Study on coating rolling contact fatigue by thermal spray based on infrared thermography technology

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Abstract
In order to predict the contact fatigue life of thermal sprayed coating, the center composite design method was used to take the experiment. Moreover, the real-time failure process was monitored by using the infrared thermal imaging technique. The influence of contact stress, coating thickness and slip ratio on the contact fatigue life was investigated by using the method of response surface. The results showed that the contact fatigue life of AT40 coating obey to normal distribution; the influence of contact stress, coating thickness and slip ratio on the contact fatigue life was statistically significant; the interaction between contact stress and slip ratio had significant effect on the contact fatigue life. The results of infrared thermal image analysis showed that the surface temperature of the contact point could reflect the degree of contact fatigue damage of the coating at a certain level, and could be used to predict the contact fatigue life of the coating. The statistical properties of the surface temperature of the contact point changed with time, it was a nonstationary stochastic process.

Keywords: Remanufacturing, Contact fatigue, Life prediction, Multi-factor, Infrared thermography technology

1. Introduction
In engineering applications, many rotating parts, such as shafts, gears and so on often retire earlier due to some minor surface damage, which greatly wasted the material's remaining life, and resulted in huge economic losses. The concept of remanufacturing, which has been emerging in recent years, can be applied to the solution to this problem. As a result of surface treatment technology, the performance and quality of remanufactured products are superior to that of prototype products. Thermal spraying technique [1] is an important surface treatment in remanufacturing engineering. It has a broad application prospects in terms of repairing surface damage of rotating parts. It has played an important role in the automotive, engineering machinery, military equipment, marine engineering and other fields, and has been an important means of cost reduction and protecting the environment. Some thermal sprayed coating, such as AT40 coating, which is used to improve the wear resistance of rotating parts, is inevitably exposed to contact stresses [2]. Coating contact fatigue life prediction is also becoming a difficult and hot issue in remanufacturing engineering. In order to ensure the safety of the remanufactured products during service, the contact fatigue failure of the coating needs to be monitored more effectively.

The contact fatigue failure is the phenomenon of surface fatigue failure under the cyclic alternating load on the surface of rolling contact friction surface, which is the process of pitting corrosion and surface peeling [3]. Pure rolling, pure sliding and rolling / sliding coexisting are three typical rolling contact relative motion state between rolling contact friction surface. Under laboratory conditions, the relative motion between the rolling contact surfaces can be controlled by setting the slip ratio [2]. Different coating thickness makes different stress distribution on the internal coating, thus affecting the service performance of the coating. Coating service life of different thickness has important guiding significance for the coating preparation[4]. Rotation speed and contact stress are the main load factors that affect the contact fatigue behavior of coating. The change of load condition will change the contact fatigue life of the coating. At present, the study of contact fatigue life of thermal sprayed coating is mainly focused on revealing the contact fatigue performance, the failure behavior and failure
mechanism under single factor conditions such as different process equipment [5-9], different material systems [10], different surface integrity [11] and different service conditions [12-15]. However, under the condition of single factor service, it is not easy to reflect the comprehensive effect of the influence factors on the coating life, and it can not judge the influence of the interaction between the factors. In the case of multiple factors, it is faced with problems such as large-scale experiments, high cost, and long study period, and it is easy to cause prediction difficulty. In the same number of influencing factors, for the orthogonal experiment design, to increase the number of the level will increase the number of trials. Compare with the orthogonal design method, the factorial design combining central composite design method can not only take into account the influence of multiple factors, but also to obtain multi-factor data through a certain scale of the experiment. It will avoid the small sample limit, effectively avoid the corrupt practice under multi-factors, and will provide a simple and feasible method for the prediction of contact fatigue life of sprayed coating.

In the contact fatigue failure process, due to the role of friction, it will inevitably lead to hot problems. The frictional heat generated between the friction pairs concentrates on a specific area of the interface, causing the surface to expand so that the area of the contact area is continuously reduced, eventually leading to contact concentration and increasing the local temperature[16-17]. All the temperature exceeding the thermodynamic temperature of the object will continue to emit infrared radiation around. Infrared thermography detection technology is based on the principle of infrared radiation, and use infrared radiation measurement method to measure the object surface temperature and temperature distribution. It is a non-destructive testing technology to test the internal defect or determine its operating status. It is suitable for measurement related to temperature changes. At present, there is no application of Infrared thermography technology to monitor the coating contact fatigue damage process, and no prediction results by using it. In this study, AT40 coating by the supersonic plasma spray was used as the research object. The contact fatigue test was carried out based on the principle of center composite design. The effects of contact stress, slip ratio and coating thickness on the contact fatigue life were investigated by the response surface regression analysis principle. In addition, by using infrared thermography technology, the influence of the temperature of the contact surface in the process of failure was studied in order to achieve the purpose of effectively monitoring the fatigue failure.

