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An investigation into the tribological behaviour of a work roll material at high temperature

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ABSTRACT

The tribological behaviour of work roll materials is always a key issue during the hot rolling of metals where high pressure and high temperature are applied to the strip. In this paper, the oxidation behaviour of a high speed steel roll material is investigated by a Gleeble 3500 thermal–mechanical simulator at 700 °C for different oxidation periods in dry air as well as in a moist atmosphere. The surface characteristics after oxidation are characterized by scanning electron microscope (SEM) and X-ray diffraction (XRD) analysis. The results indicate that the humid atmosphere has a significant effect on the surface morphology of the oxide scale. A simulation of the hot rolling process is also conducted on a mini rolling mill which is incorporated within the Gleeble 3500 simulator. Two types of roller surfaces are investigated, one is a virgin surface and the other a pre-oxidized surface with 7 μm thick oxide scale. The experimental results show that the two types of roller surface exhibit quite different tribological behaviour in terms of friction and surface roughness. The rolling force and friction of pre-oxidized rolls are higher than that of virgin surface rolls for different thickness reductions and temperatures.

1. Introduction

Due to the demands of high quality productions and high productivity, high-speed steel (HSS) rolls have prevailed for both early and last finishing stands during the hot rolling process. However, hot rolling rolls operate under extremely arduous conditions. In hot rolling, the roll surface can be heated up to 700 °C in short contact with the strip (10^{-1}–10^{-3} s), and subsequently cooled to around 100 °C by a massive water cooling. Rolls are subject to high thermal cycles, high cyclic loading and high levels of abrasion [1,2]. The wear process of rolls is complex as it is affected by various factors such as abrasive wear, oxidation wear, cracking by thermal fatigue and heat impact, fatigue wear through the detachment of the carbides, and sticking of the rolled material onto the roll surface [1–6]. High-speed steel work rolls are superior to traditional hot rolling rolls such as high chromium (HiCr) and indefinite chill iron (IC) rolls because they can operate at higher temperatures without losing their hardness, as well as possessing a higher wear resistance [1,7–9]. The thermal cycling of the rolls causes the oxidation which contributes to the deterioration of the surface quality and affects its contact behaviour with the strip. Erickson and Hogmark [10] and Hokkirigawa et al. [11] reported that the oxide scale may induce localised large scale surface damage such as banding. It has been found that the formation of oxides prevents the sticking problem by establishing an oxide–oxide contact between the work rolls and the strip [10,12]. Although many research have been done [10,12–16], the tribological behaviour of the oxides still remains unclear. Pellizzari et al. [5] found that the hard oxide layer on the roll surface can have a positive effect on the wear rate, while other researchers argue that the formation of the oxide scale on the surface transform the severe wear into a mild oxidation wear [12,17]. Vergne et al. [15,18], Molinari et al. [17] pointed out that the complex tribological behaviour of the oxides is influenced by the nature and physical properties of the oxide scale. Therefore, it is important to investigate the characteristics of the oxide scale layer formed on the high-speed steel roll surface and its tribological behaviour by simulating the hot rolling process in the laboratory.

Several test configurations have been developed to simulate the operating conditions in the roll contact, such as pin-on-disc and disc-on-disc [15,19]. A practical rolling–sliding wear test adopted a disc-on-disc configuration which involves induction heating of one disc material to represent the hot trip [5]. However, the simulation of the conditions encountered during the hot rolling process still represents a challenge for researchers [16]. In this paper, the oxidation and tribology experiments were carried out on a Gleeble 3500 thermal–mechanical simulator. The surface characteristics after oxidation were characterized by scanning electron microscope (SEM) and X-ray diffraction (XRD) analysis. It is reported here for the first time that a simulation of the hot rolling process has been carried out on a mini rolling mill that has been adapted within the

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Gleeble 3500 mechanical simulation system. Two types of roll surface were investigated in the simulation of the hot rolling process, one is a fresh metallic surface and the other is a pre-oxidized surface in dry air. Test parameters such as rolling force, surface roughness of strip and rollers were measured at different temperature and reduction to investigate the tribological behaviours after a number of simulated rolling passes.

2. Experiments

All experiments in this paper were carried out on the Gleeble 3500 thermal–mechanical simulator. The Gleeble 3500 is a fully integrated digital closed loop control thermal and mechanical testing system, which provides an accurate execution and repeatable test program. The thermal system is equipped with a direct resistance heating system that can heat specimens at a rate up to 10,000 °C/s, or can hold steady-state equilibrium temperatures. The system is also capable of performing a high cooling rate in excess of 10,000 °C/s on the specimen surface with the high thermal conductivity grips holding the specimen. Thermocouples provide signals for the accurate feedback control of the specimen temperature. The test chamber is connected to a high vacuum system. Optional protection gas can also be introduced into the chamber as required. The mechanical system is a complete, hydraulic servo capable of exerting up to 10 t of static force in tension or compression. Displacement rates up to 1000 mm/s can be achieved. Linear variable differential transformer (LVDT) transducers, load cells, or non-contact extensiometer provided the feedback to ensure an accurate execution and a repeatability of the test program. Control parameters include stroke displacement, speed and ram force.

