Rare Metal Materials and Engineering
Volume 54, Issue 6, June 2025
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Hu Yanghu, Zhang Dawei, Tian Chong, et al. Influence of Friction Condition on Cavity Filling for Large-Scale Titanium Alloy Strut Forging[J]. Rare Metal Materials and Engineering, 2025, 54(06): 1462-1466. DOI: https://doi.org/10.12442/j.issn.1002-185X.20240277.

ARTICLE

Influence of Friction Condition on Cavity Filling for Large-Scale Titanium Alloy Strut Forging

Hu Yanghu[1], Zhang Dawei[2], Tian Chong[2], Chai Xing[1], Zhao Shengdun[2,3]

[1] National Key Laboratory of Metal Forming Technology and Heavy Equipment, Xi'an 710018, China; [2] Xi'an Key Laboratory of Intelligent Equipment and Control, School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China; [3] Light Alloy Research Institute, Central South University, Changsha 410083, China

Abstract: The titanium alloy strut serves as a key load-bearing component of aircraft landing gear, typically manufactured via forging. The friction condition has important influence on material flow and cavity filling during the forging process. Using the previously optimized shape and initial position of preform, the influence of the friction condition (friction factor m=0.1 – 0.3) on material flow and cavity filling was studied by numerical method with a shear friction model. A novel filling index was defined to reflect material flow into left and right flashes and zoom in on friction-induced results. The results indicate that the workpiece moves rigidly to the right direction, with the displacement decreasing as m increases. When m<0.18, the underfilling defect will occur in the left side of strut forging, while overflow occurs in the right forging die cavity. By combining the filling index and analyses of material flow and filling status, a reasonable friction factor interval of m=0.21–0.24 can be determined. Within this interval, the cavity filling behavior demonstrates robustness, with friction fluctuations exerting minimal influence.

Key words: large-scale strut; titanium alloy; friction condition; rigid movement; cavity filling

1 Introduction

Titanium alloys widely used in the aerospace industry are high-performance lightweight materials but hard to deform[1–3]. The forging process is a common manufacturing method for producing key load-bearing components[4–6]. The strut forging fabricated from Ti-5Al-5Mo-5V-1Cr-Fe titanium alloy serves as a vital load-bearing part of aircraft landing gear[7–8]. However, the typical strut forging of aircraft landing gear features large dimensions (exceeding 2400 mm) and complex configurations, rendering the forging process of large-scale titanium alloy struts highly complex[9]. Consequently, detailed investigations are necessary to optimize the forging process.

Extensive research has been conducted on the forging process of large-scale titanium alloy struts. Some researchers have found that the preform has a great influence on the forging process and used finite element model (FEM) to design preform and preform dies[10–12]. Zhang[9] analyzed the impact of preformed shape on the forging behavior of large-scale struts. Additionally, the initial position of preform also has an influence on forging process, and Zhang et al[8] proposed an optimization method to determine the optimal initial position. The processing parameters also have important influence on the forging process[13]. Not only do the temperature, deformation, and preform have an important influence on the forging process[14–15], but also the friction is recognized as a critical factor[16]. For instance, Zhang et al[17] demonstrated the influence of friction on the metal flow under local loading way and presented that increasing the friction can improve the filling of rib cavity. The friction also has an influence on the shape of deformation zone during spline rolling process[18] and the surface quality of rolling thread[19]. However, the specific influence of friction factor on large-scale strut forging process remains unclear.

Therefore, this study focused on the influence of friction condition on cavity filling during the large-scale titanium alloy strut forging. Based on the previously optimized preform

Received date: June 12, 2024
Foundation item: National Natural Science Foundation of China (52375378); National Key Laboratory of Metal Forming Technology and Heavy Equipment (S2308100.W12); Huxiang High-Level Talent Gathering Project of Hunan Province (2021RC5001)
Corresponding author: Zhang Dawei, Ph. D., Professor, Xi'an Key Laboratory of Intelligent Equipment and Control, School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, P. R. China, Tel: 0086-29-82668607, E-mail: zhangdawei2000@mail.xjtu.edu.cn

geometry and initial position, a shear friction model and finite element numerical model were employed to analyze the influence of friction parameters on material flow and cavity filling in aircraft landing gear strut forging. New filling indexes λ_L and λ_R were defined to characterize the filling behavior of cavity under different friction conditions. Quantitative correlations among friction factors, preform rigid movement, and filling indexes were established. Furthermore, a reasonable friction parameter range was determined by evaluating the filling indexes λ_L and λ_R.

