Application of Pressure Poured Cast Wheel Technology for European Freight Service

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Abstract

North American freight railroads, and freight railways around the world, have long known about the many advantages of pressure poured cast steel wheels for freight service. Such cast wheels are designed and produced with modern technology to provide superior steel cleanliness, excellent wear resistance, and a plate shape designed to resist stresses associated with thermal loads and resist fracture. Due to extensive plant automation, efficient manufacturing methods, and proprietary manufacturing and ultrasonic inspection technologies, the pressure poured cast wheel process provides not only excellent initial value for users, but also a long lasting and safe wheel designed to minimize the total life cycle cost. This paper describes recent efforts to bring pressure poured cast wheels into European freight service. The Polish Railways have elected to take advantage of the pressure poured cast wheel and approximately seven thousand are currently in service under freight wagons. Results of laboratory residual stress testing, wheel/rail contact mechanics, multi-body systems, and finite element analysis (FEA) modeling, conducted in Poland at research organizations such as the Institute of Fundamental Technological Research of PAS (IPPT PAN), the Railway Institute in Warsaw (IK/CNTK), the Rail Transportation Department of the Silesian Technical University, and the Rail Vehicles Institute “Tabor,” in Poznan are briefly reviewed. Also, Polish field service trials of AAR Class C and ER7 pressure poured cast wheels are briefly described, and comments are provided regarding the use of AAR Class C pressure poured cast wheels in Polish freight service. Recently, wear tests have been performed at IK/CNTK in Warsaw, Poland, using a specially designed wheel/rail test rig to examine the amount and type of wheel and rail wear present for operation of various wheel types on European rail. AAR Class C, AAR Class B, and ER7 pressure poured cast wheels were tested, along with a forged ER7 wheel, and a tyred wheel type used in Poland. This testing was conducted in response to claims that pressure poured Class C cast wheels are damaging the infrastructure of Polish Railways. Further, dynamic modeling simulations were conducted by the Institute of Fundamental Technological Research PAS, and Krakow University to determine if pressure poured cast wheels were more damaging to the track structure than currently used European forged wheels. Additionally, use of pressure poured cast locomotive wheels in the UK is described, with emphasis on service experience over more than a decade of continuous use. Finally, a new pressure poured cast wheel design for 22.5/25 metric ton European freight wagon service is discussed and the FEA results are reviewed.

Introduction

Pressure poured cast wheels are widely used in North America by freight railroads and in fact approximately 75 percent of wheels in freight service (under 1.6 million freight cars) are pressure poured cast wheels. These wheels are manufactured in high-volume, technically advanced, highly automated cast wheel manufacturing plants at several North American locations. A small volume of pressure poured cast wheels are in North American passenger service, however the decision to produce almost exclusively freight wheels is an economic one, since the volume of passenger and transit wheels in North America is very low, perhaps on the order of four percent of the total wheel market. Additionally, freight car wheels are standardized in terms of size and dimensions by the Association of American Railroads (AAR) with three or four wheel sizes providing the most volume.
Pressure poured cast wheels are used by all major North American railroads, in all climates from +40°C to -40°C, with axles loads of up to 32.5 metric tons, and such wheels are known for their durability, dimensional consistency, superior rotundity, ability to resist severe thermal loads from tread braking, and excellent service performance. Due to the automated, high volume manufacturing methods utilized, the technical details of the pressure pouring process itself, and soundness of the casting, these railroads enjoy a favorable life cycle cost for wheels. Not only is the initial value proposition of the pressure poured wheel outstanding for end users, but the durability of the wheel is well known.

