Original Article

Effect of friction conditions on phase transformation characteristics in hot forging process of Ti-6Al-4 V turbine blade

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\textbf{A B S T R A C T}

This work is motivated by the fact that friction has a significant impact on the microstructures of titanium forged parts, further influencing their mechanical properties. In this paper, a 3D FE model is developed to investigate the phase transformation characteristics of Ti-6Al-4 V turbine blade in the hot forging process. Then, the effect of friction conditions on temperature and phase transformations within the forged blade are analyzed numerically and verified by experiments. The results reveal that compared with a less influence on lamellar \(\alpha + \beta\) phase, a good lubricated condition obviously increases the average volume fraction of \(\alpha\) phase, while decreases the average values of temperature and \(\beta\) phase volume fraction as well as the distribution uniformities of \(\alpha\) and \(\beta\) phases.

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1. Introduction

Titanium turbine blades are critical energy transformation components in aeroengines, and about 80\% of them are manufactured by hot forging operations [1–3]. Moreover, their fatigue life and corrosion resistance highly depend on forged microstructures, especially on the composition and content of phases [4–6]. According to previous studies, as an important forging factor, friction greatly influences material deformation and temperature evolution, resulting in the significant variations of forged phases, further leading to a genetic impact on the phases of final parts [7–9]. Therefore, an accurate prediction of the friction effect on phase transformation behaviors within the forged blade is of great importance for improving the mechanical properties of Ti-6Al-4 V turbine blade part.

Until now, some fundamental studies have been carried out on friction conditions in forming processes. Karman [10] developed a Coulomb friction model to describe the friction behaviors between workpiece and dies in a strip rolling process. Chen et al. [11] employed the above friction model to analyze the friction characteristics in a multi-stage forming process of hexagon headed bolts. Note, however, that as the
shear strength is exceeded, the application of the Coulomb model is limited owing to the overestimated frictional stress. Hence, Siebel [12] developed a shear friction model to predict the high frictional shear stress at die-workpiece interfaces, which are widely employed in blade forging processes. Hereinto, Lv et al. [13] utilized the shear friction model to analyze a multi-stage blade forging process under 3D FE simulation environment. Huang et al. [14] employed a 3D FE model embedded with the shear friction model to analyze the blade deformation characteristics in the isothermal forging process. Chen et al. [15] used the shear friction model to evaluate the variations of multi-physical fields in a blade forging process. Shao et al. [16] and Alimirzaloo et al. [17] embedded the shear friction model into a 3D FE model to optimize the geometry of preformed blades, aiming to improve the strain distribution uniformity and minimize the flash area. Notice that, although a large amount of research has been conducted on the friction behaviors and its effects in blade forging processes, none of them is directly related to the effect of friction conditions on the phase transformation characteristics.

On the other hand, focusing on the prediction of Ti-6Al-4V phase transformation behaviors, some studies have also been performed. Hereinto, for the heating process, Sha et al. [18] studied the α→β phase transformation by using a simplified Avrami model. For the cooling process, Malinov et al. [19] calculated the percentage of β→α + β phase transformation by utilizing a Johnson-Mehl-Avrami (JMA) model. Moreover, embedding the above two phase transformation models into 2D FE models, Pan et al. [20] studied the influence of cutting speed on the Ti-6Al-4V phase transformation behaviors during a cutting operation. Quan et al. [21] reported the Ti-6Al-4V phase transformation characteristics during a cylindrical billet forging process. Furthermore, based on 3D FE methods, Buffa et al. [22] studied the Ti-6Al-4V phase transformation behaviors during a friction stir welding process. Ducato et al. [23] investigated the Ti-6Al-4V phase transformation characteristics during a flange hot forging and subsequent cooling processes. However, to date, only Bruschi et al. [24] predicted the Ti-6Al-4V phase distribution in a blade section during the hot forging and air cooling operations by 2D FE simulations, and the effect of friction conditions on the phase transformation characteristics of a 3D large complex Ti-6Al-4V turbine blade is still less reported, especially on the general levels and distribution uniformities of different phases within the forged blade.

