Wear 376-377 (2017) 869–875

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Effects of ferrous powders on tribological performances of emulsion for cold rolling strips

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ARTICLE INFO

Article history:
Received 31 August 2016
Received in revised form
19 November 2016
Accepted 8 December 2016

Keywords:
Emulsion
Ferrous powder
Tribology
Cold rolling
Lubrication

ABSTRACT

An attempt was undertaken to obtain a better understanding of the effects of ferrous powders (FPs) on tribological performances of oil-in-water (O/W) emulsion for cold rolling strips. The particle size distribution of FPs in the working emulsions, which were collected from the industrial field of 1550 rolling unit, was analyzed by Malvern MS2000 laser diffraction particle size analyzer. Emulsion samples containing FPs with different particle sizes were prepared to simulate the condition of working emulsions containing FPs, and the particle sizes of FPs added in the emulsion samples were decided according to the analysis result of the particle size distribution of FPs in working emulsions. Tribological tests were further explored to evaluate load carrying properties, anti-wear and friction-reducing performances of the emulsion samples. In subsequent rolling tests, strips were also lubricated by the emulsion samples and morphologies of rolled surfaces were studied in more detail in order to obtain the mechanisms of FPs acting during rolling process. Results show that the tribological performances of emulsions are benefited from FPs with sizes smaller than or equal to 3.0 μm because of their micro-scrolling effect between rolls and strips, as well as supporting the oil film of emulsions, but FPs with sizes bigger than 3.0 μm performs as abrasive particles and aggravates abrasion, which may also leads to instability of lubricating performance of emulsions and deteriorate the quality of rolled surfaces. Benefiting from the polishing and grinding effects of FPs with sizes smaller than or equal to 3.0 μm on asperities, roughness of strip surfaces is decreased and the smoothness of surface morphology is improved.

1. Introduction

O/W emulsions are applied in cold rolling process for lubricating strips and cooling rolls. It can also help to reduce friction and abrasion between strips and rolls [1,2]. However, the abrasion between strips and rolls cannot be avoided completely, and a great amount of FPs are generated and suspended in the emulsions, consequently affecting the lubricating performance of emulsions. It is generally acknowledged that FPs have detrimental influences on technological lubrication because it may result in the reduction of stability and service life of emulsion, which leads to terrible surface quality of strips. Moreover, with the increase of concentration in the emulsion, FPs can react with fatty acid in the emulsion and therefore increase the oil consumption.

The lubricating condition that FPs are dispersed in the emulsions, which is similar to nano-lubrication condition, can be treated as liquid-solid lubrication [3]. According to theories of nano-lubrication, nano-sized and micron-sized mental particles, as well as their oxides particles, are beneficial to lubricating performances of lubricating oil. And the fundamental problem is the behavior of FPs during the lubricating process. Kumar et al. analyzed particle behaviors in the inlet zone of lubrication through a computational fluid dynamics model and found that particles with different sizes segregate from each other and have different locations in the inlet zone [4], so FPs with different particle sizes may have different influence mechanisms on the lubrication performance of emulsions. Wang and Yin have researched the effect of the particle size of FPs on friction coefficient [5], but the emphasis of their research focused on the concentration of FPs in emulsion and the particle sizes of FPs they chose were too big that cannot correspond to the reality of industrial field of cold rolling. If particle size of FPs could be defined which maximize or minimize the effects of FPs on the tribological performances, an optimum condition could be defined depending upon specific objectives, such as better tribological performances or better quality of strip surface, as a sequence that particle size of FPs could be controlled to the ideal size by magnetic filter of emulsion system. This paper is intended to research the effects of FPs with different particle sizes, which correspond to the reality of industrial field, on the tribological performances of emulsions.

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http://dx.doi.org/10.1016/j.wear.2016.12.012
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2. Experimental

2.1. Materials

The FPs for particle size analysis were centrifuged from the working emulsions, which were collected from the industrial field of 1550 rolling unit.

Commercial rolling oil for preparing emulsion samples applied in tests on tribological properties and cold rolling test was supplied by Shanghai Parker Chemical Industry Co., LTD (China). The main physical and chemical indexes of commercial rolling oil are given in Table 1.

The FPs added in emulsion samples prepared for tribological tests and cold rolling test were supplied by a professional company producing metal powder, with purities equal to 99.9%. Particle sizes of FPs chose to be added in the emulsion samples were 0.5 μm, 1.0 μm, 2.0 μm, 3.0 μm, 4.0 μm, 5.0 μm and 6.0 μm, according to the analysis result of particle size distribution of the FPs in the working emulsions. And the SEM micrographs of FPs with different particle sizes are shown in Fig. 1.

The smaller the particle size of FPs is, the higher the surface free energy is and so is agglomeration of FPs more aggravated. The agglomeration of FPs with 0.5 μm is very serious and none single particle can be found. Therefore, the FPs have to be surface-modified before added into emulsion samples in order to obtain outstanding dispersion in emulsion samples. As is shown in Fig. 1, FPs smaller than or equal to 3.0 μm are similar to sphere but FPs bigger than 3.0 μm have irregular shapes.