Recent Pressure Poured Cast Wheel Use in Europe

A previous paper described the history of cast wheels in North America and Europe, pointed out the many countries of the world that are using cast wheels and reviewed the research efforts made to improve wheel casting technology [1]. This paper also described the extensive tests that were conducted on pressure poured cast wheels, made of AAR Class C steel (0.67–0.77% carbon) at Polish research organizations such as the Rail Transportation Department at the Silesian University of Technology and the Rail Vehicles Institute “Tabor.” These tests included fatigue strength analysis of wheels in conformance with PN EN 13262 and PN EN 13979-1, extensive laboratory testing in accordance with PN EN 13262, dimensional and balancing checks, non-destructive testing, the wheel braking bench test, and a review of two separate field tests under cars of 20t/axle loads. Of particular interest from the field tests was the finding that forged UIC wheels were more susceptible to flat spots and “corrugation” damage than the Class C pressure poured cast wheels. At the end of these successful evaluations in 2007, which clearly demonstrated the suitability of pressure poured cast wheels, the wheels were accepted for use in Polish freight service, and more than 7,000 are in use.

Other countries in Europe using pressure poured cast wheels include the United Kingdom and Sweden. The UK has been successfully using a 42-inch diameter Class B (0.57–0.67% carbon) locomotive wheel for more than ten years, starting when approximately 250 new Electro-Motive Division (EMD) Class 66 locomotives were purchased by the English, Welsh and Scottish (EWS) Railway. Service experience for these wheels has been excellent with no service problems or failures reported. In 1999 a paper by Bridges outlined the considerations for pressure poured cast wheels gaining entry into the UK including mechanical properties, finite element analysis studies, and service monitoring [2]. Also Sweden has been using the pressure poured cast freight wheel on the heavy-haul iron ore line between Kiruna, Sweden and the Norwegian coast. Both of these service environments are quite severe. It was also noted by mechanical personnel in Sweden that pressure poured cast wheels exhibited fewer flat spots than other forged wheels.

Infrastructure Testing Requirement - Overview

Although several thousand Class C pressure poured cast wheels had entered service in Poland and were performing without incident, questions were raised that perhaps the cast wheels, with higher carbon content and hardness, were damaging the track, rails and infrastructure. Without any technical data available, the infrastructure personnel in Poland took action to investigate the issue. PKP Polskie Linie Kolejowe S.A. (PLK), responsible for the railway infrastructure in Poland, commissioned a study to determine the effects of the Class C pressure poured cast wheel on the infrastructure. This research work was performed by independent entities selected by PLK, including: Krakow University of Technology, The Institute of Fundamental Technological Research of the Polish Academy of Sciences (IPPT PAN), and the Railway Institute in Warsaw (IK/CNTK). The work, headed by Professor Roman Bogacz of Krakow University of Technology and the Institute of Fundamental Technological Research of the Polish Academy of Sciences (IPPT PAN) at the direction
of PLK, was commissioned to compare the dynamic interactions and wear of freight car cast and forged/rolled wheels on rails currently used in Europe.

The research program involved the following aspects: 1) Comparison of North American norms with European norms related to rails and wheels, 2) Investigation of the track/rail vs. vehicle interaction, for pressure poured cast wheels manufactured with ER7, AAR Class B and AAR Class C steel, and for UIC forged/rolled monobloc and tyred wheels, with European rails, and, 3) Wear testing of wheels and rails on the EMS 60 test stand, a specially designed wheel/rail test rig, to examine the amount of wheel and rail wear. The work in 2) also included analyzing the residual stresses in rail before and after wheel vs. rail wear testing, ultrasonic testing of the rails before and after wear testing, experimental evaluation of the wheel/rail contact stiffness and the wheel plate stiffness using mechanical and laser optics systems, and computer simulations of the dynamic interaction of a wheel running on corrugated rail

