Effect of ambient temperature on the dry sliding wear of Vanadis 4 Extra steel

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Abstract: A pin-on-disk friction and wear test was conducted to test the critical load for serious dry sliding wear of Vanadis 4 Extra steel at a sliding speed of 0.691 m/s, at room temperature, 200 °C and 400 °C respectively. Using scanning electron microscopy (SEM) and an energy dispersive spectrometer (EDS), the wear surface morphologies, wear mechanism and reasons were analysed. Results show that: with increasing temperature, the critical load for serious wear of Vanadis 4 Extra steel first increased and then decreased. The critical loads leading to serious wear were 900 N and 800 N at room temperature and 400 °C, respectively, while, there was no serious wear at 200 °C at less than 1000 N. There were abrasive particles found under different loads: as the load and temperature increased, the formation of oxide films on the worn surface plays a decisive role in wear: when applying a load smaller than the critical load, oxide films can protect and lubricate the steel substrate, presenting slight oxidative wear; when applying a load greater than the critical load, oxide films on the worn surface were ruptured and spalled, with mainly oxidative delamination wear being observed.

1. Introduction

As traditional Cr12 mould steel exhibits advantages including high hardness, high strength, favourable wear resistance, simple quenching, and small quenching deformation, it has been widely used to manufacture cold-worked mould steel with complex shapes under overload; however, there are large-sized eutectic carbide and obvious carbide networks in Cr12 high-carbon, high-chromium cold-worked die steels, early failure usually occurs in die steels due to a lack of ductility. To solve this problem, scholars have developed several types of cold-worked die steels (Vasco Die, DC53, and SDC99) with high wear resistance and good ductility, which increased the die life by two to eight times [1]. Although these steels have good ductility, they show poor wear resistance. It is known that repairing and changing die steels are usually needed in steel stamping forming of high-strength steel sheet used for automobile manufacture due to high-speed wear, leading to growing cost and interruptions to production, which bring about new challenges to cold- and hot-working manufacturing [2].

To cope with these problems, some researchers have conducted studies on the materials, wear behaviours, and surface treatment of die steels [3-4]. The Boehler-Uddeholm Corporation from Sweden released the third-generation powder metallurgy die (Vanadis 4 Extra), which is high-performance cold-worked die steel that favourably integrates ductility and wear resistance (abrasive particles, adhesion and delamination). Vanadis 4 Extra (V4E) steel exhibits stable machining stability and favourable application potential in cold-worked die steels and therefore is quite appropriate for the
punching and forming of advanced high-strength sheet steel (AHSS) for automobile manufacture [2-5]. Güneş [6] and Baykara [7] et al. researched the machinability of V4E steel under different heat-treatment conditions, used ball-on-disk contact and pin-on-disk contact forms to conduct dry friction and wear tests and demonstrated their corresponding wear mechanisms. These studies lay a foundation for the research and application of V4E steel.

The friction and wear produced in the actual production of cold-worked die steels under overload at high sliding speed are quite complex: especially, the number of oxides, thickness, morphologies, as well as shear stress and friction heat during the friction and wear process tend to cause morphological deformation, softening, and an increase in the number of internal defects in the worn surface structure. These phenomena are likely to affect the wear resistance and reliability of friction pairs [8]. As the experimental conditions used by Güneş and Baykara were greatly different from actual application, with regard to high wear speeds and overload levels, this research investigated the friction and wear behaviours as well as wear mechanisms of V4E steels under varying working conditions. This study aimed to analyse the effect of varying temperatures on the serious wear of steel, and is of significance to the increase in die steel life.

