Effect of microstructure factors on abrasion resistance of high-strength steels

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Abstract

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Current development of high strength abrasion resistant steels is mostly oriented on high hardness, martensitic concept following the hypothesis that the abrasion resistance holds a proportional tendency with hardness. The various experimental observations have suggested that the high hardness of martenzite does not guarantee a high abrasion resistance because the brittle nature of martensite can lead to decrease their abrasive wear. The aim of this work was to analyse the influence of microstructure on abrasion resistance of selected high-strength low-alloyed steels used in the industry. The abrasive wear resistance of selected steels was obtained using an ASTM-G65 three-body abrasive wear test, microstructure and wear resistance determination. It was observed that grain refinement is an effective way of enhancing the abrasion resistance. In this context, micro alloyed steels offer an attractive combination of price and performance.

Keywords: abrasive wear; working tools in agriculture; ASTM G65; mechanism of wear

Wear caused by the impact and abrasion action of hard particles is a major problem in many industrial application sand particularly in the areas of agriculture, mining, mineral processing, earth moving, etc. (Sundstrom et al. 2001).

Mechanism of wear is complex surface process in the context of factors whose intensity of reaction depends on the operating environmental conditions under which the mechanical parts are applied, on operating parameters of machines and material properties of contacting surfaces (Suchánek et al. 2009).

Classifications such as two-body and three-body abrasive wear (Vingsbo, Hogmark 1981), low stress abrasion, high stress abrasion and gouging (Larsen-Basse 1983); and soft abrasion and hard abrasion (Moore 1981) were proposed in order to describe the various types of abrasion processes.

The physical interactions between the abrasive particles and the abraded surface are studied in order to clarify the mechanisms of deformation and wear and can be divided into four types: microploughing, microcutting, microfatigue and microcracking (Zum Gahr 1987).

The variety of the types of wear leads towards the use of metallic materials, welding materials and coatings in order to ensure the highest possible wear resistance of the surface layers in working conditions (Chotěborský et al. 2011).

For effective usage of different types of steels it is indispensable to understand the phenomena of abrasion and the damage caused by hard particles; considerable effort has been done to understand the response of various materials exposed to abrasion (Rendón, Olsson 2009).

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Table 1. Chemical composition of tested steels (%)

Material	C	Mn	Si	P	S	B	Cr	Mo
Etalon 1.1013	0.06	0.35	0.05	0.01	0.01			
S355JR*	0.24	1.6	0.55	0.045	0.045			
S700MC**	0.09	1.56	0.45	0.016	0.005	0.002		0.153
Hardox 400	0.20	1.6 max.	0.7 max.	0.02	0.02	0.004	0.3–1.4	0.25–0.6

*N 0.099; **Al 0.039; Ti 0.105; Nb 0.051

The wear resistance of the working tools in agriculture affects many factors e.g. the material of tool, its hardness, microstructure, physical and mechanical properties.

Working tool in interaction with the environment e.g. composition of soil, moisture, texture, soil reaction with environment influence the resulting lifetime of the tools under wear.

Among basic factors considered to select materials for abrasion wear conditions obviously belongs a criterion of material hardness. Microstructure of materials, size and type of carbide phase also participate in the resulting abrasion wear resistance (Balla 1996).

Abrasion resistant steels in combination with a good formability and a desirable balance of strength and ductility are in high demand for industrial applications. Studies show that high strength low alloyed steels offer a good potential for use as wear resistance material. The correlation of microstructural features such as martensite, ferrite + pearlite and ferrite + martensite with abrasion resistance for a high strength low alloy steel were referred to offer a good wear behaviour (Jha et al. 2003).

Some results present the abrasion wear resistance of martensite + ferrite dual phase steel influenced by the microstructure and test conditions; wear resistance increases with increasing the volume fraction of martensite (Saghafian, Kheirandish 2007). Available information suggests that the abrasive wear resistance of materials depends on factors like microstructure (microconstituents, their size and content), and mechanical properties of materials (Zdravecká et al. 2012). However, the effect of ferrite morphology on mechanical properties and wear resistance was rarely taken into account (Deng et al. 2013).

The aim of the study is to evaluate in the laboratory conditions the wear resistance of selected low alloyed steels exposed to abrasive wear, namely three-body abrasion. Of special interest was to investigate the relation between material characteristics such as microstructure and mechanical properties and the resulting wear resistance. In this context, low alloyed steels offer an attractive combination of price and performance that has converted them into excellent competitors of highly alloyed steels and cast irons as well as ceramics.

MATERIAL AND METHODS

The microstructure of steels and cast irons is usually a heterogeneous mixture of phases with different combined physical and mechanical characteristics. These phases have a different resistance to the abrasive wear effect of particles (Suchánek et al. 2009).