Comparison of Specifications

There are a number of important differences between European norms and AAR specifications for wheels. AAR M107/208 is the document governing manufacture of wheels in North America [3]. AAR wheels are manufactured using Class L, A, B, C, and now more recently D, steel. Class C wheels are exclusively used for freight cars in North America, and are on most locomotives, while Class B wheels can be found on some locomotives, and Class A and L wheels (lower carbon) are found only in passenger service. Class D wheels are microalloy wheels used in certain freight services. The pressure poured cast wheels used in Poland are Class C steel, which has 0.67-0.77% carbon and a hardness range of 321-363 BHN. Class B wheels have a carbon content of 0.57-0.67% and a hardness range of 302-341 BHN. For both Class B and Class C wheels, the maximum silicon and manganese contents are 1.0% and 0.90%, respectively. European ER7 wheels for freight service have a maximum carbon content of 0.52%, maximum silicon and manganese contents of 0.40%, and 0.80%, respectively, and a minimum hardness of 235 BHN. North American wheels thus have significantly higher carbon contents and hardness ranges than typical European wheels. Also, the only mechanical testing requirement for North American wheels is Brinell hardness - there are no requirements for tensile, charpy and fracture toughness tests, etc., such as found in European norms. At the time of this testing, there was no European specification for cast ER7 wheels.

Residual stress measurement is not required for North American wheels, either new, or in service. North American wheels are required to have a “low stress” plate shape, and the AAR S-660 finite element analysis method is used by AAR to determine stresses in wheels under mechanical and thermal loading. The pressure poured cast wheel has a significantly different plate shape than European wheels, with more curvature of the plate designed to resist thermal stresses from long downgrade braking in service. Although deflection of the wheel design is considered in Europe, this is not a consideration in North America. Regarding rail hardness in North America, the specifications for which are governed by the American Railway Engineering and Maintenance of Way Association (AREMA), the minimum surface hardness is 310 BHN for new “standard rail” and is 370 BHN for “high strength rail” [4]. Although there is older, softer rail still used in North America, rail is generally harder than in Europe.

Wheel/Rail Wear Testing

Wear testing (unlubricated) was conducted on the EMS 60 test stand at IK/CNTK. New 920 mm diameter wheels and new 60E1 rails were used for each wear test, and each wheel type was tested three times. Pressure poured cast wheels of ER7, AAR Class B, and AAR Class C steels were
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gathered for testing. Forged/rolled wheels manufactured by a leading European manufacturer, and also tyred wheels used in Poland, were provided by PKP Cargo. Two types of European rails were tested – Thyssen/Krupp 60E1 rails provided by Krakow University of Technology and Huta Katowice (Arcelor Mittal) 60E1 rails provided by PLK. Rails were hardness tested by IK prior to wear testing and were found to be within specification. The average hardness reading for the Thyssen Krupp rail was 281 BHN and the average hardness reading of the rail provided by PLK was 284 BHN. Since it is the responsibility of the wheel manufacturer to meet specifications with regard to hardness, etc., the forged and tyred wheels were assumed to be within specification, having a minimum hardness of 235 BHN. Pressure poured cast wheels used for the wear testing had average hardness values as follows: Class C = 352 BHN, Class B = 334 BHN, ER7 = 320 BHN. (Note: These hardness readings were taken at the pressure poured cast wheel manufacturer, on the front rim face, as per AAR standards, prior to shipping the wheels to Europe for wear testing). The pressure poured cast Class B, Class C, and ER7 wheels met the appropriate AAR and EN requirements for hardness.

Wheel and rail profiles were taken at the start of testing, and after 25,000 cycles, 50,000 cycles, and 100,000 cycles of rig operation. Wheel profiles were taken with a wheel profile measurement gauge at four points around each wheel, every 90 degrees around the clock. We note that all wheels started the test with the same flange/tread profile, as machined by ZNTK in Minsk Mazowiecki, Poland. Rail profiles were taken with a rail profile measurement gauge at the center of the rails, and at points 200 mm to the left and right of center. Loading on the test stand was 55kN. In order to obtain simulated service flanging of the wheel against the rail, a 1.5 degree wheel angle of attack was applied vs. the longitudinal axis of the rail. This allowed for continuous flanging of the wheel against the rail. The test rig pulled the wheel along the rail under load, then allowed the wheel to roll back into position before another load cycle began. Figure 1 shows the EMS 60 test stand, while Figure 2 shows the wheel/rail orientation.