2. Materials and experiment procedure

V4E steel provided by Hong Chao Mould Technology Co., Ltd, Dongguan, Guangdong Province, China, was used as the pin material: its chemical composition is shown in Table 1. The primary steel, with an annealed structure, was processed into standard pin samples measuring $\phi 0.1.04 \text{ mm} \times 0.015 \text{ mm}$. The pin samples were heated to 1020 °C in a vacuum quenching furnace and insulated for 30 min, then they were quenched in oil and subjected to cryogenic treatment instantly thereafter. In the cryogenic treatment experiment, an SLX-250 cryofreezer was used. The treatment process consisted of: a temperature decrease to -145 °C at a rate of 4 °C/min, and after one hour, and then it was heated to room temperature at the same rate. Afterwards, the samples were tempered at 525 °C and insulated for 2 h. Before the experiment, metallographical sand paper was used to polish the surface of the steel, obtaining a steel roughness of $Ra \leq 0.1 \text{ μm}$. Furthermore, a TH300 Rockwell hardness tester was used to measure the hardness of the samples and the measured hardness after tempering was 61-63HRC. The W6Mo5Cr4V2 high-speed steel was used as coupling materials and processed into disks measuring $\phi 44 \text{ mm} \times 3 \text{ mm}$, a hardness of 64HRC, and a surface roughness $Ra \leq 0.1 \text{ μm}$.

| Elements | C  | Si  | Mn  | Cr  | Mo  | V  |
|----------|----|-----|-----|-----|-----|----|
| Elements | C  | Si  | Mn  | Cr  | Mo  | V  |
| C        | 1.40 | 0.40 | 0.40 | 4.70 | 3.50 | 3.70 |

The friction-wear test was conducted on a MMUD-10B and wear tester by using pin-on-disk contact forms. In the experimental process, the coupling disk fixed in the lower part of the tester was unmoved, while the pin samples installed in the upper part were rotated at a horizontal velocity with a rotation diameter of 22 mm. The pin samples and disk samples were cleaned using acetone before each test and then dried. Both samples were worn under an initial load of 100 N, and the load was increased at a rate of 100 N per test until the wear rate of the pin samples significantly accelerated; moreover test conditions also included a sliding distance of 1000 m and test temperatures of 25 °C, 200 °C, and 400 °C, as well as a sliding speed of 0.691 m/s. All tests were carried out under air conditions. Friction coefficients were automatically recorded in real-time by computer software. The mass of the pin samples before, and after, wear was measured using an FA1004N electronic balance with a precision of ± 0.1 mg to calculate the mass loss. Each test was repeated in triplicate and the average value was then obtained. Additionally, Eq. (1) was used to calculate the wear rate of the pin samples:

$$ r = \frac{\Delta m}{(L \cdot F)} \quad (1) $$

Where $\Delta m$ is the mass loss induced by wear (g), $L$ refers to the sliding distance (m), and $F$ is the load (N). An INSPECT F50 SEM was used to observe and analyse the worn surfaces.
3. Results and discussion

3.1 Wear behaviour

Figure 1 shows the change in friction coefficients of V4E steel pin samples with the variation of sliding distance under different loads at varying temperatures. As can be seen from Fig. 1a, the wear process of the pin samples presented two stages: a running-in wear stage illustrating the significant increase of initial friction coefficient with increasing sliding distance, and a stable friction stage. With increasing load, the sliding distance in the running-in stage became smaller, and even disappeared. This was because, with increasing load, the micro-protrusion on the worn surfaces of the pin samples and the samples on the coupling disks were removed by polishing, which enlarged the wear area, thus, the samples entered into their stable friction stage within a shorter sliding distance [9]. As the temperature increased, the friction coefficients tended to be firstly decreased and increased (Fig. 1a). When the initial load was 100 N, the friction coefficients and fluctuations at room temperature were maximised, and the friction coefficient and the fluctuation were minimised at 200 ℃. Stott et al. [10] pointed out that the change in temperature caused the changes in the friction coefficient, which was associated with glaze materials (oxides) forming on the worn surface: the glaze materials formed before failure can reduce the friction coefficient, however this can lead to the increase in friction coefficients when subjected to failure. As the load increased, the friction coefficient curve was shown to be similar to that under 100 N. The effect of load on the friction coefficient was small. The change in average friction coefficient with load is demonstrated in Fig. 1c: the average friction coefficient fluctuated within the range from 0.17 to 0.22. It was likely to increase when the load exceeded a certain value (critical load) at the same temperature (Fig. 1b) because the oxide film on the worn surface showed embrittlement resulting from extrusion under continuous heavy load, and large amounts of debris were left in three-body abrasion form in the wear scar, enhancing the friction force between metal friction pairs to further cause an increase in the friction coefficient [10].

