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Solid Particle Erosion Area of Rotor Blades: Application on Small-Size Unmanned Helicopters

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Abstract: Rotor blades play an important role in unmanned helicopters, and it is of great significance to study the erosion of rotor blades. In this study, titanium alloy (Ti-4Al-1.5Mn) was used as the helicopter rotor blades’ surface material. The commercial software Ansys-Fluent 18.0 was mainly used to study the erosion of solid particles on the helicopter rotor blades. The moving mesh method and the discrete phase method (DPM) were used to construct an erosion model of the blades at different speeds (500, 1000, or 2000 rpm), and at different particle mass flow rates (0.5, 1, or 1.5 kg/s). The results show that the erosion of helicopter blades is mainly observed at the leading edge and at the tip of the blades. At different particle mass flow rates, greater particle mass flow rates lead to greater DPM erosion rates. As the blade speed increases, the maximum DPM erosion rate decreases, but the severely eroded area increases. Finally, the values of the severely eroded area of the helicopter rotor blades and the ratios of the severely eroded area growth are obtained through the image processing method.

Keywords: solid particle erosion; blades of unmanned helicopters; erosion rate; erosion area; moving mesh

1. Introduction

The wear of mechanical parts is one of the main forms of mechanical equipment failure. The wear of equipment not only causes energy waste, but also causes increased equipment maintenance, and even production safety accidents. The waste of labor and material resources caused by erosion and wear is shocking. Erosion is a type of wear, usually referring to a wear phenomenon in which small particles hit the surface of materials [1]. Changes in the properties of particles and target materials also affect the changes in the material erosion rate [2,3]. The authors have carried out numerical simulation studies on the erosion of helicopter rotor blades under different materials [4]. However, this work did not conduct a specific analysis of the overall helicopter rotor blade erosion, which is worthy of further study. This erosion research can help to improve the flight performance of unmanned helicopters.

Computational fluid dynamics (CFD) is an important basis for erosion research, and many results on erosion are based on CFD. Chen [5,6] used CFD software to analyze the gas–liquid two-phase flow of an underwater hovering device, and the fluid structure change law was found after the hovering device entered the water. Haider et al. [7] and Wang et al. [8] used CFD and finite element to track the particles after erosion, and obtained the wall rebound model of the particles in complex geometric shapes, which would be helpful for future erosion research. Zhang et al. [9] applied CFD to the erosion of steam turbines and found that the maximum erosion rate density on the turbine blades is 1.9
times the erosion rate on the nozzle. This literature shows that CFD research has the potential for great development. With the advancement of computer technology and the development of commercial software, more and more experts and scholars have been paying attention to the research of erosion simulation in recent years [10–13]. Finnie [14] provided the basis for most erosion models, which were considered pioneers in the functioning of ductile material erosion models. Finnie concluded that wear and erosion is a complex function that depends on three variables: particle impact characteristics (velocity and angle), particle material, and target wall characteristics [14]. The model was based on single particle impact studies [14]. The model provided by Finnie was later improved by other researchers. Bitter [15] improved the Finnie model and pointed out that erosion was usually a combination of two mechanical processes, namely cutting and deformation. This model is considered one of the most outstanding models, but it is often ignored due to the need for many empirical constants. Grant and Tabakoff [16] developed an improved Finnie erosion model, which is still widely used, especially in the field of machinery.

So far, there are few studies on the erosion of helicopter blades. Shin [17] used Ansys-Fluent to conduct two-dimensional (2D) and 3D numerical analysis, and determined that when the main rotor blades rotate at low altitude and high speed, the helicopter erosion rate distribution shows a higher level on the surface. On this surface, the impact velocity of solid particles increases linearly toward the tip of the rotor blade. Shin wrote that the erosion of solid particles on the surface of rotating rotor blades is related to their peripheral speed, angle of attack, and length. These studies can be found in more detail in the literature [18,19]. İsmail Özen et al. [20] used Ansys-Fluent to carry out numerical studies on the erosion of solid particles of blades of different materials, and obtained helicopter blade materials that are more resistant to erosion.

