Study on the Instantaneous Temperature and Life Prediction of Polymer Gear Based on ANSYS/LS-DYNA

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Abstract. Taking the polymer gear as the research object, analyzing the instantaneous temperature rise of the tooth surface in the polymer gear through combined systematical approach of theoretical arithmetic and finite element analysis. It is found that the loading torque, compared to the rotational speed, has a more significant effect on the instantaneous temperature rise. Take the influence of the speed and the loading torque of the meshing polymer gear into full consideration, the life of the gear can be predicted. And its correctness also can be verified by experiments, which is of great theoretical value and has a promising prospect on engineering application.

Introduction

Polymer composite gears have been broadly used in the aerospace, auto-manufacturing, electronics, food and medical processing industry, etc. Its development prospect is promising¹. The heat generated by friction during the meshing of the polymer will cause the temperature of the meshing area higher than that of the gear body. And when the temperature rises, its mechanical properties will be significantly reduced, which will thus reduce the durability and shorten the life of the gear.

Eric² have proposed a new method to study the thermal behavior of polymer gears. Based on this method, a hot test bench with infrared camera was developed K. Mao³-⁴, taking acetal gear as the object of experiment, studied the surface temperature of polymer macromolecule gears and found that the changes of gear body temperature, ambient temperature and flash temperature all affect the surface temperature of the gearBobach.⁵ introduced several methods of gear thermal analysis, and studied the change of the internal temperature field of the gear under different methods, and verified the correctness of the gear temperature field. C J Hooke⁶ studied acetal gears and found that when the transmission torque increases above the critical value, the gear wear rate will drastically change from low wear rate to high wear rate.

Taking the PEEK as the gear matrix material and referring to the theory of friction, heat transfer, Hertz theory and viscoelasticity, through ANSYS/LS-DYNA analysis program, the finite element analysis model of transient dynamic temperature field of polymer gear was established, and the temperature field and the contact stress of the polymer gear are simulated and analyzed. And the gear load torque and the rotational speed which will have influence on the results were also analyzed, based on which the working life of the high polymer gear was predicted. And the reliability of this prediction was also verified by tests, the results of which can provide theoretical basis for polymer gear design.

Gear Thermal Analysis

In the transmission, the instantaneous temperature of the meshing tooth surface is higher than that of the gear body. According to the Bullock flash theory, it is known that when the gears are engaged, the instantaneous temperature, higher than the body temperature, is constantly changing, but the range of variation is very small and is limited to a very thin hot surface on the tooth surface.
Therefore, it is generally assumed the temperature of each point is set when the gear is meshing, and the body temperature of the gear teeth is regarded as a steady-state field problem.

The equations for solving the steady-state problem of temperature field are generally obtained by transforming the unsteady-state equation. The general form of the three-dimensional unsteady thermal differential equations are: [7]

\[
\frac{\partial}{\partial t} (\rho T) = \frac{\partial}{\partial x} \left( \frac{\lambda}{\partial x} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\lambda}{\partial y} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{\lambda}{\partial z} \frac{\partial T}{\partial z} \right) + \Phi
\]

(1)

\( \Phi \), the heat source strength of the temperature field, is processed as a constant. According to the Bullock theory, the body temperature of the gear teeth is treated as a steady-state field problem, Under this condition, the unsteady equation is:

\[
\rho \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} + \lambda \frac{\partial^2 T}{\partial y^2} + \lambda \frac{\partial^2 T}{\partial z^2}
\]

(2)

The temperature of the steady-state temperature field does not change with time passing by:

\[
\frac{\partial T}{\partial t} = 0
\]

(3)

Therefore, the steady-state temperature field equation is:

\[
\lambda \frac{\partial^2 T}{\partial x^2} + \lambda \frac{\partial^2 T}{\partial y^2} + \lambda \frac{\partial^2 T}{\partial z^2} = 0
\]

(4)

When conducting the finite element simulation analysis of the friction heat of the gears, in addition to the size and material parameters of the gears, the sliding friction factor is also needed.

**Determination of Sliding Friction Factor**

In this thesis, polyether ether ketone (PEEK) is chosen as a kind of new polymer material, and it is of good heat resistance and mechanical properties due to its special crystallization, and can be in long-term use at 250 °C.

In order to obtain more accurate data, the determination of the coefficient of friction of the material is measured at a MMG-10 high temperature protection friction and wear tester. The working conditions of the test are shown in Table 1. At the same time, the sliding friction coefficient of the polyether ether ketone (PEEK) is shown in Figure 1. Take the average value to get a slip friction factor of 0.34.

<table>
<thead>
<tr>
<th>Load(N)</th>
<th>Rotating speed(r/min)</th>
<th>Friction and wear state</th>
<th>Temperature(℃)</th>
<th>Time(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>200</td>
<td>Dry friction</td>
<td>20</td>
<td>3600</td>
</tr>
</tbody>
</table>

![Table 1. Friction and wear test conditions.](image)

**Figure 1. Friction and wear curve.**
Material Parameters

The properties of the polyether ether ketone (PEEK) are shown in Table 2.

