HIGH PERFORMANCE STEELS FOR WEAR APPLICATIONS

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Abstract

One of the main problems across many industries is damage to, and possible failure of, components and products due to wear. The resulting financial losses even have a measurable impact on a country's economy. Looking at the mining and related industries, wear causes expensive downtimes and production losses. To minimize the effect of wear it is vitally important to choose the correct material for component manufacture and steel, as a very versatile material, plays the most significant role. New high performance steels for wear applications have been developed and improved over the years and are available with different hardness levels. The steels generally feature high hardness combined with satisfactory toughness and show good surface quality and homogeneity.

This paper presents an overview of the metallurgy behind the application of microalloying elements, especially Nb and Mo, in quenched or quenched and tempered wear resistant steels. The important role of Nb in controlling the austenite microstructure during rolling and heat treatment is discussed. Additionally, the remarkable improvements in toughness and brittle fracture resistance, due to a very fine microstructure and finely dispersed Nb-carbonitrides in a martensitic microstructure, are highlighted. The improvement in strength and toughness properties is demonstrated by comparison of Nb microalloyed steels with Nb-free steels.

The influence of Mo on the martensite start temperature and the start of transformation times, as well as the effect of forming high hardness, $(Fe,Mo)_3C$ is also discussed, in terms of both the hardness and through-hardening behaviour of the steel, as well as the wear behaviour. Results of mechanical testing and the newest developments are presented.

Modelling is often used to predict all the microstructural effects of microalloying elements, but modern steel development also uses modelling tools to predict the final steel properties. Other modelling tools are also available to support steel selection and to determine a suitable steel grade as a function of the wear stress. One of these tools is presented in this paper.

Introduction

One of the main problems in engineering is damage to, and possible failure of, components and products due to wear. The resulting financial losses even have a measurable impact on a country's economy. Notably in the mining and raw material handling industries, excessive wear causes high downtimes due to short maintenance cycles which hinder operation in an economically viable and sustainable manner.

Large-scale wear problems, for example, in dump truck bodies, shovels, buckets and crusher units, are caused by abrasive particles, gravel or even rocks which interact with the steel through different types of motion such as sliding, rolling and impact. As a result, the failure of the components can be mainly attributed to a combination of abrasive wear and surface fatigue. Due to this fact, one of the primary requirements of these industries is to improve abrasion resistance and thus enhance the durability of the components.

The right choice of material has a large impact in defining the best solution for increasing wear resistance. Steel is the most significant material in the field of wear resistance, however, cost effectiveness, processing properties, as well as wear characteristics, have to be taken into account when defining best solutions. Driven by the need for better products with enhanced durability, new high performance steels for wear applications have been developed and improved over the last few decades and are available over a large hardness range. These steel grades feature high hardness combined with good toughness and show a good surface quality, as well as a high level of homogeneity through the thickness of the product.

This paper presents an overview of the various ways in which microalloying additions, especially Nb and Mo, can be utilised in wear resistant steels.

Real experiments are still an essential element when it comes to predicting the effects of microalloying elements. However, modern steel development is increasingly supported by modelling tools to predict the steel properties. Further modelling tools are applied to determine a suitable steel grade as a function of the wear stress and assist in choosing the appropriate steel grade. One of these tools will be presented in this paper.

Production of Wear Resistant Steels

In order to fully satisfy the increasingly stringent demands of the market for wear resistant steels, it was essential that progress was made, not only in metallurgy, but also in rolling and heat treatment techniques. In the steel works of ThyssenKrupp Steel Europe (TKSE), steel is produced according to the Thyssen blowing-metallurgy (TBM) process. The liquid steel is stirred in this procedure by blowing gas through the converter bottom; thereby a better mixing of metal and slag is achieved. The TBM process produces lower contents of phosphorus and sulphur as well as a higher degree of purity, Figure 1(a). The ladle metallurgy, Figure 1(b), is similarly important as it reduces the demands on the converter process and allows very precise control of the targeted chemical composition, specifically in controlling the sulphur content to extremely low values. This low sulphur level produces a steel with a high level of purity; which is beneficial to toughness and reduces the risk of brittle fractures, and also produces a steel with a very low level of anisotropy in terms of toughness and deformation properties.

