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# EFFECT OF Nb ON THE PROPERTIES OF A LARGE-SIZED GRINDING BALL

## VPLIV Nb NA LASTNOSTI VELIKIH KROGEL ZA DROBLJENJE

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Grinding balls are widely used in the mining industry due to their favorable properties; however, poor hardenability of large-sized grinding balls is a limitation in wide applications. The hardenability and hardness of large-sized grinding balls can be affected by microalloying elements. In this work, Nb microalloying was used to improve the mechanical properties of large-sized grinding balls. The microstructures and mechanical properties of Nb-containing grinding balls were studied in contrast to the Nb-free steel. Typical microstructures were observed with OM and SEM, respectively. The hardness was obtained with a Rockwell hardness tester. The results show that the typical microstructure of a large-sized grinding ball was mainly martensite and that the fracture surface consisted of dimples of different sizes. The prior-austenite grain size (PAGS) was decreased from 31.5 μm to 22.6 μm by adding 0.04 % Nb with a refined microstructure.

Keywords: grinding balls, prior-austenite grain size, microalloying element, hardenability

Zaradi dobrih lastnosti, se krogle za drobljenje veliko uporabljajo v rudarstvu, toda slaba prekaljivost zelo velikih krogel po njihovem preseku omejuje njihovo uporabnost. Prekaljivost in s tem povečanje trdote v globini velikih krogel lahko izboljšamo z mikrolegiranjem. V članku avtorji opisujejo izboljšanje mehanskih lastnosti velikih krogel za drobljenje rude z mikrolegiranjem na osnovi Nb. Avtorji so mikrostrukturo in mehanske lastnosti jeklenih rudarskih krogel iz mikrolegiranega jekla z Nb, primerjali z jeklom, ki ni vsebovalo Nb. Tipične mikrostrukture jekel so opazovali pod optičnim (OM) in vrstičnim elektronskim mikroskopom (SEM). Trdoto krogel so določili z Rockwellovim merilnikom trdote. Rezultati raziskav so pokazali, da je bila tipična mikrostruktura velikih krogel sestavljena pretežno iz martenzita, saj so imele prelomne površine tipičen jamičast duktilni prelom z različno velikimi jamicami. Velikost predhodnih austenitnih zrn (PAGS; angl.: prior austenite grain size) se je v mikrostrukturi zmanjšala z 31,5 μm na 22,6 μm z dodatkom 0,04 % Nb.

Ključne besede: velike rudarske drobilne krogle, velikost predhodnih austenitnih zrn, mikrolegirni element, prekaljivost

## 1 INTRODUCTION

A grinding ball, as an indispensable grinding medium, is the most consumed part in a semi-autogenous (SAG) mill.[1–3] With the gradual enlargement of SAG mills, the diameter of a grinding ball must be increased to meet the requirements of working conditions.[4–6] In a working process, a large-sized grinding ball is easy to peel off the block due to the lack of hardenability.[7–8] And a grinding ball with poor wear resistance cannot meet the requirements for industrial applications.[9] Under the conditions of wet grinding, the grinding ball is subject to wear and repeated impact, which accelerate the crushing rate.[10–11] Thus, the grinding ball must have excellent mechanical properties such as hardenability and wear resistance to meet the working conditions.[12–13] The hardness is directly dependent on the hardenability of the material, so a designed #150-mm grinding ball must exhibit high hardenability.

Nb is widely used in steels as a microalloying element for grain refinement.[14–16] In this work, the properties of Nb-free and Nb-containing grinding balls were investigated, and the feasibility of adding Nb to large-sized grinding balls to improve their hardenability was studied.