2. Sample preparation and experimental design

2.1 Coating preparation

The coating was prepared on the outer circumferential surface of the tempering 45# steel by supersonic plasma spraying equipment (JET) developed by National Key Laboratory for Remanufacturing. The surface of the substrate was blasted with corundum before spraying. Ni / Al alloy with 90% Ni and 10% Al was used as bonding layer to improve the bonding strength between coating and substrate. Al₂O₃-40% TiO₂ was used as spray coating. The coated substrate was a roller with 8mm line contact length and 0.5mm outer peripheral edge chamfering. The coating position on the roller and the size of the roller were shown in Fig.1. Spraying parameters were shown in Table 1. The same spraying time and frequencies ensured that the coating and the substrate’s cooling time, heated state and other thermodynamic factors remain the same[18-19], and the spayed coating thickness was 500-600μm. The microstructure of the coating was characterized with a scanning electron microscopy (SEM), as shown in Fig.2. The figure showed that there was no crack between the bond layer and coating, which indicated that the coating was bonded well. The structure of the coating was dense, and typical thermal sprayed layered structure could be seen.
Table 1: Supersonic plasma spraying AT40 coating parameters

<table>
<thead>
<tr>
<th>Plasma spray parameters</th>
<th>Spraying materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ni/Al</td>
</tr>
<tr>
<td>Argon gas flow / L·min⁻¹</td>
<td>100</td>
</tr>
<tr>
<td>Nitrogen gas flow / L·min⁻¹</td>
<td>30.2</td>
</tr>
<tr>
<td>Hydrogen gas flow / L·min⁻¹</td>
<td>-</td>
</tr>
<tr>
<td>Spraying voltage /V</td>
<td>150</td>
</tr>
<tr>
<td>Spraying current /A</td>
<td>360</td>
</tr>
<tr>
<td>Spraying distance /mm</td>
<td>110</td>
</tr>
</tbody>
</table>

Fig. 1: Size of roller and location of AT40 coating

Fig. 2: AT40 coating SEM photo

2.2 Surface morphologies observation

Using the AT40 coating prepared in Chapter 1, the coating had the same hardness and bond strength. In order to make the coating with different thickness as similar as possible to the internal stress state and surface roughness, the coating layer was polished by grinding wheel with the thickness of 216μm, 250μm, 300μm, 350μm and 384μm, respectively. The surface morphology is shown in Fig. 3. It can be seen from Fig. 3 that the surface roughness of the coating is similar after grinded by the grinding wheel, which avoids the influence of different surface roughness on the service performance of the coating[20-21].
2.3 Rolling contact fatigue test

Because the coating is not only affected by the service conditions such as contact stress, rotation speed and slip ratio during the process of contact fatigue failure, but also influenced by independence or interaction of the coating surface integrity indicators such as coating thickness, surface roughness, coating hardness and bond strength. It is necessary to construct a contact fatigue life prediction model which can not only cover a number of factors that affect the life of the coating, but also play an advantage of statistical methods to increase the reliability of the model.

The contact fatigue experiment was carried out by RM-1 multifunctional testing machine developed by National Key Laboratory for Remanufacturing. Under the condition of laboratory, by setting the slip ratio, the real contact state of the rolling and sliding movement of coating was simulated [14-15]. At the same time, using NEC R300 infrared thermal camera in the contact fatigue failure process for on-line monitoring, contacting and on-line monitoring diagram are shown in Fig.4 (a). Using the Hertz formula, the maximum line contact stress was calculated according to the load. The AT40 coated roller was as the test roller. As shown in Fig. 4 (b), the standard roller for the contact fatigue test was 45 # high quality carbon steel with an inner diameter of 30 mm and an outer diameter of 60 mm. The experimental scheme of contact fatigue life under the influence of three factors, such as contact stress, slip ratio and coating thickness, was used by center composite design method[22]. The experimental scheme is shown in Table 2.
In Table 2, $m_c$ represents the number of experimental points designed by the $2^k$ factor design, with $m_c$ as the number of experimental points distributed on the axis, and $m_0$ as the number of repetitions of the center point, and there are $N = m_c + m_i + m_0$ experimental points. "-1", "1", "0", "-1.68" and "1.68" respectively indicate the influence factor value $y_i$ encoded by the equation (1) shown as follows:

$$x_i = (y_i - y_{0i}) / \Delta_i$$  \hspace{1cm} (1)

In equation (1), $\Delta_i$ is the radius of the $y_i$ value interval, and $y_{0i}$ is the center point of the $y_i$ value interval.

