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Wear characteristics of flat die in flat die pellet mills based on Glycyrrhiza uralensis

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Abstract

During granulation, a serious wear problem may be found in flat die as a key component of a flat die pellet mill. Speciﬁc to this problem, Glycyrrhiza uralensis was selected as the wear-causing material to investigate the wear mechanism of the flat die. Additionally, carburizing steel (20Cr and 20CrMnTi) and stainless steel (4Cr13) commonly used in flat die were adopted to conduct wear tests. To explore the inﬂuence of Glycyrrhiza uralensis powder and rods on friction and wear properties of the above three types of steel materials, a CFT-I general-purpose tester for surfaces was applied under dry friction conditions. Moreover, x-ray diffractometer (XRD), three-dimensional proﬁlometry, scanning electron microscopy (SEM) and energy disperse spectroscopy (EDS) were used to analyze the phase compositions, surface morphologies, and elementary compositions of the samples. As demonstrated by relevant results, the inﬂuence of Glycyrrhiza uralensis on the flat die is primarily embodied in abrasive, adhesive, and fatigue wear, and a thermal oxidation reaction occurs on the surface of the flat die. By comparing the wear conditions of the three steel materials between the powder and rods of Glycyrrhiza uralensis, it is found that flat die damages caused by glycyrrhiza rods are more severe than those of its powder. Additionally, the lowest friction coefﬁcients are generated by 20CrMnTi, which are 0.40 and 0.88, respectively. In terms of the mean wear depth, its values are 1.2 and 2 μm, which are below those of 20Cr and 4Cr13. The results herein reveal that flat die made of 20CrMnTi have excellent wear and ductile fracture resistance characteristics. Hence, this study may provide a theoretical guide for selecting flat die materials.

1. Introduction

Pellet feeds have certain advantages, such as their small size and convenience for transportation, storage, and feeding [1]. They are obviously superior to common feedstuff. Therefore, the proportion of pellet feeds in compound feeds increase yearly [2]. Because of the advantages of flat die pellet mills, such as simple structure, wide applications, low power consumption per tonne, and adjustable forming density, they are extensively applied in bio-mass granular fuel and pellet feed processing [3]. However, as their key component, a flat die is subjected to the extrusion forces of compression rollers and frictional forces from feeds during granulation, which may cause wear-out failures to flat die, shorten their service life and further impair the forming quality of material granules [4].

Several scholars have investigated the wear mechanism of flat die in feed granulators. For example, Zhang et al [5] and Huang et al [6] investigated the wear mechanism of ring die in the granulator and reported that plastic deformation and micrographic cutting mainly occur on the surface of ring die. Wu et al [2] and Jiang et al [4] investigated the extrusion forming mechanism of a ring die granulator. They described the wear mechanism of ring die as the coexistence of multiple wear forms, including polishing wear, abrasive wear, and fatigue wear. According to the study on worn parts and failure mechanism of ring die in a feed granulator by Bai et al [7], it is

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clear that the wear conditions at the inlet of a ring die hole are rather serious, and the major forms of ring die wear are probably fatigue-spalling and abrasive wear. Furthermore, several scholars have investigated the wear actions of other agricultural materials on metals. Zhang [8] investigated the wear properties of white cast iron with different chromium contents against wheat powder and reported that the addition of chromium improves its wear resistance to wheat powder. By selecting alfalfa meal as the abrasive material, He et al [9] explored the wear resistance of 60Si2Mn steel against wheat powder after surface laser quenching. Liu [3] laser alloyed NiCr-Al2O3 coating on the surface of 45# steel to improve the wear resistance of flat die. Regarding the investigation of the wear conditions of key components in granulators, no wear mechanism of the flat die has been clarified yet. Besides, studies on the wear resistance characteristics of flat die against Glycyrrhiza uralensis as feeds favored by cattle and sheep can be seldom found. Thus, the frictional wear properties and the wear mechanism between Glycyrrhiza uralensis and flat die should be explored.

Herein, a CFT-I general-purpose tester is utilized to conduct frictional wear tests, further investigating the influence of Glycyrrhiza uralensis on the tribological properties of three flat die materials: 20Cr, 20CrMnTi, and 4Cr13 steel. X-ray diffractometry (XRD), three-dimensional (3D) profilometry, scanning electron microscopy (SEM) and energy disperse spectroscopy (EDS) were used to investigate the morphology of the wear test pieces to discuss the wear mechanism of the three flat die materials. Thus, this study provides theoretical guidance for selecting flat die materials.

