Original Article

Tribological analysis of wear plates in the hopper of a car dumper

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Abstract

The car dumper is the first equipment to perform work in the iron ore export production process. Its function is to remove the iron ore from each train wagon, which transports it directly from the mines to the harbor. Within the engineering system has a standardization of how the car dumper is divided. The systems of this machine are the pusher car, which has a mechanical arm that positions the wagon to be dumped; the train locker; the rotation device is mainly composed by rotational rings and clamps, that make the wagon tip; the feeder, where the ore falls and is directed to the conveyor belt. The wear plates are assembled in the hoppers at a height of 1117 mm below the car dumper in 47 positions. These plates experience impact and abrasion wear in a location difficult to be reached. To reduce maintenance a material with higher impact resistance and a good abrasion resistance was developed in laboratory and later tested in the hopper, the performance is evaluated against the original plate. Both laboratory tests and field tests confirmed the superior wear and impact resistance of a eutectic alloy for application in this car dumper.

Keywords: Car dumper; Wear plates; Abrasion; Impact resistance.

1 Introduction

The economic importance of tribology and the great need for systematic research, with improved transfer of theoretical knowledge to practice, have been recognized in recent decades.

Studies conducted by ASME in the United States indicate an economic loss of 1% to 2.5% of the gross domestic product due to wear. In Germany, a study from the 1980s reveals that wear and corrosion together contribute to a loss of 4.5% of the gross domestic product [1]. With the increasing industrial production in recent decades, it is estimated that the potential for economic losses due to wear has proportionally increased in industries. To understand the economic impact caused by wear losses, Figure 1 [2] presents the relative importance of wear in the economy. It should be considered that friction and wear are not just function of properties of materials but result from the characteristics of engineering systems (tribosystem), as friction is the resistance to movement and increases with the interactions of solids and the real contact area. Friction and wear are systemic, they depend on the entire tribosystem and are respectively serious causes of energy dissipation and material loss. Wear is a consequence of a degradation of the interaction between components, because of material stress in the vicinity of the surface.

In a component, wear may or may not be catastrophic, but most often, it leads to loss of efficiency, causes vibration, and misalignment. In extreme cases, some failures caused by wear can lead to fracture, and the formed fragments can usually damage the equipment.

Economic losses related to wear can be reduced by optimizing the organization's plant and by proper design, production, assembly, and application. Controlling the cost of wear can begin with the correct production process for manufacturing the product, which includes the selection of equipment and installation location, standardization issues, and inventory, as shown in Figure 2.

The design can effectively reduce component wear by optimizing load and movement transfer, allowing only low stress, and using appropriate materials and lubricants based on load, temperature, and environment. Wear parts can be designed for easy replacement.

The working conditions of a component depend on the type and quality of production. The degree of precision in shape, size, surface profile, and roughness influences friction and wear. However, service life also depends on the precision of assembly, exact alignment, cleanliness, and care of the component's surface.

During service, costs due to friction and wear can be reduced by controlling working conditions and vibration, cleaning the environment, and performing maintenance and repairs.

