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Failure analysis of ring die of a feed pellet machine

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Abstract: The severely worn position and failure mechanisms of the ring die of a feed pellet machine were investigated. The macroscopic and microscopic morphologies of the failed surface, the chemical composition and mechanical properties of the collected samples were analyzed using scanning electron microscopy, energy disperse spectroscopy, optical emission spectrometry, and a universal testing machine. Results show that the dip angle at the entrance of the ring die hole between the roller and ring die was severely worn. The feed powder could not be fully extruded through the dip angle at the entrance of the ring die holes, thus the density of the feed particles produced could not meet the requirements. Therefore, abrasive wear under high stress is the main reason of failure at the entrance of the ring die holes under the action of feeding powder; and cutting and fatigue spalling lead to substantial material loss. In addition, a high damp-heat environment aggravates abrasive wear on the die hole internal surface.

Key words: ring die; failure analysis; micro-cutting wear; fatigue-exfoliative wear; electrochemical corrosion

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Feed pellets are widely used in poultry and aquaculture, especially in southern China because of their comprehensive nutrition, strong stability, digestibility and absorbence [1]. As feed pellets are widely used nowadays, reducing the cost of producing them becomes urgent.

Figure 1 shows a ring die which is the key and most vulnerable component of the feed pellet machine. The ring die is made of high-quality steel and weighs up to several tons or even tens of tons. The steel for the ring die is usually 4Cr13 stainless steel, which has a high hardenability, good polishing properties, and excellent resistance to corrosion and hot oxidation. Due to its excellent properties, 4Cr13 stainless steel can be applied in several important fields, such as structural automotive applications and the petrochemical industry. During the manufacturing process, heat treatment has a significant effect on the mechanical properties of 4Cr13 components [2]. The designed service life of a ring die is 800–1000 h, and the frequent replacement and maintenance are of high cost [3]. As shown in Fig. 2, the feed pellet machine is mainly composed of a ring die and two to four grooved free-rotating or driven rotation rollers. The ring die is rotated by the driving of the rollers, and the machine works as follows [4]: (1) The feed powder and water vapor are simultaneously introduced into the working area and squeezed into the ring die holes through the entrance of the rotating rollers. (2) As the subsequent feed powder and water vapor are continuously added, the feed pellets form on the outer wall of the ring die hole, and are cut into a suitable length by the scraper. According to market investigations, the briquetting rate of feed pellets is required to be greater than 75%. Otherwise, the ring die needs to be replaced. Therefore, the durability of the ring die hole becomes the key factor for decreasing the production cost of the feed pellet.

Most of the previous research focused on optimizing the working parameters of the ring die and the rollers [5]. The ring die components experience extreme conditions such as severe mechanical stresses, hot-humid, and various corrosive conditions. To prevent premature failure of the component, the material properties of the component need to be

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Fig. 1: Ring die of feed pellet machine

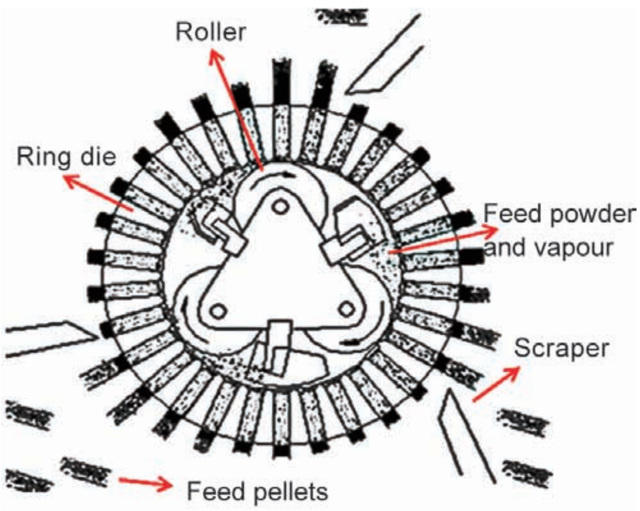

Fig. 2: Working principle diagram of feed pellet machine

improved and the failure mechanisms of the component need to be thoroughly investigated. This study aims to reveal the failure mechanism of the ring die and provide a reference for the selection of materials, and therefore improve the service life and the efficiency of the ring die.

