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Prediction of Springback and Die Compensation in TC4 Alloy Blade Forging Based on the Finite Element Method

Xiaoluo Gu [1,*], Qianzhi Peng [1], and Hongxing Lu [2,*]

[1] AECC South Industry Company Limited, Zhuzhou 412000, China
[2] Department of Mechanical and Energy Engineering, Southern University of Science and Technology, Shenzhen 518055, China
* Correspondence: xiaoluo_gu@126.com (X.G.); luhx@sustech.edu.cn (H.L.)
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Abstract: The finite element simulation method was employed to simulate the forging process of TC4 alloy blades, predicting the post-forging springback of the blades. Based on the springback data, compensation was applied to the blade forging die, and simulation experiments were conducted using the compensated die to analyze the effectiveness of springback compensation. The results indicate that the springback amount of each cross-section of the TC4 alloy blade increased with the distance from the tenon after forging. When the distance reaches 122 mm, the springback angle at that cross-section reaches 2.2°. After implementing reverse equal-amount springback compensation, most of the blade's springback was eliminated, with residual springback of 0.2°–0.4° observed in cross-sections at distances ⩾112 mm.

Keywords: blade forging; springback; compensation; finite element method

1. Introduction

Titanium alloy, represented by TC4, has high specific strength and good corrosion resistance, making it an ideal lightweight material with broad application prospects in aerospace, automotive, rail transit, and other fields [1–3]. Forging is a commonly used forming method for titanium alloys, which optimizes the microstructure and mechanical properties while obtaining the shape of structural components. Rebound is an essential phenomenon in material processing, especially in the forging process of metal materials. Rebound refers to the change in size or shape of a material after the removal of external forces, which is crucial for ensuring the part's final dimensional accuracy and shape stability. For titanium alloys such as TC4, precise springback control during forging is significant for ensuring product quality due to its wide applications in aerospace, biomedical, and other fields [4].

The optimization of TC4 forging processes is essential for reducing rebound and residual stress, ensuring component reliability. While significant advancements have been made, notably through simulation and automated design, further research is needed to address existing gaps and enhance process efficiency across various industries. (1) Residual Stress Analysis: Optimization techniques are essential for minimizing residual stress in TC4 alloy forging. X. Fang et al. [5] developed a numerical model to analyze the effects of deformation parameters on residual stress, finding that precise control over temperature, deformation degree, and speed significantly reduces stress. (2) Simulation in Process Optimization: Simulation tools such as the finite element method are pivotal in optimizing forging processes. Y. Wu and K.K. Wang [6] used DEFORM-3D to simulate ultra-high temperature forging, demonstrating that higher initial temperatures can prevent hot cracking, a common issue in traditional processes. Z. Chen and L. Ma [7, 8] used Deform software to investigate springback deformation in hot die forging of TC4 blades. They obtained various physical fields during blade forging and analyzed the distribution of elastic strain after die unloading while discussing factors influencing springback. However, they did not directly provide the springback angle values for each cross-section, limiting the reference value for die design. (3) Parameter Optimization. J. Guo et al. [9] explored the effects of heating temperature and forging speed on stress distribution during the forging of high-speed-steel rolls. Their study highlighted the importance of selecting optimal parameters to ensure efficiency and safety, suggesting that higher temperatures and lower speeds reduce stress. C. H. Li et al. [10, 11] proposed calculation formulas for springback compensation in blade forging. However, the constant terms in these formulas were not disclosed, making them impractical for direct application. (4) Automated Design of Forging Sequences. Y. Hedicke-Claus et al. [12] introduced an automated design method for multi-stage forging sequences, reducing development time and improving process efficiency. Their findings emphasize the potential of automation in achieving optimal form filling and freedom from defects.

Springback is one of the key factors affecting dimensional accuracy in the precision forging of TC4 alloy blades. Currently, there are limited publicly available studies on springback deformation in blade forging domestically and internationally. This study establishes the elastoplastic constitutive relationship of TC4 alloy. It employs the finite element method to calculate the post-forging springback of blades, providing quantitative springback measurements for each cross-section. Based on these results, corresponding compensation was applied to the forging die, with subsequent analysis of compensation effectiveness. The research provides a valuable reference for TC4 alloy blade die design.

