

Article

High-Temperature Wear Properties of 35Ni15Cr Fe-Based Self-Lubricating Die Materials

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Abstract: Hot forging dies play an important role in metallurgy, automotive, aerospace and weapons industries. However, due to the high temperature and high pressure of hot forging die and the working environment of cyclic load, the friction and wear performance of hot forging die is poor and the service life is low. The use of traditional lubricants can prolong the life of the mold, but it will cause environmental pollution, harm to workers' health and other problems. In this paper, 35Ni15Cr Fe-based self-lubricating die material was prepared by high energy ball milling and vacuum sintering. The wear properties of the materials were studied under ball-to-disc wear conditions at 600 °C. The results show that when CaF₂ content is 8 wt%, the friction coefficient and wear rate of the material are the lowest, which are 0.3 and $0.9166 \times 10^{-5} \text{ mm}^2 \text{ min}^{-1}$, respectively. When the load increases, the friction coefficient first increases and then decreases, but the wear rate continues to increase. The wear mechanism mainly includes abrasive wear, adhesive wear, oxidation wear and fatigue wear. The friction reduction mechanism is that CaF₂ is precipitated from the self-lubricating mold material and Fe and Ni are oxidized to the boss on the wear surface. The broken boss and lubricant form a lubricating film and accumulate into a glaze layer. The material can be used in high temperature forging environment without additional lubricant.

Keywords: self-lubricating; die material; CaF₂; friction and wear

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1. Introduction

Hot forging dies have very poor service conditions, and wear is the most serious form of failure. In order to reduce the friction and wear in the forging process, the most commonly used method is pre-lubrication before processing, processing also constantly add lubricant or grease, so as to reduce the forging mold temperature and friction coefficient, prolong the life of the mold [1–3]. Yang et al. [4] proposed that water-based graphite acts as lubricant and fine graphite particles are uniformly suspended in water. During hot forging, the die is lubricated with a diluted water-based lubricant and sprayed onto the heated die surface. However, the maximum operating temperature of liquid greases does not exceed 300 °C [5]. The operating temperature of hot forging dies is usually kept above 600 °C. The use of graphite lubricants often causes problems such as uneven lubrication and accumulation on corners. And degreasing agents will pollute the environment and endanger workers' health [6]. Compared with liquid greases, solid lubricants have stronger load-carrying capacity, high-temperature chemical stability, high utilization, and strong adhesion [7,8]. The self-lubricating material forms a discontinuous lubricating film with low shear strength on the surface, but under the action of frictional stress and ambient temperature, it is not enough to cover the entire composite surface. Over time, the lubricating film changes from discontinuous to full continuous, effectively reducing the coefficient of friction and wear rate. Therefore, the coefficient of friction, wear rate and surface topography are all worthy of attention and study [9,10].

Research on solid self-lubricating die materials suitable for hot forging environment can solve the lubrication problem of complex parts, prolong the life of die, and reduce the environmental pollution caused by liquid lubrication materials [11,12]. In order to solving the problem of high-temperature lubrication of variable geometry elements of supersonic aircraft engines, NASA's Dellacorte [13–15] chose Cr_3C_2 matrix with Ni-Co as the binder phase, combined with $\text{CaF}_2/\text{BaF}_2$ and Ag lubricants. PS200 self-lubricating cermet coating was prepared by plasma spraying. As an improvement, Dellacorte [16] used Ni-Cr and Cr_2O_3 as the matrix, combined with solid lubricants, PM300 series of self-lubricating materials were prepared by hot isostatic pressure sintering methods, which are suitable for air bearings, rotary face valves and butterfly valve stem. High-temperature self-lubricating materials provide a new idea for the industry to solve material problems. Wu Ze and Deng Jianxin [17,18] applied self-lubricating materials to the tool, using Al_2O_3 as the matrix, TiC as the wear-resistant phase, adding solid lubricants CaF_2 and MoS_2 , and using hot-press sintering process to prepare self-lubricating tool materials. Wang Huajun et al. [19,20] proposed a self-lubricating hot forging die with composite structure of heterogeneous materials. H11 or H13 steel was used as the matrix, and austenitic heat-resistant steel was used as the support layer. A certain proportion of cobalt-based or nickel-based self-melting alloy powder mixed with Cr_3C_2 or WC prepared metal-based ceramic material as a strengthening heat insulation layer and sprayed on the support layer by plasma powder. Li Haogang et al. [21] studied the thermochemical reaction of active element additives containing Cl, S and P on the surface of the friction pair under high temperature and pressure, forming a boundary lubrication film with low shear strength, thus reducing the friction effect. They proposed to use molecular dynamics to analyze surface modified nanoparticles, explore their distribution mechanism and influence, and reveal their distribution law. Li Changhe et al. [22,23] studied the damage formation mechanism and suppression strategy in the wear of fiber-reinforced composites, and discussed the wear mechanism, covering material removal mechanism, thermal mechanical behavior, surface integrity and damage.

Azam Beigi Kheradmand et al. [24,25] prepared Fe-sic-Cu-G metal matrix composites by hot pressing sintering in a controlled atmosphere furnace at 1000 °C and 400 MPa. The optimum chemical ratio of Fe-sic-Cu-G metal matrix composite was studied, and the wear resistance of the material was improved by adding appropriate graphite and BaSO_4 . Shashanka Rajendrachari et al. [26–28] prepared high entropy alloy by mechanical alloying and plasma sintering, and studied the progress of ball milling process and the phase transition of HEA by X-ray diffraction (XRD) and scanning electron microscopy (SEM). Finally, they investigated the microstructure and corrosion properties of yttrium-dispersed and yttrium-free bi-phase and ferrite stainless steel samples sintered by spark plasma. In previous study [29], a 35Ni15Cr Fe-based self-lubricating die materials with addition of Cr_2O_3 and CaF_2 have been prepared, and the optimum sintering temperature and time is 1320 °C and 2 h. However, there are still few reports on the effects of CaF_2 content and load on the frictional resistance of Fe-Ni based self-lubricating materials and the frictional reduction mechanism of CaF_2 in self-lubricating materials.