2 Experiment

2.1 Forging process and FEM

The forging process of aircraft landing gear struts involves closed-die forging with flash, and the die will be heated to several hundred Celsius degrees. During forging, the lower die remains fixed, while the preform/workpiece is placed on the lower die, and the upper die moves downward to make the preform into the target geometry. FEM is a powerful tool for analyzing bulk metal forming process[20–21]. A couple thermal-mechanical FEM for Ti-5Al-5Mo-5V-1Cr-Fe titanium alloy strut forging was previously established by Zhang et al[22], and further applied in prior research[8]. The same couple thermal-mechanical FEM was also adopted in this research. Specifically, an 1/2 FEM is shown in Fig.1.

FEM for the strut forging process was constructed by the FORGE software (Fig. 1) based on the optimized preforming geometry and initial position. The detailed modeling method and material parameters can be found in Ref. [8, 22]. This investigation focused on the influence of friction on cavity filling. A shear friction model was adopted in this study, and the numerical friction model is a velocity-dependent friction model[16,20,23], which is expressed by Eq. (1). Eight simulations with friction factors from m=0.1 – 0.3 were performed, according to typical frictional conditions in titanium alloy forging. Key process parameters, including working temperature, loading speed, heat transfer coefficient, etc, are listed in Table 1.

$$\tau = mK\left\{\frac{2}{\pi}\arctan\left(\frac{|u_r|}{u_0}\right)\right\}\frac{u_r}{|u_r|} \tag{1}$$

where τ is the friction shear stress; m is the friction factor, $0 \leqslant m \leqslant 1$; K is the shearing yield strength; u_r is relative velocity; u_0 is the arbitrary constant which is much smaller than relative velocity.

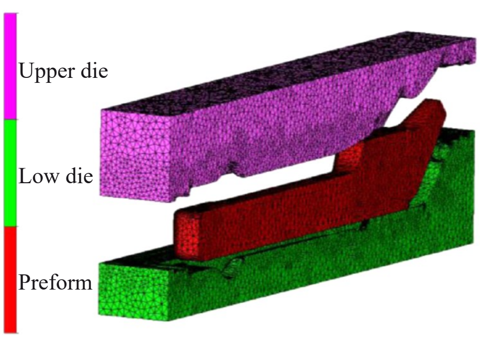

Fig.1 Adopted 1/2 FEM of strut forging process

Table 1 Main parameters for the forging process

Parameter	Value
Initial temperature of preform/°C	850
Initial temperature of die/°C	300
Room temperature/°C	20
Loading speed of upper die/mm·s^{-1}	10
Friction factor	0.1–0.3
Heat transfer coefficient between preform/die and air/ kW·m^{-2}·°C^{-1}	0.02
Heat transfer coefficient between preform and die/kW·m^{-2}·°C^{-1}	11

2.2 Filling index

Previous research[7–8] indicated that the preform/workpiece has rigid movement in the initial forging process, rendering left or right cavities susceptible to underfilling defects. Zhang et al[8] defined a filling index η for left and right cavities, which depended on the area and length of flash cavity and actual forming flash when the flash cavity was filled, as shown in Fig.2, where L_1 and L_2 are the length of flash bin and flash land, respectively. Significant geometric disparities exist between left and right cavities in terms of both area and length. This research only focused on the influence of friction on cavity filling. The strut forging without underfilling defect is the basis of this study, i.e., the left and right flash were fully formed. In this case, filling index η can be simplified. Moreover, a new filling index λ was defined to amplify the effects of friction.

The filling index λ_L reflects the cavity filling situation in left side, and λ_R corresponds to the right cavity. The λ_L and λ_R can be written as λ_i, where i=L, R. The filling index λ_i which reflects the material flowing into left and right flash cavity is defined as Eq.(2).

$$\lambda_i = \frac{S_1'}{S_1} + \frac{S_2'}{S_2} \tag{2}$$

where S_1' is the area of material in flash bin after forging, S_1 is the area of cavity for flash bin, S_2' is the area of material in flash land after forging, and S_2 is the area of cavity for flash land. λ_i is a dimensionless parameter designed to be highly sensitive to subtle variations in left/right cavity filling under a certain initial

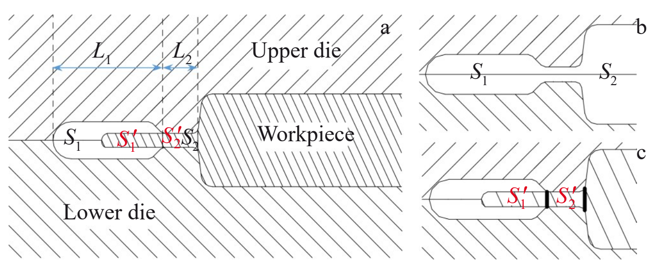

Fig.2 Sketch of actual flash and flash cavity[8]: (a) total view; (b) before filling; (c) after filling

position of preform. The closer the λ_L and λ_R, the better the cavity filling. The difference δ between λ_L and λ_R can be expressed by Eq.(3).