2. Materials and Methods

The experimental material was TC4 alloy. Its chemical composition is shown in Table 1. The temperature-dependent curves of Young's modulus, Poisson's ratio, and linear expansion coefficient for the alloy are shown in Figure 1.

Table 1. The chemical composition of TC4 alloy (wt.%).

Ti	Al	V	Fe	C	N	H	O	Other (Each)	Other (Total)
Balance	5.5–6.75	3.5–4.5	<0.3	<0.08	<0.05	<0.015	<0.2	<0.1	<0.4

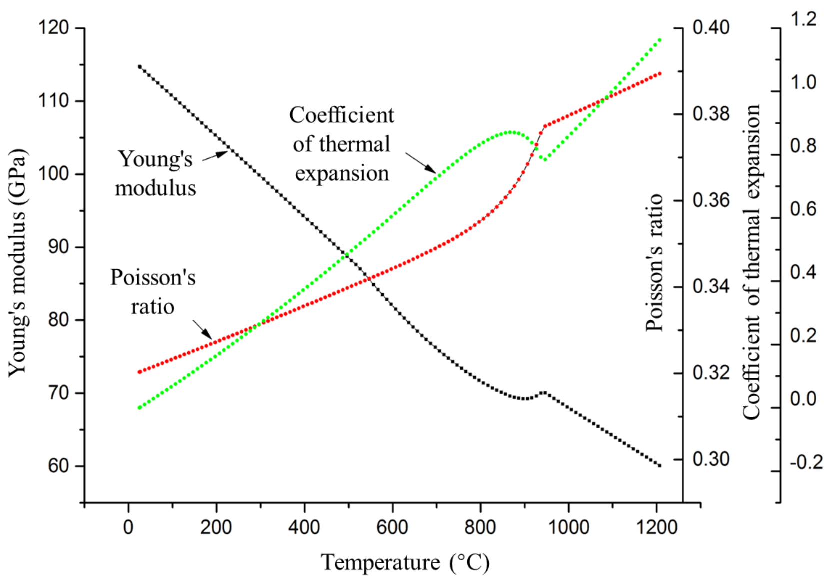


Figure 1. Temperature-dependent curves of Young's modulus, Poisson's ratio, and coefficient of thermal expansion for TC4 alloy.

Figure 2 shows the stress-strain curves of TC4 alloy under temperatures ranging from 25–1100 °C and strain rates of 0.01–100 s^{-1}.

The other parameters were as follows: friction coefficient $\mu = 0.2$, specific heat capacity of TC4 alloy $C = 530$ J/(kg·K), thermal conductivity $\lambda = 6.7$ W/(m·K), and emissivity $\varepsilon = 0.88$.

The forging simulation parameters were set as follows: initial forging temperature of 960 °C, die preheating temperature of 250 °C, and billet transfer time of 6 s. The forging equipment was a 1600-ton screw press with 350 kJ striking energy, 0.8 m/s ram speed, and 0.85 striking efficiency [13]. The die was modeled as an ideal rigid body. Figure 3 shows the models of the forging die, the initial billet, and the blade blank. The simulation employed tetrahedral meshing with an element size of 0.8 mm.

The dimensional comparison between simulation results and theoretical models was conducted using Geomagic Control software (V2012, Geomagic, Cary, NC, USA).