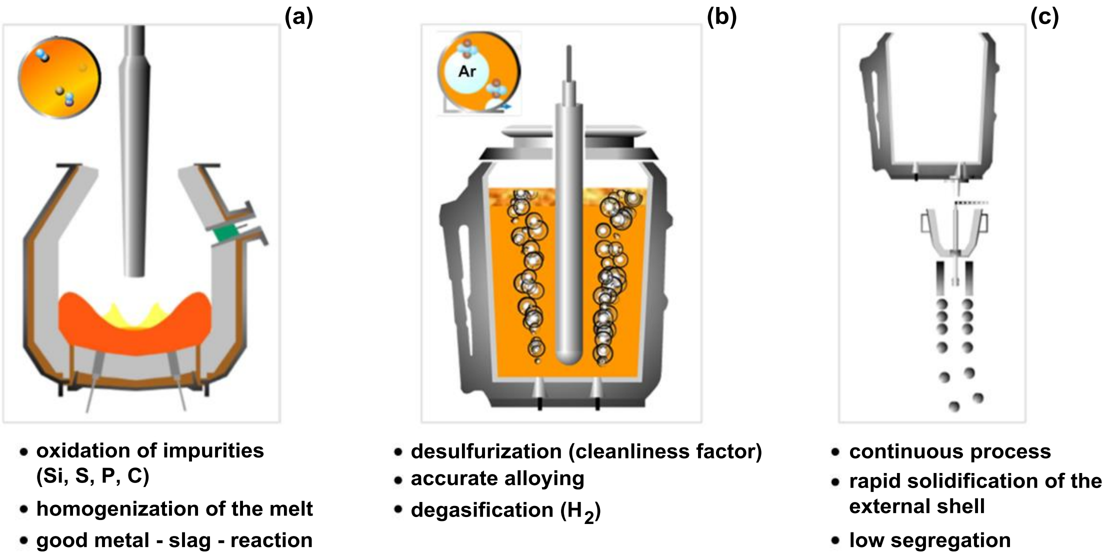


Figure 1. Steelmaking process; (a) steelmaking, (b) secondary metallurgy, (c) continuous casting.

The steels exhibit hardness values in the range 300 to 600 HB with adequate toughness properties. The steels are produced mainly by water-quenching and tempering. The steel plate is usually rolled and then re-austenitized and rapidly quenched in water in order to ensure transformation to a martensitic or bainitic microstructure. The plate can also be directly quenched after rolling (direct quenching).

The carbon content of the steel is important during rolling as this has a crucial influence on the hardness after quenching. In further studies, it was evident that the advantages of microalloying with Nb and B could be used for this group of steels. Nb has several positive effects on metallurgical mechanisms, which determine the properties of quenched and tempered steels, such as grain refinement, the retardation of transformation and precipitation hardening. A schematic assessment of the effects of Nb in comparison to other commonly used microalloying elements is given in Table I.

Table I. Schematic Assessment of the Positive and Negative Effects of Microalloying Elements

Microalloy	**Affinity to C, N**	**Fine precipitates**	**Retardation of transformation**	**Grain refinement**
Nb	++	+	+++	+++
V	+	++	o	o
Ti	+++	+/- [1]	+	+

+ positive effect
- negative effect
o no significant effect

[1] depending on Ti-content

The addition of B, together with an adequate fixing of N, shifts the transformation of ferrite to longer times and thus increases the hardenability. The combined addition of Nb and Ti leads to an effective fixing of N which leaves the B free to have a maximum effect on hardenability.