$$\delta = \begin{cases} \dfrac{\lambda_L - \lambda_R}{\lambda_R} & \lambda_L \geqslant \lambda_R \\ \dfrac{\lambda_R - \lambda_L}{\lambda_L} & \lambda_L < \lambda_R \end{cases} \tag{3}$$

3 Results and Discussion

Owing to the geometric mismatch between the preform/workpiece and the forging dies, preform/workpiece undergoes rigid movement during the initial forging process[7–8]. Finite element simulation with friction factor m=0.1, 0.2, 0.3 was used to determine whether there is rigid movement of the material in the strut forging process and to analyze how the rigid displacement varies with friction factor. The whole preform will move to the right side with the motion of the upper die, as shown in Fig.3.

Once the upper die moves to a certain extent, the preform becomes constrained and transitions to plastic deformation, and there will be no rigid movement anymore. The rigid displacement of the preform's left end is denoted as d (Fig.3). Fig.4 illustrates the relationship between the displacement and friction condition. Result indicates that displacement d decreases when the friction factor m increases. This implies that the material obtained by right cavity will decrease with increasing the friction when the workpiece is fixed to plastic deformation. Insufficient material allocation to the cavity leads to underfilling defects, as shown in Fig.5a, failing to obtain the desired forging geometry. Conversely, excessive material allocation to the cavity causes overflow, thus the metal will flow out of the cavity and into the flash bin (Fig. 5b), and therefore the forging dies cannot be closed.

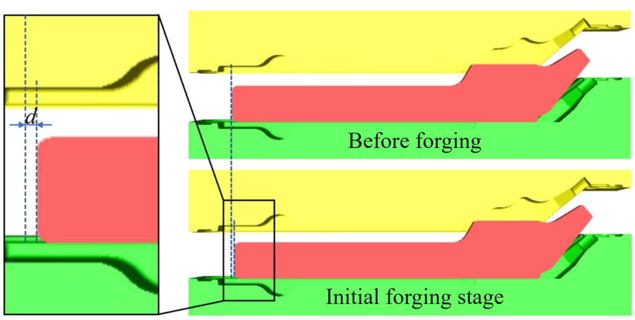

Fig.3 Rigid movement in forging process

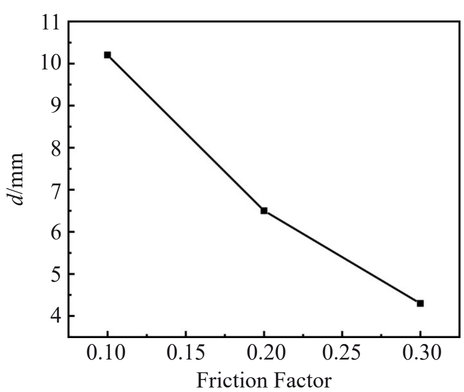

Fig.4 Displacement of rigid movement under different friction factors

Fig. 6a, 6d, and 6g show the cavity filling at the end of the forging process with friction factors m=0.1, 0.2, 0.3, respectively. Under m=0.1, the flash cavity of left side remains unfilled, and there is material overflow in the right side. It means that the shape is incomplete after forging and there is material flowing out in the right side, indicating forging failure. Under m=0.2, both left and right cavities are fully filled without overflow, representing a successful forging process. Under m=0.3, both left and right cavities are filled, while excessive materials are accumulated in the left flash relative to the right, resulting in suboptimal forming quality. These results demonstrate that frictional conditions significantly affect the robustness of the strut forging process.

To further validate material flow and cavity filling, the finite element simulation was carried out with friction factor m=0.15, 0.18, 0.22, 0.25, as presented in Fig.6b–6c and 6e–6f, respectively. Under m=0.15, the left cavity remains unfilled while overflow occurs in the right cavity. Under m=0.18, both cavities are filled, but the right flash contains significantly more material than the left one. Under m=0.22, 0.25, complete filling of both cavities is achieved without overflow, indicating successful forging outcomes.

According to above analyses, the filling indexes λ_i are calculated with m=0.18, 0.2, 0.22, 0.25, 0.3, as shown in Fig.7, in which simulation results with underfilling defects (e. g., m=0.1 and m=0.15) are eliminated. A filling index value of λ_i=2 indicates complete filling of the flash cavity, whereas λ_i=0 corresponds to a completely unfilled flash cavity.