1 Experimental details

The studied ring die was made of 4Cr13. A scrapped ring die of a feed pellet machine was analyzed in this work. When the failures occurred, the total service time of the ring die was around 760 h, which was less than the ring die design service time. As displayed in Fig. 3, the surface of the scrapped ring die was filled with rust, and a sharp corner had formed at the entrance of the die holes. As shown in Fig. 4, the entrance of ring die holes was worn off and the ring die hole became larger, which was the cause of the failure. The specimen taken from the ring die along the direction of the ring die-hole depth was prepared for the follow-up experiments. The working condition of the ring die appeared to include severe mechanical stresses and a high damp-heat feed powder environment.

Standard procedures for failure analysis were applied in this work, aiming to investigate the behavior of the ring die that failed in service. The executed failure analysis involved the following principal stages: the preservation (cleaning) of the failed surface, confirmation of the severely worn position, chemical composition analysis, metallographic analysis, and mechanical testing (hardness and impact tests) on the samples.

Firstly, a visual examination of the failed component was performed. Then, representative samples of the ring die were collected for chemical analysis and microstructural

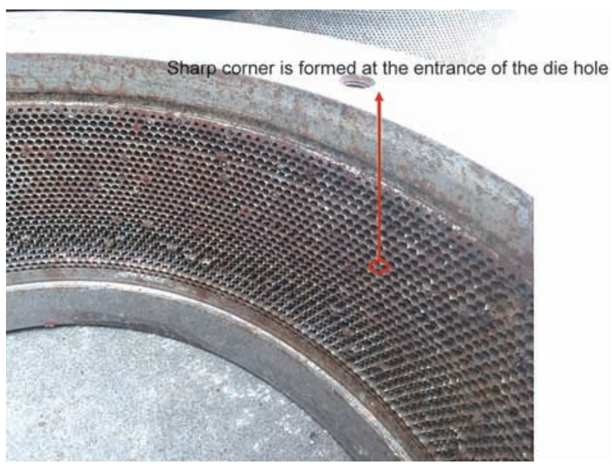

Fig. 3: Scrapped ring die

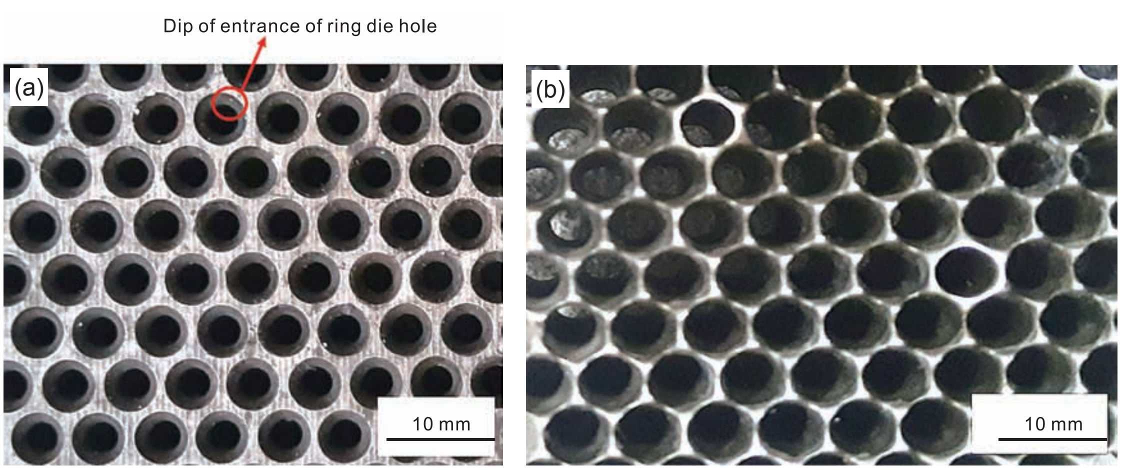

Fig. 4: Image of the entrance of the ring die hole: (a) In-service; (b) Scrapped

characterization. Chemical analysis was carried out using optical emission spectrometry, and the microstructural characterization was performed according to standard GB/T 13298-2015 [6].

Rockwell hardness (HRC) measurements were conducted at 6 different positions of the ring die, and the average values were taken as the results. The transverse section of the sample was wet ground successively by abrasive papers from P120 to P1800 followed by diamond polishing agent finishing to 0.2 μm. Then Rockwell hardness testing was carried out according to standard GB/T 230.1-2018 [7] on a universal machine (with a constant load of 98.07 kgf·mm^{-2}). Charpy impact tests were performed at 80 °C on the samples taken from 4 different positions of the ring die, and the results were averaged. The impact tests were carried out on the specimens (10 mm thickness) according to standard GB/T 229-2007 [8].

