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Microstructural, mechanical and tribological characterisation of roll materials for the finishing stands of the hot strip mill for steel rolling

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ABSTRACT

The microstructure, mechanical and tribological properties for three different materials, high speed steel, high chromium iron and indefinite chill iron, used for hot strip mill work rolls have been evaluated. Microstructural characterisation was performed using light optical microscopy, scanning electron microscopy and energy dispersive X-ray spectroscopy. The mechanical and tribological properties were evaluated using micro-Vickers indentation and scratch testing in combination with post-test microscopy. The microstructures of the investigated materials were found to be rather complex with a number of secondary phases and also materials with similar nominal composition display significant differences with respect to distribution, size and morphology of carbides. Scratch testing, including detection of friction coefficient, acoustic emission and penetration depth, gives valuable information concerning the mechanical and tribological response on a microscopic level of the investigated materials. Type, amount, distribution, size and morphology of the secondary phases in the materials have a strong impact on the surface deformation and wear mechanisms during scratching. Cracking and chipping are frequently observed in connection to the ridges surrounding the scratches. However, cross-sectional analyses of the scratched microstructures reveal that cracking of the brittle carbide phases may extend to significant depths >100 μm, reducing the mechanical strength of the material. Based on the results, it is believed that a more isotropic microstructure, e.g., obtained via a powder metallurgy process, with finer carbides would result in improved properties and performance in a hot rolling application.

1. Introduction

In the finishing stands of the hot strip mill (HSM) for steel rolling, mainly three materials are used for the work rolls. High speed steel (HSS) and high chromium iron (HCr) are used in the early stands and indefinite chill iron (IC) in the last two or three stands. The finishing line in the HSM is generally built up by six or seven stands, each containing a pair of work rolls. The conditions are aggressive with high periodic temperatures (flash temperatures of 800 °C) and rolling pressures (100–500 MPa) [1–4]. However, contact with the back-up roll may result in even higher (up to 1700 MPa) contact pressures [4]. The work rolls are exposed to violent fluctuations in temperature (generally 40–650 °C), cyclic stresses ($\pm$500 MPa) and abrasion by hard oxides and therefore demand high wear resistance and high toughness [2,3]. Wear of rolls occurs either relatively uniform on the contact surface or local in deeper wear bands. The uniform wear is mainly caused by abrasion in combination with micro chipping caused by thermal induced surface fatigue. Abrasive wear is caused by the presence of particles that are harder than the roll material in the system. In hot rolling, these particles mainly consist of hard oxides [2]. Surface fatigue is due to the large variations in temperature that the rolls are exposed to in HSM along with periodic load [2]. The development is going towards the use of HSS rolls and to enhance the wear resistance of HSS, Hwang et al. [5] recommends to increase the hardness of the hardened martensitic matrix and to increase the amount of hard and wear resistant carbides.

HSS rolls have a martensitic matrix with hard primary carbides, such as M_6C, M_2C, M_7C_3 and MC, and small secondary carbides in the matrix. The primary carbides are precipitated in the molten metal, while the secondary carbides are precipitated in the solid metal [6]. The M_2C carbides in the as-cast material are after austenitisation decomposed into M_6C- and MC-carbides [4]. The carbides in HSS are very hard and are found in a more discontinuous network than those in HCr and IC. The latter two have higher carbide content than HSS. HCr has carbides of M_7C_3-type while IC has carbides of M_3C-type as well as some graphite to ensure a good enough wear resistance [7,8]. In the 1990's carbide forming elements, such as niobium, were added to IC material in purpose

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to develop a more wear resistant material without losing the favourable properties of the IC material [8]. This carbide reinforced IC material is now widely used. Also the HCr rolls are reinforced with other carbide formers, such as niobium [8].

The development of HSS rolls has led to large improvements within hot rolling, such as higher wear resistance, better quality of the strip and extended rolling campaigns [1]. Park et al. [9] as well as Ziehenberger and Windhager [10] have found the HSS rolls to have three to four times higher wear resistance than HCr rolls. However, Belzunce et al. [7] mean that the high friction coefficient of HSS prevents their use in the last finishing stands of the mill, where strip temperature is lower, the rolling load is very high and the most important action is abrasive wear.

In a previous study by the present authors [11] it was shown that amount, size and distribution of secondary phases such as carbides and graphite have a strong impact on the wear characteristics of hot rolls due to the brittleness and chipping tendency of these phases. Consequently, more fundamental studies concerning their mechanical and tribological response in a tribological contact are needed. Here, scratch testing can be helpful in order to characterise the material response and friction. Scratch testing is a frequently used method to characterise the cohesive and/or the adhesive strength of different types of coatings [12–14]. In the conventional scratch test a Rockwell C diamond stylus (120° cone with 200 μm radius) is drawn across the surface during an increase of the normal load until some kind of well-defined coating failure occurs [15]. Scratch testing is also performed on bulk materials in order to characterise material response and surface failure mechanisms in a scratching contact, for example in connection to surface defects [16,17].