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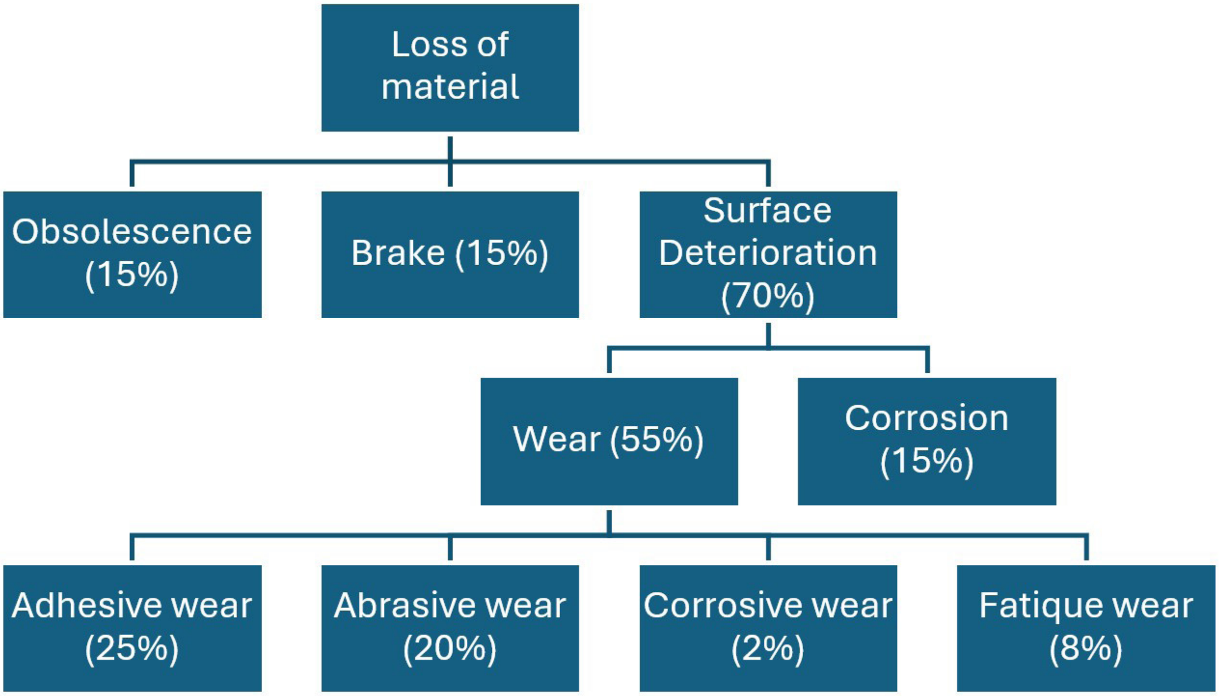

Figure 1. Causes of failure and their relative loss to the economy [2].

Therefore, studying the factors that contribute to wear is necessary to predict the occurrence of wear mechanisms. The main wear factors are:

- Metallurgical variables: Chemical composition and microstructure;
- Process variables: Contact materials, pressure, speed, temperature, and surface finish;
- Other factors: Lubrication, corrosion.

The knowledge of the component's microstructure and its influence on wear resistance is of great importance in material selection. Microstructural aspects, such as crystalline defects like vacancies, dislocations, grain boundaries, second-phase particles, can significantly affect the wear of components. The chemical composition alone cannot define the material's microstructure; however, it can be severely altered through mechanical, thermal, and thermomechanical treatments.

The selection of abrasion-resistant materials is mainly based, according to De Mello et al. [3], on their mechanical characteristics. Hardness is generally considered an important property for applications requiring high abrasion resistance. However, this correlation between hardness and abrasion resistance is only verified for single-phase materials and some types of steels, as for polyphase structures, such as alloyed steels and cast irons, the determining factors are, for example, the carbon content and the microstructure [4].

Significant differences in abrasion resistance may be exist for the same hardness value. The wear resistance of cast irons and hard steels can decrease with excessive hardness. In these cases, fracture toughness is a property that must be considered. Additionally, fracture toughness should be coupled with normal load, size, and angularity of abrasive particles [4].

Figure 2. Factors influencing the wear of structures [1].

To evaluate wear mechanisms and enable comparison between different coating compositions was proposed a test applied on a hopper of a car dumper according to Figure 3.

Technical Data of the Car Dumper:

- Wagon Discharge Rate: 90 wagons/h;
- Average Load Capacity of Wagons: 80 tons;
- Tare Weight of Wagons: 18 tons;

Figure 3. Design of the hopper and wear plates in the car dumper.

- Maximum Number of Wagons per Train: 90 units;
- Car Dumper Load Capacity: 2 x 110 tons/cycle;
- Average Discharge Cycle: 80 seconds;
- Material Handled: Pellets, Fines and Granulated Ores;
- Feeder Capacity: 4,000 t/h;
- Useful Length of Feeder Guides: approx. 5.35 m.

This application of the plate was chosen because it is a location with severe abrasion and moderate impact. Another determining factor in this analysis was the use of a material that had a relatively short lifespan, ranging from 4 to 6 months in operation. These are bimetallic plates with a hard coating composed of chromium, niobium, and boron, with a hardness of 60 to 65 HRC at a thickness of 19mm, of which 7mm is the hard layer.