Herein, in this study, Fe-Ni based high-temperature self-lubricating materials with different CaF_2 contents were prepared by high-energy ball milling and vacuum sintering. Then the ball-on-disk wear test was conducted under the experimental conditions of 600 °C, 1000 r/min and different loads. The friction coefficient and wear rate were tested, and the high temperature wear mechanism of the self-lubricating die material was studied. The study of high temperature friction and wear mechanism and friction reduction mechanism of self-lubricating hot forging die materials under the condition of hot forging provides a good foundation for the application of self-lubricating die materials to hot forging industry and tribology and other scientific research.

2. Materials and Methods

2.1. Materials Preparation

The matrix is Fe-35Ni-15Cr-5Ti-4Mo-0.2C alloy powder prepared by mechanical alloying. The particle size of powder is 13–58 μm and a purity of $\geq 99.45\%$. The hard phase is Cr_2O_3 and solid lubricant is CaF_2 . The weighing quality was accurate to 0.1 mg, placed in a ball mill jar with 2 wt% stearic acid in the order of density from small to large.

Powder mixtures were homogenised with planetary ball mill (KQM-X4/B, Boyuntong Instrument Technology corporation, Nanjing, China). The diameter of the grinding balls is 4 mm and 10 mm. The ball mills were sealed and filled with argon gas three times before milling. When the matrix powder was prepared, the ball to powder ratio was 20:1, the rotation speed and time was $250 \text{ r}\cdot\text{min}^{-1}$, 48 h. When the Cr_2O_3 and CaF_2 was added, the ball to powder ratio was 6:1, the rotation speed and time was $200 \text{ r}\cdot\text{min}^{-1}$, 2 h.

After the powder mixing is completed, the powder is placed in the mold and pressed by a hydraulic press at 800 MPa for 90s to make the powder forming. Finally, the sintering temperature and time are $1320 \text{ }^\circ\text{C}$, 2 h. (TL 1600, Boyuntong Instrument Technology corporation, Nanjing, China) Sample quantity and composition design are shown in Table 1.

Table 1. Compositions of 35Ni15Cr Fe-based self-lubricating die sample. (wt%).

Number	Fe-35Ni-15Cr-5Ti-4Mo-0.2C	Cr_2O_3	CaF_2	Density/%	Hardness/HV
0#	80	20	0	86.9	295.7 ± 13.3
1#	100	0	0	90.2	229.9 ± 9.72
2#	76	20	4	85.3	250.2 ± 12.2
3#	74	20	6	85.1	210.4 ± 6.3
4#	72	20	8	84.8	200.1 ± 7.8
5#	70	20	10	83.3	144.2 ± 6.2

According to the study of [29], the optimal sintering temperature of $\text{CaF}_2\text{-Cr}_2\text{O}_3\text{-Fe-Ni}$ based self-lubricating material is $1320 \text{ }^\circ\text{C}$. Figure 1 shows the microstructure of backscattered electron imaging of sample 4#. The white part is the matrix with gradually increasing sintering neck, the gray part is the lubricating phase CaF_2 added, and the black part is the strengthening phase chromium oxide.

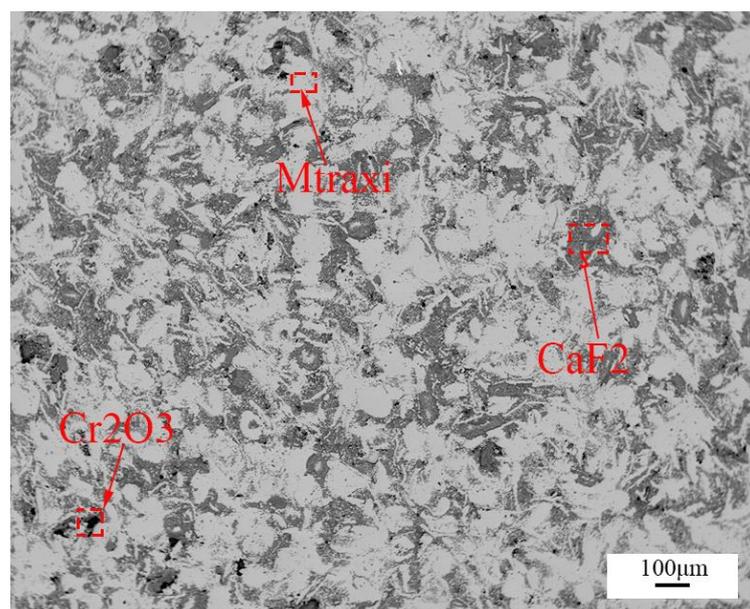


Figure 1. Microstructure of sample 4#.

2.2. High Temperature Wear Test

High temperature friction and wear performance is one of the important indexes to evaluate the comprehensive performance of hot working die [30,31]. In this experiment, the friction coefficient and wear amount of the samples were tested by the self-made ball and disc high temperature friction and wear testing machine (Model HT-1000), in order to evaluate the high-temperature wear resistance of the samples. Figure 2 is the schematic diagram of high temperature wear testing machine of ball disc.