Therefore, this paper is aimed to evaluate the effect of friction conditions on the phase transformation behaviors of Ti-6Al-4V turbine blade in the hot forging process. For this purpose, a 3D FE model coupled with phase transformation models is developed by using DEFORM-3D™ commercial software. Then, two indexes, including the average and standard deviation values, are employed to quantitatively evaluate the general levels and distribution uniformities of temperature and different phases within the forged blade. Subsequently, the effect of friction conditions on temperature and phase transformation characteristics within the forged blade is investigated in details. Finally, the reliability of simulated results is verified by experiments.

Fig. 1 shows a 1220 mm-long turbine blade with a tenon, damper platform and tip shroud and its 3D forging schematic diagram. To simulate phase transformation characteristics during the blade forging process, a 3D thermo-mechanical FE model embedded with phase transformation models is developed under DEFORM-3D™ environment. Hereinto, the workpiece and forging dies are regarded as deformable and rigid bodies, respectively.

Moreover, the materials of workpiece and forging dies are respectively Ti-6Al-4V alloy and AISI H13 steel, whose chemical compositions in weight percent refer to [25,26]. Moreover, for Ti-6Al-4 V alloy, the stress-strain curves at temperatures (25–1500 °C) and strain rates (0.001–1000 s⁻¹) refer to [27], and its Young modulus [28], thermal conductivity [29] and heat capacity [29] are described by Eqs. (1), (2) and (3), respectively. For AISI H13 steel, the corresponding material parameters refer to [30].

\[
E = 104.94 - 0.052079 \times T
\]  

(1)
Fig. 2 – A subgridding technique with tetrahedral finite element meshes (a) as well as workpiece (b) and forging die (c) mesh details.

K = 0.0131 × T + 6.45

C = 2.36 + 3 × 10^{-4} × T + 2 × 10^{-6} × T^2

Furthermore, for a heating process, the behavior of α→β phase transformation is described by a simplified Avrami model, as shown below [21]:

\[ f_{\alpha \rightarrow \beta} = 1 - \exp \left\{ A (T - T_s) / (T_e - T_s)^D \right\} \]

where \( T \) denotes the instantaneous temperature, \( T_s = 600 \) ℃ and \( T_e = 980 \) ℃ are the phase transformation starting and ending temperatures, \( A = -1.86 \) and \( D = 4.35 \) are material constants [22]. Note that the average error between the model and experimental values is less than 5% [24].

In contrast, for a cooling process, the behavior of \( \beta \rightarrow \alpha + \beta \) phase transformation is simulated by the JMA model coupled with the time-temperature-transformation (TTT) start curve. Hereinto, the beginning of the phase transformation is controlled by the TTT start curve [22], and the transformed percentage is calculated by the JMA model defined as [20]:

\[ f_{\beta \rightarrow \alpha + \beta} = 1 - \exp(-bt^n) \]

where \( t \) denotes the cooling time, \( b \) means the reaction rate constant calculated by the TTT start curve, and \( n = 1.35 \) is the Avrami index [24].

In addition, to effectively describe the interface friction behaviors between the workpiece and forging dies, a shear friction model is selected, as shown below [31].

\[ \tau = mk \]

where \( \tau \) means the frictional stress, \( m \) and \( k \) are the friction factor and shear yield stress, respectively.

Besides, to improve the precision of simulated results, a subgridding technique coupled with tetrahedral finite element meshes is employed, as presented in Fig. 2(a). The minimum mesh sizes of workpiece and forging dies are respectively 3 mm and 2.5 mm, as shown in Figs. 2(b) and (c).

Finally, the important material parameters of workpiece and forging dies as well as the forming parameters for modeling the effect of friction conditions on the Ti-6Al-4V phase transformation characteristics in hot blade forging process are listed in Table 1.

3. Results and discussion

3.1. Evaluation indexes

To quantitatively analyze the general levels and distribution uniformities of temperature and different phases, two indexes including the average and standard deviation values are selected. Hereinto, the average temperature (\( T_{avg} \)) and its standard deviation (\( T_{sd} \)) are defined as [9]:

\[ T_{avg} = \frac{\sum_i^n T_i}{N} \]

\[ T_{sd} = \sqrt{\frac{\sum_i^n (T_i - T_{avg})^2}{N - 1}} \]

where \( T_i \) means the temperature at element \( i \), and \( N \) is the number of elements. Notice that a smaller value of \( T_{sd} \) represents a more homogeneous distribution of temperature.