<table>
<thead>
<tr>
<th>Elastic Modulus/Pa</th>
<th>Poisson’s ratio/u</th>
<th>Thermal conductivity/W/m·k</th>
<th>Thermal expansion coefficient/°C⁻¹</th>
<th>Specific heat capacity/J/(Kg·°C)⁻¹</th>
<th>Density/g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.55×10⁹</td>
<td>0.4</td>
<td>0.25</td>
<td>4.7×10⁻⁵</td>
<td>1330</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Instantaneous Temperature Rise Simulation

Model Establishment

Using the three-dimensional software Solidworks to model the gear, this paper selects two involute spur gears with the same parameters. The gear parameters are shown in Table 3. The model is shown in Figure 3.

Table 3. Gear parameters.

<table>
<thead>
<tr>
<th>Module</th>
<th>Tooth numbers</th>
<th>Pressure angle</th>
<th>Face width</th>
<th>Tooth thickness</th>
<th>Topline coefficient</th>
<th>Tooth high coefficient</th>
<th>Contact ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>2mm</td>
<td>30</td>
<td>20°</td>
<td>17mm</td>
<td>3.14mm</td>
<td>0.25</td>
<td>1</td>
<td>1.65</td>
</tr>
</tbody>
</table>

In order to improve the efficiency of calculation, the Contact Sizing method is used to refine the grid on the teeth, which are more dense near the grid, sparse in other areas, the total number of the units is 174780, the nodes, 206,288.

![Gear modeling.](image1)

![Divides the grid.](image2)

Finite Element Analysis

The finite element analysis software ANSYS/LS-DYNA was introduced into the model, and the results were analyzed by LS-PREPOST post-processing software to obtain the transient temperature field and the stress distribution.

In this case, the transient friction simulation of the polymer gear is carried out to simulate the actual working conditions of the gear meshing, the torque of the driving wheel is 50r/min, the torque applied by the driven wheel to the rotating direction of the driving wheel, 20N·m, the ambient temperature was set at 20°C. The calculation time is 0.02s, the calculation step is 0.001s, the input sliding friction coefficient is 0.34, and the simulation results are analyzed and discussed.

![Polymer gear tooth surface temperature and contact stress distribution.](image3)

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From the polymer gear tooth surface temperature and contact stress distribution displayed in Figure 4, the instantaneous temperature rise of the gear is mainly occurred in the tooth surface, showing a significant temperature gradient distribution, and a large contact stress occurs at the position of the meshing point.

In order to observe the temperature distribution of the tooth surface more intuitively, tooth surface of the drive wheel was selected at the meshing when \( t = 0.012 \)s, and extract all the node information on the tooth surface, a tooth surface temperature distribution map as Figure 5 was drew.

![Figure 5. Tooth surface temperature 3D distribution map.](image)

It can be seen from Figure 5 that there are two peaks in the position of the tooth surface near the tooth root and the tooth top position, where are the gear meshing and the meshing position respectively, because the contact stress is large, so the heat flow generated by friction is also much larger than that of other meshing points, distributing along the tooth width direction, the temperature rise is also of symmetrical distribution.

**Analysis of Influencing Factors**

The factors that affect the friction of the polymer gear, besides the geometric characteristics of the gear and materials, also include the high frequency of the gears and the load torque. Then the analysis of the influence of the rotation speed and the applied torque on friction heat will be made based on the high molecular gear Drive meshing simulation results under a variety of conditions.

In order to more intuitively observe the effect of torque and speed on the temperature rise, the information of the nodes on the tooth surface when \( t = 0.01 \)s is extracted under the torque of 1N·m respectively. As mentioned above, the tooth surface temperature distribution symmetrically along the direction of tooth width can be considered to be the same. The following Figure 6 was drew to show the rotation speed and the temperature rise under torque 1N·m. At the same time in the 50r / min speed to extract the torque when \( t = 0.01 \)s is the tooth surface node information, draw the following Figure 7 shows the torque rise graph.

![Figure 6. The speed of the temperature rise map.](image)

![Figure 7. The torque of the temperature rise map.](image)

It can be seen from Figure 6 and Figure 7 that the distribution trend of the tooth surface temperature rise from the tooth height direction to the tooth top direction is the same as the 3D distribution of the tooth surface temperature analyzed above. And there is a peak in the gear meshing and striking, since the contact stress generated by these two points is large and a large
amount of frictional heat flow is thus generated. From Figure 6 and Figure 7, it can be seen that the loading torque has a greater effect on the transient temperature rise than the rotational speed. It can be considered that the loading torque is the main factor that affects the transient temperature rise.

**Life Expectancy Analysis**

There are many kinds of failure modes of polymer gears, such as fracture, pitting, wear, gluing and plastic deformation. In this paper, from the perspective of energy conservation, using the first law of thermodynamics and the analysis results of ANSYS / LS-DYNA, the time required for the gear tooth surface to reach the PEEK heat distortion temperature under various working conditions is calculated, which provides a theoretical reference for the design and practical application of polymer gear.

