WITH AN AVERAGE 770 HBN AND 27.2 KSI.(INCH)$^{1/2}$ FRACTURE TOUGHNESS MAX5A HAS SIGNIFICANTLY INCREASED THE EQUIPMENT LIFE WHEN PUMPING PHOSPHATE ROCKS.

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Abstract

With the increase of hard mineralogical content of phosphate rocks over the last twenty years so has increased the demand for materials with higher wear and corrosion resistance.
The microstructure of the newly developed Max5A hard iron ensures excellent chromium carbide distributions, cuboidal-shaped and unconnected secondary carbides all evenly embedded into a fully martensitic matrix. Such microstructure provides increased hardness and toughness.
Fracture toughness K_{IVM} was established per ASTM E1304 under plane-strain mode I opening (Chevron-notch) conditions.
The average 0.6x10^{-3} [mm^3/N/m] wear rate of Max5A was calculated according to ASTM G99 with the pin-on-disk apparatus using a diamond indenter. Max5A wear rate is substantially lower than the current Industry Standard hard iron (25% Cr).
Such optimized microstructure increases the chromium content of the depleted zone at chromium carbide – matrix interfaces which in turn increases the pH operation range to 2.35 – 13.6 (the 25% Cr Industry Standard hard iron range is pH = 3.5 – 9.5). All corrosion rates were calculated per ASTM G1.
More than three years ago Max5A was released for production. Every application it has been placed in demonstrated vast operation success and consistency.
After 10 months in a Louisiana 24/7 Fertilizer Plant operation, the Max5A "wetted end" castings are practically undamaged. The pumping slurry contains 66% phosphate rocks with a specific gravity of SG = 1.78.
In Mining Industry Max5A produced similarly good results. For example in a South America operation the service life of the Max5A "impeller" increased 260% over the previously used material, and lasted 450% longer than the hard iron manufactured by local suppliers.

Max5A has significantly lowered wear rate compared to the 25% Cr Industry Standard hard iron

Wear rate calculation

The chemical composition of both Max5A and 25% Cr Industry Standard hard iron is identical; according to ASTM A532, "Standard specification for abrasive resistant cast

iron” Class III Type A [1]. These hard irons are the most used cast wear resistant materials in the USA and worldwide.
Arrow “A” in Photo 2 shows the Rockwell C diamond indenter mounted into the vertical arm of the pin-on-disk wear testing apparatus.

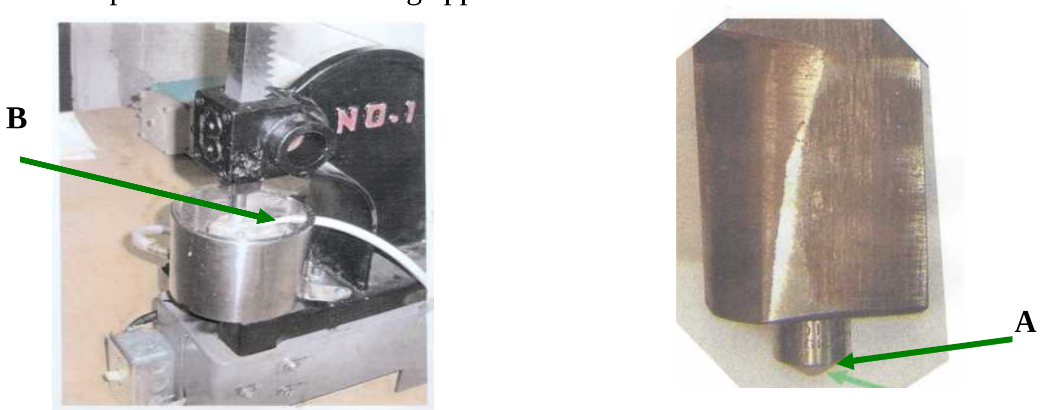


Photo 1. Pin-on-disk wear testing apparatus and enlarged view of the diamond indenter.

Table 1. Wear testing parameters

#	Parameter	Values
1	RPM	80
2	Testing time	2 hours
3	Testing temperature	72^0F
4	Mean wear groove diameter	15.875 mm
5	Sliding length per RPM	49.848 mm
6	Total sliding length	478.54 m
7	Static load	1,063 g or 10.425 Newton
8	Sample roughness	0.20 – 0.12 μm

The diamond indenter contact point with a 1-inch x 1-inch x 0.25-inch thick testing sample is constantly flushed with water – see Arrow “B”. All wear testing specimens are extracted from keel blocks with dimensional requirements per ASTM A439 “Standard specification for austenitic ductile iron castings” [2].