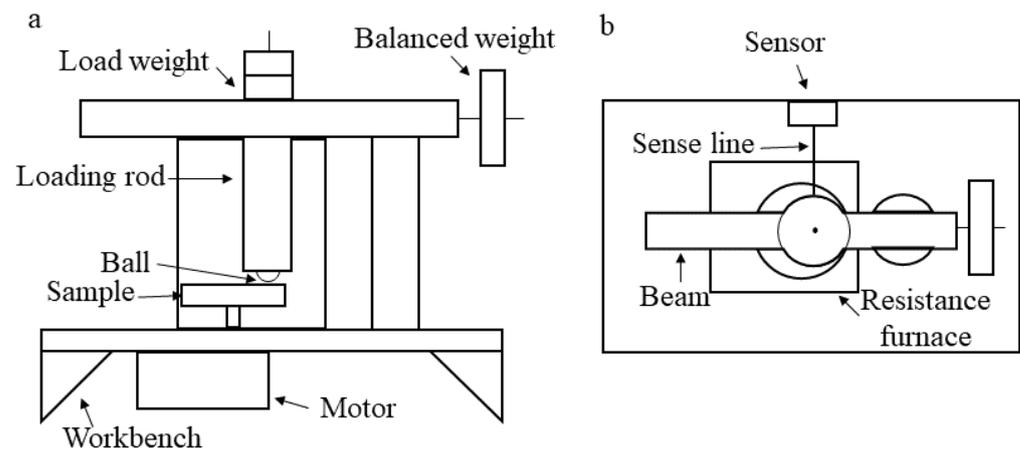


Figure 2. Ball—disc high temperature wear testing machine diagram. (a) front view; (b) top view.

Ball-disc friction and wear equipment is applied to the friction performance test of materials. The disc-shaped sample is put into the testing machine, heated to the experimental set point by the resistance furnace, and the friction coefficient of the sample under certain technological parameters is measured by sliding the grinding ball on the surface of the sample through the loading bar. The main parameters of the testing machine are: spindle speed range: 200~2800 RPM, heating furnace working temperature: 20~1000 °C, loading load range: 1~20 N, display accuracy: 0.2% FS. Before the experiment, the surface of the material was polished with water abrasive paper, and the surface was cleaned with alcohol solution and dried.

The friction and wear tests were carried out on a HT100 high temperature wear tester. The contact form was ball-on-disc, and the experimental parameters were 600 °C, 1000 r/min and different loads, the load is 3 N, 4 N, 5 N, 10 N, respectively. Wear time is 15 min. The C45 steel is selected as the ball material. The effects of load on the friction properties of the samples are investigated by testing the friction coefficient, the wear abrasive rate. Observing the friction morphology and analyzing the wear mechanism. The wear abrasive rate of the sample is defined by the volume wear rate Q , which was calculated by measuring the parameters of the wear ring and calculating according to the empirical formula [32]. The volume wear ΔV can be calculated by:

$$\Delta V = L_0 \left(r^2 \arcsin \frac{d}{2r} - \frac{d}{2} \sqrt{r^2 - \left(\frac{d}{2} \right)^2} \right) \quad (1)$$

$$L_0 = 2\pi R \quad (2)$$

where, L_0 is the average perimeter of the grinding ball movement path, R is the average radius of the wear ring, r is the radius of the grinding ball, and d is the width of the wear ring.

The volume wear rate Q can be further calculated by:

$$Q = \frac{\Delta V}{S} \quad (3)$$

$$S = ntL_0 \quad (4)$$

where, S is the total stroke of the grinding ball, n is the rotation speed of the sample, t is the test time, and L_0 is the average circumference of the wear ring.

2.3. Materials Characterization

The phase composition of samples was identified by D8 Advance X-ray diffractometer (AXS, Bruker, Bremen, Germany). The scanning rate was $5^\circ \cdot \text{min}^{-1}$, and the target used was Cu target with a scanning angle ranging from 20° to 80° . The wear morphology and the energy spectrum analysis were measured by an electron probe microanalyzer (JXA-8230, JEOL, Akishima, Japan) equipped with INCAX-ACT energy-dispersive spectroscopy.

3. Results

3.1. Effect of CaF_2 Content on Wear Performance

Figure 3 shown the worn surface of disc samples of different CaF_2 content in 600°C 5 N load and friction coefficient. Figure 3a is the matrix worn surface which has obvious scratch and peeling pit. Microcracks are observed in the partially enlarged graph, indicating the 35Ni15Cr matrix material is mainly adhesive and fatigue wear. In Figure 3b, the sample 2# worn surface has a large film formation and spalling. It indicates that the surface layer is cracked after the force is applied. As the friction progresses, the crack propagates and the surface material peels off. Belong to oxidation and adhesion wear. As shown in Figure 3c,d, the friction surface is significantly improved, forming a relatively continuous oxide film. There has a small number of peeling pits and a slight furrow, and abrasive wear begins to play a major role. As shown in Figure 3e, the oxide film formed on the worn surface is destroyed, there are many flaking and deep furrows. The adhesive wear and abrasive wear become serious. With the addition of solid lubricant CaF_2 , the effect of oxidative wear and adhesive wear of the material is effectively improved, but excessive CaF_2 reduces the hardness and strength of the self-lubrication die material, it will aggravate the wear. The direction of friction is shown by arrow.

Table 2 is EDS analysis results of worn surface. In area 1 of Figure 3a, mainly contains Fe, Cr and O elements, while Fe element content far beyond the content of matrix. It indicates that the ball material softens at 600°C and peels off to the disc surface. The wear material is oxidized and compacted on the worn surface. The worn surface contains a lot of Fe elements. At the same time, it also shows that the 35Ni15Cr self-lubricating die material has high hardness at high temperature, which makes the C45 produce a lot of wear and form a thick oxide film. The elements in area 2 is similar in content to the 35Ni15Cr matrix materials. It is the exposed substrate, due to oxide layer is peeling off by wear. Area 3 in Figure 3b is similar to 2 places, and it is also disc material composition. The difference is that the Cr content is higher, and dense chromium oxide is formed on the surface to reduce the peeling of the material. The areas of 4 and 5 mainly contain Fe, Ni, Cr, O and relatively more Ca elements, which indicates that this area mainly contains Ni/Fe oxides and CaF_2 . Oxides are compacted to form film in the process of friction. Some oxides are also a good high temperature lubricant [33,34]. These materials form a film synergistically to improve the wear properties.

