The size effect of martensite laths and precipitates on high strength wear-resistant steels

Huan Xue1,∗, Yansong Zhang1, Min Zhu1, Xiyan Yin1, Wenqian Zhang1 and Shengnan Liu1

1 Hubei University of Technology, 430068, Wuhan, People’s Republic of China
2 Central Research Institute of Baoshan Iron & Steel Co. Ltd, 430080, Wuhan, People’s Republic of China
∗ Author to whom any correspondence should be addressed.
E-mail: stone mechanics@163.com

Keywords: wear-resistant steel, size effect, tempered martensite lath, precipitate

Abstract
Low alloy high strength wear resistant steels are with high toughness, low cost and good abrasion resistance. It can effectively resist the propagation of wear cracks and prolong the service life of machine components. This paper focuses on the internal relationship between macroscopic physical properties and microscopic martensite lath and precipitate size throughout thickness of wear resistant steel. Four kinds of 40mm thickness wear resistant steels with different alloy chemical composition were produced and investigated. Results show the strength and hardness performance of ARIV are obviously higher than other three steels. ARI have a relatively large strength difference through thickness. The impact toughness of ARIV is relatively uniform, which is greater than that of the ARIII at middle layer and lower than that of the ARIII at 1/4 layer. The width of martensite lath of ARIV is relatively small, mainly 100 ∼ 300 nm, while that of ARII and ARIII is mainly 200 ∼ 400 nm. ARIV steel has shorter martensite lath band and more precipitates below 50 nm. It indicates that the size of martensite laths and precipitates of wear-resistant steels are important factors to determine its performance throughout thickness.

1. Introduction
Statistical data indicates that the economic losses caused by machine wear account for about 5% of the gross domestic product (GDP) [1]. Therefore, it is of great economic value to study high performance wear resistant materials. As an important category of wear resistant steels, low alloy high strength wear resistant steels are with high toughness, low cost and good abrasion resistance at the same time. It can effectively resist the propagation of wear cracks and prolong the service life of machine components [2, 3]. According to different requirements, wear-resistant steels designed properly are widely used in the fields of machinery, building, electric power, chemical industry and metallurgy with harsh working conditions [4, 5].

The mechanical properties of materials are significant factors affecting its wear performance. Different chemical compositions and manufacturing processes lead to different microstructure and strength properties of wear resistant materials. Regarding the effects of chemical compositions, several studies have conducted. Sun et al investigated the effects of Al contents on the properties of martensitic wear-resistant steels [6]. When the Al contents of specimens was 1.97%, the wear resistance was increased by about 11.1% compared with that of non-aluminum specimens, and the tensile strength and hardness were 1230 MPa and 38.3 HRC, reaching the peak value respectively. Cao et al pointed out that Ni and Mo had little significant effect on the martensite wear-resistant steels at low temperature tempering, but they improved the resistance softening and embrittlement of the steels at high temperature tempering [7]. Zhang et al indicated that with the increase of B contents from 0.5% to 2.0%, the hardness and wear resistance of the steel increased significantly, while the impact toughness decreased by 45% [8]. In addition, the bulk hardness and impact toughness of Fe–B–C–Cu alloy had the optimal mechanical properties with the Cu concentration increased to 2% [9]. Gr [10] and Mn [11] are proved to
enhance the fracture toughness of steels. Pedro et al. indicated that the addition of niobium alloy is an effective method to increase the wear resistance of high-strength steels [12].

In the manufacturing process of wear-resistant steels, quenching and tempering can effectively control the comprehensive properties such as wear resistance and hardness, which has been widely studied [13-16]. Abbasi et al. compared the properties of low-alloy steels after multiple tempering [17]. The results show that the tempering temperature mainly control hardness of the steels. And at same tempering temperature, double and triple tempering does not change the hardness obviously. When tempering temperature exceeds 300 °C, fracture toughness and impact toughness of the low-alloy wear resistant steels increase greatly [18]. Zhang et al. studied the effect of heat treatment on properties of wear resistant cast steel. The results show that after oil austenitizing at 1020 °C and tempering at 200 °C, the hardness and impact toughness of the steel are 58HRC and 22.92 J cm⁻² respectively, and the tensile strength reaches 1136.9 MPa [19].