## 2 EXPERIMENTAL PART

Experimental steels were smelted in a vacuum medium-frequency induction furnace, marked as A and B. A was the Nb-free steel and B was the Nb-containing microalloyed steel. After having been forged at 1325 K, ingots were processed into 85 mm × 240 mm steel bars. The alloy composition was examined with inductively coupled plasma mass spectrometry (ICP-MS). The alloy

**Table 1:** Chemical composition of the experimental steel

| Steel | C | Si | Mn | S | P | Cr | Nb | Fe |
|---|---|---|---|---|---|---|---|---|
| A | 0.87 | 0.82 | 1.1 | 0.0082 | 0.015 | 0.95 | - | Bal. |
| B | 0.87 | 0.81 | 1.1 | 0.0089 | 0.013 | 0.95 | 0.04 | Bal. |

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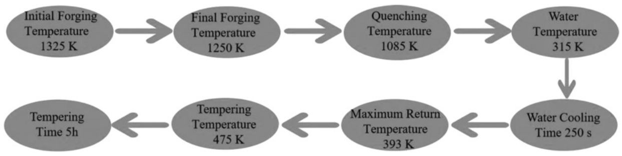


**Figure 1:** Heat treatment of grinding balls

elements are listed in **Table 1**. **Figure 1** shows the heat treatment of grinding balls.

A grinding ball was cut into semi-circular pieces with a thickness of 11 mm using a wire-cut electric discharge machine, then the two cutting planes were ground. The hardness values were measured every 7.5 mm from the center to the surface using a Rockwell hardness tester with an accuracy of 0.1 HRC. To obtain the typical microstructure, samples were polished and etched with supersaturated 4 % nitric acid in ethanol. Additional samples were heated in an electric furnace at a temperature of 1170 K for 3 h. A saturated, aqueous picric acid solution was used to reveal the prior-austenite grain boundaries (PAGBs). The PAGSs were examined using the linear-intercept method of optical microscopy (OM). To obtain fractographs, the samples were cut along the loading direction and near the fracture lip. Then they were cleaned three times in an ultrasonic stirrer and the fracture surfaces were examined with an S-4800 scanning electron microscope (SEM).

## 3 RESULTS AND DISCUSSION

### *3.1 Effect of the secondary phase on the grain size*

In accordance with the theory of the second-phase particles in iron and steel, the content of Nb in the solid solution state was limited under a certain C content and the rest was precipitated in the form of the second phase. The compounds formed by Nb and non-metallic elements had a great solubility in the molten steel. The formula for the solid solubility of Nb in austenite is as follows:[18–19]

$$\lg(c_c \cdot c_{Nb}^{0.875})_g = 2.97 - \frac{7500}{T} \pm 0.06 \qquad (1)$$

where $c_C$ and $c_{Nb}$ are the contents of C and Nb in austenite, respectively, and T is the temperature. Thus, most of the Nb elements were presented in the form of second-phase particles due to the fact that the C content of the experimental steel was 0.87 % and the austenitizing temperature was 1025 K. **Figure 2** shows that PAGS of ball A was 31.5 μm and that of ball B was 22.6 μm, indicating that Nb played a great role in the grain refinement.

According to the Hall-Petch formula, the structure and properties of steel were directly affected by PAGS.[20] The smaller the austenite grain, the better were the hardness and toughness of the steel.

$$\sigma = \sigma_0 + k \cdot d^{-1/2} \qquad (2)$$

Here, $\sigma_0$ is the lattice friction stress required for moving individual dislocations; k is the material-dependent constant known as the Hall–Petch slope; and d is the average grain size.

During the process of grain growth, the migration of grain boundaries was hindered by the secondary-phase

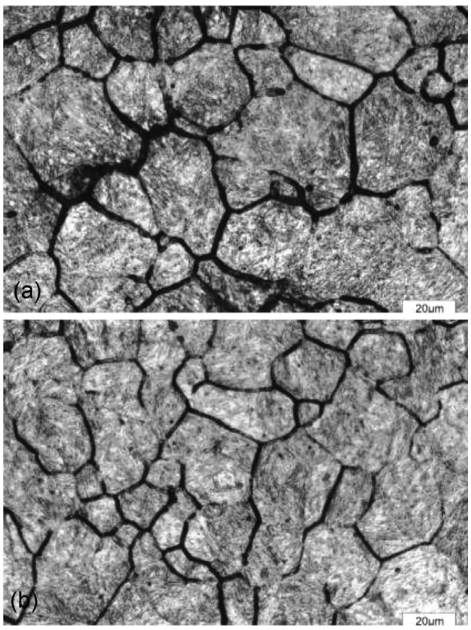


**Figure 2:** Images of the prior-austenite grain sizes: a) ball A at 1170 K held for 3 h, b) ball B at 1170 K held for 3 h