![Figure 1. The friction coefficient and average friction coefficient of pin samples at different ambient temperatures and different loads](image)

Figure 2 shows the wear rates of V4E pin samples under different temperatures and loads: the wear rate presented a slow change under the tested load range at a certain temperature, and rose sharply after reaching a critical load. The trend in the wear rate at room temperature is as follows: the wear rate increased rapidly between 100 N and 300 N and decreased between 300 N and 400 N. It was enhanced slowly from 400 N to 900 N, and presented a sharp increase between 900 N to 1000 N. When the load was 1,000 N, the wear rate was $15.65 \times 10^{-8}$ g/Nm, which was 7.9 times greater than that at 100 N. According to the change in morphology and friction coefficients of the worn surface in Fig.3, the wear rate before the sharply increasing stage was associated with slight wear, while the wear rate in the sharply increasing stage was associated with the serious wear stage, indicating critical load leading to the serious wear of the specimen at 900 N. The change in wear rate when the temperature rose to 200 ℃ is as follows: the wear rate increased rapidly between 100 N and 200 N, decreased from 200 N to 400 N, and increased slowly when the load was greater than 400 N. The wear rate under a maximum load of 1000 N was $4.4 \times 10^{-8}$ g/Nm, and the wear rate was not significantly increased.
Based on the morphology of the worn surface (Fig. 4), no serious wear was found. Due to the limits of the experiment, no bigger load was applied. Using the same method, the critical load causing serious wear of the pin samples when the temperature reached 400 °C was 800 N.

**Figure 2.** The wear rate of pin samples at different ambient temperatures and different loads

### 3.2 The observation and analysis of worn morphology

![SEM micrographs of worn surfaces](image)

Figure 3. SEM micrographs of worn surfaces at ambient temperature of 25 °C: (a) 100 N, (b) 300 N, (c) 400 N, (d) 900 N, (e) 1000 N

Figure 3 shows the worn morphology of V4E pin samples under different loads at room temperatures. At 100 N, there were many wear plough scars which were uniformly distributed on the worn surface along the sliding distance, and each wear scar was narrow (Fig. 3a). With increasing load, the worn surface also presented adhesive phenomenon in addition to ploughing (Fig. 3b). This was because, with the increase of load, the real contact area of the friction surface increased, while the frictional heat generated increased, which resulted in some parts undergoing adhesive wear to further cause increasing wear rates to different extents [11-12]. As the load continued to be increased, different oxides and smooth glazed surface were observed on the surface. When the load reached 400 N, compact oxide films were formed on the worn surface with a small number of micro-cracks, wear debris, and scar lines evincing plastic deformation (Fig. 3c). The oxidative wear mechanism exerted a greater effect, and wear rate was therefore reduced. As the critical load reached 900 N, oxide films with compact surfaces were slightly spalled (Fig. 3d), presenting typical oxidation wear and marginal delamination wear features. Furthermore, the worn surface exhibited large-sized, deep spalling grooves at 1000 N, each of which measured approximately 300 μm. A large number of micro-cracks, and plastic deformation features, were found on the surface of spalled grooves (Fig. 3e), revealing the
presence of serious wear. The results agreed with the influence seen in ferroalloy oxidation wear studies by Quinn [8], and Rabinowicz [11-12]. The influence may be summarised as follows: a glaze surface (oxide films) was formed on the worn surface under a certain load range at a certain temperature, which conferred lubrication and protection effects on the steel substrate, decreasing the wear rate and friction coefficients; when the load exceeded the critical value, the oxide films ruptured when extruded under continuous load, and large spalled areas were observed, confirming the presence of serious wear.

