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INVESTIGATION OF THE WEAR RESISTANCE OF HARDOX STEEL PLATES

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Abstract: *The Hardox steels are characterized by high resistance to wear by friction, impact strength, good ductility, weldability and the possibility of the use of machining by specialist tools. These steels are widely used for the production of machine parts resistant to abrasion for mining. Among six available Hardox steel types, the widest application in the structure of tippers have the Hardox 400, 450 and 500 types. The aim of this work was to define and compare abrasion resistance of Hardox steel plates widely used in the industry. Subject of the studies has been the most commonly used the above-mentioned Hardox steel groups, were compared with each other. The abrasive wear resistance of selected steels was obtained using a three-body abrasive wear test, microstructure and wear resistance determination. Hardness measurements and wear tests were determined in order to describe the mechanical properties. An operating experiment has been performed. It has been shown that despite almost identical of chemical composition and production processes, the investigated steels differ somewhat in structure, which influences their strength and usability.*

Keywords:*Hardox steel, wear resistant, microstructure, hardness.*

1. Introduction

Wear caused by the impact and abrasion action of hard particles is a major problem in many industrial applications and particularly in the areas of agriculture, mining, mineral processing, earth moving, etc. [1]. The present scientific, engineering and economic problem is the wear of mechanical parts equipment caused by decrease of working surfaces properties. The mechanism of wear is very complex and the theoretical treatment without the use of rather sweeping simplifications is not possible. It should be understood that the real area of contact between two solid surfaces compared with the apparent area of contact is invariably very small, being limited to points of contact between surface asperities. The load applied to the surfaces will be transferred through these points of contact and the localized forces can be very large. The material intrinsic surface properties such as hardness, strength, ductility, work hardening etc. are very important factors for wear resistance, but other factors like surface finish, lubrication, load, speed, corrosion, temperature and properties of the opposing surface etc. are equally important. 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 [2]. The wear resistance of the working tools in agriculture affects many factors e.g. the material of tool, its hardness, and 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. Based on the analysis of parameters responsible for the wear of mechanical parts, about 50% works in abrasive wear, 15% adhesive wear, 8% erosion, 8% fretting, 5% wear is due to corrosion and about 14% is just a combination of abrasive, erosive and corrosive wear [3]. The abrasive wear mechanism is basically the same as machining, grinding, polishing or lapping that we use for shaping materials. Two body abrasive wear occurs when one surface cuts material away from the second, although this mechanism very often changes to three body abrasion as the wear debris then acts as an abrasive between the two surfaces. Abrasives can act as in grinding where the abrasive is fixed relative to one surface or as in lapping where the abrasive tumbles producing a series of indentations as opposed to a scratch. The variety of the types of wear leads towards the use of specialized welding materials in order to ensure the highest possible wear resistance of the surface layers, in working conditions. One of those typical material used in industries are wear resistant plates. The equipment used in heavy industries like mining or the construction of roads must meet special requirements such as a strong wear resistance and a high tenacity, leading to a good strength-to-weight ratio. Hardox steel alloys are some of the recent used in the field [4].

