Proceedings of the 18th Int. Wheelset Congress 7-10 November 2016, Chengdu, China

Production of Railcar Cast Wheels in Sand Molds

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Abstract: Present-day operation conditions for railcar wheels involve high axle loads and velocities which lead to strict requirements to their mechanical properties characteristics and resistance to cyclic stresses. Complying the requirements come from selection of proper wheel alloy chemical composition and production method of the part. The method must guarantee absence of critical defects which may be a cause of failure for the wheel body. The present work investigates manufacturability of wheels with most economically reasonable way – by metal pouring into sand temporary mold. This method favorably compares with known cast wheels production practices which demand special maintenance for permanent and semi-permanent molds made of materials with significant differences in their heat removing abilities. The work pays closer attention to development of optimal wheel steel chemical composition including vanadium microalloying, melting conditions and selection of proper final heat treatment regimes. The up-to-date computer modeling tools and techniques were utilized during the work process, appropriate experimental data were collected and pilot batches produced. The work shows that selection of rational conditions for pouring and feeding of castings combined with optimal steel composition allows wheels production in temporary sand molds in such a way that mechanical and performance characteristics of final parts are non-inferior to whose which are typical for parts produced by traditional known methods.

Keywords: railcar cast wheels, sand casting, wheel alloys.

1 Introduction

Production of railcar wheels by steel casting isn't widespread in the world as much as wheels production by hot deformation. Widespread use of cast railcar wheels takes part in USA, Latin American countries, Canada, China and India. In European countries, including Russia, national standards specify use of rolled-steel wheels only.

Hot deformation method for wheels production ensures strain hardening due to achieving the highly dispersed metal structure, density increase and compensating or removing of initial cast structure discontinuities. Steel casting wheels production procedure isn't included the above mentioned operations of material structure and properties improving. For that reason high material strength characteristics must be provided with special chemical composition of the steel, cast structure solidity and following heat-treatment-operations. Steels for rolled wheels are not fully applicable for casting, so there is a need in development of special steels for the production method.

Available information resources aren't containing unquestionable data on fundamental performance advantages of rolled wheels vs. cast wheels [1-4, etc.]. Benefits of cast wheels production consist in significant decrease of number of processing operations, which leads to shop cost reduction. Present work investigates possibilities of cast wheels production from specially developed steels, moreover the wheels must have such configuration and mechanical properties combination which may make them acceptable for use in countries of 1520 mm gauge railway system.

2 Development of Cast Wheel Design

Typical wheelset operational cycle in the space of 1520 mm gauge means significant problem on the way of developing of easily manufacturable cast wheel part design. Rim of the new wheel must be massive so as to ensure several numbers of periodical machining operations during the whole wheelset operational period as long as tread surface experiences step by step wear. The width of non-machinable rim of new USA-type railcar cast wheel part is 35-40 mm, and for the Russian new wheel the value must be 78 mm initially. As far as new and new machining operations are performed for the wheelset it is acceptable to decrease the rim width up to 22 mm. Seems like the non-machinable wheels with initially narrow rim area are non-perspective for present day Russian railway market.

Designing process was supported with computational analysis. Stress level in the newly developed wheel was estimated with static strength calculations according to appropriate European norms [5], as well as fatigue endurance limit was calculated with the simulation based on the applicable standard method [6]. As a result of the calculations, with taking into account the data revealed in [7], the new cast wheel design was developed (Fig. 1) in such a way that it complies with requirements of interstate standard [8] which is in force on territory of Russia.

The developed wheel features a half-moon-shaped disk and stiffening element in the vital disk-to-rim area. Shape variations for other part areas are strictly limited by requirements of [8]. The weight of new cast wheel part must be 410 kg approx.

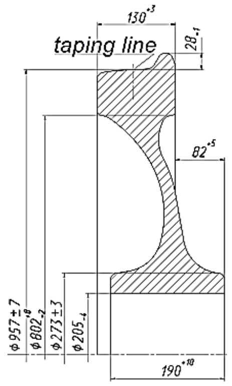


Figure 1. The configuration and principal dimensions of railcar cast wheel compatible with operational cycle at 1520 mm railway gauge

3 Development of Casting Technology

Railcar wheel is a simple shape casting, however the requirements to inner solidity, structural and material properties uniformity are very tough. One of the main factors which add complexity to casting procedure is a need to operate with high-carbon and medium-carbon steels. The steels have wide solidification range and lowered casting characteristics.