The effect of microstructure factors on abrasion resistance was experimentally tested on selected steels represented by low-alloyed carbon steels with middle and low content of carbon with different structures. Chemical composition of tested steels is given in Table 1.

Table 2 shows the mechanical properties of the steels investigated. As can be seen the hardness (HV10) varies between 156 and 420 HV10, the martensitic steel showing the highest hardness.

Table 2. Mechanical properties of tested steels

Material	Re (MPa)	Rm (MPa)	A_{50}(%)	HV10
S700MC	700	790–960	15	271 ± 16
Hardox 400	1,000	1,250	10	420 ± 35
S355JR	355	450–630	20	156 ± 6

Re – yield strength; Rm – tensile strength; A_{50} – elongation; HV10 – Hardness

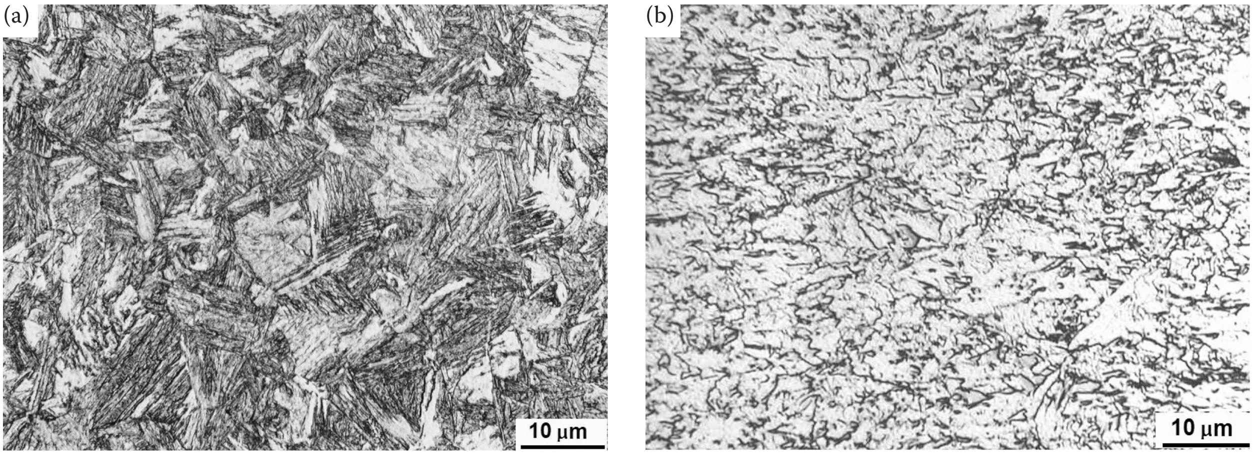

Fig. 1. Microstructure of (a) martensite – Hardox 400 and (b) acicular ferrite – S700MC

Steel with ferritic structure STN 412014 (1.1013) (Poldi s.r.o., Kladno, Czech Republic) with low-carbon content (0.045% C) is used after annealing for abrasive wear tests as a standard material. The hardness of annealed carbon and low-alloyed steel is in the range of 100–200 HV. The effect of ferritic-pearlitic microstructure on abrasion resistance was experimentally tested on typical commercial steel STN 411 523 (S355JR) (U. S. Steel Košice, s.r.o., Košice, Slovak Republic).

Of special interest was to investigate the relation between microstructure and wear properties for the micro-alloyed high-strength fine grained steel EN S700MC (U. S. Steel Košice, s.r.o., Košice, Slovak Republic). At high yield strength it has good resistance to fatigue crack growth (Hidvéghy et al. 1996). This material is characterized with very good fatigue properties and increased erosion wear resistance (Šimon et al. 1996; Zdravecká et al. 1996).

Increase of the strength properties of micro-alloyed steels is largely achieved also by precipitation hardening. Grain refinement increases the toughness of steel, which positively affects resistance to abrasion in combination with impacts because soil as a multiform working media offers a wide range of friction properties from tribological point of view.

The fine-grained structure of acicular ferrite and bainite of Steel Hardox 400 (SSAB, Oxelösund, Sweden) represents wear resistant steel from group of low-alloyed toughened machinable and weldable constructional steels. Hardox 400 steels are used in applications where good wear resistance is required. All Hardox steel types are delivered in hardened state (water quenching) and in the case of applicable hardness also can be tempered.