The workpieces used in cold rolling test were IF steels in annealed state, which were supplied by Maanshan Iron and Steel Company in China, and the dimension of the workpieces is 1.01～1.03 mm × 50 mm × 150 mm. The mechanical property parameters of the workpieces are shown in Table 2.

2.2. Preparation of emulsion samples containing FPs with different particle sizes

All emulsions prepared for tests were mixed with 96% deionized water and 4% commercial rolling oil. They were blended by magnetic stirrer on a hot plate with 60 °C constant temperature for 20 min. Then emulsions were divided into 8 portions. FPs with different particle sizes were surface-modified and then added into the different emulsion samples subsequently and dispersed equably with dispersant by stirrer. And the concentration of FPs in each emulsion sample was 300.0 mg/L, which is the upper limit of concentration controlled in the industrial field. All the eight tested samples were prepared in an exactly same way and they were just different in the particle size of FPs added. The detailed scheme of emulsion samples with FPs are shown in Table 3. Then the mixtures were blended with stirred at 1200 rpm for 20 min, in order to disperse FPs in the emulsion uniformly.

2.3. Tests on tribological properties

The load carrying capacity of emulsion is reflected by the maximum non-seizure load (P_B value) [6], which is an important parameter that determined by the emulsion viscosity, the adsorption film toughness and the sliding speed. In order to estimate the load carrying capacity of different emulsion samples, a MRS-10A four ball testing machine was used in the tests, following the ASTM D2783 standard [7]. In this technique, one steel ball under load is rotated against three steel balls held stationary in the form of a cradle while immersed in the lubricant. Tests of 10 s duration were carried out at increasing loads until the wear scar exceeds the specified value under specified loading force. The average friction coefficient of different emulsion samples was obtained from tests conducted with a 30 min duration at room temperature under a loading force of 392 N, a rotational speed of 1200 revolutions per minute [8].

Table 1
Main physical and chemical indexes of commercial rolling oil.

Project	Value	Standard
Density (g/cm^3, 15 °C)	0.84～0.94	ASTM D1298-2012
Saponification value (mg KOH/g)	135～155	ASTM D94-2007(2012)
Viscosity (mm^2/s, 40 °C)	20.0～24.0	ASTM D445-2009
Acid value (mg KOH/g)	5.5～10.5	ASTM D974-2012

2.4. Cold rolling test

To evaluate the lubricity of different emulsion samples, a four-high rolling mill of Φ95/200 mm × 200 mm with a velocity of 60 r/min and a rolling power of 35 kW was used in cold rolling test. Each workpiece was rolled with a 20% pass-reduction at each rolling pass for 5 rolling passes. The surface morphology analyses of rolled strips were conducted by a German model LEXT OLS4000 laser confocal microscope and a scanning electron microscope (SEM).

3. Results and discussion

3.1. Particle size distribution analysis of FPs in working emulsions

The FPs in working emulsions were collected for particle size distribution analysis and ultrasonic dispersion was applied before the analysis in order to deal with the agglomeration of FPs and reflect the real particle size distribution of FPs in working emulsions. The analysis result is shown in Fig. 2.

As is shown in Fig. 2, the trend of the particle size distribution obeys normal distribution. Particle sizes of FPs in working emulsions range from about 1 μm to about 5.0 μm and the maximum content sizes focus on 2.0 μm to 3.0 μm nearby. Because of the measurement accuracy of Malvern MS2000 laser particle size analyzer, it can hardly detect particles under micrometer level, but there must be a little amount of nanoscale FPs in working emulsions [9]. Therefore, the influence of nanoscale FPs will be taken into account and micron-scale FPs will be focused on. According to the result above, the particle sizes of FPs added in the emulsions to simulate the lubricating condition of working emulsions are decided as 0.5 μm, 1.0 μm, 2.0 μm, 3.0 μm, 4.0 μm, 5.0 μm, 6.0 μm and these sizes mainly cover all typical particle sizes of FPs in working emulsions.

3.2. Tribological properties

The P_B value, the friction coefficient (μ) and the wear scar diameter are three important indexes of load carrying properties, anti-wear and friction-reducing performances of the emulsion. The bigger P_B value is on behalf of stronger oil film and better lubricity of emulsions. Similarly, the less the friction coefficient is, the better friction-reducing performance of the emulsion will be [6].

Fig. 3 shows the influences of FPs with different particle sizes on the P_B value and friction coefficient. It can be seen that the P_B value variation trend is contrary to the friction coefficient variation trend. With the increase of particle size of FPs added in the emulsion, the P_B value of emulsion increases at first, and then decreases when the particle size of FPs is over 3.0 μm. Conversely, the friction coefficient decreases before increasing and achieves