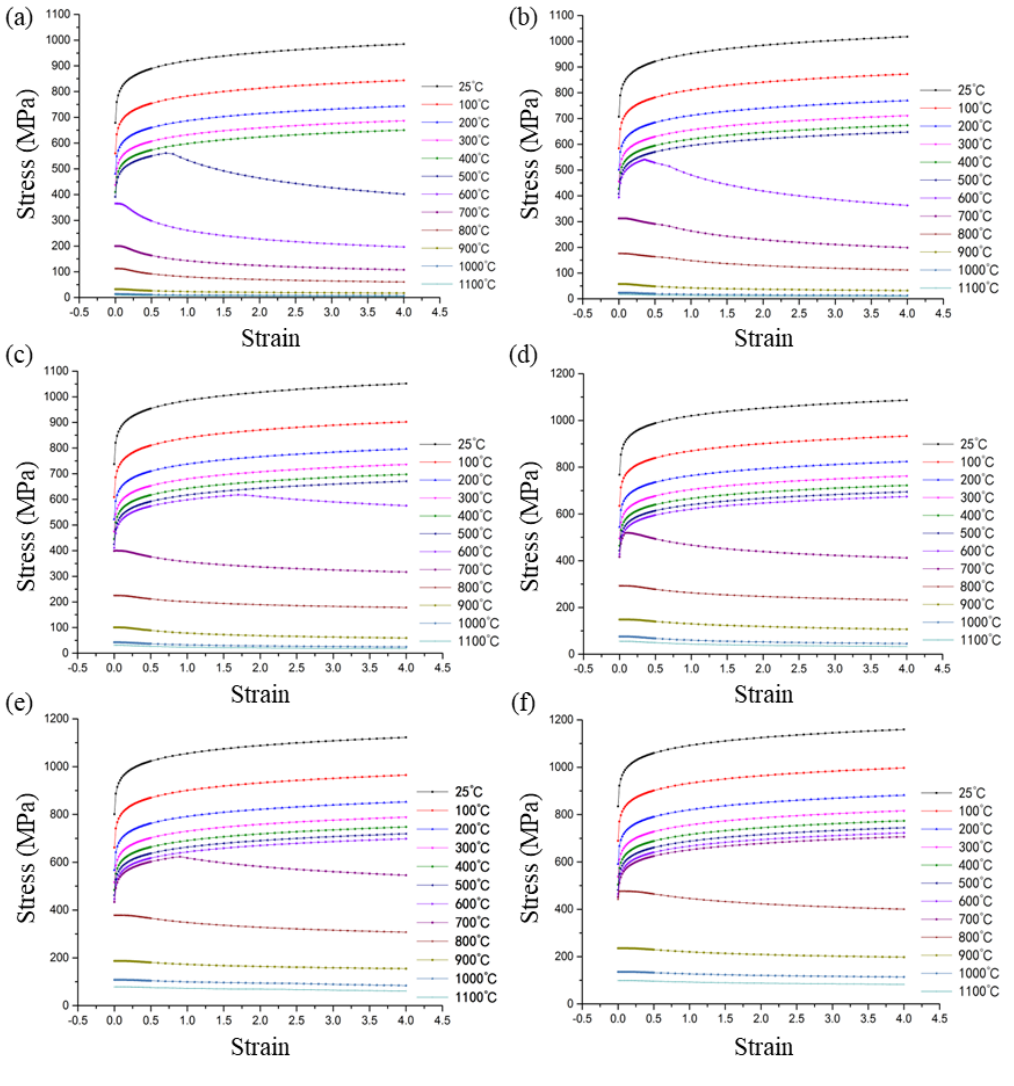


Figure 2. Stress-strain curves of TC4 alloy under different strain rates: (**a**) $\dot{\varepsilon} = 0.001\ s^{-1}$; (**b**) $\dot{\varepsilon} = 0.01\ s^{-1}$; (**c**) $\dot{\varepsilon} = 0.1\ s^{-1}$; (**d**) $\dot{\varepsilon} = 1\ s^{-1}$; (**e**) $\dot{\varepsilon} = 10\ s^{-1}$; (**f**) $\dot{\varepsilon} = 100\ s^{-1}$.

3. Results and Discussion

3.1. Springback Prediction in Forging of TC4 Alloy Blades

Using the blade tenon as a reference, the dimensional deviations between the simulated forged blade and the theoretical model were measured, as shown in Figure 4. Figure 4a, b reveals significant dimensional deviations between the simulation results and the theoretical model after the simulated forging process. The distribution pattern of these deviations follows these characteristics: (1) The dimensional deviation gradually increases from the tenon toward the blade tip, reaching a maximum deviation of ±1.8 mm at the leading and trailing edges of the blade tip. (2) When the dimensional deviation at the leading edge of a given cross-section is positive, the corresponding trailing edge shows a negative deviation. These results demonstrate that such dimensional accuracy cannot meet processing requirements for blades with a nominal machining allowance of 0.7 mm.