There are many studies on the erosion of wind turbines or turbine blades. Regarding turbines, Clevenger and Tabakoff [21] are famous scholars of our time. They studied the erosion of the radial flow into the inner surface of the turbine, which became the starting point for later research. Their purpose was to determine the erosion rate of turbines operated in dust-swallowing and solid-particle environments. They concluded that more material loss occurred in certain areas. These areas are located at the trailing edge of the nozzle (stator) blade. It has also been observed that areas with brittle materials suffer less erosion loss than plastic materials. Ryan et al. [22] further studied the influence of the wind turbine’s leading edge shield on the aerodynamic characteristics of the airfoil. They found that the use of the shield was slightly beneficial to the flow of large wind turbines. The influence of the generator was negligible at low wind speeds, but in any case, the protective cover was useful to the loss caused by the erosion of the airfoil. Roul [23] used finite element analysis (FEA) methods to study the aerodynamics and structural analysis of wind turbines, and found that the pitch angle had a prominent influence on the output of wind turbines, which could provide a new idea for turbine blade erosion protection.

Recently, some researchers have carried out research on the flow and erosion on the surface of axial turbine blades and other parts using CFD models. Mazur et al. [2] proposed a CFD simulation to determine the erosion at the main shutoff valve of the steam turbine. The results showed that the erosion process depends to a large extent on the particle’s trajectory and impact angle. Through improving the initial design of the valve, the erosion rate was reduced by 51% and the service life was increased by 100%. Blades have also attracted great interest in CFD simulation and erosion prediction studies, as they are the main targets of solid particle impact. Amezcuta et al. [24] performed a study of steam turbine nozzle erosion due to solid particles entrained in airflow. They observed severe damage to the stator blades and found that the erosion rate decreased as the particle size increased. However, they did not give the specific value of the erosion degree.

Unmanned helicopters can take off and land vertically, so they are usually used to perform tasks under poor working conditions such as in sand erosion environments. Flight in erosive environments is an urgent and special task when it is performed. Erosion research into unmanned helicopters helps not only to improve the flight performance but
also to avoid casualties, which is of great importance. This study focuses on the erosion of unmanned helicopters’ rotating blades. The erosion rate and erosion area of blades is studied in detail. The article starts with the modeling of the helicopter blades, and the erosion of the solid particles of different particle mass flow rates at different rotation speeds of the helicopter blade is analyzed thereafter. Erosion rate, area, and proportion can be observed. This provides a basis and theoretical guidance for subsequent erosion resistance research.

2. Numerical Analysis

2.1. Mathematical Model

Ansys-Fluent 18.0 software was used in the numerical research of this study, in which the discrete phase method and the moving mesh method are the main research methods.

The Lagrangian method was used to track particles, and a one-way coupling method was adopted, ignoring the interaction between particles and the influence of particles on the fluid phase. The particles were tracked by solving their equation of motion, and the collision information of the impacting particles was put into the erosion equation to finally determine the corresponding erosion rate. The particle motion equation mainly used by Fluent is Equation (1) [25]:

$$\frac{dV_p}{dt} = F_D (U - V_p) + g (\rho_p - \rho) + F_{\text{others}}$$

(1)

In the above formula,

$$F_D = \frac{18 \mu C_D \text{Re}}{\rho_p d_p^2 \cdot 24}$$

(2)

where $F_D$ (N) is the drag force per unit mass of the particle; $\mu$ (mPa·s) is the dynamic viscosity; $U$ (m/s) is the fluid velocity; $V_p$ (m/s) is the particle velocity; $\rho_p$ (kg/m³) is the particle density; $g$ (m/s²) is the gravitational acceleration; $d_p$ (m) is the particle diameter; $C_D$ is the drag coefficient; $F_{\text{others}}$ (N) is the other forces per unit mass, and Re is the relative Reynolds number.

Navier–Stokes equations are necessary for solving momentum and energy conservation equations. The generalized state equation of the Reynolds average Navier–Stokes equation is given by Equations (3) and (4):

$$\frac{\partial P}{\partial t} + \frac{\partial}{\partial x_i} (\rho U_i) = 0$$

(3)

$$\frac{\partial}{\partial t} (\rho U_i) + \frac{\partial}{\partial x_i} (\rho U_j U_j) = - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial U_k}{\partial x_k} \right) \right] + \frac{\partial}{\partial x_i} (\rho u_i u_j)$$

(4)

In this study, the K-ω SST turbulence model was used for CFD erosion analysis because the erosion analysis K-ω SST turbulence model performed under CFD software was considered to have the best convergence and sensitive results [26]. The main equations are Equations (5) and (6), which can be seen as follows:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho U_j k)}{\partial x_j} = \beta^* \rho k \omega + \frac{\partial}{\partial x_i} \left[ (\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_i} \right]$$