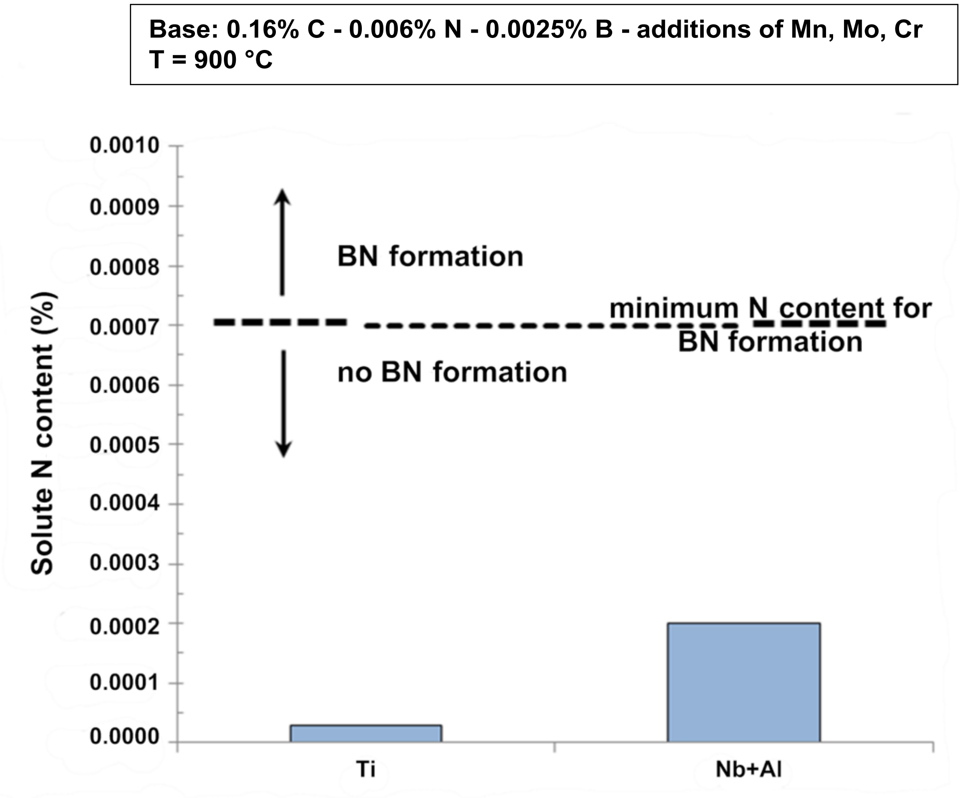


Figure 2. Solute N content depending on the used microalloying concept.

Figure 2 demonstrates that microalloying with Nb (≤0.03%) in combination with increased Al levels up to 0.10% promotes both AlN and Nb(C,N) precipitation, but also results in a significantly higher content of free N at 900 °C than by Ti microalloying. However, it is significant that in the Nb plus Al steel the content of dissolved N is below the solubility limit for the undesired development of B nitrides. Therefore, like Ti, this microalloy combination can be used to protect B, but it also has the positive effect of avoiding the formation of coarse TiN precipitates which can be detrimental to toughness. In steelmaking a well controlled sequence of adding the microalloying elements into the liquid steel is necessary during the secondary metallurgy operation.

It is important to note that microalloying with Nb has practically the same effect as the addition of Ti. Additional analytical investigations of the extracted phases showed that about 90% of the entire B content exists in solid solution in the steel, and this is true when either Ti or Nb is used as the microalloy addition. However, due to the lower formation temperatures of the AlN and Nb(C,N) particles in the Nb microalloyed steel, a substantially finer particle dispersion exists compared to the TiN precipitates in the Ti microalloyed steels, with a correspondingly more favourable effect on the material properties, as shown in Figure 3.

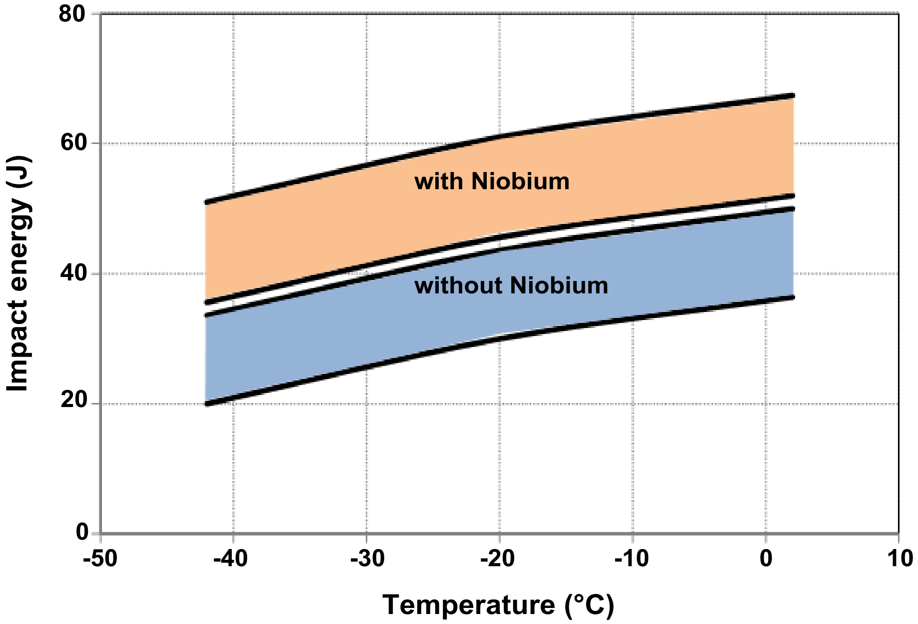


Figure 3. Effect of niobium on the Charpy impact toughness.

Microstructure

Hardness is a vitally important property for controlling the wear behaviour of the special structural steels and this is adjusted by control of the production process and selection of the appropriate chemical composition to produce the desired microstructure. The hardness is determined by the carbon content which remains dissolved in the martensitic matrix after the quench, however, the formation of a very small packet size of lath-like martensite of <10 μm is the basic precondition for optimum wear resistance. An important characteristic of lath martensite is the arrangement of the individual laths at various angles to each other, as shown in Figure 4(a) in a scanning electron microscope (SEM) image. Precipitated within this lath structure are fine carbides, which are found by analysis to be cementite $(Fe,Mn,Cr,Mo)_3C$ or ultra-fine NbC particles, as shown in Figure 4(b). These carbides can contain up to 5% Mn, Cr and especially Mo. The addition of Mo in wear resistant steels is of great importance for attaining the required hardness and for the stability of the carbides. The carbides have a high hardness of >1000 HV and, owing to their volume fraction and extremely fine distribution, they not only contribute to the high hardness of the martensitic matrix, but are also a significant factor in ensuring high wear resistance, as they are responsible for additional strengthening of the microstructure which helps to prevent crack formation. The volume percentage of hard carbides and the martensite packet size can be controlled based on the steel composition, the rolling process and the heat treatment. Detailed microstructural investigations during the wear process for these steels are in progress.