Specimens for optical microscopic (OM) analysis were taken from the ring die. Metallographic preparation consisted of polishing and etching with 5% ferric chloride hydrochloric acid alcohol. Scanning electron microscope (SEM) and energy dispersive spectrometer (EDS) were used to analyze the morphology of the worn specimen, and the failure surface of the specimen was collected along the hole-depth direction of the ring die.

2 Results

2.1 Visual inspection

As shown in Fig. 5, the entrance of the ring die hole is worn more severely than the inner surface, and many wear scars are visible at the entrance. It can be basically determined that the entrance of the ring die hole is the most severely worn position of the ring die.

2.2 Chemical composition analysis

The chemical compositions of the 4Cr13 ring die were listed in Table 1. All of the chemical compositions of the failed ring die are within the specified range.

2.2 Microstructural characterization

Figure 6 shows the microstructure of the ring die. It can be observed that the structures are mainly composed of tempered sorbites, which are dispersed with a eutectic mixture of ferrite and carbide particles [9]. These structures are in line with those of 4Cr13 stainless steel after quenching and tempering, and display the typical microstructure of normalized high carbon steel. The tempered sorbite microstructure provides this component with excellent mechanical strength.

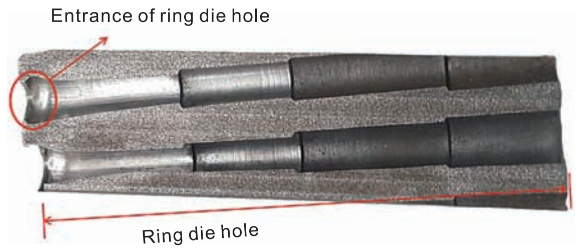

Fig. 5: Cross-sectional view of the ring die holes

Table 1: Measured and nominal chemical composition of the substrate (wt. %)

	C	Si	Cr	Mn	P	S
Measured value	0.36	0.39	12.23	0.74	0.02	0.02
GB/T 1299-2014 [10]	0.36–0.45	≤0.60	12.00–14.00	≤0.8	≤0.03	≤0.03

2.3 Mechanical properties

The Rockwell hardness test results show that the average hardness of the ring die reaches 57.6 HRC and is relatively uniformly distributed. According to standard GB/T 1299-2014 [10], it is evident that the ring die has the appropriate hardness.

The Charpy impact test results show that the average impact-absorbed energy of the ring die is 12.1 J, indicating the low absorbed energy at 80 °C, which is in accordance with its high strength martensitic microstructure and meets standard GB/T 1299-2014 [10].

As mentioned above, the results of chemical compositions, metallographic morphologies, and mechanical properties show that the material of the ring die meets the basic design criteria, suggesting that unqualified material is not the reason for the premature failure.

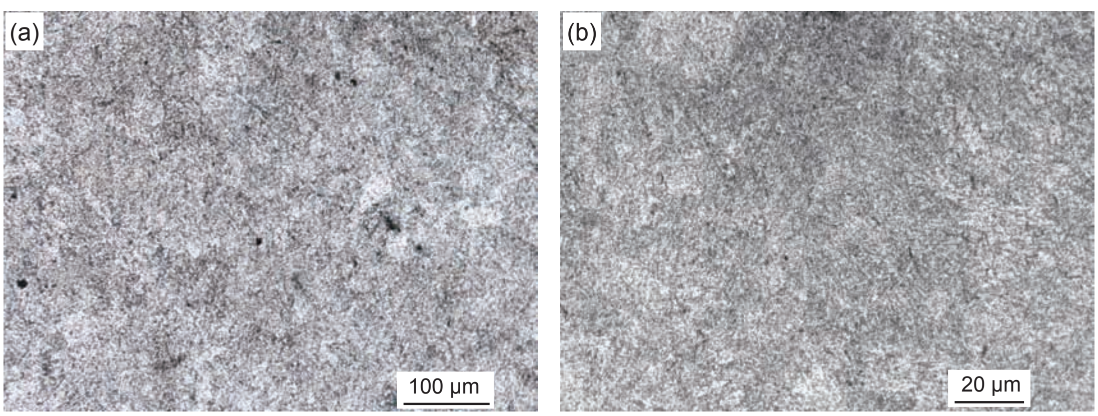

Fig. 6: Microstructure of the ring die

2.4 SEM observation and EDS analysis

SEM analysis of the surface of the ring die hole was carried out to determine the wear mechanism. Figures 7 (a) and (b) show the microscopic morphologies of the inner surface of the failed ring die hole under SEM. Minor parallel abrasive scratches are found on the worn surface. Meanwhile, many small pits are found distributed on the worn surface.