For the development of the test, it is extremely important to understand the mechanism to reduce the intervention carried out through preventive maintenance, decreasing the current need from 6 months to about 1 year, and consequently obtaining a reduction in the labor required for this activity, thereby mitigating exposure to risk.

Thus, the objective of this paper was to develop a wear plate to reduce maintenance interventions and consequently exposure to risk, facilitate maintenance and consequently reduction cost. It also aimed to ensure correct assembly and the absence of problems associated with fixation. Additionally, resistance to friction, wear, and impact were evaluated.

2 Preliminary analysis

A tribology study was conducted to identify the micromechanisms of wear on the worn plates, where the tribometer used in this laboratory test evaluation was chosen. To analyze the best material to be tested in the field, an evaluation of various materials was carried out: weld-coated plates, cast wear plates, and wear plates with chocky bars, with the aim of ranking suppliers according to this application based on the tests below:

- 2 chemical analyses via optical emission spectrometry by spark, base material and weld coating;
  - 1 rockwell hardness analysis, ASTM E18-16, only coating [5];
- 2 optical micrographic analyses, base material and coating;
  - 1 Vickers microhardness profile, ASTM E384-16 [6];
- 9 abrasive wear tests Rubber Wheel, ASTM G65-16, procedure B, with 3 tests on the surface, 3 at mid-height of the coating, and 3 near the interface;

The wear test used was of the rubber wheel type, ASTM G65-04 standard [7], procedure B, d = 1436m (2000 revolutions), load of 130N, quartz sand flow AFS 30/40 of 400g/min. The performance of the wheel/sand tribological system was periodically checked at the beginning and end of each round of tests and during wheel changes, using the AISI H13 steel standard, hardened and tempered, for a hardness of 48 HRC. The samples were weighed before and after the tests and then the volumetric loss was obtained by density.

In Figure 4, the obtained values of wear resistance of the weld-coated, cast, or chocky bar plates can be seen. The test specimens CP-K3, C3, P2, O5, C1, D1, M1, A4, N4, B1, K2, K1, and H1 showed the best wear results with average volume loss values below the overall average of 9.1 mm^3 (red line in the figure).

Regarding the industrial applications of high-chromium abrasion alloys, hypoeutectic materials with low carbon content (2 to 3% C) are generally selected for situations involving moderate abrasion and impact, while hypereutectic materials with higher carbon content (4 to 6% C) are used in applications involving severe abrasion and little or no impact. To understand the impact resistance of these coatings and their limitations for this type of mechanical stress, a repetitive impact test (1000 strikes) was conducted with an impact energy of 2 J using a 40 mm diameter bearing ball. However, it was not possible to obtain mass loss results after repetitive impact tests. Therefore, the results were evaluated by visual analysis and measurement of the diameter of the cap generated by the impact, see Figure 5.

Materials with lower volume loss values and larger cap diameters generated on the coating surface will likely have the best results in applications with moderate abrasion and impact. This can be explained by the fact that materials with sufficient ductility to absorb impact will exhibit better resistance compared to those with reduced ductility. Materials with these characteristics, when subjected to an impact or a concentrated load, deform by expansion, increasing the contact area. In this way, the unit load is decreased, preventing the compressive strength from being exceeded.

The low mass loss of materials in the moderate abrasion regime occurs due to the presence of a hard second phase in their microstructure, where this second phase acts as a barrier to the damage caused by the abrasive particle.

The quantity, size, and distribution of carbides in a steel microstructure have a distinct influence on wear resistance. For the most part, wear resistance increases as the quantity or size of carbide particles on the wear surface increases.

The Table 1 summarizes the results for the welded, cast, or chocky bar plates that were subjected to characterization in laboratory tests.

The region marked in blue in Table 1 shows the materials approved for field testing. The selection criteria was the mean loss of volume less than 9 mm^3.

These materials should be evaluated according to the type and severity regime of wear, as well as the ease of ore flow. Table 2 shows the predominant Microstructure for each type of sample tested.