Microstructure of wear-resistant steels also has vital effects on its mechanical properties. Generally, martensitic microstructure exhibits a better wear resistance performance compared to ferrite, pearlite, and bainite. Chen et al. pointed out that the shape and volume fraction of deformed twins play a decisive role in the shape and strength of medium manganese wear resistant steels [20]. Dong et al. analyzed the effect of cooling rate on microstructure [21]. The results show that when the cooling rate decreases, the proportion of pearlite increases and the residual stress decreases. TiC particles in low alloy wear resistant steels increase wear resistance of materials while ensuring hardness and strength [22]. With the increase of TiC particle contents, the wear mechanism of the materials is gradually dominated by plastic deformation, fracture and fatigue, which lead to the increase of wear resistance of the materials [23]. Du et al. carried out uniaxial micro-tensile test on lath martensite [24]. The experimental result shows that the material is strengthened by the boundary of block and sub-block, and the strengthening effect of block boundary is slightly better than that of sub-block boundary. Xue et al. studied the hardenability effect on microstructure and property of low-alloy abrasion-resistant steel [25]. In addition to the factors discussed above, martensite lath and precipitate size also have significant influences on the abrasion performance of wear resistant steel. Morito compared the effects of Mn on martensite structure in Fe-0.2C and Fe-0.2C-2Mn alloys [26]. The results showed that the addition of Mn does not change the size of martensite packets in single austenite grain, but refines the block size of martensite, which has an important influence on the martensite strength of low carbon steels. Kwang sik et al. indicated that martensite and austenite were the main factors for material strengthening and that the plastic anisotropy was related to substructure [27]. However, few studies focused on the internal relationship between macroscopic physical properties and microscopic martensite/precipitate size throughout thickness of high-strength wear resistant steel. In this paper, mechanical properties of four low-alloy high-strength wear resistant steels are presented below with the discussion focused on the size effect of grain, martensite lath length/width, substructure and precipitates.

2. Materials and Experimental Procedure

2.1. Materials

Materials used in this investigation were 40 mm thick abrasion-resistant steel ARI, ARII, ARIII, and ARIV. The chemical composition (in wt%) is listed in Table 1. ARI, ARIV steel compared with ARII, ARIII steel contain less hardenability and toughening alloy element. The C content of ARIII steel is about 0.188%, which is the lowest of these steels. The Si content of ARI and ARIII steel is higher, both at about 0.49%, which is about 0.14% higher than that of ARI and ARIV steel. The Mn content of ARI is only half of that of ARII, ARIII and ARIV steel, which is about 0.7%. ARI and ARIII steel is with lower Cu content and higher Ni and Mo content. The V element can improve the strength, toughness and wear resistance of steel. When it dissolves into austenite at high temperature, it can increase the hardenability of steel. Conversely, its presence in the carbide form reduces its hardenability. Under the condition of continuous casting cooling, TiN particles are formed. Due to its high melting point, the grain growth can be significantly inhibited in the heat affected zone (HAZ), and the addition of trace amount of Ti (<0.02%) can significantly improve the toughness of the HAZ. ARII steel is with the
highest V element content and AR III steel is with the lowest Ti content. Nb has the effects of delaying austenite recrystallization and refining grain [28], and its strong strengthening effect is $35 \sim 78$ times that of Si, $41 \sim 87$ times that of Mn, $50 \sim 117$ times that of Cr, and $87 \sim 175$ times that of Ni. The Nb content of ARIV steel is designed 1.6 times higher than other steels. The tapping temperature is controlled in $1660 \sim 1700 \, ^\circ C$. The casting blank were heated to $1220 \, ^\circ C$ and then rolled to 40mm thickness. The start and end temperature of rough and finish rolling is $1065 \, ^\circ C / 995 \, ^\circ C$ and $955 \, ^\circ C / 845 \, ^\circ C$ respectively. In quenching process, the steel plate was reheated to $870 \, ^\circ C$ and held for 8 min to ensure complete austenization, and then quenched to room temperature to form martensite. It was again reheated to $235 \, ^\circ C$ for 70 min tempering and cooled to room temperature to obtain ARI, ARII, ARIII and ARIV steel.

2.2. Experimental procedure and samples
The tensile specimens were got both from 1/4 thickness layer (5 ~ 15 mm) and middle layer (15 ~ 25 mm) as shown in figure 1. The samples size was $\Phi 10 \, mm \times 120 \, mm$, which were cut both from rolling and transversal direction. The tensile strength, elongation and section reduction tests were performed on a WE-30 universal testing machine. The hardness was measured on a BRIN200D-TL Brinell hardness tester, while the hardness specimen is with the whole thickness cross-section. Impact toughness was measured with Charpy-V instrumented test method according to standard ISO14556 on a ZWICK PSW750 instrumented pendulum impact tester. The samples were cut along transverse direction both from 1/4 thickness layer and middle layer with $10 \, mm \times 10 \, mm \times 55 \, mm$ size.

In order to comprehensively investigate the size effects of martensite laths and precipitate, the microstructure specimens were got both from surface, 1/4 thickness layer and middle layer. The microstructural features of four abrasion-resistant steels were captured by A PME3–323UN optical microscope (OM). The metallographic samples were shaped using different grits and grades of sand paper, then polished and etched with solutions of 25% HNO$_3$ mixed with hydrochloric acid. A QUANTA400 scanning electron microscope (SEM) was conducted to analyze morphology. The detailed micro-morphological analysis of the substructure and precipitated phase in the samples was conducted by JEM-2100F transmission electron microscopy (TEM).
The components of the precipitated phase were analyzed by INCA spectroscopy. The TEM foils were electropolished in a solution of 94% methanol and 6% perchloric acid at $-30^\circ$C with an applied voltage of 10V.