2.1. Oxidation test

The high-speed steel roll material used in this investigation has the following composition: C 1.96 wt%, Cr 4.85 wt%, Mo 4.47 wt%, W 3.4 wt%, V 4.00 wt%, Mn 1.26 wt%. There are mainly three kinds of carbides distributed in the material, i.e., V-rich MC carbides, Cr-rich M7C3 carbides and Mo-rich M2C carbides. The samples were oxidized isothermally at 700 °C for 30–120 min in dry air and 46.5% H_2O moist air. Compressed industrial air was used as the dry air. In the case of moist atmosphere, controlled moisture was obtained by passing industrial air through a distilled water tank which was maintained at a constant temperature. 46.5% H_2O moist atmospheres can be obtained by controlling the water temperature at 80 °C. The gas tube connecting the water tank and Gleeble chamber was pre-heated to prevent the condensation of water on the inside diameter of the tube. The following procedure was used for each of the oxidation experiments: (1) the sample was heated to the desired temperature in an argon protective atmosphere at a heating rate of 100 °C/min; (2) when the temperature reached the desired value, argon was switched off and the oxidizing atmosphere introduced; (3) after oxidation, the sample was cooled down to room temperature in the argon atmosphere.

A JEOL JSM 6490 scanning electron microscope (SEM) equipped with energy-dispersive X-ray (EDX) analysis was employed to investigate the surface morphology of the samples before and after oxidation and the microstructures of the oxide scale formed on the sample surface. An X-ray diffraction (XRD) using a GBC MMA diffractometer with monochromated Cu K_α radiation was used to analyze the phase composition of oxide scale. In order to measure the thickness of the oxide scale, oxidized samples were cold mounted in Epofix resin which were then cut through the cross-sections. SEM was used to measure the thickness of oxide scale formed on the HSS sample surface.

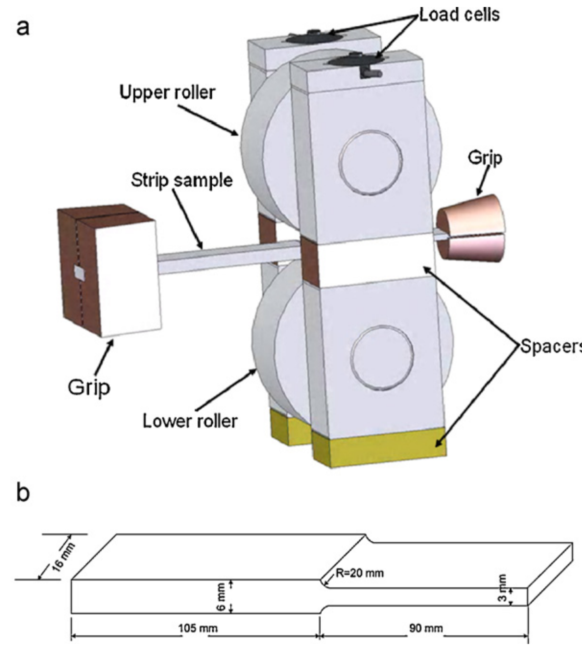

Fig. 1. (a) Schematic illustration of mini two-high rolling mill and (b) schematic illustration of strip sample.

2.2. Tribological test

Tribological experiments were carried out on Gleeble 3500 thermal–mechanical simulator with a mini-rolling mill incorporated within its chamber (Fig. 1a). The mini rolling mill is called a lateral-setting test (LST) system when compared with an upsetting rolling test (URT) [20]. There are two load cells mounted on the top of LST mini-mill just above the upper roller's shaft, therefore the rolling force can be directly measured during the test. By adjusting the thickness of the spacers between the rollers, various reductions of the sample thickness can be obtained. The strip sample is clamped by grips of the Gleeble simulator and can be heated up to the desired temperature by introducing the electric current through the sample before the hot rolling simulation. The rolling simulation is carried out by the Gleeble Digital Control System driving the moving work piece into the roll gap. The strip sample used in this investigation is mild carbon steel and Fig. 1b illustrates the shape and dimensions of the strip sample.

Two different surface morphologies of high-speed steel rolls were investigated in this experiment. One is a relatively fresh metallic surface, the other is a pre-oxidized surface with the roll surface oxidized at 700 °C for 80 min in dry air (oxide thickness was 7 μm). The strip sample was heated up to 700 °C and 850 °C in the argon atmosphere first, and then the hot rolling was performed at 15 mm/s rolling speed. The rolling force was recorded in situ by load cells during the experiments. The effect of both the strip and original surface roughness of the roll and the thickness reduction were considered. A stylus-type Hommel Tester T1000 profilometer with ISO11562 filter was employed to measure the samples' surface roughness.

3. Results and discussion

3.1. Oxidation test

Fig. 2a shows the original topography of high-speed steel roll surface. The grinding marks can be seen clearly. Fig. 2b and c shows the surface topographies after oxidation at 700 °C for 120 min respectively in dry air and 46.5% moist air. It can be seen that the