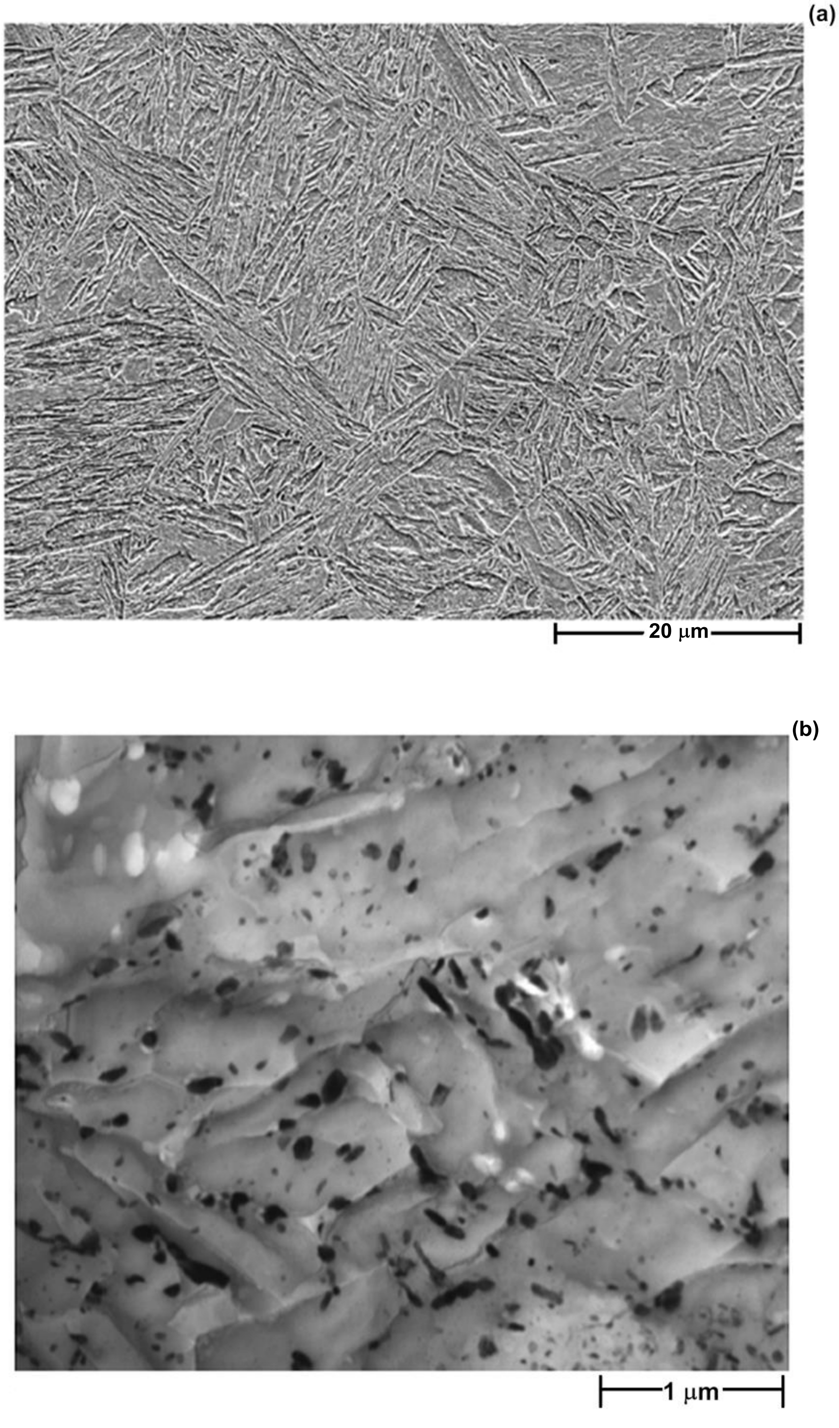


Figure 4. SEM images of the microstructure; (a) martensitic lath structure, (b) precipitated carbides.

Properties of Wear Resistant Steels

Wear resistant steels are well defined regarding their hardness. Table II provides an overview of wear resistant special structural steel plates, including delivery condition, hardness and typical CET range. In plate thicknesses up to 100 mm, the characteristic alloying elements of the steels are Mn, Cr, Mo and Ni at a C content up to 0.38% combined with microalloying elements like Nb.