Material CP05 (orange shaded) showed excellent wear resistance associated with the larger diameter of the cap, making it the material chosen for field testing. CP05 is a hypoeutectic white cast iron with chromium/molybdenum carbides dispersed in a martensitic matrix.

The Vickers microhardness profile was performed on the coatings, according to ASTM E384-17, to evaluate the effective thickness of the coating subjected to laboratory tests (Figure 6).

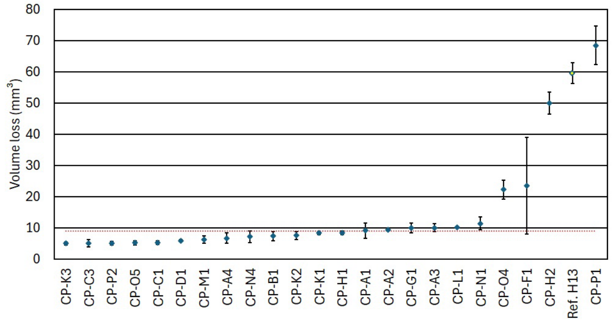

Figure 4. Average volume loss per material.

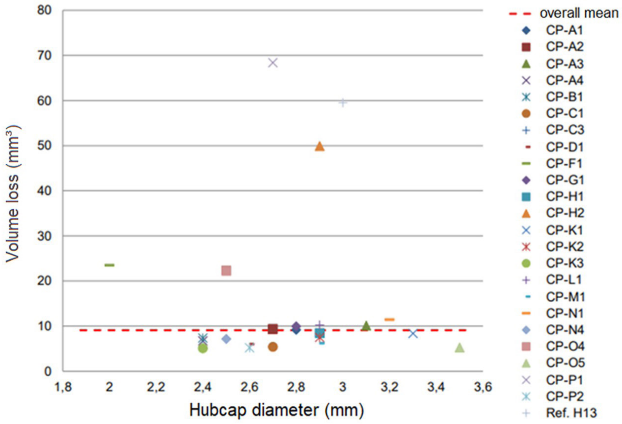

Figure 5. Volume Loss versus repetitive impact test results.

Table 1. Results of the characterization tests of steel plates

ID	Hardness (HRC)	Mean loss of volume (mm^3)	Relative wear resistance (H13=1)	Effective coating thickness (mm)	Cap diameter (mm)
CP-C3	70.0	5.1 ± 1.2	0.09	7.10	2.40
CP-K3	66.2	5.1 ± 0.5	0.09	13.10	2.40
CP-P2	60.6	5.2 ± 0.6	0.09	13.80	2.60
CP-O5	66.6	5.3 ± 0.7	0.09	13.60	3.50
CP-C1	68.8	5.4 ± 0.6	0.09	4.10	2.70
CP-D1	60.6	6.0 ± 0.3	0.10	8.10	2.60
CP-M1	63.0	6.3 ± 1.2	0.11	14.10	2.90
CP-A4	66.0	6.8 ± 1.5	0.11	5.60	2.40
CP-N4	60.8	7.2 ± 1.8	0.12	10.10	2.50
CP-B1	62.0	7.4 ± 1.4	0.12	12.40	2.40

Note: The mass loss of H13 steel has been assigned a value of 1, rates less than 1 indicate a wear-resistant material and rates greater than 1 indicate a less wear-resistant material.

Table 1. Continued...

ID	Hardness (HRC)	Mean loss of volume (mm³)	Relative wear resistance (H13=1)	Effective coating thickness (mm)	Cap diameter (mm)
CP-K2	60.8	7.5 ± 1.2	0.13	5.10	2.90
CP-K1	63.6	8.4 ± 0.5	0.14	13.10	3.30
CP-H1	64.0	8.5 ± 0.6	0.14	3.60	2.90
CP-A1	59.2	9.2 ± 2.5	0.15	5.60	2.80
CP-A2	60.0	9.4 ± 0.3	0.16	5.10	2.70
CP-G1	64.6	10.0 ± 1.6	0.17	13.80	2.80
CP-A3	64.0	10.1 ± 1.3	0.17	13.40	3.10
CP-L1	62.2	10.2 ± 0.2	0.17	7.10	2.90
CP-N1	53.6	11.5 ± 2.1	0.19	9.10	3.20
CP-O4	59.2	22.3 ± 3.0	0.37	7.60	2.50
CP-F1	71.4 (insert) 46.4 (matrix)	23.5 ± 15.5	0.39	3.70	2.00
CP-H2	38.6	49.9 ± 3.5	0.84	7.10	2.90
CP-P1	45.8	68.4 ± 6.2	1.15	13.20	2.70