2. Materials and methods

2.1. Material preparation

Glycyrrhiza uralensis cultivated in the glycyrrhiza test field of Shihezi University (Xinjiang, China) was selected and air-dried. The glycyrrhiza rod comprises organic polymer materials, such as lignin, hemicellulose, cellulose, protein, and saccharides [10]. It was smashed using a 9FZ-50 multi-function grinder (Taifeng Agriculture and Livestock Machinery Factory, China), thus producing glycyrrhiza powder and incompletely ground glycyrrhiza rods. Then, samples of glycyrrhiza powder and rods were prepared for the relevant tests. After smashing, a 300 mesh sieve was adopted to screen out and collect the glycyrrhiza powder. Moreover, the glycyrrhiza powder was further compressed at room temperature into blocks using a fatigue machine (Instron 8801, American). The corresponding compression-forming process was conducted with a 45 kN load for 10 min. Figure 1(a) represents the obtained shape. During the test, the diameter and length of the glycyrrhiza rod were defined as 8 mm × 10 mm (figure 1(a)).

Carburizing steel (20Cr and 20CrMnTi) and stainless steel (4Cr13), as common materials of flat die, were selected and named K1, K2, and K3, respectively. Table 1 presents the chemical compositions of the test materials. According to the actual working conditions, the flat die needs quenching and tempering treatment before use. Because the chemical composition and mechanical properties of different materials are different, to obtain the best properties of metal materials, different heat treatment conditions are adopted for the three metal materials. The relevant process parameters are shown in tables 2 and 3. Three materials obtain martensitic...
structure after quenching, tempered sorbite structure after high-temperature tempering, and tempered martensitic structure after low-temperature tempering. After quenching and tempering, the strength, hardness, and toughness of the samples are improved. Furthermore, an electric spark CNC wire-cut machine tool (Taizhou City Zhongxing CNC Machine Tools, China) was used to cut the samples into cuboids ($60 \text{ mm} \times 32 \text{ mm} \times 8 \text{ mm}$). To remove the surface oxidation films and rusts, the cuboids were grounded with #80, #280, #500, #800, #1000, and #2000 abrasive paper, respectively. Next, they were put in a JPS-20B ultrasonic cleaner and vibrated for 10 min in absolute ethyl alcohol. Afterward, they were dried in a 101-1B electro-thermostatic blast oven.

### 2.2. Wear testing and characterization

Dry sliding wear tests were conducted in a reciprocating form at room temperature using a CFT-I general-purpose tester (Lanzhou Zhongke Kaihua Technology Development Co., Ltd, China). Figure 1 (b) shows the corresponding wear state, and table 4 presents the relevant wear test conditions. Figure 1(c) depicts glycyrrhiza powder and rods held in fixtures. During the test, time-varying changes in the friction coefficients were recorded. In the process of granulation, the working environment when squeezing Glycyrrhiza uralensis is more complicated, and the size and direction of the compression and shear force to which Glycyrrhiza uralensis is subjected are uncertain. To simulate the working environment of glycyrrhiza when extruded, the wear condition of the specimen is analyzed. The control variable method is adopted to keep the test parameters (rotating speed, wear length, and time), working environment, and glycyrrhiza material size unified. The differences between three kinds of metal materials in the same material test environment were compared and analyzed. Due to the smooth surface of glycyrrhiza powder, the degree of wear with metal is small, and the wear marks are shallow. Therefore, the wear morphology of the metal sample surface is not easy to observe. Through our repeated tests many times, when the loading load is 150 N, the wear damage of the glycyrrhiza powder material to the metal is more obvious. And the friction environment is relatively stable. Glycyrrhiza rod specimens have dense cellulose and other components, and with the increase of loading force, the damage of glycyrrhiza rods to three metals increases significantly. When the experimental load is 30N, the specimen environment is relatively stable. The wear damage of the glycyrrhiza rod to the metal is more obvious. Therefore, the loading force of glycyrrhiza

### Table 1. Chemical composition of flat die samples substrate (wt%).

| Element | C     | Si    | Mn    | Cr    | Ti    |
|---------|-------|-------|-------|-------|-------|
| K1      | 0.18–0.24 | 0.17–0.37 | 0.50–0.80 | 0.70–1.00 | —     |
| K2      | 0.17–0.23 | 0.17–0.37 | 0.80–1.10 | 1.00–1.30 | 0.04–0.10 |
| K3      | 0.36–0.45 | ≤0.60   | ≤0.80  | 12–14  | —     |