Table II. Wear Resistant Steels and Properties

Steel grade	**Delivery condition**	**Hardness [HBW]**	**Thickness [mm]**	**Typical CET range**	**Special features**		
					Guaranteed core hardness	**Min. CVN properties**	**Others**
XAR® 300	N	270 - 340	4 - 50	0.38 – 0.43			
XAR® 400	Q(+T)	370 - 430	4 - 100	0.26 – 0.38	✓	✓	
XAR® 450	Q(+T)	420 - 480	4 - 100	0.30 – 0.43	✓	✓	
XAR® 500	Q(+T)	470 - 530	4 - 100	0.39 – 0.46	✓		
XAR® 600	Q(+T)	550 - 630	5 - 50	0.52 – 0.56			
XAR® HT	Q+T	310 - 370	40 - 100	0.37 – 0.39		✓	
XAR® 400W	Q+T	360 - 430	4 - 40	0.39 – 0.42			Heat resistant up to 400 °C

N - Normalised
Q(+T) – Quenched or Quenched and tempered depending on thickness and required properties
Q+T – Quenched and Tempered
CET – Carbon Equivalent
CVN – Charpy V notch toughness
HBW – Brinell Hardness

Influence of Alloying Elements on Through-thickness Hardness of the Plate

The hardness of the plate in the near-surface area is important, but the through-hardening properties of the steel also need to be considered. The through-hardening behaviour of the steel depends mainly on the alloy content and on the retardation of the diffusion-controlled transformations. Through-thickness hardenability depends to a lesser extent on the quenching intensity, especially in the case of very thick plates where the heat dissipation from the plate core is controlled exclusively by thermal conduction. Therefore, the more transformation-resistant the steel is owing to its chemical composition, the more likely is complete through-thickness hardening of the steel.

Mo, together with other elements such as Ni, plays an important role in allowing longer cooling times, whilst still achieving the desired core microstructure and thus boosting the achievable hardness in the core of the plate. Additionally, Mo promotes the fine grained structure of the steels and increases the yield strength.

Increased through-thickness hardenability improves the wear resistance significantly, especially in the case of abrasive wear and in applications leading to wearing out of the plate over the thickness of the cross-section. Investigations have shown that comparisons of two plates with nominally the same surface hardness, but with different core hardness profiles, show lifetime differences equal to or greater than 10%.

Mo, as with other elements such as Ni, is expensive and therefore, it is a basic necessity to be aware of the advantages of Mo alloyed steels with regard to the intended application. Through-hardened steels alloyed with Mo not only offer longer component lifetimes due to higher wear resistance as the plate becomes thinner due to wear but also reduce very expensive downtimes. Bearing in mind these important positive aspects, the higher costs of the material are quickly offset.

Wear Behaviour of Wear Resistant Steel Grades

In the most important applications for wear resistant steels, the characteristic wear type is ploughing leading to abrasive wear. Thereby, usually the plate surface gets scratched when exposed to an abrasive material, such as sand or other minerals and is finally removed - this wear mechanism is called abrasion.

A high material hardness is one important factor for promoting good wear resistance. Furthermore, a high material toughness improves the wear resistance and thus reduces the material loss by changing the wear mechanism from micro-ploughing to micro-machining.

Prior to looking at wear applications using wear resistant plates, it is advantageous to first have a look at the wear mechanism. In describing the mechanism, the tribological system is important. It is made up of different components - the base body, the counter body, ambient media, as well as structural conditions. To understand the wear process, not only one or two components are important: the whole system is relevant for each individual application.

The wear mechanism itself can be characterized by three zones: a lower shelf with low wear rates, an upper shelf with high wear rates and the associated transitional range, Figure 5. The key factor to describe abrasive wear is the hardness relationship, Hp, between the interacting wear components. If the hardness of the counter material is low in relation to the hardness of the plate, comparatively low wear occurs and the actual hardness of the plate does not make much difference and only becomes significant in the long term. With a similar or even higher hardness of the counter material compared to the plate, wear rates increase dramatically and even small differences in the hardness relationship may play an important role for controlling the lifetime of the plate. In the mining industry, for example, almost all wear applications will be found in the transitional or upper shelf zone because the abrasive’s hardness is usually close to or higher than the hardness of the plate.

