53-60.

4 Hajiahmadi S, Naeini H M, Ghadikolaee H T et al. The International Journal of Advanced Manufacturing Technology[J], 2023, 129: 3965－3978.

5 Gattmah J, Ozturk F, Orhan S. *Arabian Journal for Science and Engineering*[J], 2019, 44: 10285－10292.

6 Sen N, Tasdemir V. *Ironmaking & Steelmaking*[J], 2021, 48(7): 811-818..

7 Nie D M, Lu Z, Zhang K F. International Journal of Advanced Manufacturing Technology[J], 2018, 94: 163－174.

8 Ning F k, Zhou X, Le Q C et al. *Journal of Materials Research and Technology*[J], 2019, 8(6): 6232-6243.

9 Bruschi S , Altan T , Banabic D et al. *CIRP Annals-Manufacturing Technology*[J], 2014, 63: 727-749.

10 Barlat F, Aretz H, Yoon JW et al. *International Journal of Plasticity*[J], 2005, 21: 1009-39.

11 Hill R. The mathematical theory of plasticity[M]. Oxford University Press, 1950.

12 Dassault Systèmes. ABAQUS 6.11 analysis user’s manual, volume III[M]. Dassault Systèmes, 2011.

13 Wang Y B, Zhang C S , Wang Y H et al. *Journal of Materials Engineering and P*erformance[J], 2021, 30: 8224－8234.

14 Yan Y, Wang H B, Li Q. Journal of Manufacturing Processes[J], 2015, 20: 46－53.

15 Trieu Q-H, Luyen T-T, Nguyen D-T et al. Materials[J], 2024, 17,2872.

16 Chen M X(陈明祥). Elasticity and plasticity(弹塑性力学)[M]. Beijing: Science Publishers, 2007.

17 Li F F(李非凡), Lei L P(雷丽萍), Fang G(方刚). *Journal of Plastic Engineering*(塑性工程学报)[J], 2020, 27(1): 1-13.

18 Song F, Wang N, Su N et al. *Rare Metal Materials and Engineering*[J], 2022, 51(9): 3252-3262.

19 Yang W Z(杨文志), Yan Y(阎昱), Cao K Y(曹坤洋) et al. *Journal of North China University of Technology*(北方工业大学学报)[J], 2013, 25(3): 76-81.

20 Han F(韩飞), Sun W L(孙玮隆), Zhang R Q(张若青). *China Mechanical Engineering*(中国机械工程)[J], 2023, 34(19): 2353-2361.

采用参数优化后的Hill’48 屈服准则对镁合金“v”型辊弯成形回弹进行数值模拟研究然后通过辊弯成形实验验证

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摘 要：镁合金由于其各向异性特征，在数值模拟计算中难以准确预测镁合金板材弯曲回弹过程。为了更准确地分析镁合金“v”型辊弯成形回弹，本文利用 Matlab 应用误差优化函数优化 ABAQUS 仿真软件中 Hill’48 屈服准则所需的各向异性势值参数，采用优化后的 Hill’48 屈服准则模型对镁合金“v”型辊弯成形回弹进行数值模拟研究，将其结果与实验结果进行对比，结果表明采用优化后的 Hill’48 屈服准则后回弹变化率与辊弯成形实验成型件的回弹变化率误差在 2%以内。采用各项异性势值优化后的 Hill’48 屈服准则可以提高镁合金“v”型辊弯成形的回弹预测精度。

关键词：镁合金; 辊弯成型; 回弹; Matlab; 各项异性势值

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