### Table 2. Process parameters for quenching.

| Sample | Steel         | Heating temperature ($^\circ\text{C}$) | Holding time (min) | Cooling method   |
|--------|---------------|--------------------------------------|--------------------|------------------|
| K1     | 20Cr          | 850                                  | 110                | Water cooling    |
| K2     | 20CrMnTi      | 870                                  | 120                | Oil cooling      |
| K3     | 4Cr13         | 850                                  | 90                 | Air cooling      |

### Table 3. Process parameters for tempering.

| Sample | Steel         | Heating temperature ($^\circ\text{C}$) | Holding time (min) | Cooling method   |
|--------|---------------|--------------------------------------|--------------------|------------------|
| K1     | 20Cr          | 550                                  | 120                | Air cooling      |
| K2     | 20CrMnTi      | 200                                  | 120                | Air cooling      |
| K3     | 4Cr13         | 660                                  | 130                | Air cooling      |

### Table 4. Wear conditions of Glycyrrhiza uralensis on metals.

| State of Glycyrrhiza uralensis | Loading force (N) | Reciprocating speed ($r\cdot\text{min}^{-1}$) | Run time (min) | Reciprocating length (mm) |
|--------------------------------|-------------------|---------------------------------------------|----------------|--------------------------|
| Powder                         | 150               | 350                                         | 180            | 5                        |
| Rod                            | 30                | 350                                         | 180            | 5                        |
powder is 150 N. Considering that the wear conditions of glycyrrhiza rods are rather intensive [11], the corresponding loading force, wear length, reciprocating speed, and run-time were selected to be 30 N, 5 mm, 350 r min$^{-1}$ and 180 min, respectively. Additionally, the test was repeated three times for each sample to reduce the relevant errors.

After micro-morphology analyses on surfaces of worn samples, the worn areas were segmented into 10 mm $\times$ 10 mm metal sheets, and the samples were cleaned and dried. Then, the phase compositions of the metal surfaces were investigated using XRD (diffraction angle = 10$^\circ$–90$^\circ$; scanning speed = 10$^\circ$·min$^{-1}$). The 3D profilometer (Nanovea ST400) was adopted to characterize the morphologies of the worn areas. Moreover, SEM (Zeiss Sigma 300, Guangzhou Puchuan Testing Technology Co., Ltd) was combined with the EDS to observe the morphologies of the worn surfaces and detect surface compositions, respectively.

3. Results and discussions

3.1. Phase compositions

Figure 2 shows the XRD pattern of three samples. The three samples all contain CrC, SiO$_2$, and MnO$_2$ phases. There are no obvious peaks of SiO$_2$ and MnO$_2$. Due to the high affinity between Cr and C, the CrC phase is formed [12]. It can be seen from the figure that the diffraction peak of the CrC phase in K2 is significantly greater than that of K1 and K2. Moreover, K2 also contains TiO$_2$ compounds.

3.2. Analyses of wear testing results

Figures 3(a)–(c) shows the surface morphologies of K1–K3, which is abraded by glycyrrhiza powder. Additionally, figures 3(d)–(f) respectively correspond to the surface morphologies of K1–K3 rubbing by glycyrrhiza rods. Figure 3(g) presents the frictional coefficients between the samples and the glycyrrhiza powder in a dry sliding condition. The three samples remain in a severe wear stage for a long time and show the same variation tendencies. The friction coefficients of all samples increase with time, and within 180 min, they tend to stabilize, although no balance is achieved. The maximum friction coefficient is generated by K1, whereas K2 has a friction coefficient at the minimum. The friction coefficient of K3 ranges between those of K1 and K2. Specifically, figure 3(i) presents the friction coefficients of samples abrading by glycyrrhiza rods. At the initial stage about 40 min, the friction coefficients increase rapidly, which can be classified into a stage of run-in wear and followed by a steady wear period. More particularly, the friction coefficient of K1 is 1.1, which apparently exceeds that of K2 or K3 (i.e., 0.85). The friction coefficient curve of K3 increases rapidly in the first 40 min, increases slowly within 40–67.5 min, shows a declination tendency after 67.5 min and stabilizes after 140 min. As evident from the friction coefficient curves, the friction coefficient of the glycyrrhiza rod exceeds that of glycyrrhiza powder on the premise of the same metal material, which is about twice greater than the latter. Besides, K2 has comparatively low friction coefficients of 0.40 and 0.88.