Table 2. The EDS analysis results of different area from the wear surface (wt.%).

Area	Fe	Ni	Cr	Mo	Ti	O	Ca
1	84.31	-	3.21	-	-	12.48	-
2	38.45	32.79	20.92	3.19	2.40	2.25	-
3	32.25	20.87	31.60	2.16	6.56	4.77	1.79
4	67.06	10.18	7.37	-	-	13.38	2.01
5	70.90	7.47	5.19	-	-	12.66	3.78

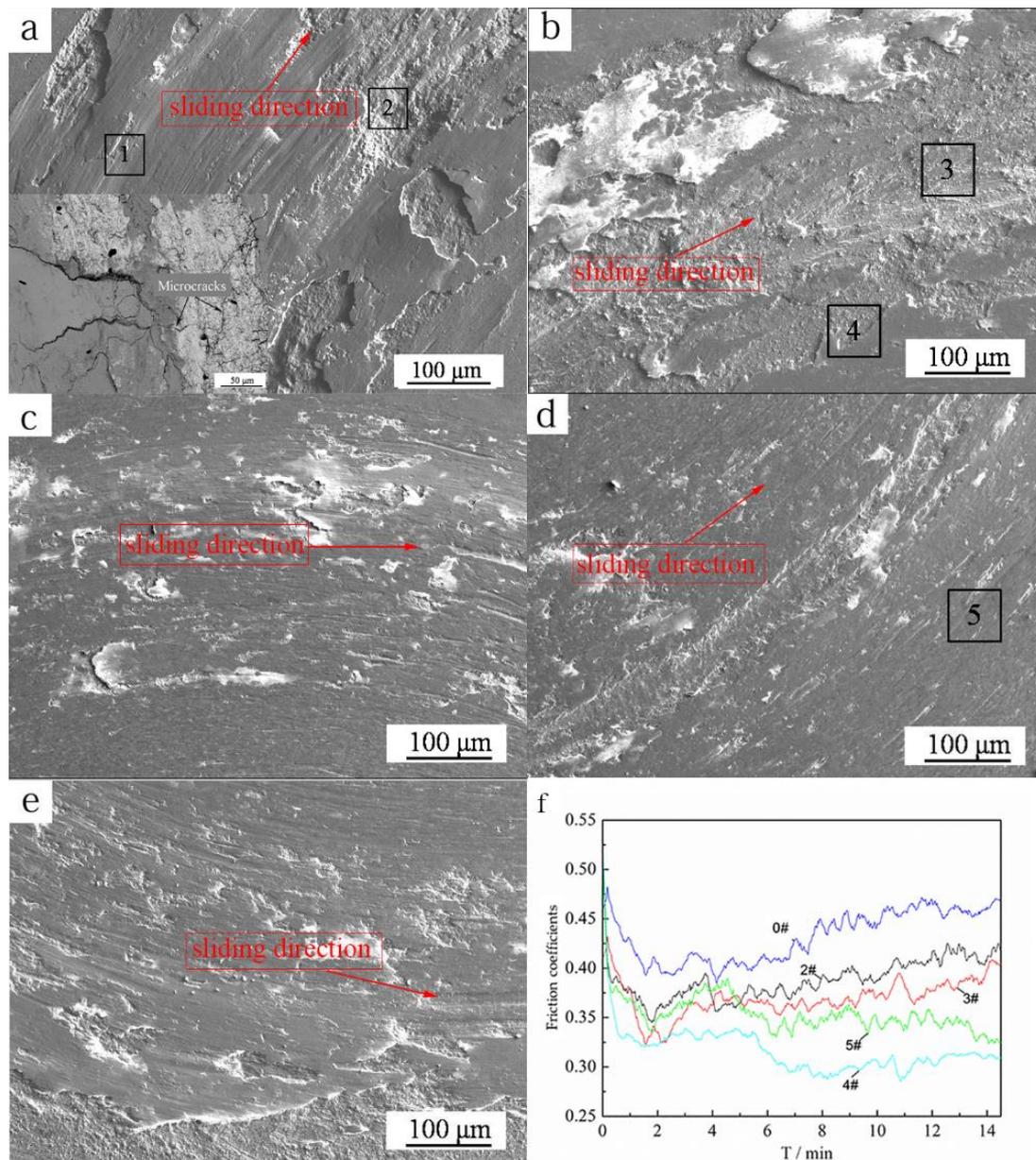


Figure 3. Micrographs of the worn surface and friction coefficient of the 35Ni15Cr Fe-based composites. (a) sample 0#; (b) sample 2#; (c) sample 3#; (d) sample 4#; (e) sample 5#; (f) Friction coefficients.

The friction coefficient of each sample increases rapidly at the beginning of friction. This is because the contact area of the grinding ball and the worn sample is very small at the initial stage of the test. The surface of the sample generates a lot of bosses, where the stress is large. After a period of experiment, the boss portion was continuously damaged and compacted, the contact area of the worn sample increased, and the friction coefficient decreased, which was minimized at about 2 min. At the same time, due to the large amount of heat generated by the friction, an oxide film is locally formed on the surface of the sample, and the oxides of Ni and Cr are also solid lubricants at high temperatures, which makes the friction process smoother. The friction coefficient of 2–4 min has a steep increase trend. This is because the oxide film area is still small, the bonding with the substrate is poor, the oxide film is cracked and peeled off, and the generated abrasive debris is brought into the wear track, causing the increase in the friction coefficient. At about 6 min, the coefficient of friction decreased and remained stable at a certain value. During repeated rubbing, when

the film forming and breaking tend to balance, Oxide and CaF_2 form a low shear strength glaze layer, which reduces the tendency of oxide film damage, and the friction coefficient is stable at a low value.