![Figure 1.EMS 60 wheel/rail wear test rig.](image)

![Figure 2. Wheel/rail orientation on test stand.](image)

Results for the wheel/rail wear testing were very favorable for the pressure poured cast wheels. For wheel wear and rail wear, the pressure poured cast wheel caused significantly less wear than the forged/rolled UIC monobloc wheel and the tyred wheel. Table 1 shows the average wear data, combined for all rail and wheel types, as measured by IK/CNTK staff, after 100,000 operation
cycles on the EMS 60 test stand. Rail wear, the primary focus of the study, was obtained from rail profiles. Wheel wear was determined on the basis of wheel weight loss from a formula/method used by the Railway Institute. From these results it is clear that the Class C pressure poured cast wheel is not having an adverse effect on rail wear. In fact, both the wheel wear and rail wear are significantly less for the Class C wheel. Test details and various profiles are contained in a report produced by IK [5]

<table>
<thead>
<tr>
<th>Wheel Type</th>
<th>Average wear of rails, mm</th>
<th>Average wear of wheels, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forged/rolled UIC ER7</td>
<td>3.86</td>
<td>898</td>
</tr>
<tr>
<td>Tyred</td>
<td>3.33</td>
<td>811</td>
</tr>
<tr>
<td>Cast ER7</td>
<td>1.46</td>
<td>350</td>
</tr>
<tr>
<td>Cast Class B</td>
<td>1.42</td>
<td>334</td>
</tr>
<tr>
<td>Cast Class C</td>
<td>1.26</td>
<td>292</td>
</tr>
</tbody>
</table>

Table 1. Average wear of rails and wheels after 100,000 cycles of operation.

Rail Longitudinal Residual Stress

Longitudinal residual stress was measured in all rails using the DEBRO 30 device before wheel/rail testing, and after 100,000 cycles, to determine if any difference in residual stress was created by the pressure poured cast wheel. There was no significant difference in the residual stresses level in various rails depending on the type of wheel. Minimal difference of residual stress along the rail is obtained for the case of rail rolled upon by the Class C wheel.

Non-destructive ultrasonic testing of rails

The rail non-destructive testing was performed before and after rolling using ultrasonic detection equipment EPOCH LYGH. There were no differences in ultrasonic indications in all rails investigated.

Experimental measurement of wheel/rail contact stiffness and plate stiffness

The determination of the wheel/rail contact stiffness and the wheel plate stiffness is important to evaluation of the wheel/rail interaction, wear of rails and the influence of vehicle on track durability. The above mentioned two kinds of stiffness were measured on the EMS 60 test stand (at IK, CNTK) using a classic mechanical method and laser method for displacement measurements Figure 3. Measurements were repeated and the average value was taken to obtain linear or nonlinear characteristics.

An example of the wheel plate measurement is shown in the left hand side of Figure 3, while the wheel/rail contact stiffness measurement is shown on the right side. Results of laser measurements of the contact stiffness and measurement of the plate stiffness, as well as nonlinear and linear...
approximated characteristics are given in Figure 4 and Figure 5. Different wheel types provide different amounts of displacement and rim rotation under loading, due to plate shape and wheel geometry. The amount of measured displacement is shown vs. applied test load. Both sides of the rim were measured (giving different displacement results due to rim rotation) and the data scatter is noted along with a polynomial curve fit.

Figure 4. Example of contact stiffness measurements and nonlinear approximated characteristics.

Figure 5. Example of the plate stiffness measurements. Force versus displacement on left and right side of the wheel and linear approximated characteristics.

Figures 6 and 7 show plate stiffness measurement results. Figure 8 shows plate stiffness results obtained by mechanical systems for the various wheel types. Once again the applied load gives...
different displacement values for the wheel types due to variations in plate shape and wheel design. Curves of displacement vs. applied test load are presented. For example in Figure 6, the PKP monobloc wheel gives less physical displacement under load, thus is considered to have a “stiffer,” less flexible, wheel plate.

**Figure 6. Results of the plate stiffness measurements (average from both sides).**

**Figure 7. Results of the wheels stiffness measurements (average from both sides).**
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Figure 8. Results of the plate stiffness measurements by mechanical system for cast wheel Class B, C, ER7, tyre, forged/rolled monobloc wheels per UIC of ER7 (average from both sides).