(5)
where $\rho$ (kg/m$^3$) is the fluid density, $\mu$ (mPa·s) is the turbulent viscosity, $\mu$ (mPa·s) is the dynamic viscosity, $F_1$ is the first blending function, and $F_2$ is the second blending function. The values of these constants are as follows [27]:

\[
\beta^* = 0.09, \quad \alpha_1 = 5/9, \quad \beta_1 = 3/40, \quad \sigma_{k1} = 0.85, \quad \sigma_{n1} = 0.5, \quad \alpha_2 = 0.44, \quad \beta_2 = 0.0828, \quad \sigma_{k2} = 1, \text{ and } \sigma_{n2} = 0.856.
\]

The main erosion equation used is Equation (7) [28]:

\[
E_{RV} = E_\theta F(\theta)
\]

\[
E_\theta = K(Hv)^{k_1} \left( \frac{V_p}{V^*} \right)^{k_2} \left( \frac{d_p}{d^*} \right)^{k_3}
\]

\[
F(\theta) = (\sin(\theta))^{n_1} (1 + Hv/(1 - \sin(\theta)))^{n_2}
\]

\[
n_1 = S_1(Hv)^{q_1}, \quad n_2 = S_2(Hv)^{q_2}, \quad k_1 = 2.3(Hv)^{0.038}
\]

where $E_{RV}$ (kg/(m$^2$·s)) is the volumetric erosion rate, $E_\theta$ (kg/(m$^2$·s)) is the erosion damage at a normal impact angle, $F(\theta)$ is the impact angle function, $\theta$ is the particle impact angle, $K$ is the particle property factor, $V^*$ (m/s) is the reference impact velocity, $d_p$ (m) is the particle diameter, $d^*$ (m) is the reference particle diameter, and $Hv$ is the material Vickers hardness. The values of the different coefficients and indices in the equation were:

$K = 65, \quad k_1 = -0.12, \quad k_2 = 0.19, \quad S_1 = 0.71, \quad S_2 = 2.4, \quad q_1 = 0.14, \quad \text{and } q_2 = -0.94$.

The erosion equation is given in Equation (11):

\[
E_R = 10^{-9} \rho_w E_{RV}
\]

where $\rho_w$ is the target density.

In order to calculate the rebound velocity and direction of particles hitting the sample surface, we used the rebound model proposed by Taslim [29]. This model includes the normal velocity component (\(e_n\), Equation (12)), and the tangential velocity component (\(e_t\), Equation (13)).

\[
e_n = 0.993 - 1.76\alpha + 1.56\alpha^2 - 0.49\alpha^3
\]

\[
e_t = 0.988 - 1.66\alpha + 2.11\alpha^2 - 0.67\alpha^3
\]

2.2. Erosion Model

The structure of unmanned helicopter rotor blades is complex. The outer layer is wrapped in alloy and the inner layer is mainly composed of a composite structure. Ti-4Al-1.5Mn is a commonly used aerospace material, considered an alloy with strong erosion resistance [4]. The elemental composition and characteristics of Ti-4Al-1.5Mn are shown.
in Table 1. Since the erosion occurs in the outer layer and the erosion of the internal composite structure hardly occurs, the titanium alloy material (Ti-4Al-1.5Mn) was used as the helicopter rotor blades’ surface material in this study.

| Table 1. Elemental composition (%) and characteristics of Ti-4Al-1.5Mn. |
|-----------------|----------------|----------------|----------------|----------------|
|                 | Ti             | Al             | Mn             | O              |
| Ti-4Al-1.5Mn    | Balance        | 3.5–5.0        | 0.8–2.0        | 0.15           | 0.55           |
|                 | Density (kg/m³) | Hardness (Vickers) | Young’s Modulus (Pa) | Bulk Modulus (Pa) | Shera Modulus (Pa) |
|                 | 4500           | 330            | $9.6 \times 10^{10}$ | $1.14 \times 10^{11}$ | $3.53 \times 10^{10}$ |