The calculation parameters of abrasive wear rate of different CaF_2 content are shown in Table 3. Figure 4 shows the volume wear rate of samples with different CaF_2 content. It can be seen that the wear rate of the sample decreases first and then increases with the increase of CaF_2 content, and the wear rate of is the lowest when CaF_2 content is 8%. The amount of wear is not only related to the coefficient of friction, but also to the mechanical properties of the material. As the content of CaF_2 increases, the friction coefficient of the sample gradually decreases, and the quality of the lubricating film becomes better, resulting in a decrease in the wear rate. However, with the increase of CaF_2 , the hardness and strength of the material decreases obviously. During the friction process, the plastic deformation occurs, and the cracks are generated and propagated in the sub surface area. The material peels off and the abrasive wear rate increases. XRD analysis (Figure 5) of the 4# sample before and after the abrasion reveal that the sintered phases of the sample are mainly Fe-Ni-Cr, (Fe, Ni), Cr_2O_3 , CaF_2 , indicating that during the sintering process, most of the previous phases still retain their original characteristics. After wear, the peaks of NiCrO_3 were found but there are no peaks of CaCrO_3 . We think that it may be wrapped in the glaze layer.

Table 3. Calculation parameters of wear rate under different CaF_2 contents.

Number	R/mm	d/mm	r/mm	n/r·min ⁻¹	t/min
1	5.14 ± 0.02	1.83 ± 0.02	1.75	1000	15
2	5.01 ± 0.02	1.80 ± 0.02	1.75	1000	15
3	5.01 ± 0.02	1.55 ± 0.02	1.75	1000	15
4	5.00 ± 0.02	1.40 ± 0.02	1.75	1000	15
5	4.66 ± 0.02	1.66 ± 0.02	1.75	1000	15

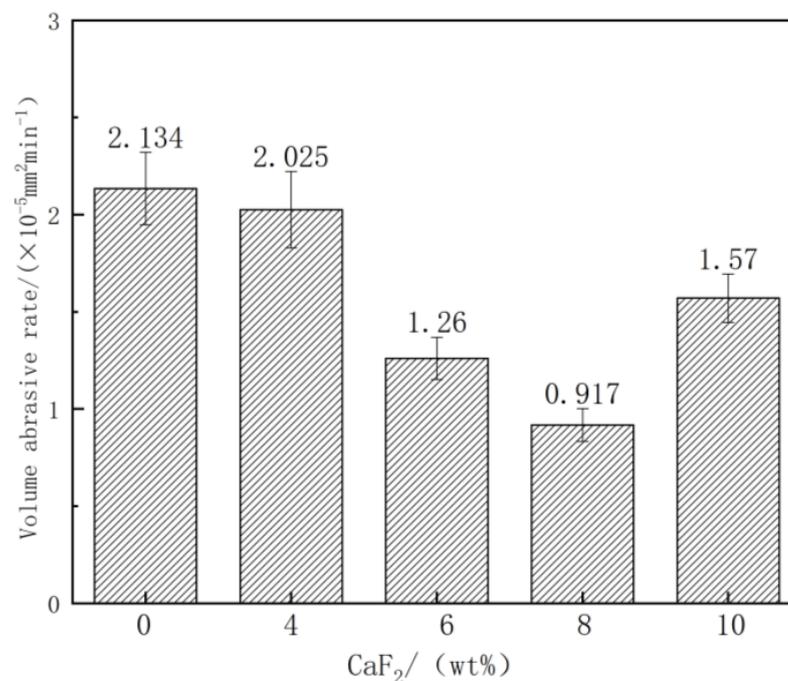


Figure 4. Abrasive wear rate of disc with different CaF_2 content.

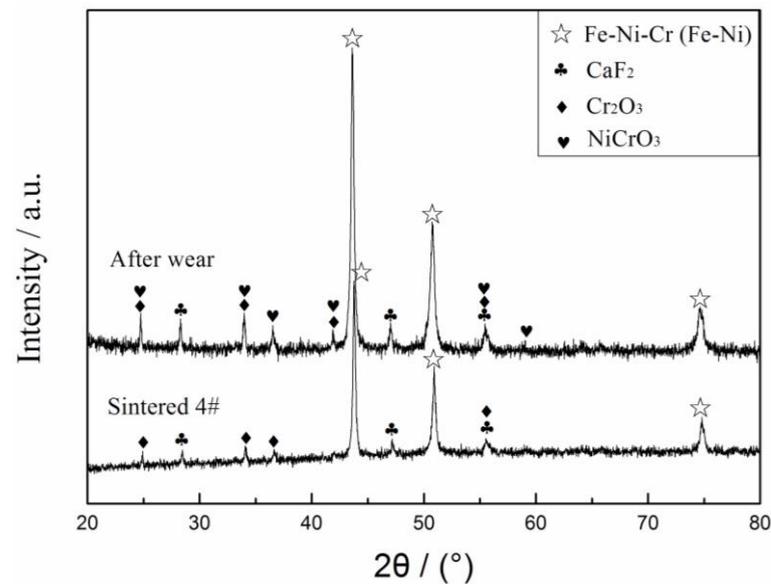


Figure 5. X-ray diffraction patterns of sample 4#.

