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Properties of Railway Wheels Made of Metal with Increased Copper Content

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Abstract

The content of non-ferrous metals and, in particular, copper is limited by numerous standards regulating the chemical composition of steels. Thus, for instance, according to the Ukrainian standard for wheel steel, the residual content of nickel, chromium, and copper should not exceed 0.25% each. According to the international UIC standard, this content should not exceed 0.30% each. The residual copper content according to the Japanese standard is allowed to be not more than 0.35%. Many steelmakers are concerned about the presence of copper due to its red shortness. However, the beneficial effect of Cu on hardenability and transformation kinetics is well-known, enabling the formation of a structure with a high density of dislocations at cooling rates feasible in industrial conditions, thus imparting high initial strength to the matrix. Experimental smelting was conducted in the open-hearth furnaces to obtain 0.15-0.60% of copper in the metal. It was found out that the resistance of slag truck wheels made of metal with increased copper content against the formation of ridge notches, which are the main reason for repairs of these wheels during operation, is significantly higher than that of serial ones.
KEY WORDS: *wheel steel, copper, red shortness, strength, dislocation density, wheel resistance, ridge notch*

1. Introduction

Other common alloying elements, it inevitably accumulates in steel during recycling. Currently, the copper content in general-purpose steel already significantly exceeds 0.1%. In the future, further copper "contamination" of these steels may be expected, as the proportion of scrap metal in their production will increase. Thus, it is necessary to consider all positive and negative consequences of this tendency. Despite numerous advantages that may be obtained from copper alloying, it is obvious that many steelmakers are concerned about the presence of copper as it may cause red-shortness. But nowadays, the problem of red-shortness can be solved by proper control of the steel chemical composition and process parameters. Obviously, this kind of information must be readily available before copper alloying of steels becomes more widespread. In our opinion, it is essential to comprehensively research the effects of copper additives in iron-based alloys.

The favorable effect of Cu on hardenability and transformation kinetics makes it possible to obtain a structure with high dislocation density at industrially feasible cooling rates and, thus, to impart high initial strength to the matrix. By adding copper, it is possible to obtain a mixed microstructure consisting of martensite and lower bainite (without upper bainite). Such microstructure is the most preferable in terms of strength and toughness of the material [1].

Therefore, it would be wrong to disregard the content of impurity alloying elements, because it is in small amounts that they have the strongest influence on the critical cooling rate. As our study has shown, the undercount of the content of chromium, nickel and copper leads to the fact that the properties of bandages and wheels with the same content of carbon and manganese have significant differences [2]. Furthermore, the hardenability of steels containing vanadium depends on the temperature of heating for hardening, and this must be taken into account when selecting heat treatment modes.

The paper presents the results of research on the influence of copper on the quality of wheel steel and performance characteristics of railway wheels.

2. Requirements of Global Standards to The Chemical Composition of Wheel Steel

Creation of new, more wear-resistant materials is of great importance for increasing the durability of railway wheels.

Currently, we can speak about several established systems of standards that regulate the requirements for the design of wheels and their properties for the possibility of operation on the largest railroad networks of the world. These include standards M-107/M-208 of the Association of American Railroads (ARR), International Union of Railways (UIC), the analogue of which is EN 13979-1 of the European committee of Standardization (CEN). Despite the common objectives, each of these regulatory bases has different approaches to assessing the strength and reliability of railway wheels, thus determining a unique set of target functions and constraints in solving the complex problem of improving the durability of railway wheels.

Today, solid-rolled railroad wheels in all countries are manufactured from high quality carbon steel. Usually, steel of different chemical composition is used for manufacturing wheels depending on the operating conditions of the rolling stock. According to the requirements of the AAR M-107/M-208 standard, heat-hardened wheels intended for operation in different conditions are manufactured in classes L, A, B, C and D: class A – high-speed operation with severe braking conditions but with moderate wheel loads; class B – high-speed operation with severe braking conditions and heavier wheel loads; class C – high loads and light braking conditions; class L – high-speed operation with more severe braking conditions than for other classes and low axle loads; Class D – high loads with increased resistance to wear and light braking conditions.