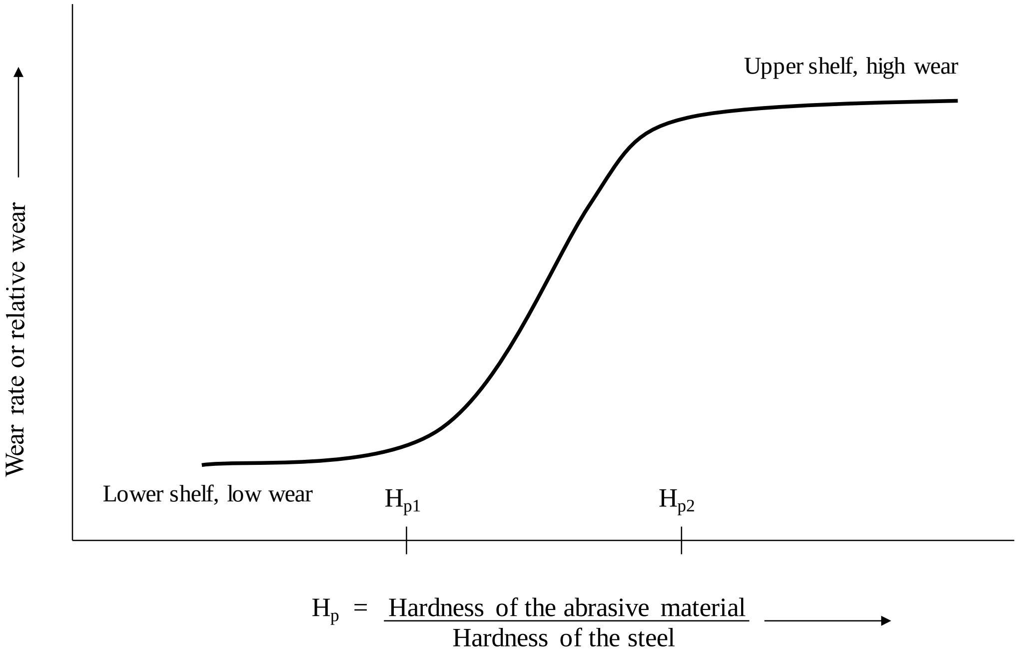


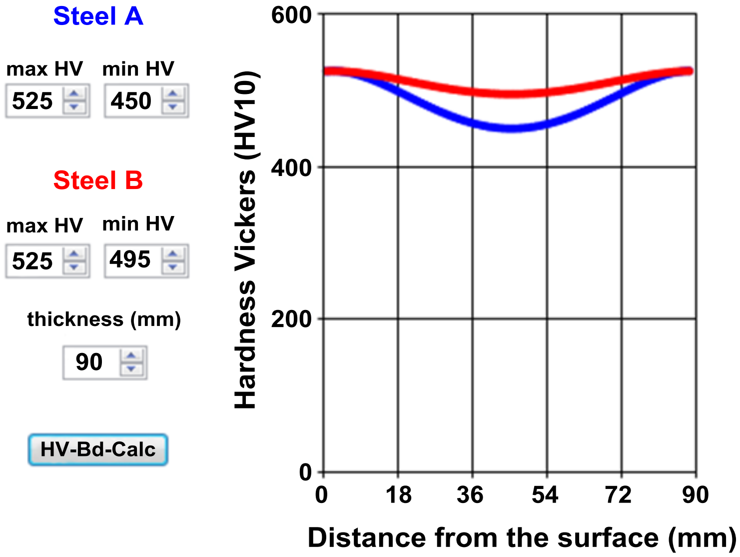
Figure 5. Schematic characterization of the wear mechanism.

From this point of view it becomes clear that hardness variations within the plate, especially from surface to core, can influence the wear resistance and thus the lifetime of the component. Different core hardness values will influence the lifetime of the component, such that as wear takes place and exposes new material, if the core hardness is higher then the increase in wear rate will be minimized and the lifetime of the component prolonged compared to a plate with a low core hardness.

Lifetime Estimation

To take the aspects described above into account, TKSE has developed a new calculation model, based on field and laboratory test results, for estimating wear behaviour and calculating the benefits to lifetime of a through-hardened plate manufactured at slightly higher costs compared to a non-through-hardened plate. A calculated example is given in the following section for plates with equal surface hardness but different core hardness profiles.

The surface hardness of both plates was 525 HV (~ 500 HB), while steel A has a core hardness of 450 HV and steel B has a core hardness of 495 HV, as shown in Figure 6. The starting thickness of the plates is taken as 90 mm and the replacement thickness of the plate shall be 15 mm. Sand with a hardness of around 750 HV has been selected as the abrasive material. By using the plate until a 15 mm residual thickness, the lifetime of the more through-thickness hardened plate B exceeds the less through-thickness hardened plate A by ~ 13%, Figure 7 - a remarkable lifetime difference and an important factor when looking at maintenance, downtimes and production loss.



Steel A

max HV 525

min HV 450

Steel B

max HV 525

min HV 495

thickness (mm) 90

Figure 6. Specified plate hardness.