Hardox steels are used in applications where a good wear resistance is needed with wide loads parameters, for example in fedding devices, crushing mills, sieves, shaft pins, skip hoist elements, conveyors, blades, gear and sprocket wheels, self-dumping cars elements, loading machines, trucks, front casting bulldozers, buckets and worm transporters [2]. Hardox low-alloy steel achieves high strength properties due to appropriate composition of the alloying additives at a relatively lower price in comparison with other structural steel [5]. Hardox steel differ depending on the species and plate thickness, carbon content and alloying elements. Nickel with a content from 0.25 to approximately 2.50% does not form a carbide in these steels but causes lowering of the austenitizing temperature and lowers the transition temperature of the material in the brittle fracture. Manganese is added at a level of 1.0 to 1.6%, improving the durability of this steel and increasing its hardenability by solution hardening. Manganese as an austenite stabilizer reduces the carbon content in pearlite and reduces the ferrite grains during the hot rolling process. Carbide forming elements, such as Cr, Mo, Ti, V, W, increase the time which is taken to start transformation diffusion, thereby the hardenability of the steel is increasing. Furthermore, the content of molybdenum in an amount from 0.25 to 0.60% influences the positive effect of secondary hard-ness and reduces the occurrence of the temper brittleness for temperature in the range be-tween 250–400ºC. The presence of molybdenum in steel is even more important because of chromium which causes an increased brittleness of the steel after tempering. This effect is also observed for phosphorus and other elements in trace amount [6]. The producer was a Swedish group SSAB-Oxelösund. Currently ironwork in SSAB produces seven types of such steels. The basis for the classification is hardness in Brinell scale, exception Hardox Extreme and Hardox HiTuf [7]. The Hardox steels are characterized mainly by high resistance to wear friction, weldability, good ductility and machinability [8]. The disadvantage of Hardox is low corrosion resistance what can limit their application in aggressive environments. Subject of this studies has been the most commonly used group of Hardox steels (Hardox 400, Hardox 450 and Hardox 500). The type. Hardox 400 is the steel with the widest application on the Polish market. These sheets are used for applications related to the extension of working hour and increasing capacity, in such elements as loaders, bulldozers, buckets or trays. The required range of hardness in a combination with high ductility is achieved by quenching and tempering. Hardox 450 steel is used widely in many industries as a material for components in excavators, containers, dump trucks, sieves hoppers or crushers. Increasing the hardness to 425-475 HBW may increase the durability of components relating to Hardox 400 up to 50%. It has been observed that durability of element from Hardox 450 which work in contact with abrasive materials such as basalt and granite has increased. Steel can provide a tempered martensite structure with mixed bainitic areas, which may result from the separation of chemical composition. After normalizing the microstructure consists of ferrite and pearlite unlike in the steel in delivery state. The next steel is Hardox 500 which hardness depends on plate thickness. High mechanical properties allow to use Hardox 500 steel for such elements as crushers, flooring and plow mixers [5-8].

Due to too low amount of publications about them, it was necessary to use material information published by manufacturer. An attempt to clarify the effect of wear resistance on investigated steel groups has been made in the study. The main argument to write this study was the lack of work on this subject. The aim of the study is to evaluate in the laboratory conditions the wear resistance of three types of Hardox steels (Hardox 400, 450 and 500 types) 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.

2. Material and methods

Hardox steels (400, 450 and 500) specimens used for wear tests with 60x20x6 mm dimensions were cut from plates. These steels is produced by a Swedish metallurgic company SSAB. Hardox steels are categorized according to their alloy components and the hardness. The basic range of the steel has the five-number code for determination of the Brinell hardness; 400, 450, 500, 550, 600. The increasing code number means higher hardness, abrasion resistance, tensile strength and on the other hand it means also decreasing ductility, toughness and weldability [5]. The initial hardnesses of the investigated steel were measured as 410, 460, 510 HB, respectively. The specimens were grinded up to 1200 mesh emery papers, and then polished with alumina powder of 1 μm grain size. The chemical composition and mechanical properties of tested Hardox steels are listed in Table 1 and Table 2; respectively [9].

Table 1 Chemical composition of the steels type Hardox (SSAB)

Material	**Chemical elements content, [max %]**								
	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Mo**	**B**
Hardox 400	0.15	0.7	1.6	0.025	0.01	0.5	0.25	0.25	0.004
Hardox 450	0.19	0.7	1.6	0.025	0.01	0.5	0.25	0.60	0.004
Hardox 500	0.30	0.7	1.6	0.025	0.01	1.0	0.50	0.60	0.004

Table 2 Mechanical properties of the steels type Hardox (SSAB)

Material	**Hardness [HBW]**	**Yield Strength [N/mm^2]**	**Tensile Strength [N/mm^2]**	**Elongation [%]**
Hardox 400	370-430	1000	1250	10
Hardox 450	425-475	1200	1400	10
Hardox 500	470-530	1300	1550	10