3.2. Effect of Load on Wear Performance

As shown in Figure 6a, When the load is 3 N, the compressive stress between the ball and disc is low, and the shearing force is low. The formation of the lubricating film on the surface effectively protects the integrity of the friction surface. There are many debris particles on the worn surface. According to EDS analysis (Table 4), the worn surfaces at area 1 and 2 in Figure 6a mainly contain Fe, Ni, Cr, O elements and a few Ca elements. The element content is similar to that of the 35Ni15Cr Fe-based self-lubricating die material. There are more O elements in the area 2, indicating that the white debris particles are oxide particles generated by disc materials during the friction process. And due to the low load, some of the debris particles cannot be compacted to form an oxide film and remain on the worn surface. When the load is 4 N (Figure 6b), a shallow furrow appears on the worn surface with a little of debris particles remaining on the surface. The wear mechanism is mainly oxidative wear and abrasive wear. The content of Fe in the area 3 is richer than area 1, because the ball material C45 steel begins to wear to the disc surface. As the load increases (Figure 6c), the formation of the lubricating film becomes continuous, and the worn surface has more small peeling pits, accompanied by slight furrow, indicating that the wear at this level is mainly abrasive wear. When the load is increased to 10 N (Figure 6d), the worn surface is severely, and a large amount of oxide film is formed and falls off. It can be seen from Table 4 that the proportion of Fe elements in the area 4 continues to increase, the elements of Ni and Cr decrease sharply. This is because the samples and the grinding ball are seriously worn under high load, and the crack initiation increases shortly. Ball surface material falls off to the surface of the disc due to adhesion and fatigue wear. The direction of friction is shown by arrow.

Table 4. The EDS analysis results of different area from the worn surface (wt.%).

Area	Fe	Ni	Cr	Mo	Ti	O	Ca
1	48.72	21.83	13.12	2.16	0.77	11.55	1.85
2	36.96	11.19	14.84	-	2.98	30.13	3.90
3	61.95	13.03	10.63	-	0.51	11.17	2.71
4	78.08	5.09	3.34	-	-	12.28	1.21

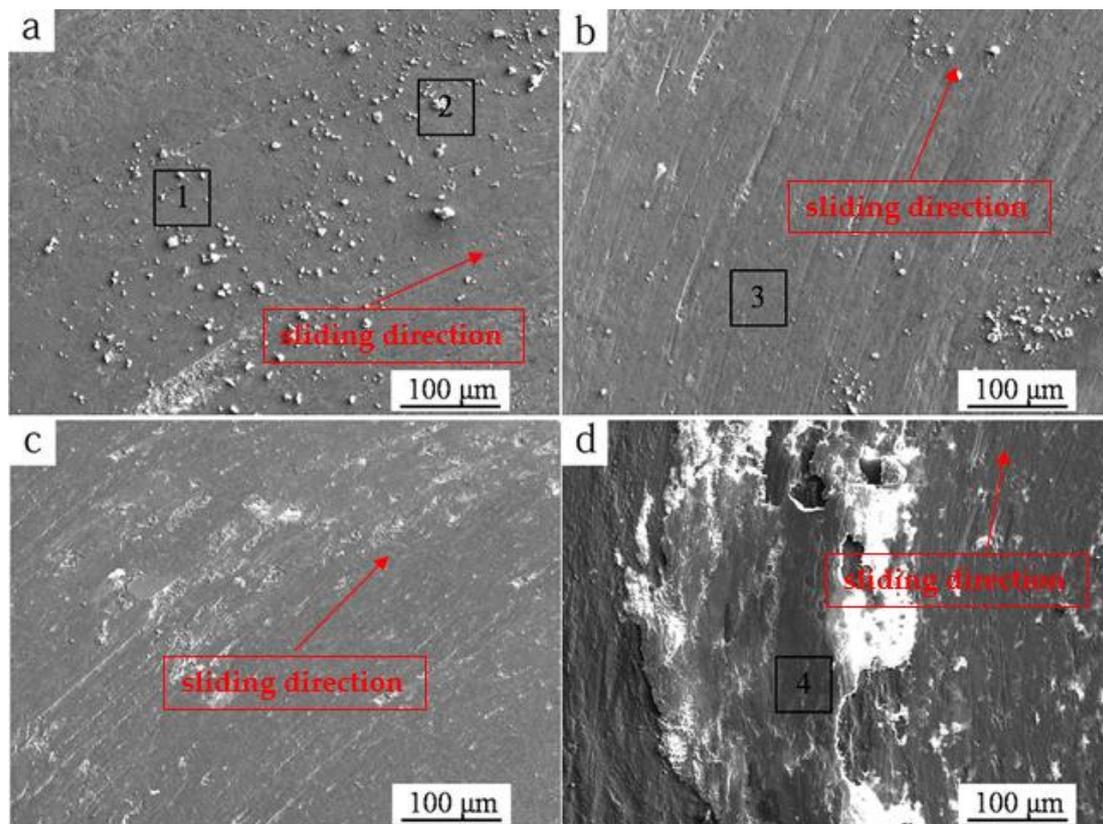


Figure 6. The wear morphology of samples 4# at different loading (a) 3 N. (b) 4 N. (c) 5 N. (d) 10 N.

It can be seen from the Figure 6 that the friction coefficient of the sample 4# is gradually decreased with load increase firstly, and starts to rise after 10 N load. According to the classical tribological formula [35]:

$$A_r = K_1 \cdot F^{\frac{2}{3}} \quad (5)$$

where, A_r is the actual contact area, K_1 is the elastic contact coefficient, and F is the normal load.

In the wear process, the actual contact area A_r of the friction pair is exponentially related to the load F . The larger the load, the larger the A_r . The frictional force is proportional to the A_r , so the friction coefficient is inversely proportional to $\sqrt[3]{F}$. When other conditions are fixed, the friction coefficient will decrease when the load increases. However, when the load increases to a certain level, the contact type turns into a plastic contact with the softening and plastic deformation of the interface. In the Formula (5), A_r and F are no longer proportional, and the friction coefficient begins to rise.