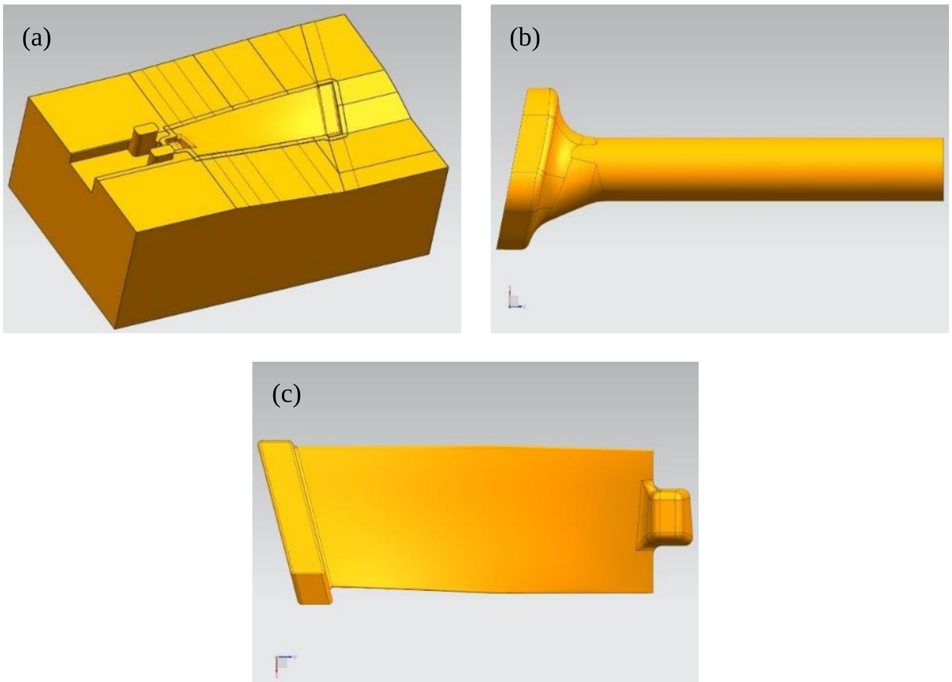
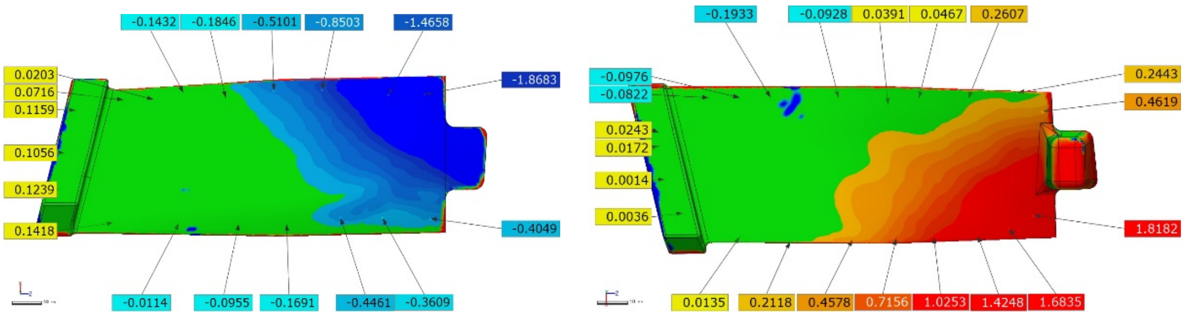


Figure 3. Models of (**a**) forging die, (**b**) initial billet, and (**c**) blade blank model.



(a) **(b)**

Figure 4. Dimensional deviations between simulation results and theoretical model: (**a**) back direction, (**b**) front direction.

Figure 5 shows the comparison between the theoretical cross-sectional shape of the blade and the simulated cross-sectional forged shape at different distances from the origin. It is evident from the figure that each cross-section of the blade does not fit its theoretical position but instead exhibits a certain amount of springback in the opposite direction of the blade's twist after forging. This springback increases with the distance of the cross-section from the origin (the origin is located at the tenon position). Springback is almost negligible when the distance is less than 59 mm. However, as the distance increases, springback becomes more pronounced. At 122 mm, the leading and trailing edges of the cross-section significantly deviate from their theoretical positions. Measurements indicate that the springback angle at this cross-section reaches 2.2°.