The nitrided specimens were etched with 3% Nital solutions for cross-section analyses and metallurgical examinations. Hardness tests were applied to each specimen. Three hardness values were taken from the specimens. To evaluate the abrasion resistance of tested materials a dry sand rubber wheel abrasion test was used. The specimens were ultrasonically cleaned in acetone and weighed before and after each test. The force applied pressing the test coupon against the wheel was 120 N loading force on the specimens and 6000 revolutions of the rubber wheel at 220 rpm. Test samples of the specified dimensions were cut from wear of the deposit were surface ground was smooth. Then the tested specimens were weighed with accuracy 0.0001 g as required in ASTM G65 between and after the test. Wear resistance compared to steel Hardox 500. After the wear tests, the wear tracks developed on the surface of the samples were analyzed by a Scanning Electron Microscopes (SEM). In the present work, different type Hardox steel plates widely used in the industry 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.

Volume loss, [mm^3] = mass loss [g]: density [g/cm^3] x 1000 (1)

3. Results and discussions

Microscopic examinations allows to define structure of tested materials. Metallographic examinations do not indicate any of internal or external defects as shown in Figure 1. The microstructure of all investigated steels is martensite-bainitic characterized by regularity of blocks, which may result from the separation of chemical composition. Steels that have been tested are characterized by coarsely acicular martensitic structure. The microstructure of Hardox 500 has tempered martensite orientation with small carbide precipitates coherently distributed within the grains of martensite what is associated with increasing carbon content. The microstructure composition Hardox steels determine in addition to the carbon content also addition of alloying elements: nickel, manganese, chromium, molybdenum and also boron. Their impact on the microstructure composition and mechanical properties of Hardox steels is different, and their quantities are carefully chosen to strict regulation of mechanical and technological properties of these steel [10].

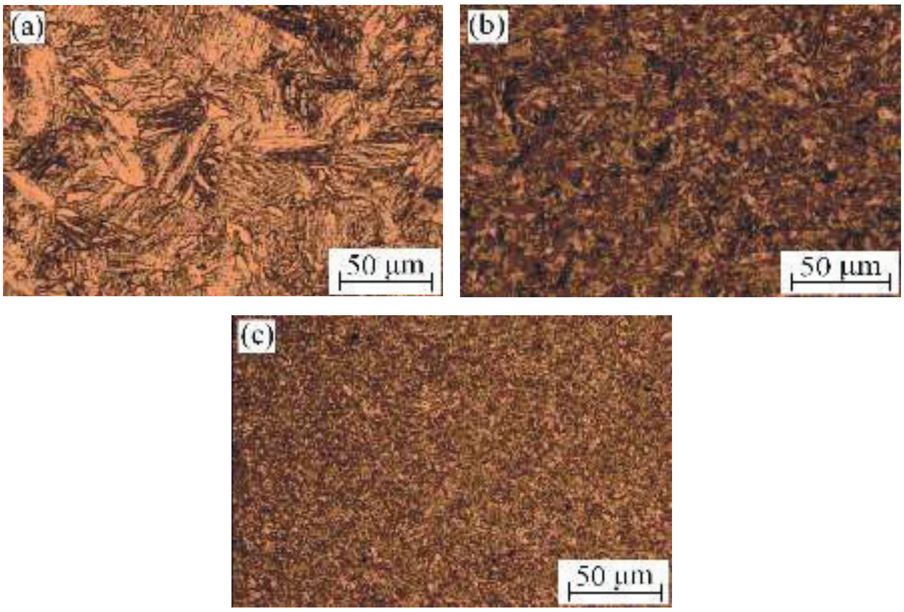

Figure 1 Microstructures of Hardox 400 (a), Hardox 450 (b) and Hardox 500 (c) steel plates

Three-body abrasive wear test was taken for experiment with different types of Hardox steels. Three-body abrasion is the combination of the micro-cutting wear mechanism and the plastic wear mechanism. REF: Effect of microstructure factors. Mass loss was reported directly and relatively in comparison to the mass loss with the reference to Hardox 500 steel plate and given in Table 3. In all samples, the density value was taken as 7.72 g/cm3. In all samples, the density value was taken as 7.72 g/cm^3 according to SSAB. Wear resistance tests shows, that the best properties has Hardox 500 wear plate. Wear resistance of Hardox 500 is higher than other tested steels. Heat treatment in Hardox steel manufacturing process is a process used to increase strength by producing precipitates of the alloying material within the metal structure. Heat treatments strengthen materials by allowing the controlled release of constituents to form precipitate clusters which significantly enhance the strength of the component.