3. Results and discussion

3.1. Mechanical properties

3.1.1. Tensile properties

Figure 2 and figure 3 compare the yield stress and ultimate tensile strength difference in middle and 1/4 layer. The yield strength and tensile strength of ARIV are around 1200 MPa and 1500 MPa respectively, which are obviously higher than other three steel grades. The average yield strength of ARI is around only 1100 MPa which is the lowest. The strength and plasticity performance of ARIII and ARIV wear resistant steels at 1/4 position and 1/2 position have little difference. However, ARI has a relatively large difference in strength, the maximum difference is more than 150 MPa. Because the content of hardenability elements of ARI series is the least, which leads the central part of the plate has not been fully quenched. The transverse strength of ARIE wear resistant steel is larger than that of rolling direction, and the ductility index elongation of ARIE wear resistant steel is better than that of rolling direction. A little difference is exhibited between ARIII and ARIV wear-resistant steel in the vertical and horizontal direction. The rolling strength value in the position 1/4 of ARI is slightly larger than that in the transverse direction. Figure 4 shows the plastic performance elongation in middle and 1/4 layer of four
The elongations of four steel grades at 1/4 thickness is better than 1/2 position. The plasticity of ARII and ARIII is better than that of ARI, which should be greatly related to the use of alloy elements. The elongation of ARIV is significantly lower than that of other steels, which is due to the relatively large amount of C and Mn elements used in its composition system, resulting in higher strength and slightly insufficient plasticity.

3.1.2. Hardness distribution

Brinell hardness value is the most important index of wear-resistant steel, and its characterization value directly determines its product grade. Hardness distributions along thickness direction of four steels are compared in figure 5. The hardness surface values of ARI and ARII are very close, around 455HBW. While, ARIV steel has the largest surface hardness which is about 460 HBW. The heart hardness value of ARII decreased obviously to 411HBW. Although the surface hardness of ARIII is lower, about 430HBW, it is relatively uniform in thickness distribution. The average hardness of ARIV in the thick section is 445.4, the standard deviation is 10.1, and the relative standard deviation is 2.23%. Overall evaluation based on surface and full thickness hardness is that ARIV has the best performance of the four steels.

Although ARI has the least amount of strengthening elements such as Mn, Cr, Mo and Ni, its hardness performance is similar to ARII and ARIII due to the high content of C and Nb. Similarly, C content and Nb content of ARIV are the highest 0.215% and 0.022%, and other alloy elements are lower than ARII and ARIII, nevertheless the hardness performance is the best. It can be found that C element and Nb element play a very important role in the strengthening process of wear-resistant steel, and the influence of these two elements on the strengthening of wear-resistant steel is greater than other elements.
Figure 7. Surface microstructural characterization of ARI to ARIV: (a) Surface microstructure of ARI, (b) Surface microstructure of ARII, (c) Surface microstructure of ARIII, (d) Surface microstructure of ARIV.

Figure 8. 1/4 layer microstructural characterization of ARI to ARIV: (a) 1/4 layer microstructure of ARI, (b) 1/4 layer microstructure of ARII, (c) 1/4 layer surface microstructure of ARIII, (d) 1/4 layer microstructure of ARIV.
3.1.3. Toughness

The larger impact energy is corresponding to stronger crack resisting ability. Instrumented impact tests were carried out of four wear-resistant steel products from the rolling direction at 1/2 and 1/4 thickness layer, respectively. Compared with the general impact test, the Instrumented impact test can record more information of the crack process of material. It can not only test the total impact energy, \( W_t \), i.e. impact toughness, but also distinguish the crack initiation energy, \( W_i \), and the crack propagation energy, \( W_p \). The total energy \( W_t = W_i + W_p \), and the initiation/propagation ratio \( R_i = W_i/W_p \).

Figure 6 compares the impact toughness in middle and 1/4 thickness layer of four kinds of steel. The impact toughness at 1/4 layer of all steels are larger than the impact energy at middle layer. The impact energy at different thickness positions is with large difference of ARI, ARII and ARIII steel. \( R_i \) of four steels at 1/4 layer are 2.3, 2.4, 1.8, 2.6 respectively. While \( R_i \) of four steels at middle layer are 1.6, 3.3, 1.7, 3.6 respectively, which is with larger differences due to the hardenability variation. The impact toughness of ARIV is relatively uniform, which...
Figure 11. Scanning electron microscope images of microstructure: (a) the microstructure of ARI magnified 2500 times, (b) the microstructure of ARI magnified 5000 times, (c) the microstructure of ARII magnified 2500 times, (d) the microstructure of ARII magnified 5000 times, (e) the microstructure of ARIII magnified 2500 times, (f) the microstructure of ARIII magnified 5000 times, (g) the microstructure of ARIV magnified 2500 times, (h) the microstructure of ARIV magnified 5000 times.
is greater than that of the ARIII at middle layer and lower than that of the ARIII at 1/4 layer. The impact toughness of ARII and ARIII is greater than that of ARI, which is corresponding to the yield stress at the corresponding position. Therefore, it can be inferred that there is a certain correlation between the value of impact energy and yield stress. The larger yield stress is, the larger energy is needed to promote the plastic zone. From the perspective of composition system, this is because the content of toughening elements (Ni, Mo) of ARII and ARIII is more than that of ARI.