The steel surface microstructure was evaluated by microscope Neophot 21 (Carl Zeiss Jena GmbH, Jena, Germany). Structure of Hardox 400 is martensite-bainitic characterized by regularity of blocks (Fig. 1a). The microstructure of high-strength steel S700MC (U.S. Steel Košice, s.r.o, Košice, Slovak Republic) is characterized with fine

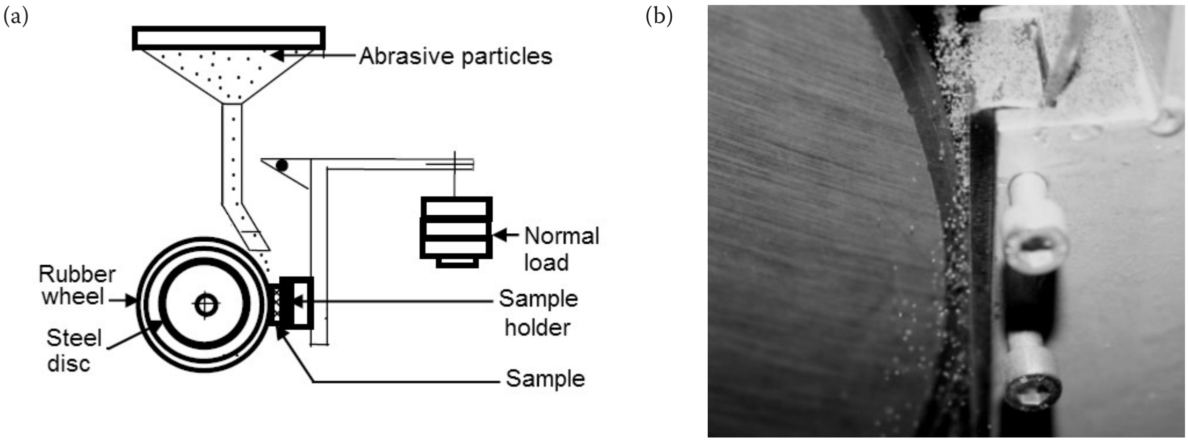

Fig. 2. Abrasion tester principle (a) and detailed view on friction pair (b)

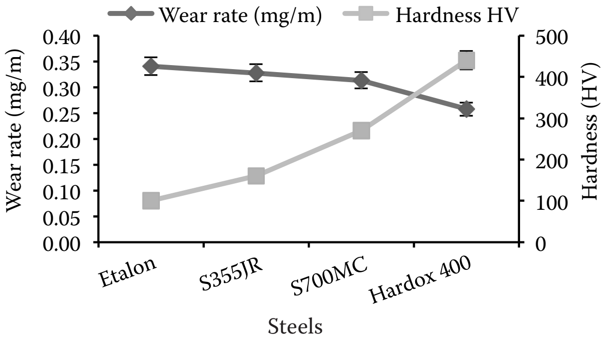

Fig. 3. Relative abrasion wear resistance and hardness of tested steels

grains of acicular ferrite and upper bainite of only several μm (Fig. 1b) (Šmida, Bošanský 2000).

To evaluate the abrasion resistance of tested materials a dry sand rubber wheel abrasion test (Fig. 2) was used. The specimens were ultrasonically cleaned in acetone and weighed before and after each test. Dimensions of the tested specimens were 68 × 22 × 6mm. The weight losses with precision of 1×10^{-4} g were calculated from the measured samples weights before and after tests. Minimum of four tested samples were obtained from each material. Relative abrasion wear resistance Ψ determined by equation was applied as a criterion of assessment:

$$\Psi = \frac{W_{etalon}}{W_{sample}}$$

where:

W_{etalon} – average weight loss of etalon sample body (g)

W_{sample} – average weight loss of samples of tested material (g)

The abrasive effect was induced by particles flowing between sample and the rotating grinding wheel. This way enables the conditions close to performance of machinery working in the soil to be simulated. Parameters of test were as follows:

– sliding distance: 716 m,
– tip speed of disc: 2,3 m/s,
– loading force on sample: 40,52 N,
– used abrasive-foundry sand: 0–36 Provodín KO-III-32-38-C/D-STN 72 015,
– mesh size of 0.8 mm.

In the present work, low alloyed steels containing to 0.20% wt. C were investigated by three-body abrasion test. The relation between material characteristics such as microstructure and mechanical properties and the resulting wear resistance was studied.

RESULTS AND DISCUSSION

Three-body abrasive wear test was taken for experiment with different types of steels. Abrasive wear rate as a function of hardness for the steels investigated is shown in Fig. 3.

As indicated in the Fig. 3, the tendency does not clearly follow hardness as a function abrasive wear rate. Expected higher abrasive wear resistance of martensite structure was reduced compare to acicular ferrite structure and their hardness.