Figure 7 shows the friction coefficient of sample No. 4 under different loads. The friction coefficient decreases with the increase of load. When the load reaches 5 N, the friction coefficient is stable at 0.28. When the load increases to 10 N, the friction coefficient increases to 0.37. According to the parameters in Table 5. Figure 8 shown the abrasive wear rate (Q) of the self-lubricating die material 4# samples under different loads. With the increase of the load, the abrasive wear rate increases continuously. When the load is low, the shearing force between the lubricating film and the substrate is small, and the surface material can remain intact. As the load increases, the compressive strength of the material is limited, and microcracks begin to form. When the plastic deformation increases to a certain extent, the surface oxide layer begins to break and fall off, resulting in an increase in wear rate.

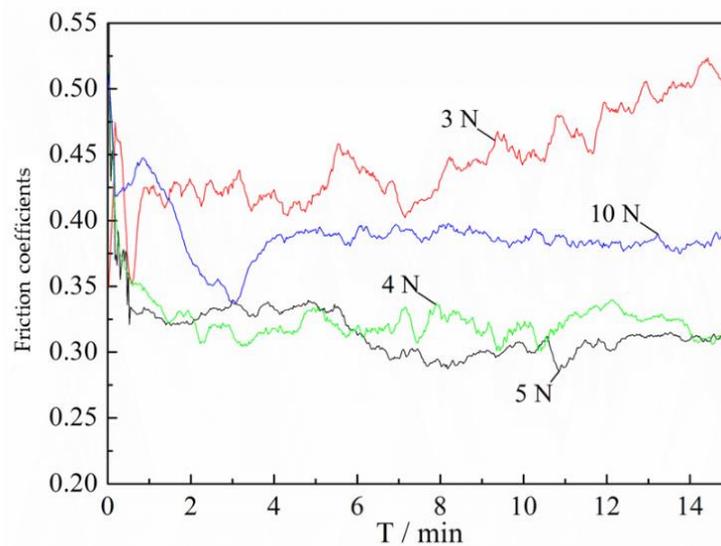


Figure 7. Friction coefficient of sample 4# with different load.

Table 5. Wear rate parameters under different loads.

Load/g	R/mm	d/mm	r/mm	n/r·min ⁻¹	t/min
200	4.43 ± 0.02	4.43 ± 0.02	1.75	1000	15
300	5.32 ± 0.02	5.32 ± 0.02	1.75	1000	15
500	5.00 ± 0.02	5.00 ± 0.02	1.75	1000	15
1000	9.82 ± 0.02	9.82 ± 0.02	1.75	1000	15

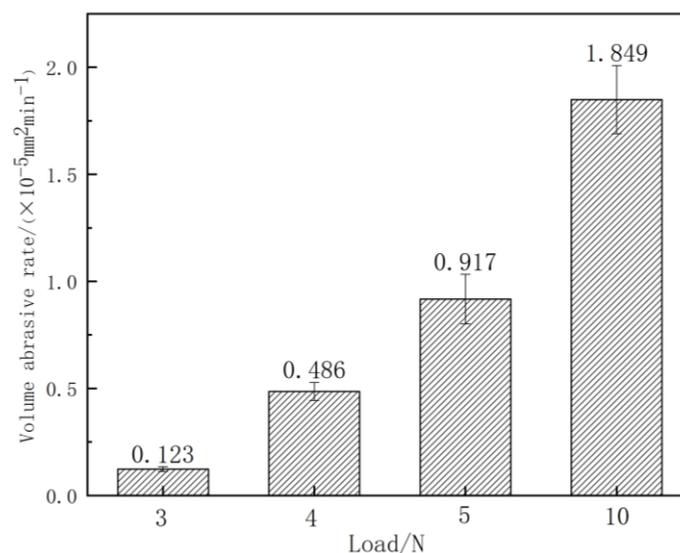


Figure 8. Abrasive wear rate of disc with different load.

According to the previous study and the result above, a schematic diagram of the formation process of the lubrication film during the wear at 600 °C is given in Figure 9. The self-lubricating die material consists of an 35Ni15Cr matrix, a strengthening phase Cr₂O₃ and a high-temperature solid lubricant CaF₂ (Figure 9a). Before forging, as the preheating temperature rises, CaF₂ separate out from inside, and attached to the surface due to the thermal stress. At the initial forging stage (Figure 9b), the material is under high temperature and heavy load. The friction coefficient begins to rise as the oxide of Fe-Ni oxide and chromium oxide is formed by oxidation bumps on the worn surface. The oxidation

bosses appear on the worn surface, friction coefficient begins to rise. Oxidation boss is broken and compacted under the shear stress of grinding blank, and the debris become to form a lubricating film together with the extruded CaF_2 , and the friction coefficient begins to decrease. In the middle of wear (Figure 9c), the shear resistance of the lubricating film is weak, and fatigue cracking occurs under cyclic forging. The solid lubricant in the matrix continues to be extruded, and a complex reaction occurs to form chromate (NiCrO_3 , CaCrO_4), which is compacted together with the oxide debris to form a lubricating film. Achieving a cycle of falling off, formation, re-breaking and reformation, the friction coefficient begins to fluctuate. After multiple forging (Figure 9d), the surface lubricating film accumulates to a certain thickness to become a glaze layer, the shear strength is sufficient to keep the lubricating film stable, and the wear is significantly reduced, and the friction coefficient is stable in a lower value, forging can work in high temperature environments without external lubricant.