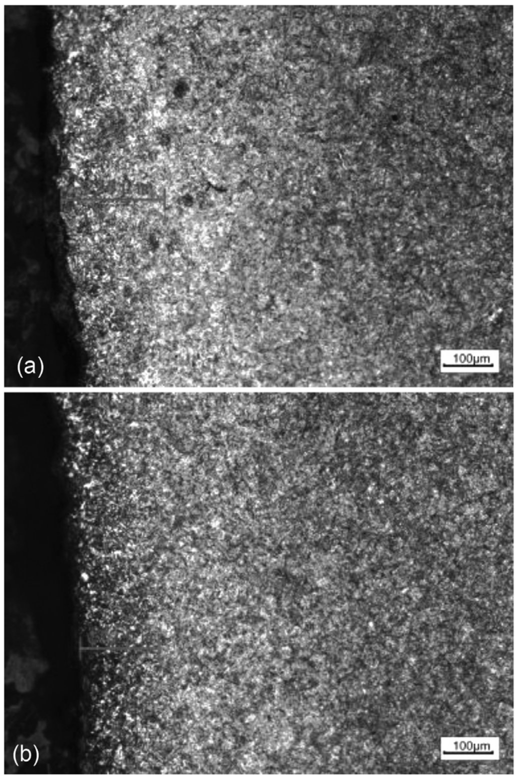


**Figure 3:** OM images of surface decarbonization: a) ball A heated at 1250 K for 5h, b) ball B heated at 1250 K for 5h

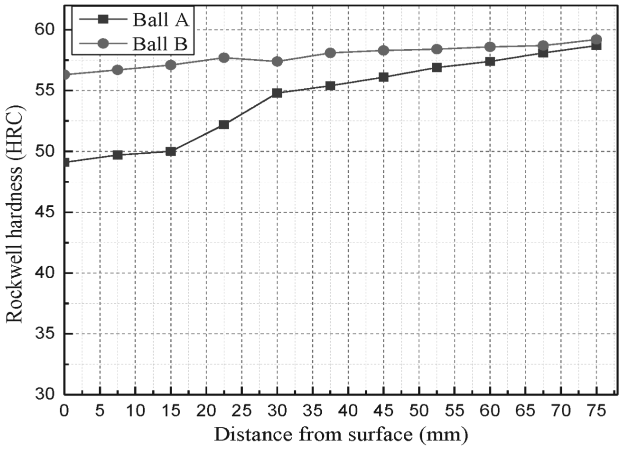


**Figure 4:** Hardness-distribution curves of the grinding balls

particles in ball B. When a grain encounters second-phase particles in the process of growth, the movement of the grain boundary is cut off. When the grain boundary reaches the maximum interface, its continuous movement increases the grain-boundary area. At this time, the particles drag the grain-boundary movement and pin the grain boundary. The deformation of grains at the grain boundaries is more coordinated, which makes them difficult to deform, hence a reinforcement of the grain boundaries occurs.[18] Consequently, the secondary phase in the steel is critical for preventing the coarsening of austenite grains at high temperatures.

### *3.2 Decarburization layer and the hardness measurement*

**Figure 3** shows that the surface decarbonization of grinding ball A was more serious than that of grinding ball B. The thickness of the decarburized layer on the surface of ball A was roughly 224 µm and that of ball B was roughly 172 µm. The carbon diffusion rate decreased significantly with the addition of Nb. The addition of Nb had a significant effect on reducing the decarbonization tendency at the surface, improving the degree of influence on the carbon diffusion and showing good decarbonization resistance.