After determination of above parameters of the particular wheel, we can predict the dynamic behavior of the rail vehicle at given traveling speed. Simulations were then conducted.

**Computer simulation of dynamic interaction of wheel with corrugated rail (bogie interaction with track, one corrugated rail).**

Let us consider a cargo car bogie which is moving along straight track having one corrugated rail. A pictorial of the bogie is shown in Figure 9, while the shape of corrugated rail is shown in Figure 10.

Figure 9. Scheme of the bogie used in dynamic simulations.
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For simulation typical European rail 60E1 is used. The shape of corrugated rail is assumed to be sinusoidal with amplitude of 10, 20, and 30 µm, wave length 100 mm and length of corrugated rolling surface equal to 1,000 mm. The traveling speed assumed using is a few values in the range (20 – 100 km/h). Evaluation of forces and power of wear is studied using modified in our laboratory “Simpac” program.

\[ Z = A(1 - \cos kx) \]

![Figure 10. Shape of corrugated rolling surface of the rail.](image)

From simulated interaction of the cargo bogie with corrugated track it is visible that the forces acting during motion at various speeds, are much less for pressure poured cast steel wheels than for the forged/rolled monobloc wheels manufactured with ER7 steel per UIC. Also the wear of the rolling surface is less for pressure poured cast wheels than for the forged/rolled wheels manufactured with ER7 steel per UIC. The difference is not as large as in the case of experimental investigation on the EMS60 stand, but this study provides additional positive information and supports results conducted by IK/CNTK.

Computer dynamic simulation results are presented in several following figures. Figure 11 shows the simulated dynamic response of a wheel operating at 80 km/hour on corrugated rail. Figure 12 shows the intensity of wear for a wheel running on corrugated rail at 80 km/hour.

![Figure 11. Response of the wheel interacting with corrugated rail at speed 80 km/h (amplitude A= 10 µm, front wheel of the bogie, right side).](image)
The expression used for calculation of intensity of wear is as follows:

\[ I_w = |Cx^*Tx| + |Cy^*Ty| \]

Where: \( Cx \) = longitudinal creepage, \( Cy \) = lateral creepage, \( Tx \) = longitudinal creep forces, \( Ty \) = lateral creep forces.

**Figure 12.** Intensity of the wear during interaction with corrugated rail, speed 80 km/h, amplitude \( A = 10 \mu m \), front wheel of the buggy, right side.

From these simulation results we see that the pressure poured Class C cast wheels are not causing additional dynamic forces over those imposed by forged/rolled. In fact the accelerations and wear intensity values are less for the cast wheels than for the forged/rolled wheels.

**Discussion of Results**

Conventional wisdom in some circles has held that if a harder wheel steel is used, greater wear of the rail will occur. These full scale wheel/rail flanging wear tests at IK/CNTK should dispel that notion once and for all. In fact, an Australian paper from 1983 deals with this very issue. Mutton and Epp [6] reported on 20 tonne axle load tests where the wear rate of standard carbon rails at high flanging stresses is higher for softer wheel materials. They attributed the increase in rail wear rate to be “partly due to deterioration of the wheel flange profile by both wear and plastic flow, giving rise to more severe contact conditions.” Further, Mutton and Epp [6] stated that “higher strength materials are likely to retain modified profiles for longer periods.” Echoing this information, another technical paper by Marich and Mutton [7] reported data showing that harder rails reduce the wear rate of various wheel steels. Standard carbon rail was shown to increase the wear rate of Class C, Class B and BSC wheels when compared to the wear rate associated with hardened rail. Marich and Mutton [7] stated that, “This is at least partly due to the higher rate of profile deterioration in the softer material by both wear and plastic flow, giving rise to more severe contact conditions.”