### 3.2. Microstructural characterization

Figure 7–10 show the microstructure characteristics of the surface layer, 1/4 layer and middle layer of the four kinds of steels. The surface of ARI is complete tempered martensite, a small amount of bainite appears from the 1/4 layer, and the content of bainite increases in the heart of plate. The surface layer and 1/4 layer of ARII are tempered martensite, with a small amount of bainite in the heart. ARIII and ARIV have uniform structures, both of which were tempered martensite. There is a certain relationship between the strength of wear-resistant steel and the content of bainite. The bainite content of ARI, ARII and ARIII decreases successively, and the strength value increases gradually. The bainite structure does not significantly improve the impact toughness of the material. The content of ARII bainite is the highest, however the impact energy is the lowest from the perspective of impact toughness. The denser the martensite slats are, the higher the strength and hardness values are. According to the metallographic diagram, the martensite laths of ARIV is denser than that of ARIII and ARII, and the martensite lath is shorter. Its corresponding strength and hardness value are larger than that of ARII and ARIII. A small amount of central segregation occurred in the middle layer of ARI and ARII, as shown in figure 10(a) and (b).

In order to further investigate the characteristics and differences of fine microstructure, the morphology of 1/4 layer of ARI, ARII, ARIII and ARIV was observed under scanning electron microscopy, as shown in Figure 11(a)–(h). The main structure of all steel grade is martensite. ARI and ARII contain a small amount of bainite structure, where bainite content of ARI is slightly more than ARII, which is basically consistent with the results of metallographic. The direction of martensite lath is almost the same within the crystal, whereas the direction of martensite lath between the crystals is more disorderly, without obvious rule. The geometrical size of martensitic lath has a great influence on the performance of martensitic steel. However, due to the limited magnification of the equipment, it is impossible to observe individual martensitic elements. Only the length of

---

**Figure 12.** The substructure morphology of 1/4 layer of ARI (a) Tempered lath martensite, (b) Tempered bainite, (c) Lath combining, (d) High density dislocation.
martensitic lath band composed of martensitic elements can be observed from a relatively macroscopic view, while the width of a martensitic element cannot be quantified. As the martensite lath grows in the grain, the grain size of the sample is also estimated for reference. It should be noted that the martensite lath observed under scanning electron microscope has a certain phase. The lath shown in the picture is not the real length of the lath. Relatively, the longer lath beam is closer to the actual size. Scanning electron microscope images method according to [26] was used to determine the grain size and martensite lath length. The most representative lath beams in the visual field were counted in statistics, and the results were shown in table 2.

| Steel No. | Grain size range (μm) | Martensite lath length range (μm) |
|-----------|-----------------------|----------------------------------|
| ARI       | 10 ~ 16               | 9 ~ 12                           |
| ARII      | 7 ~ 13                | 6 ~ 7                            |
| ARIII     | 7 ~ 12                | 7 ~ 8                            |
| ARIV      | 6 ~ 10                | 4 ~ 7                            |

Figure 13. The precipitate morphology and energy spectrum of 1/4 layer of ARI: (a) Tempered martensite + Precipitate (b) Precipitate (c) Precipitate energy spectrum.

martensitic lath band composed of martensitic elements can be observed from a relatively macroscopic view, while the width of a martensitic element cannot be quantified. As the martensite lath grows in the grain, the grain size of the sample is also estimated for reference. It should be noted that the martensite lath observed under scanning electron microscope has a certain phase. The lath shown in the picture is not the real length of the lath. Relatively, the longer lath beam is closer to the actual size. Scanning electron microscope images method according to [26] was used to determine the grain size and martensite lath length. The most representative lath beams in the visual field were counted in statistics, and the results were shown in table 2.

The grain size of ARI is relatively large, ranging from 10 μm to 16 μm, and the length of martensite lath is also relatively large, reaching 9 μm to 12 μm. The grain range of ARIV is the smallest, and the length of martensite lath is relatively the smallest, which indicates that the length of martensite lath is directly related to the grain size, and the grain boundary limits the growth of martensite. The grain size of ARII and ARIII is equivalent to the length of martensite lath. The grain size and martensite lath length of ARI are the biggest in four steels, where its strength and toughness is the lowest. Although the grain size and martensite length of ARIV are relatively small, its width is slightly larger than that of ARII and ARIII, and the martensite lath ends are round, and the tips are not obvious.