The geometric details of the helicopter rotor blades used in the simulation are shown in Figure 1. The 3D model was constructed using the software Solidworks 2016 at a scale of 1:1. Figure 2 shows the main airfoil parameters of the blades. The airfoil used for the blades was NACA2412, which is a typical general-purpose airfoil. The takeoff weight of the small unmanned helicopter simulated in this study was 200 kg. As shown in Figure 3, the solid particle erosion model of helicopter rotor blades was established in the Ansys Geometry module. The model is divided into a rotation domain and a quiescent domain. In order to simulate the flying state of the unmanned helicopter in a dusty environment, the rotor blades rotated at high speeds (500, 1000, or 2000 rpm) in the rotation area. Helicopter rotor blades are complex curved surfaces, so the unstructured meshing method of tetrahedral elements was adopted. Different domains require different mesh refinement, as shown in Figure 4. As the entire quiescent domain ① in Figure 4c is large, the average size of the elements in the quiescent domain is drawn as 100 mm. Meanwhile, the rotation domain ② and rotor blades ③ need to be drawn with finer element size, as the average element sizes are 20 mm and 10 mm respectively. The detailed sizes of the total number of elements and nodes in each area are shown in Table 2. The skewness value of the mesh quality in each area is also given in Table 2. The average skewness value is 0.25. The mesh quality was considered excellent and could be used for numerical calculations.

Figure 1. Model of a helicopter rotor blade: (a) 3D model; (b) 2D model and main dimensions.
Figure 2. Airfoil of the helicopter rotor blades.

Figure 3. Finite element model and boundary setting.

Figure 4. Mesh generation of the blade erosion model: (a) the overall mesh; (b) the section mesh; (c) the area mesh.
Table 2. Details of the mesh.

| Mesh Area | Element Average Size | Total Number of Notes | Total Number of Elements | Skewness |
|-----------|----------------------|------------------------|--------------------------|----------|
| 1         | 100 mm               | 358,570                | 2,060,721                | 0.33     |
| 2         | 20 mm                | 360,363                | 2,001,113                | 0.21     |
| 3         | 10 mm                | 11,841                 | 41,368                   | 0.20     |

Afterwards, the blades model was imported into Ansys-Fluent 18.0 to conduct the erosion study of the moving mesh, the erosion parameters under the discrete phase model (DPM) model were defined, the particle was defined as SiO$_2$, the particle density was 2200 kg/m$^3$, and the incident velocity was defined as 20 m/s [30], which was perpendicular to the inlet surface. The particle mass flow rate was preferentially defined as 0.5 kg/s, and regular particles with an average diameter of 100 µm were injected at the entrance at the same impact velocity, while different blade rotation speeds were set (500, 1000, or 2000 rpm). Since the erosion boundary of the helicopter rotor blade was solved under transient conditions, the particle incident time was set to end after 180 s. The simulation parameters are shown in Table 3.

Table 3. Simulation parameters.

| Materials                  | Ti-4Al-1.5Mn |
|----------------------------|--------------|
| Sand Size (µm)             | 100          |
| Particle velocity (m/s)    | 20           |
| Speed (rpm)                | 500          |
| Flow Rate (kg/s)           | 0.5          |

3. Results and Discussion

3.1. Blade Erosion at Different Speeds

The erosion of blades of different materials (titanium alloy (Ti-4Al-1.5Mn), magnesium alloy (Mg-Li9-A3-Zn3), or aluminum alloy (Al7075-T6)) has been studied previously. It was found that the erosion resistance of titanium alloy (Ti-4Al-1.5Mn) is better than the other two materials, so it was selected as the blade material in this study. One of the purposes of this research was to reveal the erosion conditions of each area during the blade rotation process. Therefore, the erosion of blades at different speeds (500, 1000, or 2000 rpm) at a mass flow rate of 0.5 kg/s were studied first. The three-dimensional erosion rate distributions of blades at three speeds are shown in Figure 5.
It can be observed in Figure 5 that the erosion of the tip of the blade was more serious, that the most erosion occurred on the leading edge of the blade, and that the trailing edge of the blade was hardly eroded. The two-dimensional line graph of the erosion rate in Figure 6 is more intuitive than in Figure 5.

Figures 5 and 6 show that the erosion of the blade tip was more serious, that the maximum erosion rate appeared near the blade tip, and that large areas of erosion occurred near the tip of the pressure surface of the blade. The rotation speed was much greater than the incoming wind speed, and the rotation plane and the incoming wind speed were not on the same plane. In this case, the blade tip was more susceptible to erosion due to the large inertial force which caused the particles to not have enough time to enter the center of rotation.