To ensure the safety and enforceability of the experiment, we set the slip ratio range of 0% to 100%, the rotation speed of 300r / min, contact stress range of 0.5 - 0.7GPa. The thickness of the coating was the thickness after being grinded by the wheel, including 216μm, 250μm, 300μm, 350μm and 384μm 5 kinds. According to the center composite design principle, the experimental parameters and results are shown in Table 3.
3. Results and Discussion

3.1 Statistical Law Analysis of Contact Fatigue Life

Using the Kolmogorov-Smirnov test [23] (K-S test), the test statistic is selected as follows:

$$D = \max \left[ \frac{|F_n(x_i) - F_0(x_i)|}{\log_2 n} \right]$$

Where $F_n(x)$ denotes the cumulative probability function of the sample and $F_0(x)$ denotes the distribution function of the distribution to be tested. The normal test was taken for the data in Table 3 with the given significance test level of 0.05. The test showed that the significance was 0.701, which was more than 0.05. It was considered that the contact fatigue life under the influence of contact stress, coating thickness and slip ratio was normal.

3.2 Effect Analysis of Contact Fatigue Life Influencing Factor

In order to treat mathematics conveniently, we note the contact stress for $y_1$, the slip ratio for $y_2$ and the coating thickness for $y_3$. Respectively, $y_1$, $y_2$ and $y_3$ was for coding transformation: $x_1 = (y_1 - 0.5790)/0.0484$, $x_2 = (y_2 - 40)/15$, $x_3 = (y_3 - 300)/50$. The relationship between the factor levels and the coding is shown in Table 4.

<table>
<thead>
<tr>
<th>Coding</th>
<th>$y_1$</th>
<th>$y_2$</th>
<th>$y_3$</th>
</tr>
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<tbody>
<tr>
<td>+1</td>
<td>0.6254</td>
<td>55%</td>
<td>350</td>
</tr>
<tr>
<td>-1</td>
<td>0.5285</td>
<td>25%</td>
<td>250</td>
</tr>
<tr>
<td>0</td>
<td>0.5790</td>
<td>40%</td>
<td>300</td>
</tr>
<tr>
<td>-1.68</td>
<td>0.6551</td>
<td>15%</td>
<td>216</td>
</tr>
<tr>
<td>+1.68</td>
<td>0.4913</td>
<td>65%</td>
<td>384</td>
</tr>
</tbody>
</table>

Using $x_1$, $x_2$ and $x_3$, the influence of contact stress, slip ratio and coating thickness and its interaction effect on the contact fatigue life were investigated by making use of the response surface method. The F test was used to test. Through analyzing, the significance value of contact stress, coating thickness and slip ratio on the contact fatigue life was 0.0199, 0.0239 and 0.0091, respectively, which were all smaller than the given significance level 0.05. It indicated that the influence of contact stress, coating thickness and slip ratio on the contact fatigue life was significant, among which the slip ratio was the most significant. For the interaction effect, the test results are shown in Table 5.
From Table 5, it could be seen that the interaction of contact stress and slip ratio had significant effect on the contact fatigue life. The interaction images are shown in Fig. 6.

From Fig. 6 (b), and (c), it could be seen that the 3D surface had no obvious twist, which indicated that there was no strong interaction between contact stress and rotation speed, coating thickness and slip ratio. From Fig. 6 (a), there were obvious distortions in the 3D surface, which indicated that there was a strong interaction between the contact stress and the slip ratio, rotational speed and slip ratio. The results showed that the significant influence of contact stress and slip ratio on the contact fatigue life of sprayed coating was not affected by the third factor, the contact stress and the slip ratio were the main influencing factors.