The scope of this work is to investigate the microstructure and mechanical properties on a micro level for HSS, HCr and IC hot strip mill work roll materials. Matrix hardness and carbide amount, -type and -hardness as well as Young's modulus are characterised along with the mechanical and tribological response to scratching. The latter is characterised in order to get a better understanding of what is happening to the brittle carbides in a tribological contact.

2. Experimental

2.1. Materials

Five different types of hot work roll materials were characterised in the present study; two High Speed Steel (HSS), two enhanced indefinite chill iron (IC) and one high chromium iron (HCr) grades, see Table 1. All materials were delivered by Åkers Sweden AB in a spin casted (centrifugal casted) and heat treated condition. Three of the roll materials are commercial, while two (HSS2 and IC2) are under development.

2.2. Microstructural characterisation

The microstructures of the materials were characterised by light optical microscopy (LOM, Leica DMRME), SEM (scanning electron microscopy, FEG-SEM Zeiss Ultra 55) and EDS (energy dispersive X-ray spectroscopy, Oxford Instruments INCA PentaFET-x3). In order to be able to distinguish the phases of the material, the LOM investigation was performed on polished and etched (3% Nital etchant) samples while the SEM investigation was performed on polished samples using the backscatter electron detector in combination with EDS point analysis. The percentage of phases were calculated in area per cent (area%) by a stereological method where a 2D systematic grid of crosses was randomly used on five different SEM micrographs (area $740 \times 480\ \mu m^2$ and $480 \times 240\ \mu m^2$) for each work roll material [18].

2.3. Hardness indentation

The macro-hardness of the materials was measured by macro-Vickers indentation (Reicherter Briviskop) with 30 kg load. The hardness of the matrix and the different secondary phases were measured by micro-Vickers instrumented indentation (CSM Micro Combi Tester) with 20 g and 10 g load, respectively. In order to avoid any influence from the surrounding matrix, the micro-hardness measurements of the carbides were only performed on the largest carbides found in the metallographic prepared sample. Loading in micro-Vickers testing was performed during 30 s. The load was then constant during 15 s and unloading was performed during 30 s. Young's modulus and hardness was calculated from the indentation curve (load vs. indentation depth) by Oliver–Pharr's model [19]. The hardness was obtained in the unit GPa, but was calculated into Vickers (kg/mm^2). All hardness measurements were made on fine polished samples at ambient air conditions (21–22 °C, 25–26% RH).

2.4. Scratch testing

The mechanical and tribological response during scratching was evaluated by using a commercial scratch tester (CSM Revetest) equipped with a Rockwell-C diamond stylus. Scratch testing was performed at ambient air conditions (21–22 °C, 25–26% RH) using a constant load of 50 N (diamond stylus radius 200 μm) or 5 N (diamond stylus radius 50 μm), a speed of 10 mm/min and a scratch length of 10 mm. During scratching, the friction coefficient (μ) and acoustic emission (AE) were continuously recorded and monitored. After the scratch testing procedure, the scratch tested samples were evaluated by SEM and 3D optical surface profilometry (Wyko NT9100) in order to evaluate the influence of microstructure on plastic deformation behaviour (scratch hardness), cracking tendency and wear characteristics. The scratch hardness H_s was calculated, using Eq. (1) where d is the scratch

Table 1
Chemical composition (min–max values in wt%) and secondary phase content of the work roll materials investigated.

	C[a] (%)	Si[a] (%)	Mn[a] (%)	Mo[a] (%)	Cr[a] (%)	Ni[a] (%)	V+Nb[a] (%)	Secondary phases
HSS1	1–2	0.5–1.0	0.5–1.5	2–5	3–7	0.5–1.5	2–8	M_6C, M_2C, M_7C_3, MC
HSS2	1–2	0.5–1.0	0.5–1.5	1–4	4–7	0.5–1.0	5–8	M_6C, M_2C, M_7C_3, MC
IC1	3–4	0.5–1.5	0.5–1.6	0.2–0.8	1.5–2.5	4–5	1–4	M_3C, MC, graphite
IC2	3–4	0.5–1.5	0.5–1.6	0.6–1.2	1.5–2.5	4–5	1–4	M_3C, MC, graphite
HCr	2–3	0.6–1.0	0.8–1.2	1.0–1.5	15–20	1.0–1.5	< 0.5	M_7C_3, MC

[a] Values given by Åkers Sweden AB (the exact compositions are confidential).