Note: The mass loss of H13 steel has been assigned a value of 1, rates less than 1 indicate a wear-resistant material and rates greater than 1 indicate a less wear-resistant material.

Table 2. Description of the metallographies of the samples of sheets coated by welding or casting or chockbar

Customer identification	Predominant microstructure
CP-A1	Hypereutectic white cast iron with Cr carbides dispersed in a martensitic matrix
CP-A2	Hypereutectic white cast iron with Cr carbides dispersed in a martensitic matrix
CP-A3	Hypoeutectic white cast iron with Cr carbides dispersed in martensitic matrix
CP-A4	Hypoeutectic white cast iron with Cr/Mo carbides dispersed in a martensitic matrix
CP-B1	Hypoeutectic white cast iron with Cr carbides dispersed in a martensitic matrix
CP-C1	Hypoeutectic white cast iron with Mo/V carbides dispersed in a martensitic matrix
CP-C3	Hypoeutectic white cast iron with Mo/V carbides dispersed in a martensitic matrix
CP-D1	Hypereutectic white cast iron with Cr carbides dispersed in a martensitic matrix
CP-F1	WC/Co insert in hypereutectic nodular cast iron matrix with martensitic matrix
CP-H1	Hypereutectic white cast iron with Cr carbides dispersed in a martensitic matrix
CP-K1	Hypoeutectic white cast iron with Cr/Nb carbides dispersed in a martensitic matrix
CP-K2	Hypoeutectic white cast iron with Cr/Nb carbides dispersed in a martensitic matrix
CP-K3	Hypoeutectic white cast iron with Cr/Mo carbides dispersed in a martensitic matrix
CP-H2	Ferritic matrix Cr/Mo/Ti/V alloyed tool steel

Table 2. Continued...

Customer identification	Predominant microstructure
CP-O4	Hypoeutectic white cast iron with Cr carbides dispersed in a martensitic matrix
CP-O5	Hypoeutectic white cast iron with Cr/Mo carbides dispersed in a martensitic matrix
CP-G1	Hypoeutectic white cast iron with Cr carbides dispersed in a martensitic matrix
CP-L1	Eutectic white cast iron with Cr carbides dispersed in martensitic matrix
CP-M1	Hypoeutectic white cast iron with Cr/Mo carbides dispersed in a martensitic matrix
CP-N1	Hypoeutectic white cast iron with Cr/Ti carbides dispersed in a martensitic matrix
CP-N4	Hypoeutectic white cast iron with Cr carbides dispersed in a martensitic matrix
CP-P1	Tempered martensite
CP-P2	Hypoeutectic white cast iron with Cr carbides dispersed in a martensitic matrix