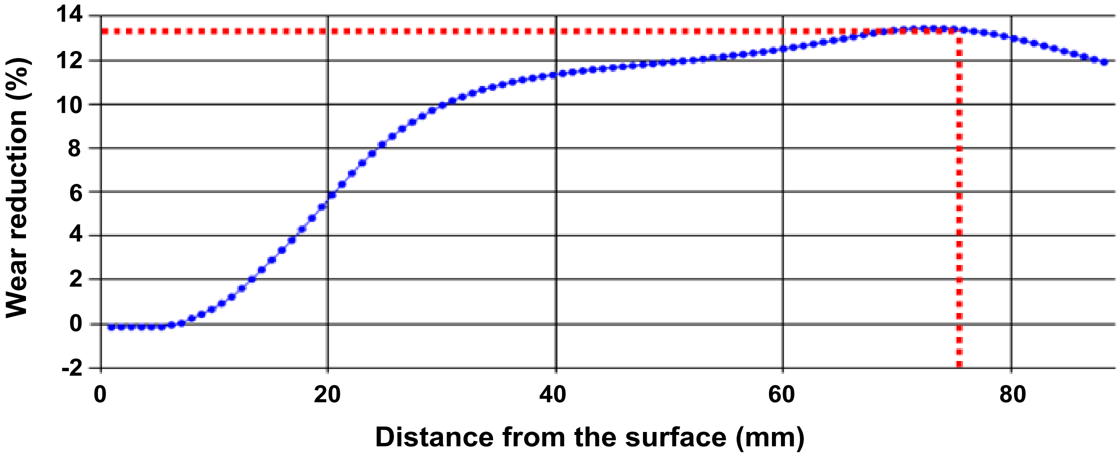


Figure 7. Resulting wear increase/decrease.

Field Test in a Semi-autogenous Grinding Mill (SAG Mill)

In order to verify the positive effects of the Nb-microalloying concept on the wear behaviour as compared to Nb-free steel grades, comparative field tests in a SAG-Mill have been carried out.

SAG-mills are used in raw materials processing to reduce the size of ore by impact and abrasion. Lifting bars carry larger rocks and grinding balls to the side of the mill whereupon they drop down on to the feed. As a consequence, the ore is reduced in size. However, depending on the mills' operating parameters (ball charge, ore charge, temperature, etc.) lifting bars are heavily exposed to abrasion and impact wear. The lifetime of lifting bars greatly affects the overall mill performance; thus manufacturers, as well as operators, aim to maximize the durability of the former by choosing material with high impact and abrasive wear resistance.

In this field test, four test bars, two of them XAR® 500, the others a competitor's material (Nb-free), offering the same hardness level of 500 HB, were installed in the middle ring of the shell of a SAG-mill which was operating in Canada. After 3,306 hours of operation and a material throughput of more than 935,000 tons, the bars were removed and the worn-off areas on the cross sections were measured. Figure 8 presents the results of the contour measurements. The XAR® 500 plate had lost 151.00 cm² on the cross section versus 153.86 cm² from the competing material, accounting for a difference of 1.9% on total wear. Even though the difference in wear appears to be very low, it should be noted that the hardness values of both tested materials are at the same level of 500 HB. The only difference was the different microalloying concept.

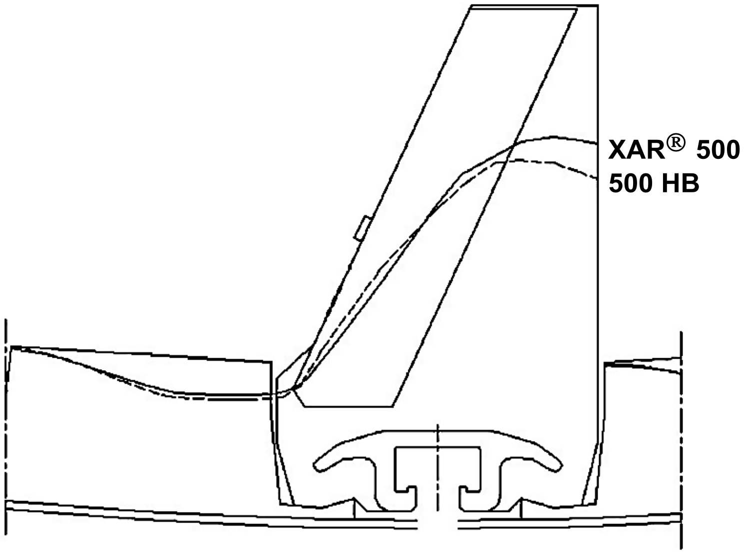


Figure 8. Cross section of lifting bars (initial and after operation).

As a result, the field test in the SAG-Mill verified the positive effect of a Nb-microalloyed concept on the wear behaviour. In this context, considering the lifetime of a lifting bar and the downtimes caused by the exchange of these components, any service time extension leads to an economic benefit.