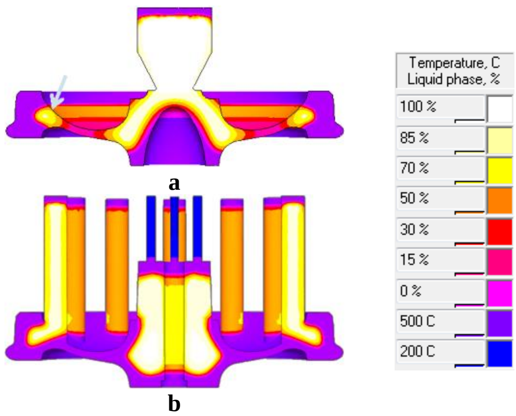


Figure 2. Temperature-phase fields at the critical moment of wheel casting formation according to computational analysis of ABC (a) and Griffin (b) casting technologies

The absolute majority of cast wheels are produced at present days by two technologies [9] each of which involves graphite as a main component of the foundry mold. So called ABC technology is based on metal pouring in graphite mold with sand lining on the part that forms a disk surface. Sand lining works as a thermal insulator, therefore it is achievable to feed the thick rim through thin disk. As a result of that the solidification unidirectionality is realized for the whole volume of the casting: rim solidifies first, disk is next and hub is lust. Griffin technology provides wheels production by low-pressure die casting and the die is made of graphite. Hot spot in the disk-to-rim area are compensated with risers. Unidirectional solidification isn't observed for the whole casting body: disk solidifies first, then rim and hub solidify independently.

Technology development for predeveloped wheels production was carried out through computational analysis in PoligonSoft and ProCAST casting simulation software. Calculation results showed that the wheels shaped in a way compatible to Russian market may be hardly produced by conventional technologies. In case the ABC concept is used, there is a problem of guarantied shrinkage defects in the disk-to-rim area (Fig. 2, a). Very thick disk only may feed the problem area, but the measure leads to inacceptable part weight increase. Calculations proved effectiveness of additional disk heat insulating with a low-conductivity insulator integrated into sand lining – the measure [10] adds a complexity to the technology, however initially it was described and applied for relatively thin rim. Calculations imitating Griffin technology concept showed that only installing of 14 massive heat-insulated risers of 70 mm diameter might feed the problem area in the cast wheel of desired design (Fig. 2, b).

Both methods are based on graphite molds production, which requires purchasing and appropriate servicing of the special machinery equipment, reusable graphite die maintenance. Under the conditions of access to railway castings foundry utilized vacuum-film (so called V-process) and no-bake sand molding it was decided to fix the reachable molding processes as a basis for the casting technology developing. The discovered optimal technology solutions proved by computer modeling were later put into practice and finally improved through appropriate trials.

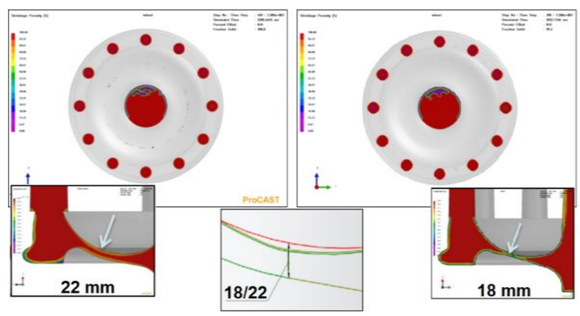
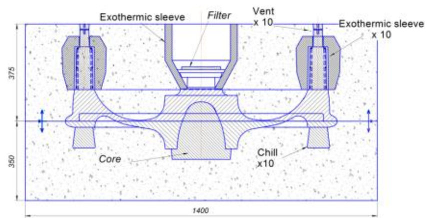


Figure 3. Disk thickness influence on porosity occurring in the event of significant melt overheating and thermal reasons for defects formation