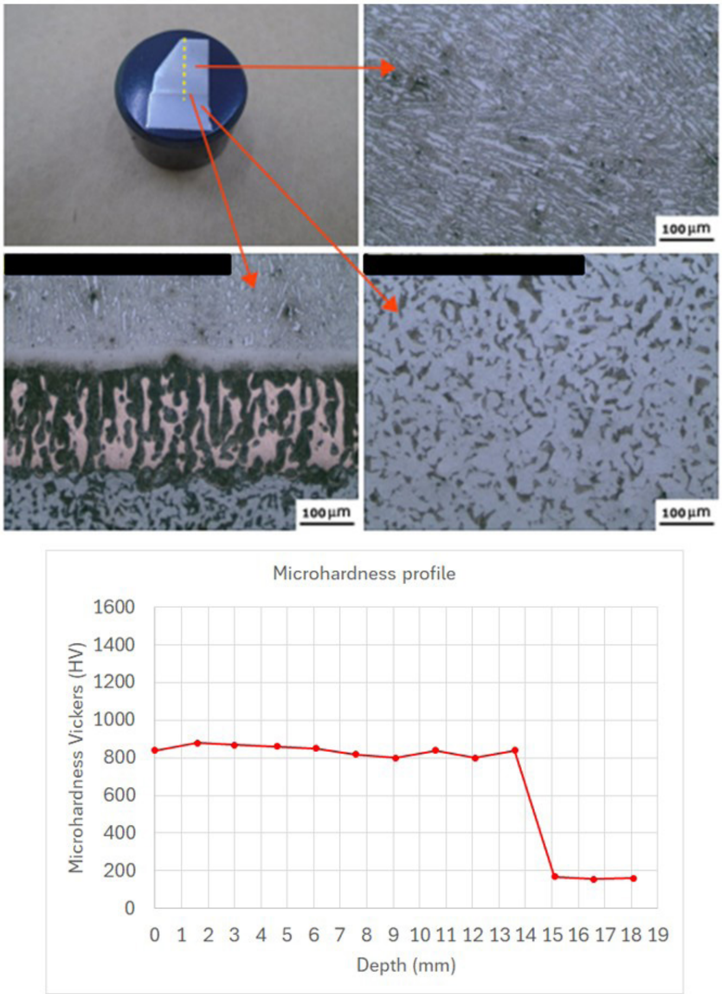
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Figure 6. Optical micrograph and microhardness profile of the CP05 sample: Coating, interface, and material.

3 Methodology

The plates were manufactured in dimensions of 1250 mm × 1620 mm, and the current fastening system is maintained according to the original design for field testing. The sample chosen for the field test was CP05: a hypoeutectic white cast iron with chromium/molybdenum carbides dispersed in a martensitic matrix (Figure 7).

The material handled was iron ore, predominantly pellet feed and sinter feed composed of hematite, magnetite, etc. It is worth noting that despite the inherent variation of the material handled over time, all plates were subjected to the same type of ore and operation during the tests.

The KPIs, were defined in conjunction with the manufacturer as shown in Table 3 below.

The plates were installed in a location of moderate abrasion and impact in the car dumper hopper (Figure 8 and Figure 9) and were tested for about 14 months without any failure or excessive wear.

Even though laboratory tests have indicated which would be the best materials to be tested in the field, there is no guarantee that the field conditions would be the same as those submitted in the laboratory tests. Therefore, in the field tests, it was decided to apply all the materials to be tested at the same time and subjected to the same wear conditions, that is, almost the same tribological system, changing only the lining material.

Table 3. Goals defined for the field test

Key Process Indicator	Performance requirement
Iron ore handled (kton)	Minimum 14.366 kton
Fixation of plates	Absence of fixation problems
Assembly issues	Absence of problems associated with assembly