Processing Properties of Wear Resistant Steel Grades

While mechanical properties such as high hardness and toughness levels are essential to improve the wear characteristics of wear resistant steel grades, providing suitable processing properties (weldability, cutting, formability, etc.) are often equally important for the manufacturer of wear resistant components or products. A certain minimum carbon content is vital to achieve the desired hardness levels in wear resistant grades. However, an increasing carbon content also leads to the necessity for preheating prior to welding or cutting, which has to be carried out to reduce the risk of cold cracking and excessive hardening of the cut edge or weld seam.

Thermal cutting and welding operations are sometimes conducted on-site, for example, in surface mining, limiting the availability of the appropriate processing conditions. One of the main objectives in the development of wear resistant steel grades was to optimize the chemical compositions of these grades by reducing the alloying content and consequently the carbon equivalent. Table II provides an overview of the typical carbon equivalent ranges of wear resistant steel grades produced by the Heavy Plate Unit of ThyssenKrupp Steel Europe. Table III shows the recommended preheating temperatures to minimize the risk of cold cracks during thermal cutting, as an example. Preheating is generally necessary for CET values over 0.32% or for increasing plate thicknesses. Recent developments in the production of wear resistant steel grades have enabled the use of lower CET values; thus facilitating welding/cutting with reduced or even without preheating for higher plate thicknesses. As a result, manufacturers are able to make significant savings in terms of costs and processing times.

Table III. Preheat Temperatures for Flame Cutting of Wear Resistant Steel Grades

<table>
<tr><th rowspan="2">Steel grade</th><th colspan="15">Plate thickness (mm)</th></tr>
<tr><th>≤5</th><th>≤10</th><th>≤15</th><th>≤20</th><th>≤25</th><th>≤30</th><th>≤35</th><th>≤40</th><th>≤45</th><th>≤50</th><th>≤55</th><th>≤60</th><th>≤65</th><th>≤70</th><th>>70</th></tr>
<tr><td>XAR® 300</td><td colspan="6">-</td><td colspan="2">75 °C</td><td colspan="2">100 °C</td><td colspan="5">Not available</td></tr>
<tr><td>XAR® 400</td><td colspan="10">-</td><td colspan="5">75 °C</td></tr>
<tr><td>XAR® 450</td><td colspan="7">-</td><td>75 °C</td><td colspan="4">100 °C</td><td colspan="3">125 °C</td></tr>
<tr><td>XAR® 500</td><td colspan="3">-</td><td colspan="5">100 °C</td><td colspan="4">125 °C</td><td colspan="3">150 °C</td></tr>
<tr><td>XAR® 600</td><td>-</td><td colspan="2">100 °C</td><td colspan="2">150 °C</td><td colspan="2">175 °C</td><td colspan="3">200 °C</td><td colspan="5"></td></tr>
</table>

Outlook and Further Developments

For further developments, a more detailed knowledge regarding dependencies between steel properties and wear behaviour is increasingly important. Methods for mathematical modelling of the wear behaviour of wear resistant structural steels as a function of the material properties and the environment are advantageous in supporting the selection of materials for wear applications. The development of mathematical models for computational estimation of the wear behaviour of XAR steels in relation to material and counter-material properties is therefore the subject of current research. Initial model developments have since found their way into practice like the aforementioned tool to consider through-thickness hardness of the wear plates.

To improve the wear resistance further, the use of multi-layer steels consisting of high-hardness outer layers and a softer more flexible inner layer can be considered. The wear resistant steel grade TriWEAR®, Figure 9, combines both high wear resistance and good toughness and therefore improves the lifetime of components such as screen bars or hammer crushers with resulting significant economic benefit.

Figure 9. Multi-layer wear resistant steel.

Conclusions

Modern wear resistant steels with surface hardness levels up to 600 HB widely use alloying elements C, Mn, Cr and Ni, supplemented by additions of Mo and especially Nb. Mo helps to improve the hardenability of the steels, especially in thicker sections, and Nb significantly improves the toughness by facilitating the control of the austenite structure and the final martensitic microstructure.

To judge the benefits and to find the best possible alloy for an individual wear application, TKSE has developed a calculation tool, based on field and laboratory tests, with which it is possible to rate the technical benefits of high priced alloying elements against the cost factor.

A field test involving lifting bars in a SAG-Mill verified the positive effect of a Nb-microalloyed concept on the wear behaviour.

Hardness and toughness are the two basic demands of a wear resistant steel, however it is difficult to improve both of these properties, as generally improving one of them has a deleterious effect on the other. New developments involving multi-layer steels combining a tough inner layer with very hard outer layers are the subject of current research and one such wear resistant steel grade, TriWEAR®, is showing very promising initial results. More detailed results will be shown in the future.