Table 3 Results of abrasive wear resistance tests

Material	Mass before test [g]	Mass after test [g]	Mass loss [g]	Volume loss [mm^3]	*Relative abrasive resistance
Hardox 400	72.54	71.29	1.25	161.91	1.40
Hardox 450	73.58	72.49	1.09	141.19	1.22
Hardox 500	71.86	70.97	0.89	115.28	1.00
*Relative abrasive wear resistance to Hardox 500					

Hardness test results of the investigated Hardox steels were tabulated in Table X. It was determined close to producer datasheet value, guaranteed by manufacturers that hardness test results of Hardox steels. The initial hardness of the Hardox 400, 450 and 500 steels were measured as 410, 460 and 510 HB, respectively, the martensitic steel showing the highest hardness. After abrasion; hardness values of the Hardox 400, 450 and 500 steels increased by 2.7%, 5.6% and 6.2% respectively. Highest surface hardness and the increase in hardness have Hardox 500 wear plate. It also explains the places of use of these steels, the increase in hardness values of the steel causes the carbide forming elements (Cr, Mo) with the effect of abrasion. This situation can be explained by the microstructure of steels. The presence of molybdenum in the range of 0.25-0.60% has a positive effect of hardness. Furthermore, nickel and manganese in the presence of chromium contribute to this process [1].

Table 4 Hardness test results of Hardox steels before and after abrasion

Material	Average hardness test results [HB]	
	Before abrasion	After abrasion
Hardox 400	410	421
Hardox 450	460	486
Hardox 500	510	542

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 [11]. Images of all the investigated Hardox steels after wear resistance tests as observed in Figure 2 show deformed microstructure of worn subsurface layers of the steels investigated after the wear test. After the wear tests, the formation of relatively thick subsurface layers of deformed materials was observed. The microstructure of these triplets is different. The investigated steels can be used as an alternative to each other when the wear surfaces are examined; in light of the results of abrasion testing.

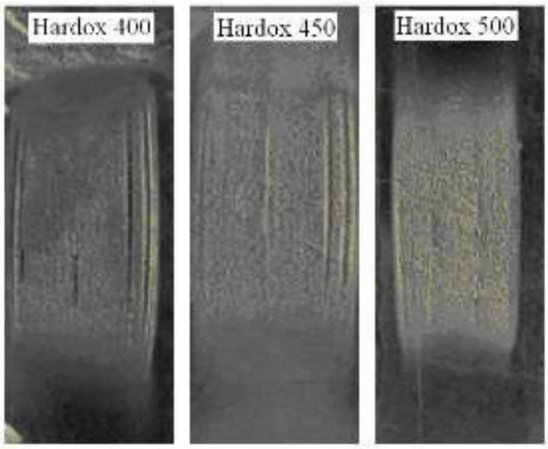

Figure 2 Images of the Hardox specimens after wear resistance tests

4. Conclusions

In the submitted study, the test results for all the investigated Hardox steels have been presented. Based at the work results, the following conclusions could be formulated:

- The properties of wear resistance are highly sensitive to structural changes. Wear resistance of material depends on the state of the microstructure, the chemical composition and the presence of factors that affect continuity of the materials.
- Hardness is not always the determining factor that most affect. An important factor of the wear resistance is also the material microstructure.
- All tested steels are characterized with complex structures of post-martensitic orientation. The phase structure, the closest to each other are: Hardox 400, 450 and 500.
- It is important in terms of research to facilitate responses to constructors using Hardox steels, which is a safe operation life of structural elements made of Hardox steels for wear.
- The development of high wear resistant steels is mainly focused on high-hardness martensitic that the abrasion resistance maintains a tendency proportional to hardness.
- High-performance low-cost wear-resistant steels are required for industry applications. Use in the appropriate fields considering its characteristics of the most commonly used Hardox steel plates, results in significant material and economy savings, due to wear and costs.

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