Like temperature, the average and standard deviation values of \( \alpha \) phase volume fraction can be calculated by:

\[ \bar{f}_{\alpha \text{avg}} = \frac{\sum_i^n f_{\alpha,i}}{N} \]
Table 1 – Material parameters of workpiece and forging dies as well as forming parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Workpiece</th>
<th>Dies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Ti-6Al-4V</td>
<td>AISI H13</td>
</tr>
<tr>
<td>Young’s modulus (MPa)</td>
<td>Eq. (1)</td>
<td>[27]</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.342 [32]</td>
<td>0.3 [33]</td>
</tr>
<tr>
<td>Density (Kg/mm³)</td>
<td>$4.43 \times 10^{-5}$ [34]</td>
<td>$7.8 \times 10^{-5}$ [35]</td>
</tr>
<tr>
<td>Thermal conductivity (W/(s °C))</td>
<td>Eq. (2)</td>
<td>[29]</td>
</tr>
<tr>
<td>Heat capacity (J/(s °C))</td>
<td>Eq. (3)</td>
<td>[29]</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.7 [36]</td>
<td>0.7 [37]</td>
</tr>
<tr>
<td>Convection coefficient (N/(s mm °C))</td>
<td>0.02 [38]</td>
<td>0.02 [39]</td>
</tr>
<tr>
<td>Heat transfer coefficient (N/(s mm °C))</td>
<td>5 [29]</td>
<td></td>
</tr>
<tr>
<td>Environment temperature (°C)</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Workpiece initial temperature (°C)</td>
<td>950</td>
<td></td>
</tr>
<tr>
<td>Forging die initial temperature (°C)</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Equiaxed α phase initial volume fraction (%)</td>
<td>27.2</td>
<td></td>
</tr>
<tr>
<td>β phase initial volume fraction (%)</td>
<td>72.8</td>
<td></td>
</tr>
<tr>
<td>Lamellar α + β phase initial volume fraction (%)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Dwell time before forging (s)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Forging stroke (mm)</td>
<td>116.8</td>
<td></td>
</tr>
<tr>
<td>Forging velocity (mm/s)</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Friction factor</td>
<td>0.1/0/0.2/0.3/0.4/0.5/0.6</td>
<td></td>
</tr>
</tbody>
</table>

\[ f_{\alpha|avg} = \sqrt{\frac{\sum_{i=1}^{n} (f_{\alpha|i} - f_{\alpha|avg})^2}{(N-1)}} \]  

Where $f_{\alpha|avg}$ denotes the average volume fraction of α phase, $f_{\alpha|avg}$ means its standard deviation value, and $f_{\alpha|i}$ is the volume fraction of α phase at element i. Note that a smaller $f_{\alpha|avg}$ value denotes a more uniform distribution of α phase. Besides, for β and lamellar α + β phases, the same calculation methods are employed, although the formulas are not given here.