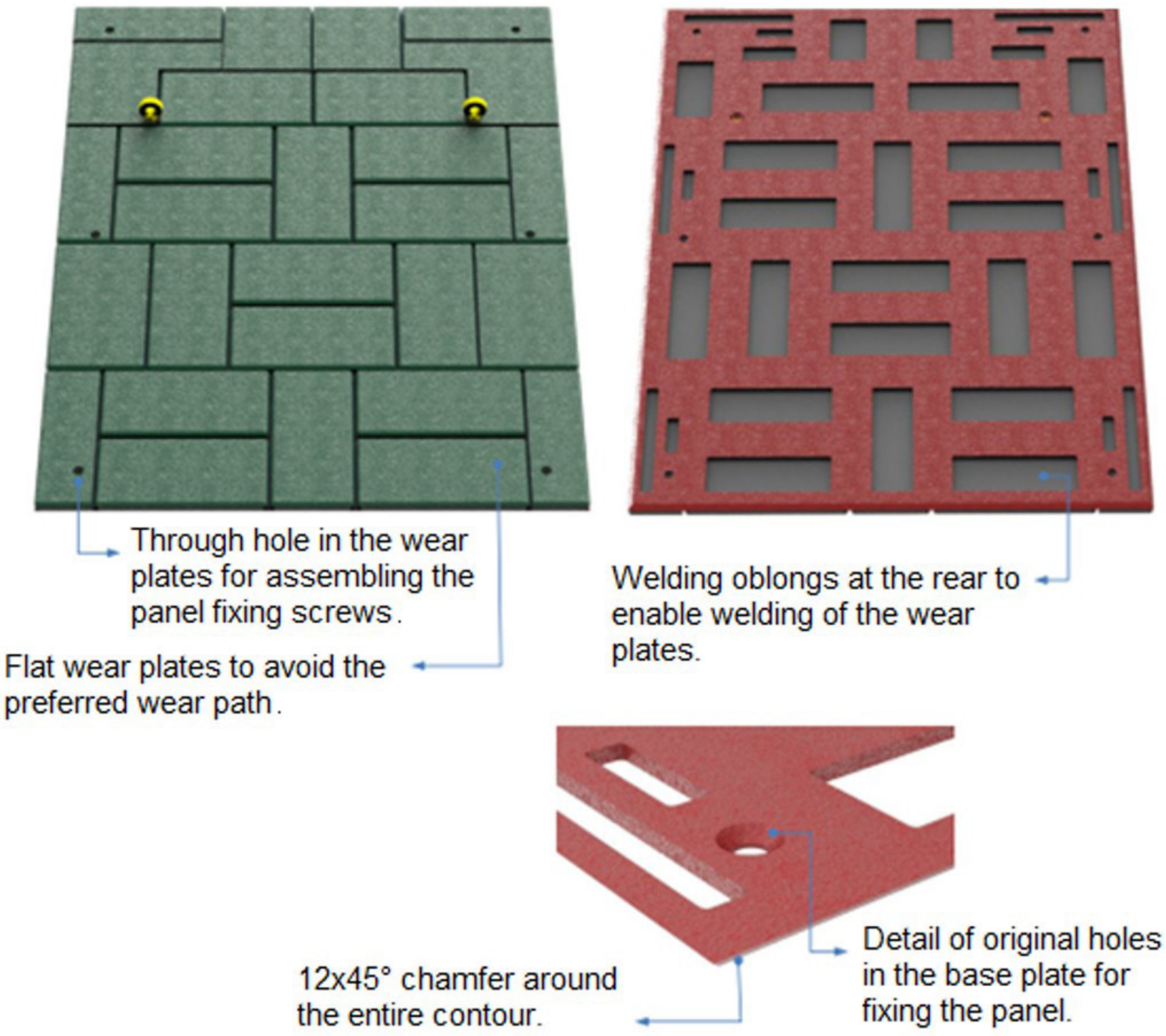

Figure 7. Illustrative image of the front and rear view of the panel with cast plates.