According to the law of conservation of energy, that is, the first law of thermodynamics, for a closed system\(^{(3)}\):

\[
dU = \delta Q - \delta W .
\]

\[
\delta Q = 2\pi \frac{n}{60} \times T_s t .
\]

\[
\delta W = \frac{1}{2}mv^2 .
\]

\[
dU = cm\Delta T_m .
\]

\[
\Delta T_m = T_6 - (T_c + T_t) .
\]

Polymer gear wear process involves adhesion, heat softening, bond breakage, adhesion and shedding. When the contact interface temperature reaches the material heat distortion temperature, it is considered that the gear is on the violent wear stage, and the polymer gear is reaching the theoretical life. Through the formula (6), combined with the results of finite element analysis of polymer gear life prediction analysis, the results are shown in Table 5.

<table>
<thead>
<tr>
<th>Rotating speed life/h</th>
<th>1N·m</th>
<th>5N·m</th>
<th>10N·m</th>
<th>15N·m</th>
<th>20N·m</th>
<th>25N·m</th>
<th>30N·m</th>
</tr>
</thead>
<tbody>
<tr>
<td>50r/min</td>
<td>701.22</td>
<td>471.28</td>
<td>233.63</td>
<td>158.44</td>
<td>117.78</td>
<td>87.81</td>
<td>72.50</td>
</tr>
<tr>
<td>250r/min</td>
<td>475.07</td>
<td>93.85</td>
<td>46.52</td>
<td>32.79</td>
<td>22.76</td>
<td>18.05</td>
<td>14.23</td>
</tr>
<tr>
<td>500r/min</td>
<td>234.11</td>
<td>46.73</td>
<td>23.06</td>
<td>15.24</td>
<td>11.33</td>
<td>8.94</td>
<td>7.28</td>
</tr>
<tr>
<td>1000r/min</td>
<td>113.79</td>
<td>22.56</td>
<td>11.23</td>
<td>7.42</td>
<td>5.49</td>
<td>4.35</td>
<td>3.59</td>
</tr>
<tr>
<td>1500r/min</td>
<td>74.52</td>
<td>14.97</td>
<td>7.45</td>
<td>4.92</td>
<td>3.66</td>
<td>2.90</td>
<td>2.35</td>
</tr>
</tbody>
</table>

Table 5. Under the conditions of gear life prediction.
Figure 8. Different speed, load torque under the gear life.

It can be seen directly from the figure8 that the service life of the polymer gear decreases with the increase of the rotational speed and the loading torque, which indicates that the high-molecular gear is suitable for long-term use under the condition of low speed and low torque.

Test Validation

In order to verify the correctness of the above analysis methods, the friction and wear performance of the acetal gear was tested by the intelligent composite gear test rig. The intermediate transition torque value decreases as the gear transmission speed increases. Through the friction and wear test of the acetal gear, the relationship between the gear surface temperature and the rotational speed and the loading torque is obtained, as shown in Figure 9. Figure 10 shows the wear behavior of the acetal gear at a load torque of 7.5 N·m and a speed of 1000 r/min.

Figure 9. Different speed and loading torque under the surface temperature.

Figure 10. Acetal gear cycle times and wear behavior.

It can be seen from Figure9 that the surface temperature of the acetal gear is gradually increasing with the increase of the test speed and the loading torque, which is consistent with the result of the analysis. When the friction heat temperature reaches the material heat distortion temperature, the gears begin to enter the violent wear stage. It can be seen from Figure 10 that under the test of loading torque of 7.5N·m and speed of 1000r/min, the acetal gear enters the violent wear stage when the number of cycles reaches $1.2 \times 10^6$, and the gear can be estimated according to the following formula A calculation of the time require:

$$N = 60n_{at}$$

(10)

After the calculation, the time required to reach the limit cycle under the test conditions is 20h, which is very close to the theoretical calculation of this paper, which confirms the reliability of the predicted life of the polymer gear.
Summary

(1) The finite element program ANSYS/LS-DYNA is used to simulate the transient friction temperature of the polymer gear, and the instantaneous temperature distribution of the gear tooth surface is obtained. It is found that the temperature rise is mainly concentrated on the gear tooth surface. The analysis found that the transient frictional heat generated at the position of the engaging-in and engaging-out was large because the frictional heat flux at these two locations was much larger than the frictional heat flow generated at other locations.

(2) Simulate the meshing of the polymer gear under different working conditions to further analyze the influence of the rotational speed and the loading torque on the transient frictional heat. By calculating and comparing, it is found that the increase in rotational speed and loading torque lead to the rise of the temperature of the transient frictional heat. From the fig that displayed the influence of speed and load torque on the transient temperature rise, we can see that compared to the speed, the influence of load torque on the transient temperature rise is more obvious.

(3) According to energy conservation and the finite element analysis results, the time required for the gear tooth surface to reach the PEEK heat distortion temperature is calculated, and the service life of the polymer gear is estimated. Finally, the correctness of theoretical analysis is verified by real experiments, which provide theoretical reference for the design and practical application of polymer gear.

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Reference