3.3. Substructure and precipitate

The plates of steel ARI, ARII, ARIII and ARIV were cut into thin slices in 1/4 and 1/2 thickness layer respectively. Then the foil samples of TEM were prepared by the thin slices. After deep etching the cross section of the sample, the secondary extracted carbon copy sample was prepared. The microstructure, substructure and
Precipitate of the sample were observed in JEM-2100F transmission electron microscopy, and the components of the precipitate were analyzed by INCA spectroscopy. The TEM image method was used to determine the size of martensite lath and precipitate [26]. Representative martensite lath and precipitate in the visual field were counted in statistics.

Figure 12. shows the substructure morphology of the 1/4 layer of ARI. The microstructure is combined with tempered lath martensite, a small amount of lath bainite and high density dislocation. A large number of acicular tempered carbides are distributed in the martensite lath. Strip M/A islands or discontinuous lamellar carbides can be found between the bainite lath. The martensite lath is slender with large length-width ratio. The lath widths are mainly 100 ～ 300 nm and a few are 500 ～ 1000 nm. Some of the laths have fuzzy boundary and obvious combination characteristics. The tempered carbide is mainly ε-Fe2C. At the same time, there are many uniformly distributed irregular or rectangular precipitates (Nb, Ti)(CN), whose size is mainly 15 ～ 50 nm, a small amount is 50 ～ 130 nm, and a very small amount is greater than 130 nm, as shown in figure 13. Figure 14

Figure 14. The substructure morphology of middle layer of ARI (a) Tempered lath martensite (b) Lath bainite (c) Lath combining (d) Dislocation pined by fine precipitates.

Figure 15. The precipitate morphology and energy spectrum of middle layer of ARI.
**Figure 16.** The substructure morphology of 1/4 layer of ARII (a) Tempered lath martensite (b) Quenched martensite + Tempered martensite (c) Heterogeneous microstructure (d) Twin Substructure + Acicular ε carbide.

**Figure 17.** The precipitate morphology and energy spectrum of 1/4 layer of ARII (a) Acicular ε carbide + Fine spherical precipitates (b) Tempered martensite + Precipitate (c) Precipitate energy spectrum.
shows the substructure of the middle layer of ARI sample. Compared with the 1/4 layer, the microstructure of the sample is still dominated by lamellar tempered martensite, while the amount of bainite is increased, and the tempered carbide is coarsened. (Nb, Ti)(CN) precipitates increased in size and quantity, as shown in figure 15.

Figure 16 shows the substructure morphology of the 1/4 layer of ARII. The dominant microstructure of the sample is lath tempered martensite with a very small amount of quenched martensite and twinning substructure with high density dislocation. A large amount of acicular tempered carbides \( \varepsilon \)-Fe\(_2\)C present diffuse distribution. The martensite lath interface is clear, while the size is not uniform. The lath width is mainly 200 ~ 400 nm. Some 600 ~ 1200 nm width lath and lamellar martensite mixes between slender lath bands. About 150 nm width quenched lath martensite appears at a local area. In addition, there are many irregular or spherical (Ti, Nb) (CN) precipitates presents in the lath, which are evenly distributed. The precipitate size is mainly 8 ~ 50 nm, and a small amount is 50 ~ 170 nm, as shown in figure 17. Compared with the 1/4 layer of ARI, the length and width of martensite lath are smaller, and the size of tempered carbides and precipitates are smaller too.
shows the substructure of the middle layer of ARII. The microstructure is lath tempered martensite with a small amount of bainite. The number of precipitated phases of (Nb, Ti)(CN) is slightly more than that of the 1/4 layer of ARII, with a slightly larger size, as shown in figure 19.

Figure 20 shows the substructure morphology of the 1/4 layer of ARIII. Compared with the 1/4 layer of ARII, the length and width of martensite lath are larger, most of which are arranged in parallel. The width of martensite lath is mainly 200 ~ 400 nm. Some 500 ~ 1000 nm width lath and lamellar martensite mixes between slender lath bands. About 150 nm width quenched lath martensite appears at a local area. The number of precipitates is less than that of ARII, with a main size of 6 ~ 50 nm and a small amount of 50 ~ 150 nm. The types are mainly (Nb, Ti)(CN), and a small amount of Nb(CN), as shown in figure 21. Figure 22 shows the substructure morphology of the middle layer of ARIII. Compared with the 1/4 layer of ARIII, the width of the thin lath band increases, and more lamellar martensite of the twin substructure appears. In addition, (Ti, Nb) (CN) precipitates also increases, as shown in figure 23.
Figure 24 shows the substructure morphology of the 1/4 layer of ARIV. The main microstructure is also lath tempered martensite. Compared with the 1/4 layer of ARIII, the martensite lath band is shorter, the fine lath is thinner. The number of short and coarse lamellar martensite is increased, and the orientation is disorderly. The width of martensite lath is mainly 100 ~ 300 nm. Some 500 ~ 1000 nm width needle-lamellar martensite mixes between slender lath bands. The number of precipitates increased with the main size of 7 ~ 50 nm and a small amount of 50 ~ 170 nm. The main precipitates types are Nb (CN) or (Nb, Ti)(CN). Compared with the 1/4 layer of ARII, the number of precipitates below 50 nm slightly increase, and the number of precipitates above 50 nm decrease, as shown in figure 25. Figure 26 shows the substructure morphology of the middle layer of ARIV. Compared with the 1/4 layer of ARIV, the martensite lath width is more uniform, the direction tends to be the same. The short and thick acicular lamellar martensite is reduced, and the number of twin substructures is increased significantly. (Ti, Nb)(CN) precipitates increase in both number and size, as shown in figure 27.
Figure 24. The substructure morphology of 1/4 layer of ARIV (a) tempered lath martensite (b) Quenched martensite (c) Needle-lamellar martensite (d) acicular $\varepsilon$ carbide + Fine spherical precipitates.