During the forging process, the material undergoes plastic and elastic deformation simultaneously. When the die is unloaded, the plastic deformation remains permanent, while the elastic deformation recovers due to the removal of external forces, resulting in blade springback [14]. The springback magnitude gradually increases with the distance from the tenon. This occurs primarily because the tenon is the reference datum in springback analysis. Consequently, the springback observed at distant cross-sections represents the combined effect of their springback plus the accumulated springback from all nearer cross-sections toward the tenon.

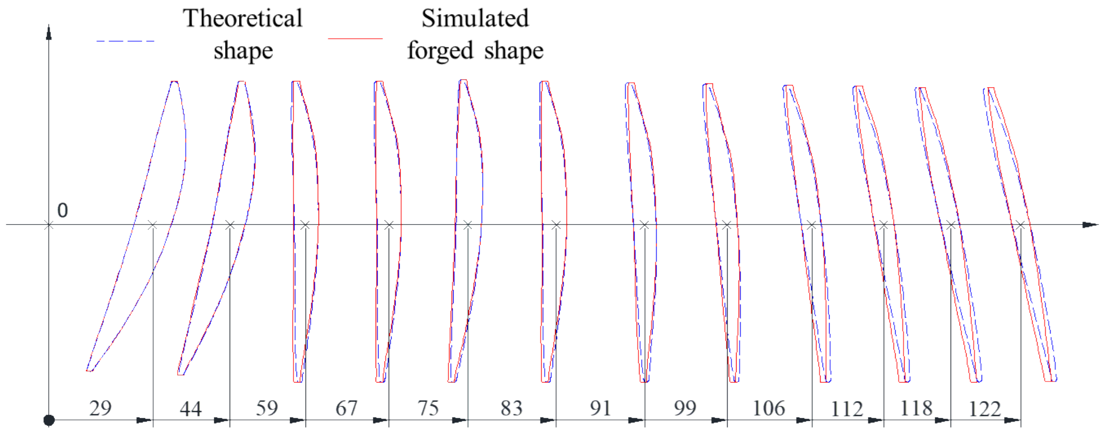


Figure 5. Theoretical cross-sectional profile of the blade versus simulated results.

3.2. Die Springback Compensation and Simulation Results

Figure 6 shows the relationship between the springback amount of each blade section and its distance from the origin. Based on these results, an equal-magnitude reverse compensation was applied to each corresponding die section. The compensated die was then used for forging simulation experiments.

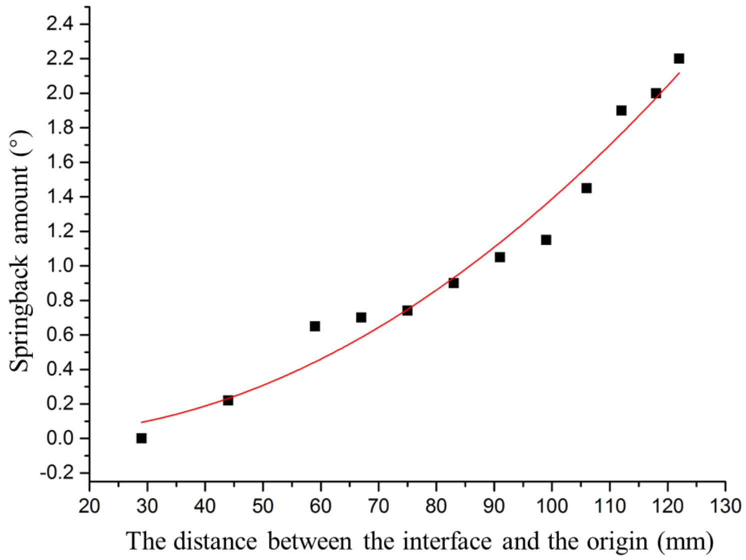
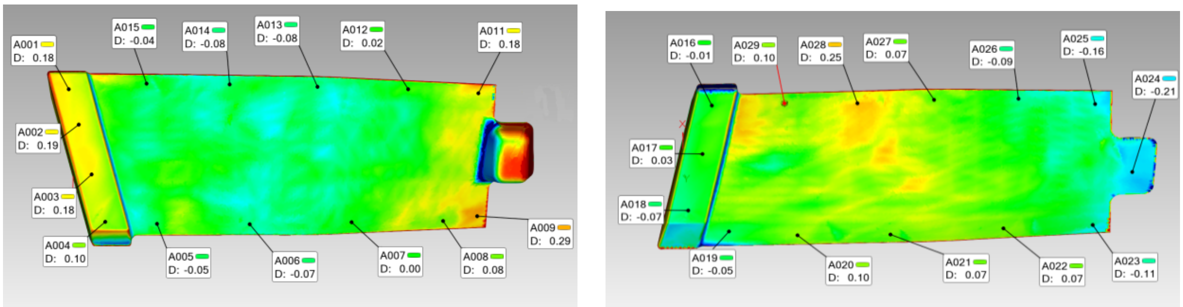