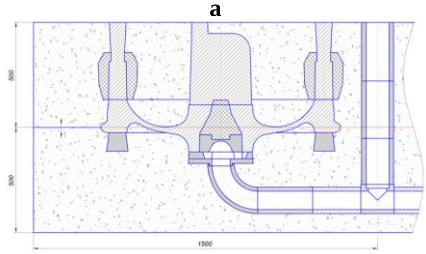
Castings were placed horizontally in the mold, flange down to ensure guarantied good quality for the element. Calculations and practical trials showed that presence of flange small protrusion doesn't break rim solidification unidirectionality. Thick rim and hub booth need feeding in case the wheel is produced in sand molds. Disk may tend to nondirectional solidification. It was proved that pouring temperature decrease is an effective measure for removing the mentioned tendency and disk axial porosity prevention. If the pouring temperature control can't be done strictly configuration features may straightly improve solidification directionality. The measure is connected with adding of appropriate tapering from left and right sides to the disk center to make the area thinnest (Fig. 3). However, the measure makes some problems. In case the geometry is changed with thinning of the central area the wheel part becomes weaker, while thickening of right and left disk areas makes the part heavier and may amplify hot spot in the dangerous rim area.

As a result of calculations and trials the final technology concept included rim feeding with regularly spaced 10-12 risers in exothermic sleeves. Zones between risers must be chilled from the bottom with steel chills to guarantee porosity prevention. The central sand core installed into hub makes the element lighter, helps to feed it easier and decreases the amount of machining work.

Two casting technologies were introduced – bottom pouring of two castings in the mold and top pouring through the ceramic filter installed in the central hub riser surrounded by exothermic sleeve (Fig. 4). The sleeve allows heat-up the riser and decrease its size, while the filter, which is initially installed in the sleeve bottom, floats up to the liquid free surface after the end of pouring. So the filter ensures laminarization of the liquid metal stream and finally works as an additional heat insulation of the riser. Rim feeding system is the same for both technologies.



a



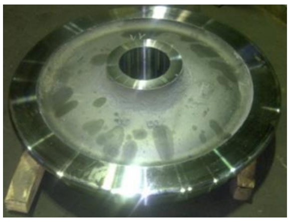
b

Figure 4. Casting technologies for production of wheels pilot batches: a – top pouring through the hub riser; b – bottom pouring of two castings

The method of pouring through the hub riser showed low compatibility with V-process molds. At the end of pouring metal and appropriate mold area form closed “pocket” at the top hub region, that caused failure of the mold at the place. It was proved experimentally that the failure may be prevented by installing vents which is inclined in such a way to avoid intercrossing with hub riser. However, the measure makes the molding procedure too complicated.

By the reason it was decided to produce the mold for top pouring with ester-cured phenolic sand only, while the molds for bottom pouring were still produced with V-process technology. Additional benefit of bonded no-bake mold is improved stability of its surface covered with refractory coating while it interacts with liquid metal for long period. The fact allows stabilize the wheel castings surface quality and prevents sand drops on it. Disadvantage of the mold is an increased tendency to gas evolving due to binder gasification, which may lead to appropriate casting defects. The tendency may be controlled through decrease of binder content in the mix, avoiding the over-compacted sand regions with poor gas permeability, arranging the vent pin holes during molding procedure.

a



b

c

Figure 5. Experimental cast wheels at different production stages: a – after the shot-blasting and removing of risers and gating system;
b – after the rim quenching and final machining;
c – solidity checking with liquid penetrant inspection

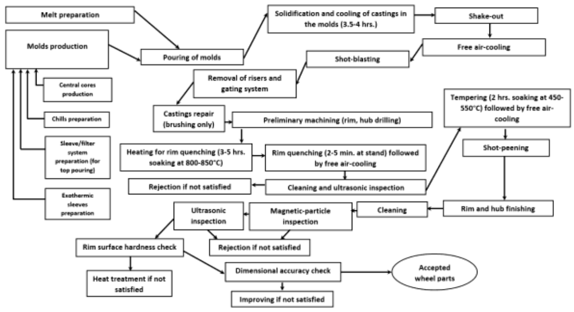


Figure 6. Manufacturing operations sequence for production of pilot batches of cast wheel parts

In terms of automation, no-bake molding for the wheel is more favorable than V-process because the casting technology requires installing a large number of riser sleeves. Planning of large-scale manufacturing of wheels in sand molds must take into account the prolonged solidification time in comparison with graphite molds: complete solidification of the casting including risers takes about 1.5 hrs., cooling in the mold prior to shake-out needs 3.5 hrs. Top pouring allows 17% metal economy per one casting in comparison with bottom pouring. Ratio of the mass of casting without risers and gating system to liquid metal gross is no less than 75% for top pouring. Per totality of advantages the technology of top poring through wheel’s hub riser into bonded sand mold is considered as prioritized.