The microstructure shows significant differences for S700MC and Hardox 400 (Fig. 1). For acicular ferrite and upper bainite the fine grains are still visible. Some of studies have shown that by decreasing the grain size, the abrasion resistance increase continuously. Grain refinement of acicular ferrite in micro-alloyed high-strength is an effective way to deflect the propagation of cracks and increases the impact toughness and abrasive wear resistance (Zhou et al. 2008).

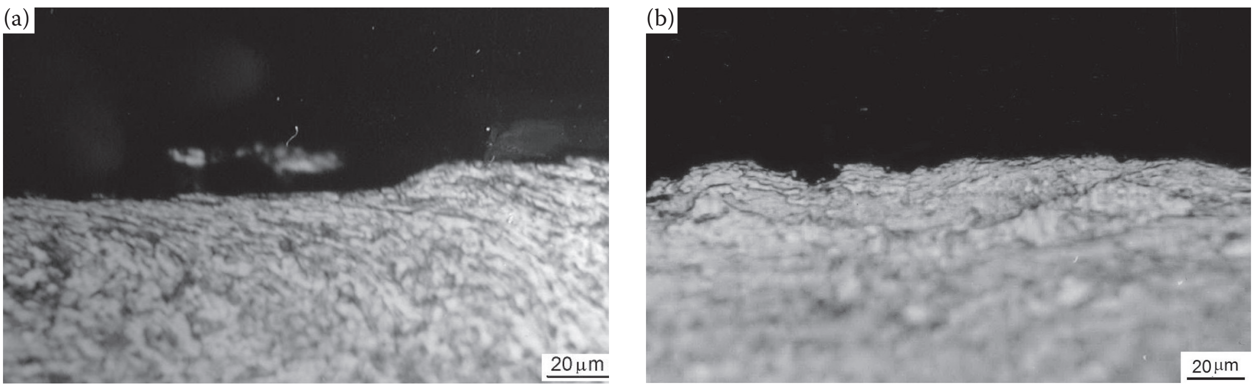

Fig. 4. Polished and etched cross sections of steels investigated (a) tribolayer of martensitic structure and (b) tribolayer of acicular ferrite structure

Polished and etched cross sections as observed in Fig. 4 show deformed microstructure of worn subsurface layers of the steels investigated after the wear test. After abrasion tests the generation of a relatively thick sub-surface layers (tribolayers) of deformed materials was observed. The microstructure of these tribolayers differs.

Three-body abrasion is the combination of the micro-cutting wear mechanism and the plastic wear mechanism. It seems that abrasive particles at repeated passes would create trundle pits at the surface of the specimens and would lead to repeated plastic deformation of the material (Lu et al. 2001).

In the 3-body abrasion particles are free to roll in the interface. The rolling of abrasive particles pressed in the interface leads to localized deformation on the surfaces, similar to a microindentation mark. The wear mechanisms correlated with the grooves are characterized by tips with plastic deformation, typical of microploughing. Ridges were removed after repeated deformation due to successive passage of abrasive particles on wear surface. Thus, it is important to consider the fact that certain phases and microstructures, although showing similar hardness, may be beneficial under some abrasive conditions (Moore 1974). Hardness should be considered the rough criterion for material selection on an element subjected to erosive ± abrasive wear (Hejwowski et al. 2000). Grain refinement can be expected as an effective way to improve the wear resistance. A number of studies showed that by decreasing the grain size the abrasion resistance increase continuously. (Chotěborský et al. 2009; Xu et al. 2013). Brittle properties, yield stress and tensile strength are considered mainly in terms of abrasion with slight impacts. In real operation of agricultural tools also dynamic load due to influence of slight impacts participates on wear (Zdravecká et al. 2012). Based on experimentally obtained results and the high mechanical properties of steel S700MC and also on laboratory tests we can recommend this material as substitution for the original one for star-shaped part of soil crusher.

CONCLUSION

The development of high-strength wear resistant steels is mainly focused on high-hardness martensitic conception based on the hypothesis that the abrasion resistance holds proportional tendency with hardness. However, various experimental observations suggest that high hardness of martensite does not guarantee high abrasion resistance compared to steel with lower relative hardness, but better ductility/toughness, and brittle martensite nature often leads to lower performance.

Therefore, high-strength steel hardened to martensite at low tempering temperatures with max. hardness does not provide max. wear resistance under combined action of abrasion and impact. The hardness is not always the decisive factor that affects the wear resistance at the most. An important factor of the wear resistance is also the microstructure of the concrete material.

High-performance low-cost wear-resistant steels are required for industry applications. Practical tests under real conditions and economic aspects are decisive for application of steel S700MC as a suitable material for abrasive wear conditions with slight impacts.

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