Figure 25. The precipitate morphology and energy spectrum of 1/4 layer of ARIV (a) Precipitates above 50 nm (b) Precipitates below 20 nm.
4. Discussion

The mechanical performance of wear-resistant steel has a certain relationship with bainite content. ARI, ARII, ARIII bainite content decreases in turn, and the strength value increases gradually. ARI has the highest bainite content, but the impact energy is the lowest in terms of impact toughness. Similarly, a small amount of bainite tissue can be found in the heart of ARII, while no bainite appears in ARIII. As a result, the impact energy of the center layer of ARII is lower than that of ARIII. The denser the martensite lath is, the higher its strength and hardness. The martensitic slat of ARIV is denser and the martensitic slat bundle is shorter than that of the ARII and ARIII, the corresponding strength and hardness value are larger. In combination with mechanical properties, the longer the martensitic slats are, the lower the strength and toughness are. The existence of lath bainite in ARI steel destroys the continuity of matrix and reduces its strength and toughness.

The comparison of the main size and characteristics of microstructure and precipitates are shown in table 3. The similarities microstructure of the four tested steels are that all contains tempered lath martensite, and a large
Table 3. Sizes of martensite lath and characteristics of Substructure and precipitate.

| Steel No. | layer | Length of martensite lath μm⁻¹ | Width of martensite lath nm⁻¹ | Substructure characteristics | precipitate characteristics |
|-----------|-------|--------------------------------|-------------------------------|----------------------------|-----------------------------|
| ARI       | 1/4   | 9 ~ 12                          | 100 ~ 300                     | Slender martensite lath with large length-width. A small amount 500 ~ 1000 nm martensite. Some fuzzy boundary and combination characteristics laths. A small amount of bainite. | The tempered carbide in 1/4 layer is mainly ε-Fe2C. Many uniformly distributed irregular or rectangular precipitates (Nb, Ti)(CN). The tempered carbide coarsens in the heart. The size and number of precipitates (Nb, Ti)(CN) increase. |
|           | 1/2   |                                  |                               | Bainite content increases. |                                |
| ARII      | 1/4   | 6 ~ 7                           | 200 ~ 400                     | Slender lath martensite with clear interface and uniform size. A very small amount 600 ~ 1200 nm martensite. Locally quenched martensite with width of 150 nm. | Many irregular or spherical precipitates (Ti, Nb)(CN) in the 1/4 layer, with uniform distribution and mainly 8 ~ 50 nm. The number of precipitates (Nb, Ti)(CN) in the heart is slightly more than that in the 1/4 layer. |
|           | 1/2   |                                  |                               | The microstructure type is the same as 1/4 layer. A small amount of local bainite. |                                |
| ARIII     | 1/4   | 7 ~ 8                           | 200 ~ 400                     | A small amount of 500 ~ 1000 nm lath or lamellar martensite mixed. About 150 nm quenched martensite locally visible | The slightly small number of precipitates in the 1/4 layer. The size is mainly 6 ~ 50 nm. The type is mainly (Nb, Ti)(CN), and a small amount is Nb(CN). The number of precipitates (Ti, Nb)(CN) in the heart increased. |
|           | 1/2   |                                  |                               | Microstructure type is the same as in 1/4 layer. The width of fine lath increases. The lamellar martensite of twinning substructure increases. |                                |
| ARIV      | 1/4   | 4 ~ 7                           | 100 ~ 300                     | Shorter and finer martensite lath. The number of short and coarse lamellar martensite increases and the orientation is disordered. Mixed with 600 ~ 1000 nm needle-lamellar martensite | The number of precipitates increases in the 1/4 layer. The size is mainly 7 ~ 50 nm. The type is mainly Nb(CN) or (Nb, Ti)(CN). Compared with ARII and ARIII, the number of precipitates below 50 nm is slightly more and above 50 nm is less. |
|           | 1/2   |                                  |                               | The microstructure is similar to that in 1/4 layer. Lamellar martensite contents decrease. The number of twin substructures increases significantly. |                                |
number of acicular ε carbides and fine (Nb, Ti) (CN) precipitates are dispersed on the lath, along with high-density dislocations, playing a major role in hardening and strengthening, and having excellent toughness at the same time.