Figures 3(h) and (j) reflect the wear parameters of K1–K3. Clearly, the wear parameters of K2 and K3 are far less than of K1. In these figures, Sa represents the surface roughness of the worn samples. Specifically, the surface...
roughness values of K1 are calculated to be 3.47 and 10.02 μm, and the average depths of wear depth are 5 and 10 μm, respectively. Additionally, the surface roughness values of K2 are 2.55 and 2.01 μm, and the average depths of its wear depth are 1.2 and 2 μm. Furthermore, K3 has surface roughness values of 3.11 and 2.23 μm, and its average depths of wear depth are 1.8 and 3.0 μm. Under the circumstance that glycyrrhiza powder serves as the material causing wear, K1 has an average depth of approximately four times greater than K2. However, if glycyrrhiza rods are selected, the average depth of K1 is five times higher than that of K2. Through comparative analysis, it is found that K1 has a rather great wear depth and surface roughness after wear. This finding indicates that it is much easier for the oxidation film on the frictional layer of K1 to be damaged, which remains consistent with the fact that its friction coefficient is rather high. Concerning K2 and K3, their average depth and surface roughness values are comparatively low in all cases. This trend indicates that the oxidization films formed during abrasion play a protective role in this process, preventing the substrates from further oxidizing during abrasion.

3.3. Microstructures of worn surface
3.3.1. Samples worn by glycyrrhiza powder
Figures 4(a), (d), and (g) show the micro-morphologies of K1–K3 before their abrasion by the glycyrrhiza powder. Evidently, the surfaces of K1–K3 are all rather clean and show no obvious scratches before being worn. The remaining figures are micro-morphologies of K1–K3 suffering abrasion by the glycyrrhiza powder. Clearly, all three samples are worn to diverse degrees. For example, several rather deep furrows on the K1 surface have been severely worn, producing much debris from the wear. Additionally, sliding occurs as the grinding defects spread, indicating that plastic deformation occurs on the surface, which is accompanied by adhesive and abrasive wear. A possible reason is that an adhesive effect is formed between the glycyrrhiza powder and the wear debris during its abrasion by K1. Because of such an effect, abrasive wear is more intensive. Eventually, several wear debris materials are generated and stick to the surfaces of the sample. In terms of K2, the grinding defects on its surface are rather shallow and narrow. In this case, micro-cuttings and furrows take form, leading to abrasive wear. Furrows are present on the surface of K3, and both abrasive and fatigue wear are incurred.
Figure 5 displays the EDS analysis results of the sample surfaces. By analyzing the changes during the wear test in the content of element C on the surface, it becomes clear that the content of element C culminates at the furrow. Such a phenomenon signifies that C transfers in the glycyrrhiza powder during friction, increasing C content \[11\]. C, O, Si, Cr, and Mn are present on the worn surfaces of K1–K3. These elements give rise to oxidation films containing SiO2 and MnO2 on the worn surfaces, which corresponds to the results of XRD analysis. These films play the role of being well-lubricating \[13–15\]. The filling effect of SiO2 plays a role in reducing friction. During the wear process between the sample and Glycyrrhiza uralensis, the weak bonding particles gradually peel off, and the worn surface is repaired by filling scratches, which plays a role in protecting the friction surface \[16–18\]. The formation of MnO2 can improve the microhardness and corrosion resistance of the substrates \[19,20\]. K2 also contains Ti, which can form TiO2 on the surface in case of wear. It has the effect of friction reduction and wear resistance \[21–25\] to prevent further damage to the friction layer, which makes K2 have good wear resistance.

3.3.2. Samples worn by glycyrrhiza rods

Figures 6(a), (e), and (i) present the micro-morphologies of K1–K3 unworn by the glycyrrhiza rods. Before the wear test, the surfaces of all samples were clean and had no obvious scratches. When the samples abrade by glycyrrhiza rods, the surface abrasion becomes more serious. Observing the wear conditions between the samples and glycyrrhiza rods in figure 6 shows that the sample surfaces have been worn to different degrees. More particularly, many furrows and some wear debris appear on the K1 surface, indicating the occurrence of adhesive and abrasive wear. The surface of K2 is flat and shows micro-furrows. Besides, abrasive wear occurs on its surface. Plastic deformations occur on the surface of K3 where furrows are formed, and onto its surface, wear debris sticks. Furthermore, both adhesive and abrasive wear occurs on the K3 surface. During abrasion, the temperature of the glycyrrhiza rods increases, and the contact surface turns charred. Besides, figures 6(d), (h), and (l) show that pores and broken glycyrrhiza fibers are formed on the surface of glycyrrhiza rods. Among them, surface cuts on the surface of glycyrrhiza rods worn by K2 are flat and stratified to some extent.

By comparing the wear conditions of K1–K3 against the glycyrrhiza rod, K2 outperforms K1 and K3 in wear resistance and plastic resistance characteristics. Regarding K1 and K3 with surfaces seriously worn, their wear resistance and plastic resistance characteristics are rather poor in the same condition. In combination with figure 3, the wear resistance of the metal is proved to be associated with friction coefficients and wear depth. Considering that K2 has good wear resistance, its friction coefficient and wear depth are low.