Figure 6. Relationship between springback amount and cross-section distance from the origin.

Figure 7 presents the dimensional comparison between the simulation results after die compensation and the theoretical model. By comparing Figures 4 and 7, it can be observed that the dimensional accuracy significantly improves compared to pre-compensation conditions, with an error margin of ±0.3 mm.

Figure 8 compares the cross-sectional shapes of the theoretical and forged parts after die compensation. By comparing Figures 5 and 8, it can be observed that the springback has significantly improved after die compensation. Only sections located more than 112 units from the origin exhibit measurable springback, with springback angles ranging approximately between 0.2°–0.4°.

The above results demonstrate that the reverse compensation approach effectively eliminates forging springback of the TC4 alloy blade.



(a) **(b)**

Figure 7. Dimensional deviation between die simulation results after die compensation and theoretical model: (**a**) back direction, (**b**) front direction.

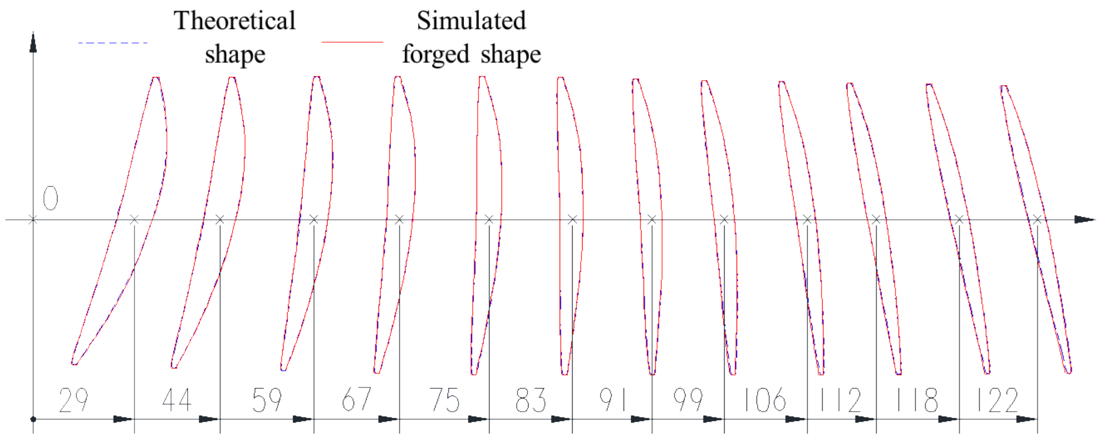


Figure 8. Comparison between the theoretical cross-section shape and simulation results after die compensation.

4. Conclusions

Based on the elastoplastic constitutive relationship of TC4 titanium alloy blades, this study investigated the forging springback of TC4 alloy blades using the finite element method. The main findings are as follows:

(1) The springback amount of each cross-section increases with the distance from the tenon.

(2) When the distance from the tenon is less than 59 mm, the dimensional error caused by springback is negligible. At 122 mm, the springback angle reaches 2.2°.

(3) Applying reverse equal-magnitude compensation can eliminate most of the springback. In this case, the springback in cross-sections with a distance ⩾112 mm from the tenon is approximately 0.2–0.4°.

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