The black horizontal lines on the abscissa in Figure 6 are not continuous but densely scattered, and they are not points with a zero erosion rate, nor are they points with an erosion rate much smaller than the $10^{-6}$ set. It could be inferred that the erosion that occurred on the blades was very intensive and that the erosion rate in individual areas was high. However, Figure 5 shows that the blade erosion distribution is not very regular, which may be related to the change of the airflow field caused by the rotation of the blade. As the speed of the blade increased, the erosion area of the blade became larger because the blade with a fast speed came in contact with more particles in the same amount of time. However, it was interesting that the maximum erosion rate of the blade was reduced with a faster blade speed, due to the shortening of the particle collision time.
Figure 6. Scatter plot of blade erosion distribution of a particle mass flow rate 0.5 kg/s at different speeds: (a) 500 rpm; (b) 1000 rpm; (c) 2000 rpm.

The linear velocity value of the rotation blade is shown in Figure 7, and the static pressure of the rotation blade is shown in Figure 8. Comparing Figure 6 with Figure 7 and Figure 8, it can be found that the severely eroded area at the root of the blade was small.
or even nonexistent, because the lower the linear velocity is, the lower the pressure near the blade root. However, there was no maximum erosion rate at the tip of the blade with the highest linear velocity. It was deduced that there might be a critical velocity corresponding to the maximum erosion rate within a certain speed range.

Figure 7. Linear velocity at each position of the blades: (a) three-dimensional contour; (b) two-dimensional chart.
3.2. Blade Erosion at Different Particle Mass Flow Rates

The particle mass flow rate is also considered an important factor causing the erosion of the material surface. Therefore, an unmanned helicopter blade erosion simulation under the impact of different particle mass flow rates was carried out in this section.

The simulation process was to inject different particle mass flow rates (0.5, 1, or 1.5 kg/s) at the entrance of the entire flow field in Figure 3, while other conditions and parameters remained unchanged. The erosion area and the degree of erosion can be observed in Figures 5, 9, and 10 at different particle mass flow rates (0.5, 1, or 1.5 kg/s) and different rotation speeds (500, 1000, or 2000 rpm). At different particle mass flow rates and at the same speed (e.g., 0.5, 1.0, or 1.5 kg/s, at a speed of 500 rpm), the erosion area of the blade was almost unchanged and only the erosion rate of the blade was changed.

**Figure 8.** Static pressure on the blade: (a) three-dimensional contour; (b) two-dimensional chart.

**Figure 9.** The three-dimensional erosion rate at a particle mass flow rate of 1 kg/s, at different blade speeds: (a) 500 rpm; (b) 1000 rpm; (c) 2000 rpm.
Figure 10. Three-dimensional erosion rate at a particle mass flow rate of 1.5 kg/s, at different blade speeds: (a) 500 rpm; (b) 1000 rpm; (c) 2000 rpm.

Figures 6, 11, and 12 show scatter plots of the two-dimensional erosion rates and the regional distribution of blades at different particle mass flow rates and at different speeds. The results intuitively indicate that the erosion of the blades became more serious as the particle mass flow rate increased. The eroded area was also closer to the tip of the blade. The erosion rate of the blade decreased with increasing speed at the same particle mass flow rate, which was consistent with the conclusion obtained in Section 3.1.
Figure 1. Scatter plots of the blade erosion distribution at a particle mass flow rate of 1 kg/s, at different speeds: (a) 500 rpm; (b) 1000 rpm; (c) 2000 rpm.
Figure 12. Scatter plots of the blade erosion distribution at a particle mass flow rate of 1.5 kg/s, at different speeds: (a) 500 rpm; (b) 1000 rpm; (c) 2000 rpm.
3.3. Eroded Area

Digital image processing is the use of computers to process images [30]. Image recognition technology is a common method in image processing, and is used in this section. Mainly, feature extraction is performed after image preprocessing (enhancement, restoration, and compression), and then image classification decisions are made [31].

The erosion rates of unmanned helicopter rotor blades at different speeds and particle mass flow rates had already been studied. The image recognition method to extract severely eroded areas was used to process the images in Figures 5, 9, and 10. The total pixel units of the two blades were 17,750 and the total surface area of the two blades was 191,059.90 mm². The number of pixels in the severely eroded area was also obtained. In Tables 4–6, Ai means the value of the severely eroded area of the left blade, Pi means the ratio of the severely eroded area of the left blade to the area of the left blade, and PL and PR correspond to the values of the right blade. |AR+i| = |AR + Ai| means the sum in the severely eroded area of the two rotor blades, |ΔAR+i| = \[\frac{[(A_{R+i})_{i+1} - (A_{R+i})_i]}{(A_{R+i})_i} (i = 1, 2, 3)\] means the ratio of the severely eroded area growth of the left blade and the right blade.