### 3.3. Effect of friction condition on phase transformation

#### 3.3.1. α phase evolution and distribution

Fig. 5 shows the variations of $f_{\alpha|avg}$ and $f_{\alpha|sd}$ versus the friction factor. It can be found that the value of $f_{\alpha|avg}$ decreases from 20.6% to 12.6% with the increase of m from 0.1 to 0.6. This phenomenon is related to the increase of $T_{\alpha|avg}$ mentioned in Section 3.2. Specifically, enhancing friction can increase the average temperature of the forged blade, leading to the occurrence of α→β phase transformation, thereby resulting in decreasing the average volume fraction of α phase. Conversely, $f_{\alpha|avg}$ can be observed that the value of $f_{\alpha|avg}$ increases from 6.4% to 9.3% as increasing the m from 0.1 to 0.6, which suggests that the distribution uniformity of equiaxed α phase decreases with a poor lubricated friction condition. This phenomenon is found by the work of Sun et al. [40], who also found the surface temperature of AISI-5140 triple valve increases as the friction condition becomes worse. Moreover, compared with a 4.7% increase of $T_{avg}$, a nearly 94% increase is found in the $T_{sd}$, which increases from 33.4° to 64.8° as increasing the m from 0.1 to 0.6. This phenomenon is mainly related to the friction and deformation heating effect. Specifically, the intense friction enhances the inhomogeneous deformation of the forged blade, further increasing the nonuniform distribution of deformation heat, thereby resulting in a nonuniformity distribution of temperature within the forged blade. This explanation can be supported by the work of Luo et al. [9], which reported that the increased friction factor can bring a greater metal flow resistance at the workpiece surface and decreases its deformation uniformity. Furthermore, Fig. 4 directly shows the temperature distribution of the forged blade. It can be observed that the lowest and highest temperature are located at middle and flash areas, respectively. Besides, the temperature distribution uniformity of the forged blade obviously decreases with the increase of friction factor, which is highly consistent with the variation of $T_{sd}$ presented in Fig. 3.
mainly related to the increase of \( T_{sd} \) (Fig. 3). To be specific, the intense friction decreases the distribution uniformity of temperature within the forged blade, further resulting in a more inhomogeneous distribution of \( \alpha \) phase, thereby leading to the increase of \( f(\alpha)_{sd} \). Moreover, Fig. 6 presents the volume fraction distribution of \( \alpha \) phase within the forged blade. It can be observed that the maximum and minimum values of \( \alpha \) phase volume fraction are about 27.2% and 0%, respectively. Furthermore, converse to temperature, the lowest and highest volume fractions of \( \alpha \) phase are located at flash and middle areas, respectively. Besides, the high volume fraction area of \( \alpha \) phase becomes small as increasing the friction factor, which shows a good agreement with the temperature distribution presented in Fig. 4.

3.3.2. \( \beta \) phase evolution and distribution

Fig. 7 shows the variations of \( f(\beta)_{avg} \) and \( f(\beta)_{sd} \) versus the friction factor. Unlike \( f(\alpha)_{avg} \), it can be seen that the value of \( f(\beta)_{avg} \) increases from 76.6% to 84.6% with the increase of \( m \) from 0.1 to 0.6. This phenomenon is also attributed to the occurrence of \( \alpha \rightarrow \beta \) phase transformation caused by the increase of \( T_{avg} \), which has been discussed in Section 3.3.1. Moreover, compared with a 10.4% increase of \( f(\beta)_{avg} \), a nearly 46.6% increase is found in the \( f(\beta)_{sd} \), which increases from 6.4% to 9.4% as increasing the \( m \) from 0.1 to 0.6. This phenomenon is also related to the increase of \( T_{sd} \), and indicates that the friction condition has a more significant effect on the \( \beta \) phase distribution uniformity than its average value within the forged blade. Furthermore, Fig. 8 shows the volume fraction distribution of \( \beta \) phase within the forged blade. It can be observed...
that the maximum and minimum volume fractions of β phase are about 67.5% and 100%, respectively. Unlike α phase, the β phase shows an opposite distribution trend. Hereinto, the lowest and highest volume fractions of β phase are located at middle and flash areas, respectively. The above phenomena are also related to the α→β phase transformation as mentioned above. Besides, like α phase, the distribution uniformity of β phase within the forged blade decreases with the increase of friction factor, showing a consistent with the evolution of \( f_{(\alpha+\beta)_{sd}} \) presented in Fig. 7.