In Europe, wheels are mainly manufactured in accordance with the requirements of EN13262 from carbon steel with pearlitic structure with low ferrite content, in ER6, ER7, ER8, ERS8, ER9 grades.

Selection of chemical composition of steels and development of heat treatment modes for wheels to create a certain structural state will increase wear resistance, contact fatigue and resistance to brittle fracture.

Special requirements of the main standards are applied to the content of copper in steels for railroad wheels. According to the AAR M-107/M-208 standard, the copper content for wheels of classes L, A, B, C should not exceed 0.35%. The same norms on chemical composition are given in the standard A551/A551M.

The European Standard EN 13262 and British Standard BS 5892 regulate copper content up to 0.30%.

In contrast, the Indian Railways Standard for solid rolled wheels IRS R-19-93 specifies the maximum copper content of 0.20%.

In Ukraine, carbon steel for the manufacture of solid rolled railway wheels is used in accordance with the standard DSTU HOST 10791-2016 (Table 1).

Table 1

Chemical Composition of Wheel Steel in Accordance with DSTU HOST 10791-2016

Grade	Content, % in Steel					
	Carbon	Manganese	Silicon	Vanadium	Sulphur	Phosphorus
					not exceeding	
1	0.42-0.54	0.80-1.20	0.40-0.60	0.08-0.15	0.035	0.040
2	0.53-0.67	0.50-0.90	0.20-0.42	-	0.035	0.040

At that, the content of nickel, chromium and copper should not exceed 0.25%.

3. The Effects of Copper on the Properties of Iron-Carbon Alloys

For a long time, copper has been considered an unfavorable element in steel because it causes brittleness at elevated temperatures [3]. Despite the fact, that it may cause red-shortness, corrosion resistance and mechanical properties of steel can be improved by adding copper as an alloying element [4].

Experiments when copper was added to structural steels for its ability to impart resistance to atmospheric corrosion began in 1916 in the United States. The first commercial use of atmospheric corrosion resistant steel containing copper occurred between 1933 and 1935. Copper additions ranging from 0.25 to 0.5% in carbon and low alloy steels significantly increase the resistance to atmospheric corrosion, and these steels have been called weathering resistant steels [5].

The ability of copper alloyed steels to resist atmospheric corrosion is not the main reason that today gives impetus to the development of copper containing steels. Until recently, it has not been fully recognized that in addition to improved corrosion resistance, copper alloying can make a significant contribution to the mechanical properties of steel.

Copper can contribute to the hardening of steels through solid solution strengthening. This hardening occurs at a level of about 12 MPa with a copper addition of about 0.5%. Apart from solid solution strengthening, copper can also enhance the hardenability of steels. In addition, since copper is an austenite stabilizer, it lowers the austenite-to-ferrite transformation temperature, resulting in finer ferrite grains in the structure.

Copper, if its content in steel exceeds 0.75%, has a favorable effect on dispersion hardening and grain refinement due to the formation of nanoscale copper sulfide precipitates during reheating [6]. Copper additives also increase the fluidity, which in turn increases the castability of the steel.

A study of the effect of martensitic deformation on dispersion hardening during tempering showed that as-quenched martensite exhibited predictable behavior: dispersion hardening increased at higher tempering temperatures and longer tempering times. It was found that dispersion hardening in cold-rolled martensite was independent of tempering time and tempering temperature. Furthermore, higher yield strength increase was observed in unrolled material (200 MPa) compared to 120 MPa in cold rolled material. As for copper hardening of solid solution, it occurs when copper is dissolved in the ferrite matrix.

However, this hardening mechanism takes place only in case of low dislocation densities [7]. Furthermore, there is an increase in cast iron hardness and tensile strength with increasing copper content due to dislocation hardening mechanisms. In particular, with the addition of even 1% copper, the increase in σ_b values of high-strength cast iron can be 100...200 MPa [8].