Interestingly, an earlier British Steel research paper by Babb and Lee [8] from the 1970’s, dealing with abrasive wear testing on a smaller laboratory wheel/rail wear test rig, also suggested similar findings to the results in this study. This paper concluded that, “...increasing the hardness of either specimen reduces both its own wear and that of the mating specimen. This suggests that in service harder tyres wear the rails less than softer tyres and vice-versa, harder rails wear the wheels less than soft
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North America has long successfully used harder Class B and C wheels to increase wheel wear life and reduce life cycle costs, without noting any related track damage, and the same could be the case for Europe. Also, based upon the test data, the increase in rail life for changing to a Class B (similar to ER9) pressure poured cast wheel instead of using the forged/rolled ER7 wheel is more than two and one half times!

Of additional interest is the superior wheel wear and rail wear performance of the pressure poured cast ER7 wheel vs. the forged/rolled ER7 wheel. These results, obtained by independent European testing organizations, suggest a significant life cycle cost benefit for use of pressure poured cast ER7 wheels. Finally, we again note that these wear test data were obtained on a full scale wheel on rail test rig, not from a laboratory bench wear testing device, thus adding credibility to the results. The paper by Bogacz and Czyzczula contains additional details related to this project [9].

A New Pressure Poured Cast Wheel Design for Europe

A new pressure poured cast wheel design (36LD) has been created for 22.5t/25t European freight service, and wheels have been manufactured for testing in accordance with European norms. The new wheel design is a departure from the typical North American cast wheel design, primarily in order to meet European requirements for deflection. Extensive finite element analysis simulations were performed, including the mechanical assessment as per UIC 510-5. The results revealed that the wheel design has a maximum Von Mises stress of 314.3 MPa vs. the specified maximum of 343 MPa in criteria 1. Also the criteria 2 fatigue stress result value is 136.4 MPa, which is less that the 145 MPa maximum for un-machined plates. Results from the simulated thermal mechanical analysis show significantly better deflection (maximum lateral displacement) and residual hoop stress results than for the typical European UIC wheel design. Results are shown in Tables 2 and 3, respectively.

### Table 2. Lateral displacement for 36 LD cast wheel design and UIC wheel design from simulation.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>36LD Cast Wheel</th>
<th>UIC Wheel Design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New Wheel (mm)</td>
<td>Worn Wheel (mm)</td>
</tr>
<tr>
<td>Load Case 1</td>
<td>+1.5/-0.5</td>
<td>0</td>
</tr>
<tr>
<td>Load Case 2</td>
<td>+1.5/-0.5</td>
<td>0</td>
</tr>
<tr>
<td>Load Case 3</td>
<td>+1.5/-0.5</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 3. Average rim residual hoop stress from simulation.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>36LD Cast Wheel</th>
<th>UIC Wheel Design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New Wheel (MPa)</td>
<td>Worn Wheel (MPa)</td>
</tr>
<tr>
<td>Load Case 1</td>
<td>6.59</td>
<td>52.08</td>
</tr>
<tr>
<td>Load Case 2</td>
<td>11.64</td>
<td>112.5</td>
</tr>
<tr>
<td>Load Case 3</td>
<td>15.5</td>
<td>187.7</td>
</tr>
</tbody>
</table>

Conclusions

Wheel/rail wear testing and dynamic modeling simulations show that the Class C pressure poured cast wheel is not more likely to damage track and infrastructure than currently used forged/rolled and tyred wheels. Wheel wear and rail wear are significantly less for the cast Class C wheel, and also for the cast ER7 and cast Class B wheels, than for ER7 forged/rolled and tyred wheels. A new pressure poured cast wheel design for Europe, the 36LD, has shown excellent computer modeling simulation results vs. the UIC wheel design. Physical testing, and a field trial for the 36LD wheel, are expected soon in Europe. We hope that European railway operators and end users will soon enjoy the many benefits and improved life cycle costs of pressure poured cast wheels in freight service.
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References


5) IK Railway Institute, Materials and Structures Laboratory LK, “Wear Test of Rail Used in Europe vs. Cast and Forged/Rolled Wheels on Stand EMS60 – Project No. 2605/22,” Warsaw, Poland, July, 2010.