The difference of product performance mainly depends on the difference of type and size of microstructure and precipitates. The microstructure of ARI, ARIII, and ARIV steel at 1/4 layer are the same, most of which are tempered martensite. The microstructure of ARI steel is a mixture of tempered martensite and a small amount of lath bainite, and the content of bainite in the heart is higher than in 1/4 layer. The width of martensite lath of ARI steel and ARIV steel is relatively small, mainly 100 ~ 300 nm, while that of ARII and ARIII steel is slightly larger, mainly 200 ~ 400 nm. The martensite lath of ARI steel is mainly in slender parallel arrangement with a tendency to combine. The martensite lath of ARIV steel is relatively short with clear interface and uneven thickness.

The needle-lamellar martensite with width of 500 ~ 1000 nm is mixed between fine lath bands, and the arrangement direction is irregular. The length of martensite laths of ARII and ARIII steels is between ARI and ARIV, mainly in parallel arrangement.

As shown in figures 12 and 14, the microstructure of ARI steel has a small amount of lath bainite, which reduces the hardness and strength. There are strip M/A islands or discontinuous lamellar carbides between bainite laths. This brittle band structure destroys the continuity of the matrix and is unfavorable to plasticity and toughness. Compared with the 1/4 layer, the structure in the heart of ARI steel has more lath bainite, which makes the strength slightly reduced and the toughness significantly reduced. With the same heat treatment conditions, the appearance of lath bainite indicates that the hardenability of ARI steel is insufficient, which may be due to the lack of Mn and other alloying elements that contribute to hardenability.

It can be seen from figures 16 and 18 that the microstructure in the 1/4 layer of ARII steel is lath tempered martensite, while it contains a small amount of lath bainite in the heart. Thus, the strength and plastic and toughness in the heart are lower than those in the 1/4 layer. As shown in figures 20 and 22, compared with the 1/4 layer of ARII steel, the martensite laths of ARIII steel are mainly in parallel arrangement with smaller width, and the size of precipitates is smaller. Therefore, the strength and hardness are improved, and the plasticity and toughness are equivalent.

ARIV steel is with the highest content of Ti and Nb, the grain refinement and precipitation strengthening effect are obvious. Figures 24 and 26 indicate that compared with ARIII steel, the martensite lath band of ARIV steel is shorter, and the fine lath is thinner. The number of short and coarse martensite increases, whose size is relatively small. The arrangement direction is chaotic, which increases the grain boundary strengthening. At the same time, the number of fine precipitates below 50 nm is further increased, which has a strong pinning dislocation strengthening effect. Therefore, ARIV steel has the highest strength and hardness, and has excellent toughness.

5. Conclusions

Four 40 mm thick abrasion-resistant steel ARI, ARII, ARIII and ARIV with different alloy elements were investigated. The specimens were got both from surface, 1/4 thickness layer (5 mm ~ 15 mm) and 1/2 thickness layer (15 mm ~ 25 mm) to investigate internal relationship between macroscopic physical properties and microscopic martensite/precipitate size throughout thickness. The major conclusions derived from the present investigations are:

1. The strength and hardness performance of ARIV are obviously higher than other three steel grades. ARI has a relatively large strength difference through thickness.
2. The impact toughness of ARIV is relatively uniform, which is greater than that of the ARIII at middle layer and lower than that of the ARIII at 1/4 layer.
3. Four tested steels are all contains tempered lath martensite, and a large number of acicular ε carbides and fine (Nb, Ti) (CN) precipitates.
4. The width of martensite lath of ARI steel and ARIV steel is relatively small, mainly 100 ~ 300 nm, while that of ARII and ARIII steel is slightly larger, mainly 200 ~ 400 nm. Compared with other steels, ARIV steel has shorter martensite lath band and more precipitates below 50 nm.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.
References