Every hardness value was measured six times and averaged, and the hardness distribution was shown in **Figure 4**. From 1/4 R to the surface, the hardness of grinding ball A was slightly lower than that of grinding ball B. From the center to 1/4 R, the hardness of ball A decreased sharply, resulting in an uneven stress distribution. In the working process, ball A was easy to crack and break. With the increase in the distance from the center, the hardness increased smoothly for ball B. The hardness range for ball B from the center to the surface was 56.3–59.2 HRC, and the hardness almost had a homogeneous distribution.

### *3.3 Microscopic observation*

**Figures 5** and **6** show that the microstructures of the surface, 1/2 R and the center were obtained with OM. **Figure 5** shows that the microstructure of grinding ball A was composed of martensite at the surface. The microstructure was mainly martensite and bainite at 1/2 R. At the center, the microstructure was mainly martensite and

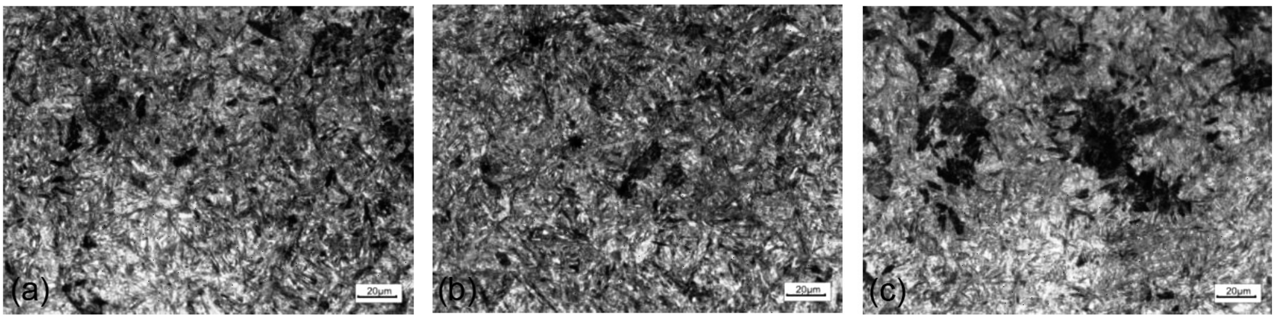


**Figure 5:** OM images of grinding ball A: a) surface, b) 1/2 R, c) center

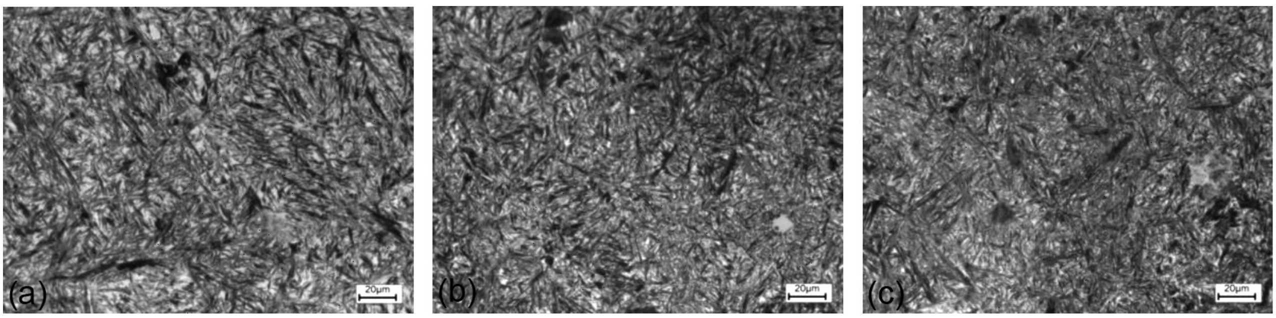


**Figure 6:** OM images of grinding ball B: a) surface, b) 1/2 R, c) center

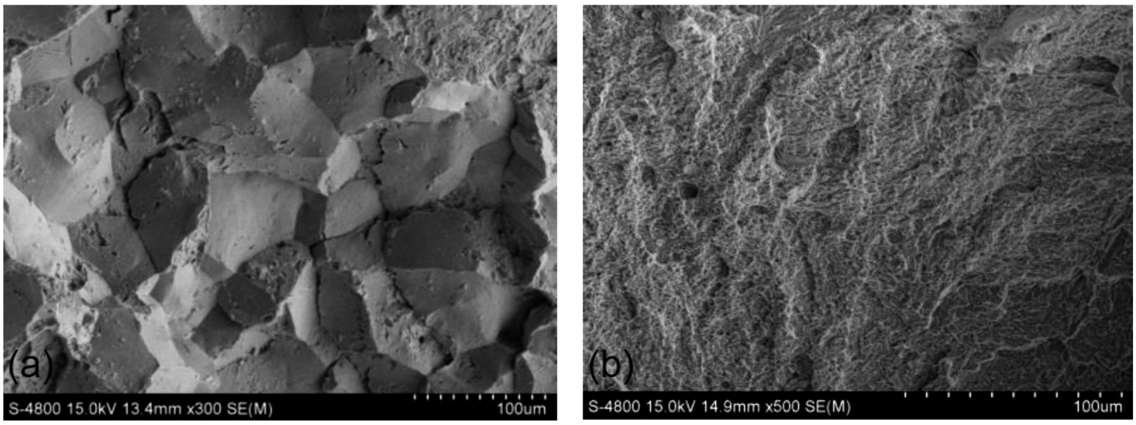


**Figure 7:** SEM fractographs of grinding balls: a) sample A, b) sample B

pearlite, of which the latter amounted to more than half. The center of grinding ball A was not hardened, so the performance was poor. **Figure 6** shows that the surface of grinding ball B was a mixed martensite structure. At 1/2 R, the microstructure mainly included martensite and a very small amount of bainite. At the center, the microstructure was composed of martensite and a small amount of retained austenite (RA). A small amount of RA can improve the impact toughness and fracture resistance of a grinding ball. The distribution of martensite from the center to the surface was uniform and there was no preferred orientation. Thus, the addition of Nb made the grinding ball harden completely.