Surface morphologies at the entrance of the failed ring die hole are shown in Fig. 8 (a) and (b). It can be seen that, compared with the inner surface of the ring die hole, a certain degree of spalling and a deeper groove are found on the worn surface of the entrance of the ring die, which is related to the greater stress on the entrance surface. This also confirms the result of visual analysis that the most severe wear damage is at the entrance of the ring die hole.

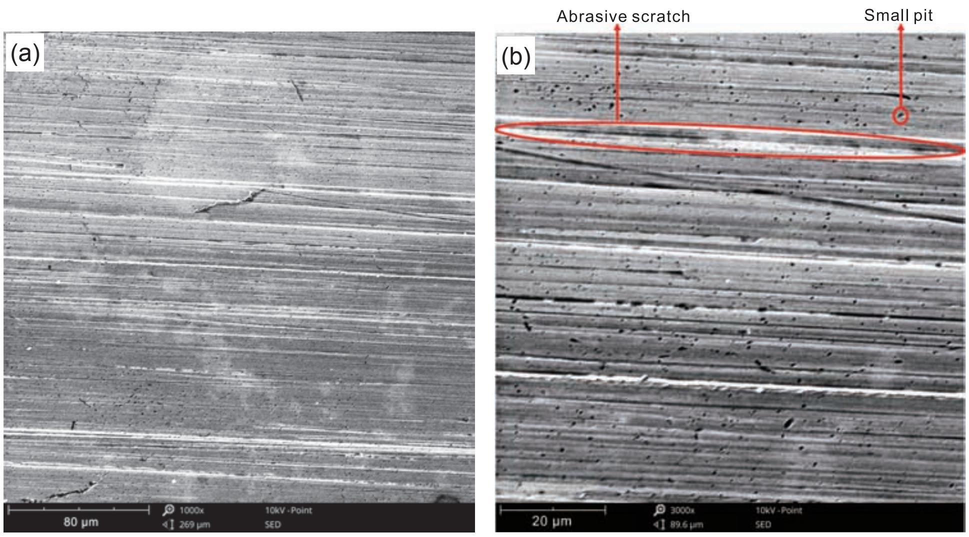

Fig. 7: SEM micrographs of the inner surface of the ring die hole

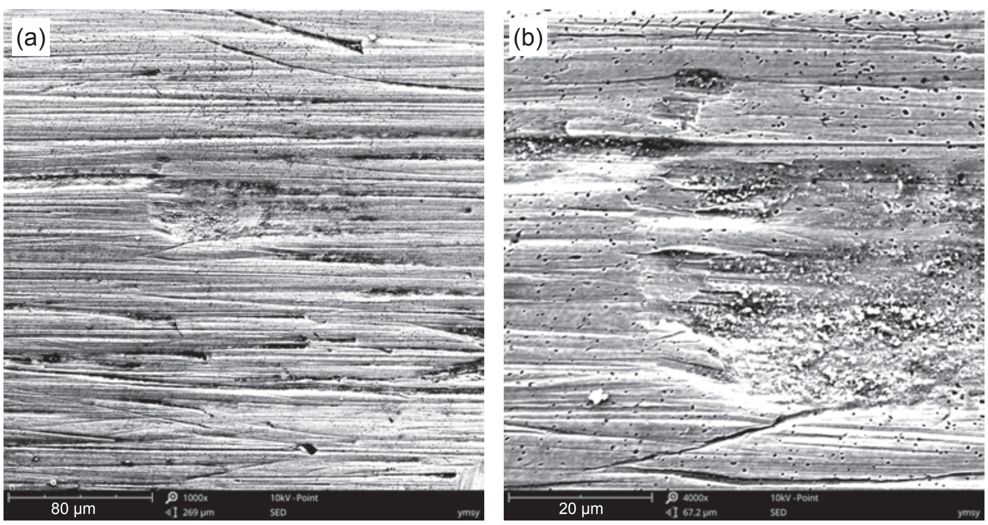

Fig. 8: SEM micrographs of the entrance surface of the ring die hole

To find the reason causing the small pits, backscatter electron (BSE) and EDS were used for the microscopic morphology analysis of the ring die. As shown in Fig. 9 (a), many particles are found in the microscopic morphologies on the ring die sample. The particles are smaller than 2 μm and diffusively distributed in the material. By means of EDS [Fig. 9 (c)], it is determined that the chemical compositions of these particles marked on Fig. 9 (a) are mainly composed of carbon (C, 1.94wt.