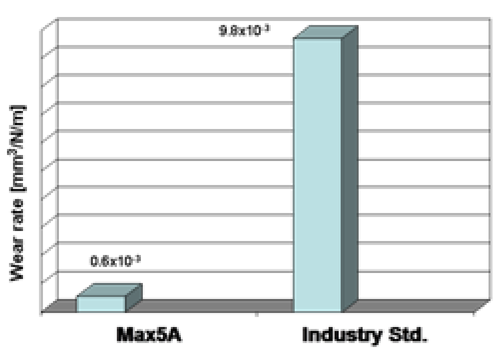


Figure 1. Comparative wear rates of Max5A and 25% Cr Industry Standard

Total sliding distance [m] and static load [N] seen in Table 1 were utilized to calculate the wear rates [3].

The wear rate of Max5A with 780 HBN was $0.6x10^{-3}$ [mm^3/N/m] versus $9.8x10^{-3}$ [mm^3/N/m] the wear rate of 25% Cr Industry Standard with 650 HBN.

Wear groves topography

Because wear rates values are low the wear grooves topographies of Max5A and 25% Cr Industry Standard were investigated with SEM at X17 and X18 SEM magnifications – see Photo 2 and Photo 3.

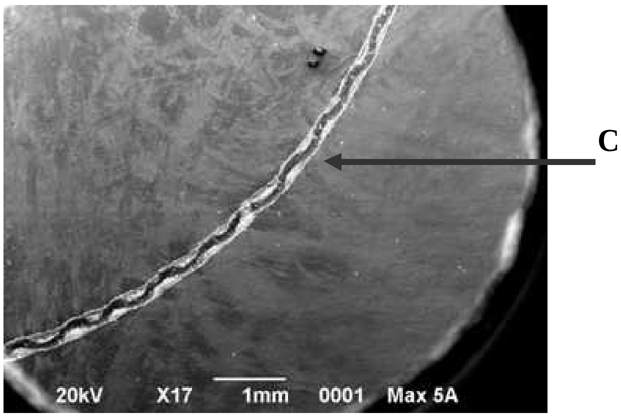


Photo 2.

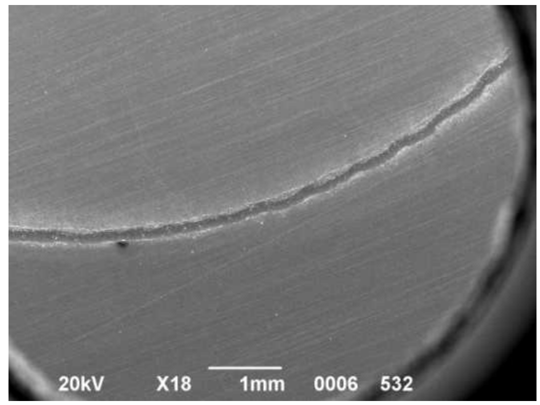


Photo 3.

Photo 2 and 3. Low magnification SEM wear grove views of Max5A and 25% Cr.

The 780 HBN hardness prevents penetration into the Max5A sample of the vertical diamond indenter, and generates lateral load components. Arrow "C" shows a sinusoidal wear groove surrounded by white ring areas. These were produced by slight lateral indenter movements caused by miniscule clearance between the indenter arm and the guiding arm hole.

The 650 HBN hard Industry Standard wear sample groove is clean and straight since the vertical indenter penetration encounters lower penetration resistance.