**Figure 7** shows the fracture surfaces of samples A and B. A clear rock-sugar pattern can be observed on the surface of sample A. At the end of some grains, sharp surfaces with an angle of roughly 90 degrees can be seen. The fracture morphology of sample B includes dimples and tearing edges of different sizes, indicating ductile fracture. On the fracture surface of sample B, large dimples are surrounded by small dimples, which can absorb a large amount of deformation energy and hinder the initiation and propagation of cracks.

## 4 CONCLUSIONS

The effect of Nb on the properties of large-sized grinding balls was investigated in this research. It was concluded that a finely distributed Nb-containing secondary phase can hinder the growth of the grains and refine the PAGS from 31.5 μm to 22.6 μm. The distribution of martensite from the center to the surface was uniform, and the thickness of the decarbonized layer was obviously decreased. The fracture surface changed from a rock-sugar pattern to fine dimples; thereby, the toughness of large-sized grinding balls was greatly improved. The hardness range of the Nb-containing grinding balls from the center to the surface was 56.3–59.2 HRC, and the hardness exhibited an almost homogeneous distribution.

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## 5 REFERENCES

[1] K. P. Simba, M. H. Moys, Effects of mixtures of grinding media of different shapes on milling kinetics, Minerals Engineering, 61 (**2014**), 40–46, doi:10.1016/ j.mineng.2014.03.006

[2] D. Cuhadaroglu, S. Samanli, S. Kizgut, The effect of grinding media shape on the specific rate of breakage, Particle and Particle Systems Characterization, 25 (**2009**) 5–6, 465–473, doi:10.1002/ppsc.200800001

[3] C. Aldrich, Consumption of steel grinding media in mills, Minerals Engineering, 49 (**2013**), 77–91, doi:10.1016/j.mineng.2013.04.023