As a result of calculative and experimental work the casting technologies were tuned for the sufficient level which ensures defect-free wheels production (Fig. 5). Manufacturing operations sequence which allows achieving of good wheel parts from sand mold made castings is given in Fig. 6.

4 Development of the Chemical Composition of Wheel Steel

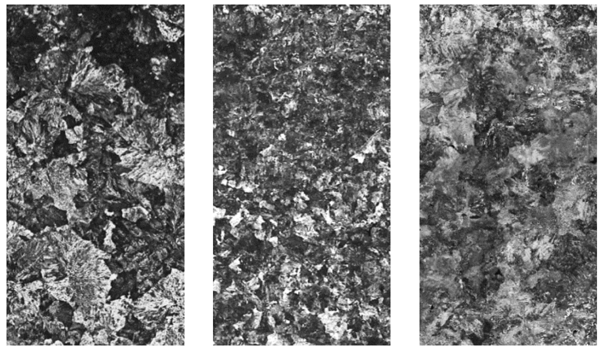
The main objectives of the study were the development of a chemical composition of the steel for cast wheels and search for optimal parameters of all the wheel processing steps to achieve the desired level of mechanical properties and performance characteristics. Basic requirements for steels are the following: high strength, including the hardness of at least 320 HB at a distance of 30 mm from the tread surface, high impact strength (up to –60°C) and low degree of structure imperfections [8].

A marked improvement of mechanical properties and performance characteristics of steels for wheel castings can be reached by the addition of micro-alloying elements. Vanadium helps to reduce the austenite grain size, increase yield strength, ultimate strength and impact strength; chromium is essential for increasing hardenability and for uniform hardness distribution. The experiments have shown that for the considered steel types an increase of chromium content by 0.1% yields to an increase of the material strength characteristics by 50 MPa. Modern chemical composition design concepts for freight cars railway wheels [11-14] were taken into account while developing the steel compositions, which are the following: reduction of carbon content and additional alloying by chromium. This leads to the formation of bainitic structure, which provides a more stable level of strength and performance characteristics.

Initial search of optimal steel composition was performed by means of computer thermodynamic simulation. The used physically based models allowed to calculate the material strength characteristics, depending on the steel chemical composition and cooling conditions. As a result, several experimental steel compositions were developed:

- Steel1 – medium carbon steel, alloyed with manganese and vanadium;
- Steel2 – medium carbon steel with decreased carbon content, alloyed with chromium and vanadium;
- Steel3 – medium carbon steel, alloyed with chromium and vanadium.

A series of industrial heats of the named steels were produced using an electric arc furnace. For the refinement and improvement of initial as-cast structure an addition of alloys containing barium and rare earth metals and argon bubbling of steel melt was carried out in the ladle. Comprehensive studies of the as-cast structure and influence of heat treatment conditions on the steels structure and properties were carried out on the cast wheels with different chemical composition, alloying conditions, etc.



a b c

Figure 7. Panoramic photos of as-cast microstructure of the rim area of the experimental steels (×50): a – Steel1; b – Steel2; c – Steel3

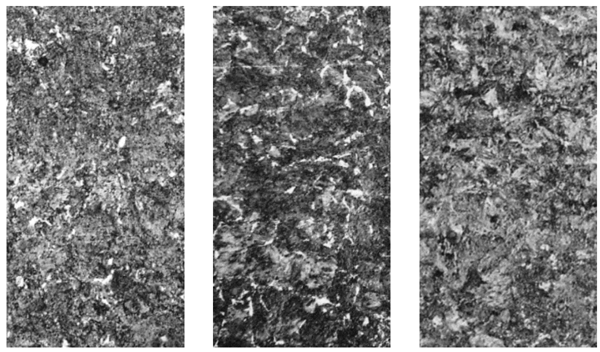


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Fig. 8. Photographs of rim microstructure (30 mm from the tread surface) (×500): a – Steel1 (fine perlite, pearlite and incomplete ferritic network); b – Steel2 (fine perlite and ferritic network); c – Steel3 (fine perlite and rare ferrite inclusions)

Typical results of studies of as-cast structure (grain size, microporosity, nonmetallic inclusions) obtained for the experimental steels are given in Table 1. Represent tive photographs of as-cast structure of these steels are given in Fig. 7.

