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Dry sliding wear of an induction-hardened, high-silicon medium-carbon microalloyed steel

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ABSTRACT

Microalloyed (MA) medium carbon steels are promising materials as a replacement of quenched and tempered (*Q–T*) grades. The dry sliding behaviour of an induction hardened medium carbon MA steel, compared to *Q–T* steel, in the same surface hardening condition, was investigated. The MA steel showed a higher frictional stability and wear resistance than the *Q–T* steel. The transition from the mild oxidative wear regime to the severe adhesive wear regime occurred under more severe sliding condition for the MA steel. This can be ascribed to the superior hardness of the bulk material and also to its higher tempering stability, induced by the strengthening precipitates, that enhance the load bearing capacity of the MA steel and hence the stability of the protective oxide layers.

1. Introduction

The use of small additions of V, Nb, and Ti in low-carbon steels has been successfully used for the production of low carbon High Strength Low Alloyed steels (HSLA) that are widely used for pipelines, bridges, automotive components and other structural applications [1–4]. However, the low carbon content (< 0.2 wt%), typical of these steels, limits the maximum achievable hardness and tensile strength and therefore hinders their use in applications where higher mechanical properties are needed.

In high performance applications, for example for the transportation sector, medium carbon (0.4–0.5 wt%) steels are widely used, which are typically plastically deformed by high temperature rolling and/or forging, then heat treated by quenching and tempering (*Q–T*), so as to obtain the desired level of strength, fatigue and wear resistance. These steels are alloyed with combinations of Mn, Cr, Ni, Mo and also B for hardenability and can be produced to a wide range of hardness, depending on carbon content and tempering conditions [5].

In the last years, microalloyed (MA) medium carbon steels have gained acceptance as a replacement of traditional *Q–T* grades, for a variety of automotive and engineering applications [6–11]. For example, the use of MA steels for crankshafts production has been shown to be a viable alternative to *Q–T* steels, particularly in engines that require significant improvements in performance. The driving force for the use of MA medium carbon steels is cost reduction and energy saving that results from eliminating expensive alloying elements and from separate post-forging heat treatments. Moreover, the machinability of the resulting microstructure is generally superior to that of tempered martensite, at the same strength level [12]. The high strength of MA steels is obtained by microalloy addition of strong carbonitrides formers (V, Nb and Ti), as for conventional HSLA, and controlled thermomechanical processing. The precipitation of very fine strengthening phases, during thermomechanical processing, increases material strength by grain refinement and precipitation hardening. Steel composition and processing schedules have been properly developed, enabling the use of the components in the as-deformed plus controlled-cooled condition. Directly cooled MA steels are produced with a variety of microstructures, from ferrite-pearlite to fully bainitic. In ferritic-pearlitic MA steels, strength increase is also achieved through increase of the pearlite volume fraction.

It is well known that a wear resistant surface, supported by a tough core, is one of the most important requirements of several machine parts, such as drive gears, cams, steering parts, bearing, bearing races, etc. An adequate wear resistance is also necessary for steels used in the mining, earth moving and railroad industries. *Q–T* medium carbon steels are often surface hardened by induction hardening which, due to the short heat treatment cycle, leads to a high potential for cost savings and furthermore it provides less deviation of the mechanical properties and less decarburization. Also in MA steels, the relatively high carbon content allows to increase their surface hardness by induction hardening, but very few literature data are reported on its effect on microstructure [13] and wear resistance [14–16]. An interesting aspect is that in these steels the presence of Nb, V, Al and Ti leads to formation of carbides, nitrides and carbonitrides that can: (i) retard grain growth during the austenitizing process; (ii) increase the hardness of the martensite

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and consequently its wear resistance; (c) improve the tempering response of the material [17]. Induction hardening of medium carbon MA steels, for example, can be applied to the journal radius regions of crankshafts, that are especially prone to high cycle fatigue [12], or to parts of earthmoving machines undergoing intensive wear damage, such as track-type tractor chains [18].

For this reason, the present study aims at investigating the tribological behaviour, under dry sliding conditions, of an induction hardened medium carbon MA steel, by comparison with conventional *Q–T* steel, in the same surface hardening condition.

The MA steel used in the present investigation is a recently developed high Si steel, featuring higher fatigue strength than conventional microalloyed steels. A high Si content leads to some positive effects in MA steels [19]: higher hardness of ferrite, higher volume fraction of proeutectoid ferrite, more beneficial ferrite distribution and, finally, lower tendency to formation of brittle bainite, which reduces ductility and deteriorates machinability. Moreover, an increase of Si could be an interesting way of increasing the toughness of MA steels [20].

2. Experimental

2.1. Materials

The chemical composition of the high Si medium carbon MA steel, used in the present work, is given in Table 1. The conventional *Q–T* 35KB2 steel, whose chemical composition is reported in Table 2, was used as reference material.