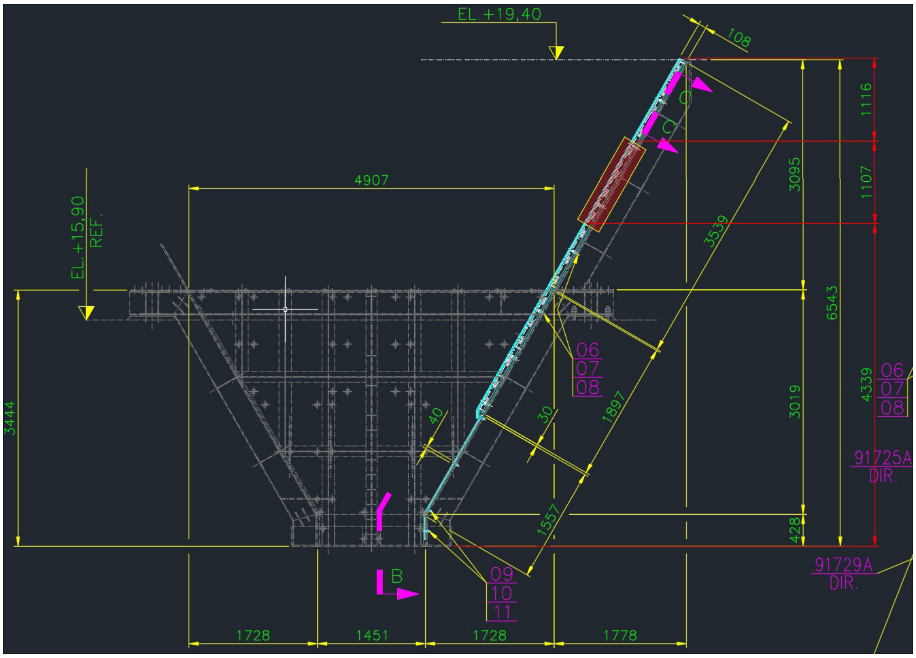

Figure 8. Location of the plate application in the car dumper hopper.

Figure 9. Wear plates installed in April 2022.

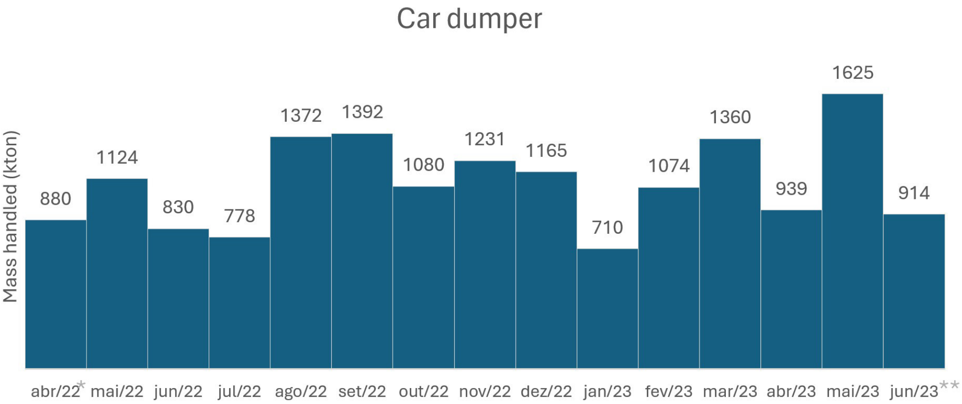

Figure 10. Mass handled in the car dumper during the tests.

Figure 11. Status of the wear plates after a 1-year test period.

Figure 12. Status of the wear plates after a 2-year test period.

Table 4. Results & Goals

Key Process Indicator	Performance requirement	Result obtained	Result
Iron ore handled (kton)	Minimum 14.366 kton	16.474 kton	Aproved
Fixation of plates	Absence of fixation problems	Absence of fixation problems	Aproved
Assembly issues	Absence of problems associated with assembly	Absence of problems associated with assembly	Aproved

4 Results and discussions

The Figure 10 presents a summary of the mass handled in the car dumper during the tests realized from April 2022 to June 2023 (442 days of operation), totalizing 16.474 kton.

The monitoring of inspection and maintenance activities carried out during this period found that the wear plates did not experience excessive wear causing any hole and material loss in about 1 year in operation (Figure 11).

The Figure 12 shows the current condition of the tested plate, which after 2 years of installation is still performing satisfactorily.

Thus, according to the established KPIs, Table 4 shows the results of the field test applied in the Test Service Request (TSR).

It was not possible to quantify the mass loss after the test because the plates are still installed in the equipment in difficult to access locations and with a good expected useful life.

5 Conclusions

The wear plates used in the car dumper tests showed performance results that met the specified acceptance requirements of the analysis in the KPIs as shown in Table 3, confirming a satisfactory result obtained in the G65 rubber wheel abrasion tester [7] in Figures 4 and 12.

Therefore, both laboratory tests and field tests confirmed the superior wear and impact resistance of CP05 among the tested materials. CP05, which is a eutectic alloy, showed the best results, possibly due to the size, shape and distribution of the M7C3 carbides.

The gains from this work include a useful life three times longer than the material that was installed in this location and less exposure of people to risk due to the reduction of change interval in replacement of these plates.

The development was finalized through the issuance of a report containing information regarding the fulfillment of the defined indicators, thus being approved for this application, which can be replicated for all car dumpers at points of higher abrasion and impact.

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