[4] J. L. Salazara, L. Magneb, G. Acuñac, Dynamic modelling and simulation of semi-autogenous mills, Minerals Engineering, 22 (**2009**) 1, 70–77, doi:10.1016/ j.mineng.2008.04.009

[5] S. Morrell, Modelling the influence on power draw of the slurry phase in autogenous (AG), semi-autogenous (SAG) and ball mills, Minerals Engineering, 89 (**2016**), 148–156, doi:10.1016/j.mineng.2016.01.015

[6] W. Valery Jnr, S. Morrell, The development of a dynamic model for autogenous and semi-autogenous grinding, Minerals Engineering, 8 (**1995**) 11, 1285–1297, doi:10.1016/0892–6875(95)00096-9

[7] E. Albertin, S. L. Moraes, Maximizing wear resistance of balls for grinding of coal, Wear, 263 (**2007**) 1–6, 43–47, doi:10.1016/j.wear.2007.02.013

[8] C. W. Li, Z. Y. Gao, Effect of grinding media on the surface property and flotation behavior of scheelite particles, Powder Technology, 322 (**2017**), 386–392, doi:10.1016/j.powtec.2017.08.066

[9] T. Chandrasekaran, K. A. Natarajan, Kishore, Influence of microstructure on the wear of grinding media, Wear, 147 (**2007**) 2, 267–274, doi:10.1016/0043–1648(91) 90184–V

[10] W. J. Bruckard, G. J. Sparrow, J. T. Woodcock, A review of the effects of the grinding environment on the flotation of copper sulphides, International Journal of Mineral Processing, 100 (**2011**) 1–2, 1–13, doi:10.1016/j.minpro.2011.04.001

[11] K. Ravishankara, P. S. Rameshb, B. Sadhasivama, Wear-induced mechanical degradation of plastics by low-energy wet-grinding, Polymer Degradation and Stability, 158 (**2018**), 212–219, doi:10.1016/j.polymdegradstab.2018.10.026

[12] C. Camurri, C. Carrasco, O. Z. Hernandez, Proposed heat treatment conditions to improve toughness of steel grinding balls, Metallurgia Italiana, (**2007**) 9, 23–29

[13] T. W. Chenje, D. J. Simbi, E. Navara, Relationship between microstructure, hardness, impact toughness and wear performance of selected grinding media for mineral ore milling operations, Materials & Design, 25 (**2004**) 1, 11–18, doi:10.1016/s0261-3069(03)00168–7

[14] B. Chokkalingam, S. S. M. Nazirudeen, Investigations of micro-alloyed cast steels, Materials and Technology, 43 (**2009**) 3, 171–174

[15] G. Suleyman, E. M. Akif, K. Hasan, Effect of the addition of niobium and aluminium on the microstructures and mechanical properties of micro-alloyed PM steels, Mater. Technol., 50 (**2016**) 5, 641–648, doi:10.17222/mit.2015.248

[16] B. Chokkalingam, S. S. M. Nazirudeen, S. Ramakrishnan, Investigation into the mechanical properties of micro-alloyed as-cast steel, Mater. Technol., 45 (**2011**) 2, 159–163

[17] Q. L. Yong, Secondary Phases in Steel, Metallurgical Industry Press, (**2006**) 1, 39–57

[18] S. Wu, X. C. Li, J. Zhang, Effect of Nb on transformation and microstructure refinement in medium carbon steel, Acta Metallurgica Sinica, 50 (**2014**) 4, 400–408, doi:10.3724/SP.J.1037.2013.00538

[19] L. Lin, B. S. Li, G. M. Zhu, Effects of Nb on the microstructure and mechanical properties of 38MnB5 steel, International Journal of Minerals, Metallurgy and Materials, 25 (**2018**) 10, 1181–1190, doi:10.1007/s12613-018-1670-z

[20] P. Lehtoa, H. Remesa, T. Saukkonen, Influence of grain size distribution on the Hall-Petch relationship of welded structural steel, Materials Science and Engineering: A, 592 (**2014**), 28–39, doi:10.1016/j.msea.2013.10.094