3.3.3. \( \alpha + \beta \) phase evolution and distribution

Fig. 9 shows the variations of \( f_{(\alpha+\beta)_{avg}} \) and \( f_{(\alpha+\beta)_{sd}} \) versus the friction factor. Unlike \( f_{(\alpha)_{avg}} \) and \( f_{(\beta)_{avg}} \), it can be seen that the value of \( f_{(\alpha+\beta)_{avg}} \) remains nearly unchanged (about 2.9%) with the increase of \( m \) from 0.1 to 0.6. This finding indicates that the friction condition has a less influence on the average volume fraction of \( \alpha + \beta \) phase. This is mainly because the large forging velocity (500 mm/s) results in a short forging time (0.23 s), which is insufficient to conduct \( \beta \rightarrow \alpha + \beta \) phase transformation during the blade forging process. This explanation can be supported by the work of Pan et al. [20], which described the Ti-6Al-4V TTT curves in details. Moreover, notice that the few volume fraction of \( \alpha + \beta \) phase is mainly related to the \( \beta \rightarrow \alpha + \beta \) phase transformation occurring in the dwell process (10 s) prior to the blade forging process. Furthermore, like \( f_{(\alpha+\beta)_{avg}} \), the value of \( f_{(\alpha+\beta)_{sd}} \) also remains at the same level (about 0.35%). This finding indicates that the distribution uniformity of \( \alpha + \beta \) phase is much higher than the ones of α and β phases within the forged blade. In addition, Fig. 10 shows the volume fraction distribution of \( \alpha + \beta \) phase within the forged blade. It can be observed that the maximum and minimum volume fractions of β phase are about 1.5% and 5.5%, respectively. Besides, in accord with the variation of \( f_{(\alpha+\beta)_{sd}} \) (Fig. 9), it can be found that the distribution of \( \alpha + \beta \) phase is homogeneous and remains nearly the same for each friction conditions.

4. Experimental verification

For Ti-6Al-4V alloy forging process, the friction factor measured by Zhu et al. [41] is approximately 0.3 under glass lubricant condition. Hence, to verify the effectiveness of simulated results, glass lubricant-assisted hot forging experiments are conducted by using a SPKA 22400 clutch screw press in Wuxi Turbine Blade Co., Ltd. and compared with simulated results. Note that the other process parameters keep the same, as listed in Table 1. It can be seen from Figs. 11(a) and (b) that

![Fig. 8 – Volume fraction distribution of β phase vs. friction factor.](image1)

![Fig. 9 – \( f_{(\alpha+\beta)_{avg}} \) and \( f_{(\alpha+\beta)_{sd}} \) variations vs. friction factor.](image2)

![Fig. 10 – Volume fraction distribution of lamellar α + β phase vs. friction factor.](image3)
the geometries of experimental and simulated blades show a good agreement. Moreover, Fig. 11(c) shows the microstructures of the forged blade at P1 and P2 areas after a subsequent air cooling process, which is mainly consisted of equiaxed α phase and lamellar α + β phase. Furthermore, Fig. 11(d) compares the simulated results with experimental ones in the volume fraction of equiaxed α phase at P1 and P2 areas, which shows a good consistency. Hence, the developed 3D thermo-mechanical FE model can well simulate the phase transformation characteristics of Ti-6Al-4V turbine blade in the hot forging process, and its simulated results are effective and accurate.

5. Conclusions

In this paper, using 3D thermo-mechanical FE methods, the friction effect on the temperature and phase transformation characteristics of Ti-6Al-4V turbine blade in the hot forging process is analyzed, and then verified by experiments. Following conclusions are achieved:

1. The values of $T_{avg}$ and $T_{ad}$ increase as increasing the friction factor, which indicates that the average and distribution nonuniformity of temperature decrease with a good lubricated condition. This is mainly because a better lubricated condition can decrease the heat generation on the surface of workpiece and increase the homogeneous deformation of the forged blade, resulting in weakening the friction and deformation heating effect, thereby leading to a lower average value and more uniform distribution of temperature within the forged blade.

2. The value of $f_{(α)avg}$ is negatively correlated with the friction factor, which can be attributed to the α→β phase transformation caused by the increase of $T_{avg}$. Moreover, unlike the $f_{(α)avg}$, the value of $f_{(α)ad}$ shows an opposite evolution trend, which is mainly related to the increase of $T_{ad}$. The above phenomena indicate that the average volume friction and distribution uniformity of equiaxed α phase within the forged blade decrease with a poor lubricated condition.

3. The values of $f_{(β)avg}$ and $f_{(β)ad}$ are positively related to the friction factor, which suggests that the average value of β phase volume fraction increases and its distribution uni-
formity becomes worse with a poor lubricated condition. Moreover, the friction condition has a less influence on lamellar α + β phase within the forged blade. This is mainly because the short time caused by high forging velocity is insufficient to conduct β→α + β phase transformation during the blade forging process.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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