Figure 4 shows the morphologies of worn surfaces under various loads at 200 ℃. At 100 N, wear of abrasive particles was found on the worn surface and the wear scar was shallower than that at room temperature, accompanied by adhesive wear and more dispersed debris smaller than 3 μm (Fig. 4a). As the load exceeded 400 N, the entire worn surface was sufficiently covered with compact oxide films and presented large-sized carbides measuring 20 μm. These large-sized carbides scraped the sample surfaces, resulting in deep grooves (Fig. 4b). Moreover, when the load increased to 1000 N, the oxide films on the worn surface were damaged to cause further generation of spalled grooves measuring 80 μm and spalled scales measuring 15 μm (Fig. 4c). The wear mechanism mainly involved both oxidation wear and plastic deformation. The wear process at 200 ℃ was similar to that at room temperature, however the oxidation rate exhibited a large change with rising temperature, which was conducive to the formation of oxide films: wear rates and friction coefficients were therefore decreased and the load leading to serious wear was increased.

Figure 4. SEM micrographs of worn surfaces at 200 ℃: (a) 100 N,(b) 400 N,(c) 1000 N

Figure 5 shows the morphologies of worn surfaces under various loads at 400 ℃. Figure 5a shows that: at 100 N, much fine debris adhered to the smooth surface. Such results showed that oxidation at 400 ℃ was more significant than that at 200 ℃: as the load increased, oxidation was accelerated, which was mainly manifest by slight oxidative wear (Fig. 5b), conforming to oxidation wear models developed by Quinn[8] and Rabinowicz[13] et al. As illustrated in Fig. 5c, at 900 N, grooves resulting from the spallation of the oxide films with varying sizes occurred on worn surface, and many fatigue cracks appeared on parts of the surface along the vertical sliding direction. This was due to thermal effect produced by rising temperatures and mechanical friction, leading to the generation of the large quantity of cracks parallel to the sliding direction on the worn surface. In such a case, oxygen was liable to penetrate the surface of the cracks and then react with the surface of the substrate, to produce
multi-layered oxide films. Afterwards, oxide film strength tended to decrease with the decrease of film thickness. As the load increased, the oxide film on the surface of the steel underwent spallation under frictional load, meanwhile, new oxide films were formed on the spalled zones: such an oxidation-spallation process was cyclic leading to significant increases in the wear rate [12-15]. Furthermore, significant frictional heat was generated under the joint effect of rising temperature and mechanical friction, which caused the temperature of the worn surface to increase, and decreased the hardness of the substrate and sub-surface. Consequently, plastic deformation was generated which further led to heat-adhesion, thus causing the sharp increase in wear rate[16-17].

4. Conclusions
The critical load for the serious dry sliding wear and wear mechanism of V4E cold-work steel were investigated using a pin-on-disc wear tester. The conclusions can be summarised as follows:

(1) At a sliding speed of 0.691 m/s, critical loads causing the serious wear of V4E steel were 900 N and 800 N at room temperature and 400 °C, while there was no serious wear seen at 200 °C under loads of less than 1000 N.

(2) As the temperature increased from room temperature to 400 °C, the friction coefficient first decreased and then increased, while the average friction coefficient was approximately 0.2.

(3) There were abrasive particles found under different loads: as the load and temperature increased, oxidation accelerated; the formation of oxide films on the worn surface played a decisive role in the wear process: when applying a load below the critical load, oxide films can protect and lubricate the steel substrate, showing slight oxidative wear; when applying a load greater than the critical load, oxide films on the worn surface were ruptured and spalled, mainly indicating oxidative delamination wear.

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