The filling index λ_L increases with increasing the friction factor m, whereas the filling index λ_R decreases. Under m=0.18, λ_L is close to 0 but λ_R is equal to 2. Under m=0.3, λ_L is about 2 but λ_R is about 0.2. This is consistent with the earlier conclusion obtained from the influence of friction on displacement of rigid movement of the preform. As friction factor increases, the rightward rigid displacement of the preform decreases before the plastic deformation of workpiece, diverting less material to the right cavity but more to the left. It

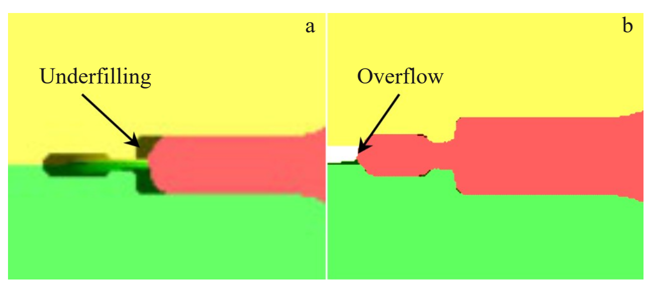

Fig.5 Schematics of underfilling (a) and overflow (b) phenomena

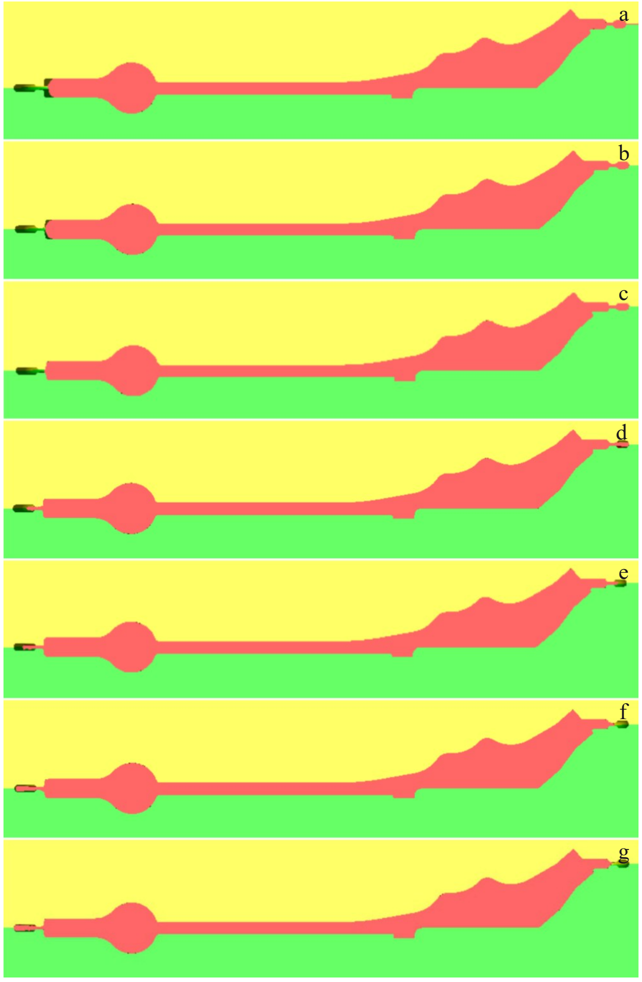

Fig.6 Cavity filling with different friction factors: (a) m=0.1; (b) m=0.15; (c) m=0.18; (d) m=0.2; (e) m=0.22; (f) m=0.25; (g) m=0.3

should be noted that fully filling the flash cavity is neither the intended design goal nor an ideal state for strut forging[8]. Instead, an optimal forging process requires balanced filling of both left and right flash cavities. In this case, the cavity filling for the large-scale forging can be ensured while maintaining relatively low forging loads.