In some cases, copper alloyed steels are used as tribomechanical materials. For instance, when increasing the copper content in cast iron up to 10%, an inverse linear dependence of the coefficient of friction in a pair with steel on the amount of alloying element was recorded [9]. The amount of copper additions in steel depends on the desired effect and the use of the final product. However, by controlling the amount of copper content in the alloy, it is possible to obtain a combination of improved mechanical and physical properties.

Considering the fact that the total copper, nickel and chromium content in wheel steel in a number of plants varies from 0.18 to 0.5% or 3 times, it is of interest to investigate the effect of copper on the characteristics of railroad wheels.

4. Experimental Studies on the Effect of Copper on the Properties of Railroad Wheels

To evaluate the effect of copper on the technological properties of steel (including resistance against cracking during hot deformation), a metal was melted. The chemical composition thereof is given in Table 2 [10].

The obtained steels were used to produce 840 mm diameter wheels for cast iron trucks operating with increased (up to 0.4 – 0.5 MN) axle load, at low travel speeds (up to 15 km/h) and without application of braking heat load to the wheel rim.

Table 2

Chemical Composition, %, of Experimental Steels with Increased Copper Content

Melting	Open-Hearth Furnace Capacity, t	C	Mn	Si	P	S	Cu	V
1	250	0.65	0.70	0.29	0.009	0.030	0.18	-
2	10	0.56	0.92	0.35	0.023	0.018	0.30	-
3	10	0.59	0.60	0.31	0.028	0.024	0.38	0.00
4	10	0.64	0.60	0.29	0.017	0.025	0.40	0.08
5	10	0.72	0.80	0.38	0.032	0.010	0.40	0.08

During the manufacturing of wheels made of steel with increased copper content, no deterioration of its technological properties was observed. There were no signs of copper "sweating out" when heating the billets for rolling, there were also no cases of tearing on the billets. Deterioration of machinability of wheels of some melts is caused by increased strength of steel due to high carbon content and the presence of vanadium. After machining, wheels from experimental steel underwent thermal hardening: they were heated to a temperature of 830 – 860^{0}C, and then subjected to vertical hardening during 130 – 150 s, followed by tempering at a temperature of 470 – 500^{0}C.

The hardness distribution over the cross-section of wheel rims manufactured from steels of different melts is quite uniform, and the hardened layer extends to a considerable depth. The maximum strength is observed in the wheel rim made of steel of melting 5 (0.72% C, vanadium and copper additives) (Table 3). With approximately the same content of carbon and manganese in steels of melts 1 and 4, the hardness of the latter is 25 HB higher, which is due to the hardening effect of vanadium and copper.

At one of metallurgical plants, experimental wheels made of carbon steel and steel with vanadium and copper additives were subjected to operational tests under a slag truck. Simultaneously, the durability of mass-produced wheels operating under identical conditions was observed.

It was found that the resistance of high-strength wheels of slag trucks made of experimental steels against flange wear, which is the main cause of repair of these wheels in operation, is much higher than mass-produced ones [10]. In general, the service life of experimental wheels is more than twice as long as that of conventional wheels made of steel with lower carbon content (lower limit of 0.45%) and low strength properties (at least 800 MPa).

Table 3

Mechanical Properties of Wheel Rims of the Experimental Batch at a Depth of 30 mm

Melting	Tensile Strength, MPa	Elongation at Fracture, %	Reduction of Area, %	Hardness HB
1	1000	15.5	35.0	285
2	1000	16.0	33.0	277
3	990	16.5	35.0	277
4	1110	14.5	32.0	311
5	1150	13.5	22.0	311
According to HOST 10791-81	911 – 1107	not less than 8	not less than 14	not less than 255

5. Conclusions

Prospects of copper content increase due to steel recycling are shown.

The requirements of global standards to the chemical composition of wheel steel are analyzed.

Specific data on the effect of copper on metals of various functional purposes, as well as the results of experimental studies of technological properties of railway wheels with increased content of copper are given.

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