%), chromium (Cr, 18.77wt.%) and iron (Fe, 79.29wt.%). Considering that the sample has been thoroughly cleaned with ethanol in the ultrasonic cleaner before the SEM examination, it is affirmed that these particles are carbide particles.

The worn morphology of the entrance of the ring die hole is shown in Fig. 9 (b). Comparing the carbide particles in Fig. 9 (a) with the pits in Fig. 9 (b), it can be seen that the size and shape of the small pits and carbide particles are almost identical.

3 Discussion

The failure reason of the entrance of the ring die could primarily be ascribed to abrasive wear. Furthermore, the three-body abrasive wear and the fatigue flaking could then be concluded as the failure mechanism due to the existence of micro-flaking pits in some areas and a great number of furrows on the worn

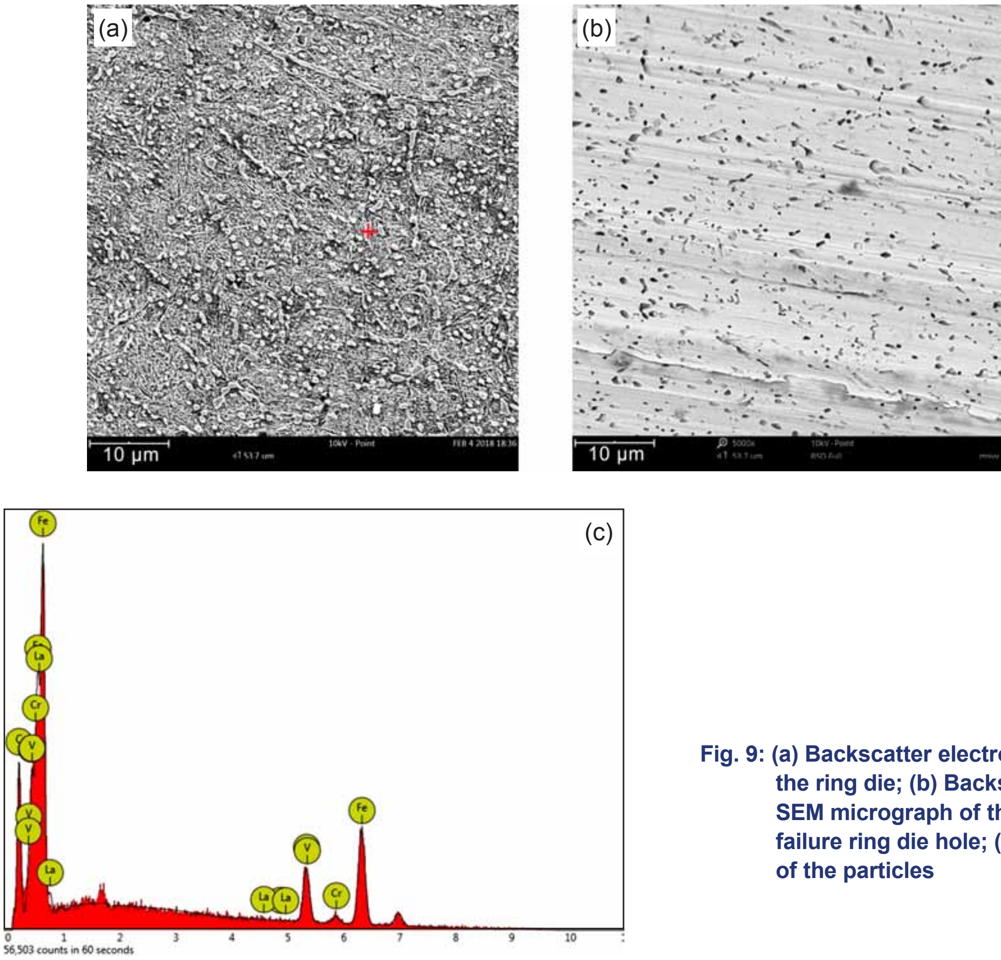

Fig. 9: (a) Backscatter electron micrograph of the ring die; (b) Backscatter electron SEM micrograph of the entrance of the failure ring die hole; (c) EDS spectrum of the particles