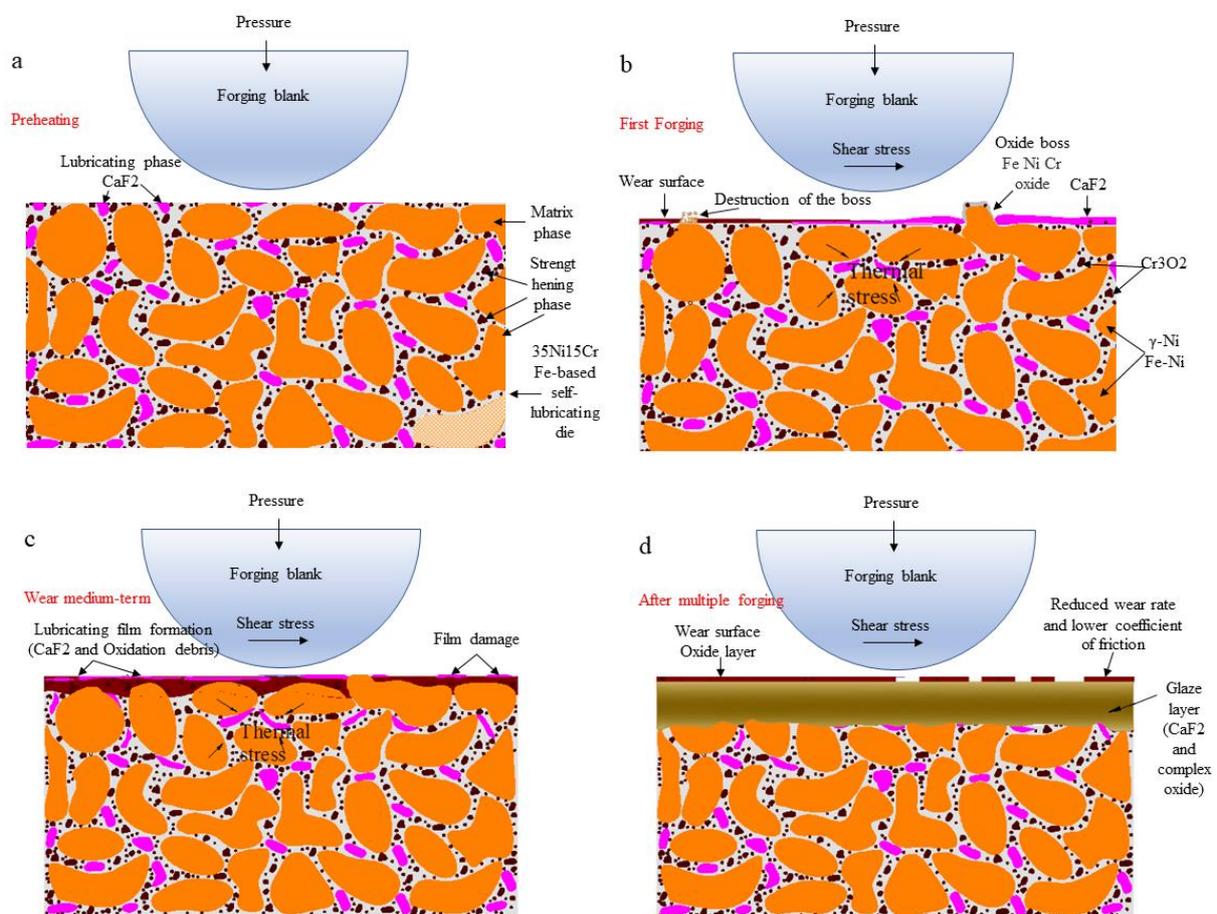


Figure 9. Schematic illustration for the wear mechanism of the 35Ni15Cr Fe-based self-lubricating die materials at varied period. (a) preheating; (b) first forging; (c) Wear medium-term; (d) After multiple forging.

4. Conclusions

Based on the research of Fe-nickel base hot forging die material, a new type of 35Ni15Cr Fe-based self-lubricating die material was prepared in this paper. The effects of CaF_2 content and load on the friction and wear properties of the materials were studied, and the friction reduction mechanism of self-moistening sliding form materials was studied. The microstructure morphology, element content distribution, phase composition, wear rate and friction coefficient were analyzed. The main conclusions are as follows:

(1) Through the wear morphology, element distribution and high temperature friction and wear experiment, it is found that when the CaF_2 content is 8%, the friction coefficient

is 0.3, and the wear rate is $0.9166 \times 10^{-5} \text{ mm}^2 \text{ min}^{-1}$, the wear resistance is the best. When the CaF_2 content is less than 8%, the friction coefficient decreases with the increase of CaF_2 content, mainly due to adhesion and oxidative wear. When the content of CaF_2 is more than 8%, the friction coefficient begins to rise, and the abrasive wear plays a major role. The wear rate decreases first and then increases with the increase of CaF_2 content.

(2) In the experiment of high temperature friction and wear, the abrasive wear rate of the self-lubricating material continues to increase with the increase of the load from 3 N to 10 N, while the friction coefficient first decreases and then increases. When the load is 5 N, the friction coefficient of the material is stable at about 0.32 with the progress of the wear test, and the main effect of oxidation wear is. When the load exceeds 10 N, oxidation wear, fatigue wear and adhesive wear act together.

(3) In the process of using the self-lubricating die material, the lubricating phase CaF_2 first precipitates to the surface, and the Fe-Ni-Cr oxide is generated on the wear surface, and the friction coefficient increases. With the increase of temperature and load, the oxide bulges are crushed under shear stress, and the debris forms a lubricating film with CaF_2 , and the friction coefficient begins to decrease. The friction surface is broken and the lubrication film is formed alternately. Finally, the lubrication film glaze layer with a certain thickness is formed. The wear is obviously reduced and the friction coefficient is maintained at a small value.

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