After the conducted analysis of the experimental data it can be concluded that the level of non-metallic inclusions of steel meets the requirements of the applicable standard [8]. The castings made from Steel1 and Steel3 show marked microporosity and rough as-cast structure characterized by extensive borders of primary crystallites (4-6 mm and more); at the same time the castings made from Steel2 did not show so pronounced structure defects. These imperfections of as-cast structure can be the cause of low mechanical properties, especially impact strength and plasticity [15, 16]. After all the necessary processing steps (Fig. 6) a set of mechanical tests, microstructure analysis of the material and fracture toughness tests of wheel rim was carried out on the wheel castings selected from the experimental heats of different steels. Table 2 provides the information on the best mechanical properties achieved on the discussed steels, first of all, by realizing the optimal regimes of rim quenching and subsequent tempering. Fracture toughness tests demonstrated that all the steels meet the applicable requirements [8]: more than 50 $MPa{\cdot}m^{1/2}$.

Steel2 showed the best combination of strength, plasticity and toughness (especially at a temperature of -60°C). This fact can be attributed to an optimal combination of the major alloying elements (C, Mn and Cr), finer as-cast microstructure compared to other steels, and low microporosity level. Fig. 8 shows the typical photographs of microstructure of investigated steel in the rim area of cast wheels.

As a result of the experiments taking into account the proximity of the achieved properties to the standard requirements, the chemical composition, melting conditions, alloying, casting and heat treatment of castings made from the experimental Steel2 were found to be the most appropriate for the manufacture of wheels in sand molds [8].

Table 1. As-cast Structure Characteristics of the Experimental Steels

Steel	Non-metallic inclusions, severity levels			Micrporosity in wheel rim		Micrporosity in wheel disk		As-cast grain size in wheel rim, μm	As-cast grain size in wheel disk, μm
	Sulfides	Oxides	Nitrides	Content, %	Average size, mm	Content, %	Average size, mm		
Mn-V Steel1	1-2	1	1	0.2	0.01	0.68	0.013	1087	900
Cr-V Steel2	2	1	-	0.03	0.016	0.05	0.016	422	655
Cr-V Steel3	2	1	-	0.2	0.018	0.65	0.023	623	589
GOST 10791-2011 requirements, not more than									
T	1.5-2	1-2.5	-	-					

Table 2. Mechanical Properties of Cast Wheels

Steel	Rim						Disk						
	UTS, MPa	YS, MPa	A, %	Z, %	HB[1]	KCU, J/ cm^2 +20ºC	UTS, MPa	YS, MPa	A, %	Z, %	HB[2]	KCU, J/ cm^2 +20ºC	KCU, J/ cm^2 –60ºC
Steel1	1010	793	3.7	6.0	326	21.7	813	543	3.1	5.9	289	25	17
Steel2	1043	800	4.7	7.0	322	27.9	903	495	13.5	24.8	276	32.5	31
Steel3	1123	860	2.6	6.9	368	10.8	943	533	4.1	6.6	311	10.6	8
GOST 10791-2011 requirements													
T	>1020	-	≥9	≥16	>320	≥18	$\le 0{,}9{\cdot}UTS_{rim}$	-	-	-	$\le HB^1$-30	≥18	≥15

[1]Hardness of the rim at a distance of 30 mm from the tread surface; [2]Hardness of the point A according to GOST 10791-2011

5 Conclusions

The result of the present work shows possibility of production of railcar cast wheels with acceptable solidity level utilizing sand molds. The prioritized casting technology for that is based on steel pouring into no-bake mold through ceramic filter placed at the hub riser cavity.

The highest and more stable level of strength, plasticity and impact material properties was achieved with pouring of medium carbon steel with decreased carbon content, alloyed with chromium and vanadium due to optimal combination of main alloying elements, fine as-cast structure and minimal level of structural imperfections. Improving of above mentioned characteristics of mechanical properties of wheel steel may be associated with melt cleanliness control, development of inoculation and microalloying technologies for obtaining the fine as-cast structure, heat-treatment regimes, including thermocycling for refinement of austenite grains.

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