[1] Chen H H. 2012 Application Manual of Wear-resistant Materials 2nd edn (Beijing: China Machine Press)
[2] Zhang C Y, Li Z R, Li Y Y, Zhou X M, Fang D, Ye Y S, Yuan Y L and Wu H H 2020 Study on mechanical properties and microstructure of the ultrastrong low alloy wear-resistant steels Mater. Res. Int 92 2000155
[3] Jiang Z Q, Fu H G, Yin E S and Tian, Y T 2011 Investigation and application of high strength low alloy wear resistant cast steel Mater. Technol 26 58–61
[4] Wei S Z and Xu L J 2020 Review on research progress of steel and iron wear-resistant materials Acta Metall. Sinica 56 523–38
[5] Luo H W and Shen G H 2020 Progress and perspective of ultra-high strength steels having high toughness Acta Metall. Sinica 56 494–512
[6] Sun Y F, Lv Y Z, Wang L L, Shen J J, Jia X C and Zhao J Y 2013 Effect of aluminum on microstructure and properties of martensitic wear-resistant and heat-resistant steel Oxid. Met 80 113–24
[7] Cao Y, Wang Z D, Kang J, Wu D and Wang G D 2013 Effects of tempering temperature and Mo/ Ni on microstructures and properties of lath martensitic wear-resistant steels Journal of Iron and Steel Research (International) 20 70–5
[8] Zhang C L, Li S H, Lin Y H, Ju J and Fu H G 2020 Effect of boron on microstructure evolution and properties of wear-resistant cast Fe–Si–Cr–B alloy Journal of Materials Research and Technology 9 5564–76
[9] Yi Y L, Xing J D, Wang M J, Yu Y L and Jian Y X 2017 Effect of Cu on microstructure, crystallography and mechanical properties in Fe–B–Cu alloys. Materials Science & Engineering A 708 274–84
[10] Jian Y X, Huang Z F, Xing J D and Wang B Y 2015 Effects of chromium addition on fracture toughness and hardness of oriented bulk Fe–B crystals Mater. Chaucut 110 138–44
[11] Jian Y X, Huang Z F, Xing J D, Guo X Z, Wang Y and Lv Z. 2016 Effects of Mn addition on the two-body abrasive wear behavior of Fe–3.0 wt% B alloy Tribol. Int 103 243–51
[12] Oliveira P G B, Aureliano R T J, Casteletti L C, Filho A I, Neto A L and Totten G E 2020 Effect of low-temperature austempering and quenching and partitioning treatments on adhesive wear resistance of high-silicon multiphase steels J. Mater. Eng. Perform 29 3542–50
[13] Haiko O, Somani M, Porter D, Kantanen P, Kömi J, Ojala N and Heino V 2018 Comparison of impact-abrasive wear characteristics and performance of direct quenched (DQ) and direct quenched and partitioned (DQ&P) steels Wear 400–401 21–40
[14] Liang L, Yan L X, Li G H, Cao Y, Deng X T and Wang Z D 2021 Effect of heat treatment on microstructure and mechanical properties of low-alloy wear-resistant steel NM450 Mater. Res. Express. 8 045606
[15] Dhokev N B, Maske S S and Ghosh P 2021 Effect of tempering and cryogenic treatment on wear and mechanical properties of hot work tool steel (H13) Mater. Today Proc 43 3006–13
[16] Wen E D, Song R B and Xiong W M 2019 Effect of tempering temperature on microstructures and wear behavior of a 500HB grade wear-resistant steel Metals 9 45
[17] Abbas E, Luo Q and Owens D 2019 Microstructural characteristics and mechanical properties of low-alloy, medium-carbon steels after multiple tempering Acta Metall. Sinica 39 274–88
[18] Fu H G, Xiao Q and Fu H F 2005 Heat treatment of multi-element low alloy wear-resistant steel Materials Science & Engineering A 396 206–12
[19] Zhang J C, Zhang T and Yang Y T 2021 Microstructure and properties evolution of Nb-bearing medium Cr wear-resistant cast steel during heat treatment J. Iron. Steel Res. Int 28 739–51
[20] Chen J, Wang J J, Zhang H, Zhang W G and Liu C M 2019 Evolution of deformation twins with strain rate in a medium-manganese wear-resistant steel Fe–8Mn–1C–1.2Cr–0.2V J. Iron. Steel Res. Int 26 983–90
[21] Dong C, Wu H B and Wang X T 2019 Effect of cooling rate on microstructure, hardness, and residual stress of 0.28C–0.22Ti wear-resistant steel J. Iron. Steel Res. Int 26 866–74
[22] Deng X T, Huang L, Wang Q, Fu T L and Wang Z D 2020 Three-body abrasion wear resistance of TiC-reinforced low-alloy abrasion-resistant martensitic steel under dry and wet sand conditions Wear 452–453 203310
[23] Huang L, Deng X T, Li C R, Jia Y, Wang Q and Wang Z D 2019 Effect of TiC particles on three-body abrasive wear behaviour of low alloy abrasion-resistant steel Wear 434–435 202971
[24] Du C, Hoenfagels J P M, Vaes R and Geers M G D 2016 Block and sub-block boundary strengthening in lath martensite Scr. Mater 116 117–21
[25] Xue H, Peng W Y, Yu L, Ge R, Liu D, Zhang W Q and Wang Y 2020 Effect of hardenability on microstructure and property of low-alloy abrasion-resistant steel Materials Science & Engineering A 793 139901
[26] Morito S, Yoshida H, Maki T and Huang X 2005 Effect of block size on the strength of lath martensite in low carbon steels Materials Science & Engineering A 438 237–40
[27] Kwak K, Mayama T, Mine Y and Takashima K 2016 Anisotropy of strength and plasticity in lath martensite steel Materials Science & Engineering A 674 104–16
[28] Wang Q, Sun Y, Zhang C Y, Wang Q F and Zhang F C. 2018 Effect of Nb on microstructure and yield strength of a high temperature tempered martensitic steel Mater. Res. Express 5 046501