3.3 Analysis of infrared thermography characteristic parameters

By the characteristics of the RM-1 contact fatigue testing machine, the surface temperature of the contact surface was monitored by the NEC R300 infrared camera to the purpose of obtaining the surface temperature of the contact point, as shown in Fig. 7. Here is the contact point temperature of the surface temperature of the near contact point. The contact point temperature varies with time as shown in Fig. 8. The contact point temperature at failure, and the temperature difference from beginning to failure is shown in Table 6.
It could be seen from Fig. 8 that during the contact fatigue failure process, the temperature of the contact increased with time, and the temperature rose sharply at the moment when the coating failed to break. According to the statistical hypothesis test, it could be seen that the significance value of the normality test of the contact point temperature and the temperature difference was 0.584 and 0.612, respectively, which was higher than the given significance level of 0.05, and the contact point temperature and the temperature difference were considered to be normal. Thus, the Pearson correlation test[24] was used to test the correlation between the contact point temperature and the temperature difference and the contact fatigue life. The significance values were 0.061 and 0.068, respectively, which were greater than 0.05. The results showed that there was no statistical linear correlation between the contact fatigue life and the contact point temperature and the temperature difference. The contact point temperature and the temperature difference were very random. It could be seen from Fig. 9 that the surface temperature of the contact point did not increase with the increase of the contact fatigue life of the coating. From the point of view of temperature change, the difference reflects the magnitude of the temperature mutation. In the process of contact fatigue, the rate of temperature mutation affected the contact fatigue life, the faster the temperature rose, the shorter the life of the coating.
It could be seen from Table 7 and Fig. 10 that the contact point temperature was not normal during the contact fatigue failure process, and its probability density function curve showed a multimodal state, indicating that the distribution of the contact point temperature changed with time. This statistical characteristic further indicated that the contact point temperature was a nonstationary stochastic process, and when the coating damage occurred or developed, it would lead to the nonstationarity of the temperature signal. At each stage of the coating damage, the contact point temperature had a different distribution (Table 7).

![Probability density curve of the contact point temperature](image)

**Fig. 10 Probability density curve of the contact point temperature**

<table>
<thead>
<tr>
<th>Assume test parameters</th>
<th>Contact point temperature during failure</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Std. Deviation</td>
<td>0.6311</td>
<td>0.15715</td>
<td>0.27494</td>
<td>0.1689</td>
<td>0.25396</td>
</tr>
<tr>
<td>Kolmogorov-Smirnov Z</td>
<td>2.473</td>
<td>1.333</td>
<td>1.226</td>
<td>1.341</td>
<td>1.344</td>
<td>1.309</td>
</tr>
<tr>
<td></td>
<td>Asymp. Sig.</td>
<td>0.000</td>
<td>0.057</td>
<td>0.099</td>
<td>0.055</td>
<td>0.054</td>
</tr>
</tbody>
</table>

According to the regularity of the existence of cracks in the different damage stages observed by scanning electron microscopy and the statistical regularity of the contact point temperature, the damage process was divided into five stages, as shown in Table 7. Stage I was a plastic deformation stage with a shorter duration. Due to more asperity formed in grinding (Fig. 3), it was prone to plastic deformation under shear stress, while the grinding of the asperity was not taken away in time by the lubricating oil, so stay in the contact between the formation of abrasive wear, resulting in friction heat, making the crack initiation and expansion, exacerbated the coating failure. Stage II was a large number of crack initiation and development stage, the temperature fluctuation trend was more significant. Due to the existence of micro-defects such as voids and microcracks, the main crack initiation was easy to propagate along the pores and microcracks under the action of cyclic stress, and the development of failure damage lead to the change of temperature distribution. Stage III and stage IV were the existence and expansion stages of crack stability. The temperature change was stable, but there was no obvious fluctuation trend. This stage accounted for about 50% of the whole failure process. Stage V was crack failure to fracture failure stage, this stage had a shorter duration, and the temperature of the contact point at the moment of crack fracture was significant. Due to the accumulation of heat during the friction contact process, the instability of the crack caused the coating to be removed in a large area, thus forming the abrasive grains and squeezing into the crack gap with the lubricating oil, which increased the chance of crack propagation and accelerated the failure of the coating.

4. Conclusions

Under the laboratory conditions, the contact fatigue life test of the coating under rolling and sliding action was realized by setting the slip ratio. The three factors of contact stress, coating
thickness and slip ratio affected on the AT40 coating were investigated by using the principle of central composite design. The influence of friction heat on the fatigue damage during the contact fatigue failure process was studied by infrared thermography technology. Response surface regression analysis showed that the effect of slip ratio, contact stress and coating thickness on the contact fatigue failure of coating was significant. The interaction between contact stress and slip ratio on contact fatigue failure was significant. The results of infrared thermography analysis showed that the temperature of contact point could reflect the degree of contact fatigue damage of the coating at a certain level, and it could effectively predict the contact fatigue life of the coating. The contact point temperature had high randomness during the contact fatigue failure process. It was a nonstationary stochastic process. The linear correlation between the contact point temperature and the life was not significant.

Acknowledgments

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References