The elemental analyses are conducted on the surfaces of the test samples (figure 7). As forces and heating are generated, their surfaces are severely worn. In the grinding defects of K1–K3, the content of O is rather high, indicating that sharp thermal oxidation reactions occur on their surfaces. Respectively, the content of O in the...
Figure 5. EDS-based analysis results of sample surfaces worn by glycyrrhiza powder: (a) K1, (b) K2, and (c) K3.

Figure 6. (a), (e) and (i) Micro-morphologies of unworn K1–K3, (b) and (c) morphologies of K1 worn by glycyrrhiza rods, (f) and (g) morphologies of K2 worn by glycyrrhiza rods, (j) and (k) morphologies of K3 worn by glycyrrhiza rods, and (d), (h) and (l) surface damages of glycyrrhiza rods.
grinding defects of K1–K3 is calculated to be 36.7%, 2.4%, and 15.5%, respectively. Clearly, the oxygen contents in K1 and K3 are 15.3 and 6.5 times that of K2, respectively. This trend signifies that the wear resistance of K2 is rather strong. Because of dramatic oxidation reactions of K1 and K3, their surfaces are severely worn, corresponding to the facts of their surface morphologies. In contrast to K1, the oxidation reaction of K3 is less intensive, indicating that the wear resistance of the latter is superior to that of the former. This phenomenon is consistent with the curves of low wear depth and friction coefficients in figure 3. In terms of K2 suffering microcutting, the wear depth on its surface is rather shallow. By analyzing variations in the elemental content of K2, evidently, the contents of C, O, Si and Ti are increased in the grinding defects, whereas those of Cr and Mn are decreased. This trend is probably because SiO$_2$, TiO$_2$, and MnO$_2$ produced on the surface of K2 form oxidation films (figure 2) that can act as solid lubricants. Besides, these solid lubricants play a protective role during friction, preventing the substrate surfaces from being further oxidized or damaged in this course and also further decreasing the corresponding friction coefficients. This trend remains consistent with a low wear depth, as shown in figure 3.

For the same sample worn by glycyrrhiza powder and rods, its degree of wear differs. Although oxidation reactions occur when the sample is abraded by glycyrrhiza powder and rods, the thermal oxidation reaction between the glycyrrhiza rod and the sample can be fiercer. In this context, the sample surface is more severely oxidized, and the sample can be worn to a greater degree, generating more wear debris. Because of the crude fibers, glycyrrhiza rods apply a strong destructive force and cutting action on the sample surface. Thus, the furrows on the sample surface can be rather deep. On the whole, furrows can be found in samples K1–K3 worn by the glycyrrhiza. Moreover, the surface of K1 where plastic deformations occur is seriously damaged, which is also accompanied by adhesive and abrasive wear. K2, with strong oxidation resistance, shows high ductile fracture and wear resistance characteristics, and abrasive wear is dominant on its surface. On the K3 surface, fatigue, adhesive, and abrasive wear are primarily dominant. Thus, a flat die made of 20CrMnTi should be selected for flat die granulators. However, the materials are crushed to the greatest extent when the granulator is in service to alleviate the wear of the flat die and extend their service life.
4. Conclusions

This study investigates how glycyrrhiza affects the wear resistance performance of flat die made of different metals in feed granulators. The following conclusions can be drawn from the results herein:

(1) For the flat die samples worn by glycyrrhiza rods, their friction coefficients are twice greater than those worn by the glycyrrhiza powder. Additionally, both the wear depth and surface roughness of glycyrrhiza rods worn by flat die are above those of glycyrrhiza powder, which is caused by the crude fibers of the rods.

(2) Compared with 20Cr (K1) and 4Cr13 (K3), 20CrMnTi (K2) has lower friction coefficients and average depths. Specific to glycyrrhiza powder and rods, the friction coefficients of 20CrMnTi (K2) are 0.40 and 0.88, respectively, and the average wear depths are 1.2 and 2 μm.

(3) Under the wear of glycyrrhiza, the oxidation degree of 20CrMnTi (K2) is far below that of 20Cr (K1) and 4Cr13 (K3). With strong wear resistance and plastic resistance characteristics, 20CrMnTi (K2) mainly shows abrasive wear on its surface. As regards 20Cr (K1) and 4Cr13 (K3), whose surfaces are most severely worn, adhesive, abrasive and fatigue wear principally occur during abrasion. Therefore, 20CrMnTi (K2) has excellent wear resistance.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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