The production process of the MA steel includes the following main steps:

- EAF steelmaking – Bloom casting – Rolling to billets 135 mm × 135 mm (reduction 6.2 ×)
- Reheating to 1150 °C – Rolling to ø28 mm bars (total reduction 183 ×).
- Cooling to room temperature at about 0.5 °C/s.

The mechanical properties and the prior austenite grain size of the MA and 35KB2 steels, both before and after induction hardening, are reported in Table 3. Strength in the MA steel is derived from a combination of grain size control, pearlite volume fraction, solid solution strengthening and precipitation hardening.

Flat specimens of both steels (MA and 35KB2) for the sliding tests were induction hardened. Induction hardening, in fact, is widely used to produce hard, wear-resistant surfaces on the workpiece, while retaining the bulk material unaffected. Induction hardening of the steel sliders was conducted by the stationary (single shot) method on a 400 kW, 3/10 kHz inverter, with a heating time of about 5 s. All sliders were quenched to 25 °C with a 2% concentration of aqueous polymer quenching medium. The induction hardened sliders were subjected to the same furnace temper treatment: 190 °C for 1 h.

Rockwell hardness tests, with 150 kg load (HRC), were carried out on both steels after induction hardening. Three measurements were made for each sample to obtain satisfactory statistical reliability. Due to the small size of the flat tribological specimens ($5 \times 5 \times 70$ mm^3) all the cross section was induction hardened, therefore the same hardness was measured both in the surface and in the bulk.

Samples for metallographic analysis were mechanically ground, polished according to ASTM E3-11 [21], and chemically etched with Nital2 to reveal grains and phases. The microstructural characterisation was carried out by optical microscopy (OM) and Scanning Electron Microscopy (SEM), with Energy Dispersive Spectroscopy (EDS) (Zeiss EVO 50 EP microscope with Energy Dispersive Spectroscopy (EDS) microprobe Oxford INCA 350). Image analysis was carried out on the optical and SEM micrographs using the ImagePro-Plus 4.5.0 software. The prior austenite grain size was determined according to ASTM E112 [22].

2.2. Tribological tests

Dry sliding tests were carried out using a flat-on-cylinder tribometer (block-on-ring contact geometry), which is described in further detail elsewhere [23]. Flat specimens ($5 \times 5 \times 70$ mm^3) of the induction hardened MA and 35KB2 steels were used as stationary sliders, whilst the rotating cylinder (40 mm diameter) was the SAE52100-EN100Cr6 steel, heat treated to 63 HRC. Surface roughness of the mating materials was evaluated before tests by a Hommelwerke T2000 stylus profilometer (tip radius: 5 μm). Fixed sliders and rotating countermaterial were similarly surface finished to a roughness R_a = 0.06 μm.

Sliding tests were carried out at ambient conditions of temperature and humidity (relative humidity ranging from 50% to 60%), under normal loads ranging from 10 to 75 N (generating maximum Hertzian contact pressures [24] from 60 to about 170 MPa) at sliding speeds of 0.3 and 1.8 m s^{-1}, over a sliding distance of 1000 m. Four repetitions, for each testing conditions, were carried out. During the tests, the friction force and vertical displacement, which is related to total wear (i.e. cumulative wear of both stationary slider and rotating cylinder), were continuously measured by means of a load cell and a Linear Variable Differential Displacement Transducer (LVDT), respectively. The coefficient of friction (COF) and wear data were recorded as a function of the sliding distance. After the tests, wear scar depths and widths on sliders were evaluated by stylus profilometry. Wear volumes were calculated according to ASTM G77-05 [25].

The morphology and composition of the wear scars on the sliders were analysed by 3D-digital microscopy as well as by SEM–EDS to identify the dominant wear mechanisms. Wear debris was collected at the end of each test and analysed both by SEM/EDS and X-Ray Diffractometry (XRD) performing θ–2θ scans from 20° to 100° with a 0.02° step size and a 2 s dwell time. A CoKα radiation source was used, with a 35 kV accelerating voltage and a 30 mA filament current.

3. Results and discussion

3.1. Materials characterisation

The high Si MA steel, in the as-rolled condition, showed a fine microstructure, consisting of 60 ± 0.8% pearlite and 40 ± 0.8%

Table 2
Chemical composition (wt%) of the conventional *Q–T* 35KB2 steel.

C	Si	Mn	P	S	Cr	Ni	Ti	Al	N	B
0.35	0.25	0.70	0.024	0.018	0.20	0.120	0.050	0.026	0.120	0.003

Table 1
Chemical composition (wt%) of the high Si MA steel.

C	Si	Mn	P	S	Cr	Ni	Mo	V	Ti	Cu	Al	N	Nb	Fe
0.36	1.25	0.99	0.02	0.06	0.17	0.10	0.020	0.12	0.006	0.25	0.020	0.01	0.003	Bal.