The difference δ between λ_L and λ_R is an index to quantify the symmetry of the left and right cavities. The less the

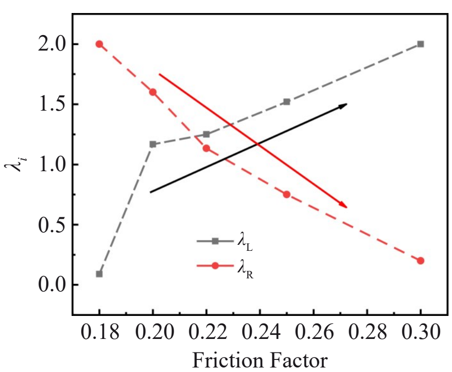

Fig.7 Filling index under different friction factors

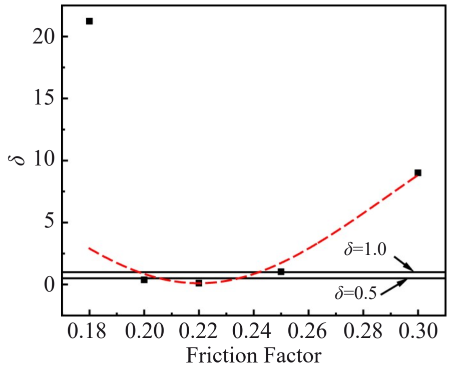

Fig.8 Difference δ between filling indexes under different friction factors

difference δ, the more consistent the left and right cavity fillings. Fig.8 illustrates δ values under m=0.18, 0.2, 0.22, 0.25, 0.3. Once the flash land cavity is filled, the flash system assumes its functional role, enabling high-quality forging. When λ_i>1, the flash land cavity is sufficiently filled. Moreover, in consideration of $0 \leqslant \lambda_i \leqslant 2$, a δ <1 criterion identifies acceptable filling situation of both left and right cavities. In this case, reasonable friction factor interval is 0.198 – 0.242 according to fitting curve in Fig. 8. In consideration of inhomogeneity of lubricant for large-scale forging, it is necessary to increase margin and to narrow the scope. Then, a stricter criterion δ<0.5 can be used as an evaluation index for acceptable filling situation of both left and right cavities. In this case, reasonable friction factor interval is 0.206 – 0.234 according to fitting curve in Fig. 8. It can be seen from Fig. 6 and Fig. 7 that the left flash cavity still retains filling potential under relatively large friction condition, and the cavity of flash land is also filled for right side cavity at the same time. Considiering these factors, a reasonable friction factor interval of m=0.21–0.24 is recommended for industrial implementation.

4 Conclusions

1) The influence of friction condition on the forging process of large-scale titanium-alloy landing gear struts is investigated. A new filling index is proposed to quantify material flow into left and right flashes while amplifying friction-induced variations.

2) There is a rigid movement of preform to the right side during the initial forging process, and the displacement decreases monotonically with increasing the friction factor. A friction factor increment from 0.1 to 0.3 reduces the rigid displacement by approximately 6 mm, significantly altering material distribution prior to plastic deformation. The rigid movement amplifies the influence of friction on cavity filling.

3) Friction has an important influence on the material flow and cavity filling. For m<0.18, the left flash cavity remains unfilled while the right cavity experiences overflow. For m>0.18, complete cavity filling is achieved, but filling situations of left and right flash are different.

4) According to the filling index and the difference between

filling indexes, a reasonable friction factor interval of 0.21 – 0.24 can be determined under the optimized preform geometry and initial position. Within this interval, material flowing into left and right flash cavities reaches a balance.

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摩擦条件对大型钛合金支柱锻造型腔充填的影响

胡阳虎[1]，张大伟[2]，田　冲[2]，柴　星[1]，赵升吨[2,3]

(1. 金属成形技术与重型装备全国重点实验室，陕西 西安 710018)

(2. 西安交通大学 机械工程学院 西安市智能装备与控制重点实验室，陕西 西安 710049)

(3. 中南大学 轻合金研究院，湖南 长沙 410083)

摘　要：钛合金支柱锻件是飞机起落架关键承载零件，常用模锻工艺制造支柱零件。摩擦条件对锻造过程的材料流动和型腔充填有重要影响。针对前期优化的坯料形状和初始放置位置，采用数值模拟方法研究了剪切摩擦因子m=0.1~0.3范围内摩擦条件对大型支柱锻造过程材料流动和型腔充填的影响。提出了一个可反映材料流入左右飞边状态，并放大摩擦影响结果的新充填指标。结果表明：锻造初期工件向右刚性移动的距离随摩擦因子m的增加而减小；当m<0.18时，支柱锻件左侧出现未充满缺陷，但右侧出现型腔溢流现象。应用提出的充填指标结合材料流动和充填状态分析，确定合理的摩擦条件范围为m=0.21~0.24；在该摩擦条件范围内，摩擦条件波动影响较小，型腔充填行为稳定。

关键词：大型支柱；钛合金；摩擦条件；刚性移动；型腔充填

作者简介：胡阳虎，男，1984年生，硕士，高级工程师，金属成形技术与重型装备全国重点实验室，陕西 西安 710018，电话：029-86322563，E-mail：18091790947@163.com