surfaces at the entrance of the ring die. It is obvious that the failure reason of ring die is not simply the wear process, as the main composition of the pellet feed is trace minerals, salt, protein, and plant fiber, while the surface hardness of the ring die already reaches 57.6 HRC. Based on the above microscopic morphology analysis, the process of the three-body abrasive wear and fatigue flaking can be inferred: as the feed powder enters the ring die hole under the rolling of the rollers, the density of the feed powder increases dramatically due to the extrusion of the entrance of the ring die hole. Reciprocated sliding contact between contacting surfaces results in a cyclic shearing and a plastic deformation on the material surface. Trace minerals or some hard particles in the feed powder are pressed into the surface of the material under the action of normal stresses. Due to the shearing stress, the sliding particles form furrows on the surface of the material. The SEM micrograph of the entrance surface of the ring die hole in Fig. 8 (a) shows that the worn surface has lots of furrows. The three-body abrasive wear is the major form of wear during the service time [11-16]. Under the continuous action, the furrows gradually grow wider and deeper along with the removal of the base materials. The residual stresses reduce the fatigue performance of steel components during dynamic loading [17-18]. The extrusion and sliding of feed powder results in the accumulation of cyclic plastic deformation and the appearance of fatigue flaking [Fig. 8 (b)]. Apparently, this debris would also serve as the third body and be added to the subsequent three-body abrasive wear.

The small pits are not caused by wear, because of the average size of the third-body should be about 5 μm according to the sizes of the furrows, much larger than the small pits (less than 2 μm) [Fig. 9 (d)]. As mentioned above, the small pits are caused by falling off of carbide particles. One hypothesis is that the galvanic cell structure is formed between the metallic matrix and the carbide particles in the hot and moist feed powder environment. Electrochemical corrosion is caused by galvanic cell reaction where carbide particles serve as anode, metallic matrix as cathode and some substances in the feed powder as ion transport medium. The corrosion of the metallic matrix causes the gap between the metallic matrix and the carbides. Furthermore, the continuous mechanical vibration or wear during the operation of the ring die accelerates the falling off of the carbide particles, resulting in small pits [19-22]. The small pits deteriorate the mechanical properties of the material surface, and the peeling off of carbide particles, which are hard particles, also leads to the decrease of wear resistance. Meanwhile, wear promotes the exposure of new material, which corrodes more easily in the electrolyte. The small pits can become a stress concentration point on the surface of the material, which will cause fatigue flaking from this point on. This could perfectly explain the entrance of the ring die hole is severely worn even though its hardness reached 57.6 HRC. Therefore, it can be concluded that the major wear mechanism of the entrance of the ring die hole is a combined effect of third-body abrasive wear, fatigue-exfoliative wear, and electrochemical corrosion.

Furthermore, the abrasive particles consist of the hard particles in feed powder and the flaking off debris.

Based on the above failure analysis results, several countermeasures are then proposed as follows:

(1) Properly increase the holding time during the heat treatment of the ring die to fully melt the carbides.

(2) Spraying ceramic coating on the entrance of the ring die hole will effectively improve its resistance to wear and corrosion.

4 Conclusions

(1) The entrance of the ring die hole is the most severely worn position of the ring die through visual inspection. It has been further confirmed by the microscopic morphology analysis of the worn surface.

(2) The small pits formed on the surface deteriorate the mechanical properties and wear resistance of the material surface, and promote fatigue flaking, which is also an important part of the failure mechanism.

(3) The major wear mechanism of the entrance of ring die hole is a combined effect of third-body abrasive wear, fatigue-exfoliative wear and electrochemical corrosion. The abrasive particles consist of the hard particles in feed powder and the debris of the flaking off.

(4) Countermeasures of extending the holding time of heat treatment and ceramic coating are given to prolong the service time of the ring die.

Acknowledgements

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