The results in Tables 4–6 show that the severely eroded area of the blades increased significantly, and that Pt and Pr also increased with increasing blade speed at the same particle mass flow rate. The ratios Pt and Pr of the severely eroded area were between 0.67% and 3.88%. The values of P_{i+1} - P_{i}, Pr, and Pt after subtracting each other was from 0.02% to 0.38%. As the blade speed increased, the |AR+i| increased while the ratio |ΔAR+i| decreased. It was inferred that a large number of particles hit the surface of the blade and caused a severely eroded foundation area at the beginning of the erosion. As the erosion progressed and the blade speed increased, some particles impacted the eroded foundation area, which did not obviously increase the total severely eroded area.

Table 4. The erosion area and proportion of a severely eroded blade (0.5 kg/s).

| i | Flow Rate, Blade Speed | Ai (mm²) | Pt | As (mm²) | Pr | AR+i (mm²) | ΔAR+i |
|---|------------------------|---------|---|---------|---|------------|-------|
| 1 | 0.5 kg/s, 500 rpm      | 1335.51 | 0.67% | 1967.91 | 1.03% | 3303.42    | 1.97   |
| 2 | 0.5 kg/s, 1000 rpm     | 3095.17 | 1.62% | 4356.17 | 2.28% | 7451.34    | 2.26   |
| 3 | 0.5 kg/s, 2000 rpm     | 4738.29 | 2.48% | 7413.12 | 3.88% | 12151.41   | 0.63   |

Table 5. The erosion area and proportion of a severely eroded blade (1.0 kg/s).

| i | Flow Rate, Blade Speed | Ai (mm²) | Pt | As (mm²) | Pr | AR+i (mm²) | ΔAR+i |
|---|------------------------|---------|---|---------|---|------------|-------|
| 1 | 1.0 kg/s, 500 rpm      | 1485.53 | 0.78% | 1719.53 | 0.90% | 3205.06    | 1.12   |
| 2 | 1.0 kg/s, 1000 rpm     | 2674.84 | 1.40% | 4296.85 | 2.25% | 6973.69    | 1.17   |
| 3 | 1.0 kg/s, 2000 rpm     | 4700.07 | 2.46% | 7069.22 | 3.70% | 11176.29   | 0.68   |
Table 6. The erosion area and proportion of a severely eroded blade (1.5 kg/s).

| $i$ | Flow Rate, Blade Speed | $A_i$ (mm²) | $P_i$ | $A_r$ (mm²) | $P_r$ | $|A_{R+L}|$ (mm²) | $|A_{R+L}|$ |
|-----|------------------------|-------------|-------|-------------|-------|------------------|---------|
| 1   | 1.5 kg/s, 500 rpm      | 1318.31     | 0.69% | 1757.75     | 0.92% | 3076.06          |         |
| 2   | 1.5 kg/s, 1000 rpm     | 3228.91     | 1.69% | 4451.70     | 2.33% | 7680.61          | 1.50    |
| 3   | 1.5 kg/s, 2000 rpm     | 5426.10     | 2.84% | 7125.53     | 3.73% | 12,551.61        | 0.63    |

4. Conclusions

The erosion behavior of unmanned helicopter rotor blades covered by titanium alloy (Ti-4Al-1.5Mn) at different rotation speeds and at different solid particle mass flow rates were the main object of study, and this was simulated numerically.

(1) Through the analysis and comparison of Ansys-Fluent simulation results, it is obvious that the greater blade speed was, the larger the erosion area was at different blade speeds, and the erosion areas of the blades mainly occurred on the leading edge and on the tip of the blades. However, the maximum DPM erosion rate was reduced. It was also concluded that as the particle mass flow rate increased, the DPM erosion rates of the blades increased significantly. These rules were consistent on the left and right blades.

(2) Through image processing, the severely eroded area of blades and the ratio values were calculated. The ratios $P_i$ and $P_r$ of the severely eroded area were between 0.67% and 3.88%. The values of $P_{i_\text{se}} - P_{i_\text{se}}$ ranged from 1.68% to 2.85%, and the value range of $P_{n_i}$, $P_{r_i}$, and $P_{l_i}$ after subtracting each other were from 0.02% to 0.38%. This also verified conclusion (1).

New materials have been widely used as a coating, which lays a foundation for erosion resistance. Following work can consider whether new material can be used as a coating for blades, and whether it performs better than a metal coating.

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