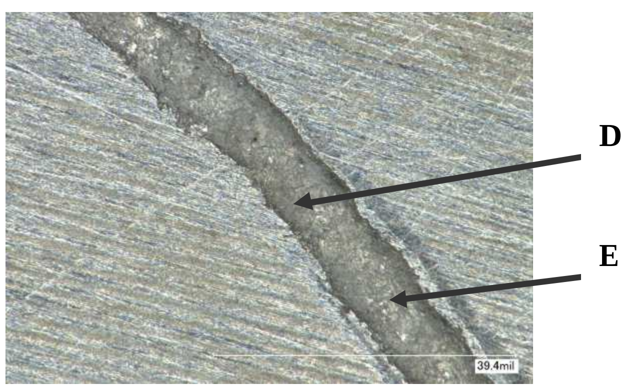
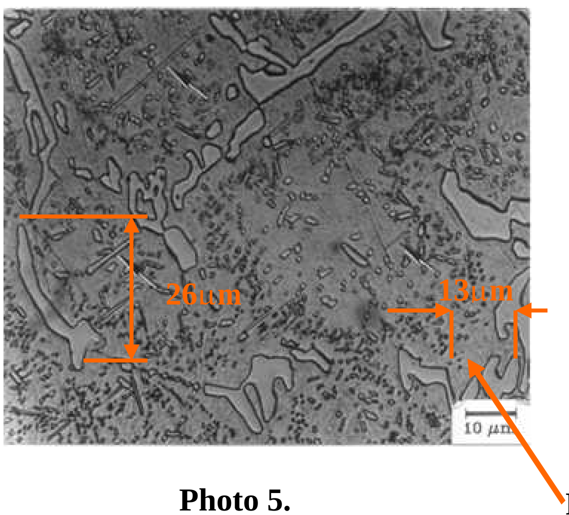


Photo 4. SEM wear groove view of a second Max5A tested sample.

At X2, 000 magnifications the SEM Photo 4 shows the plastically deformed wear groove contours of a second 780 HBN Max5A sample also tested with the pin-on-disk apparatus. Under the combined action of vertical load and rotational movement, compressive stresses accumulate material in front of the indenter. One such area is seen with Arrow “D”. Tensile stresses develop behind the indenter and remove material, like indicated in the example shown with Arrow “E”.
The cyclic plastic deformations of Max5A indicate elevated toughness.

The pH operational range of Max5A is notably greater than 25% Cr Industry Standard

Optimized microstructure enhanced the Max5A corrosion resistance
The SEM view of Photo 5 shows the 25% Cr Industry Standard microstructure while Photo 6 shows the Max5A microstructure. Both magnifications are X1,200 and used 36% concentrated hydrochloric acid reagent.
Their average length of the main M_7C_3 chromium carbides is 26-µm in 25% Cr Industry Standard and 9-µm in Max5A (nearly 3 times shorter).



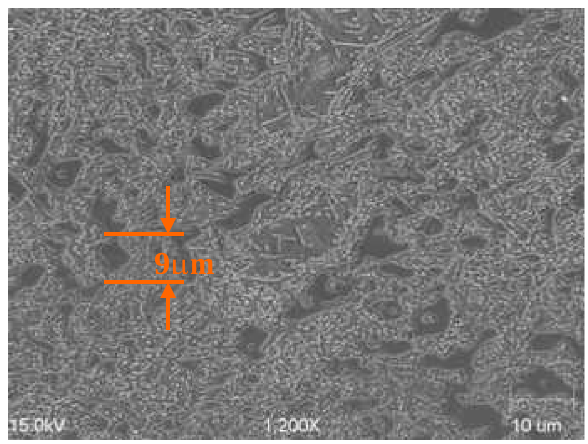


Photo 5. **Photo 6.**

Photo 5 and Photo 6. SEM optical microstructure views of 25% Cr Industry Standard and Max5A

Arrow “F” shows the chromium depleted zones (denuded zone) which surround primary and eutectic carbides of 25% Cr Industry Standard. The largest area width is 13-µm. During primary and secondary solidification, chromium migrates into chromium carbides, generating severe chemical gradients with 54% chromium in the chromium carbides and 9 – 13% chromium in the depleted zone which minimizes passivation conditions.

The large chromium differences in the chromium carbides and matrix cause different electrode potentials and produce microscopic galvanic cells. This increases the corrosion attack in the “depleted zones”.

Elongated and dot shaped secondary chromium carbides are embedded into the 25% Cr Industry Standard matrix. The longest secondary carbide is 25-µm while the size of the dot-shaped secondary carbides is less than 1-µm. These secondary carbides are non-uniformly distributed.

Within the matrix, smaller chromium migration occurs at the matrix – secondary carbide interfaces; nevertheless it diminishes the corrosion resistance around the $M_{23}C_6$ secondary carbides.
Due to unique manufacturing processes the secondary carbides of Max5A are cuboidal shaped, unconnected and evenly randomized which maintains uniform chromium contents and provide passivation within the fully martensitic matrix.

Establishing the pH range of Max5A and 25% Cr Industry Standard

- 25% Cr Industry Standard: pH = 3.5 – 9.5
- Max5A: pH = 2.3 – 13.6

The corrosion rate of Max5A at pH = 3.2 was 17 MPY while at pH = 13.6 the corrosion rate was “nil” – see Fig.2.

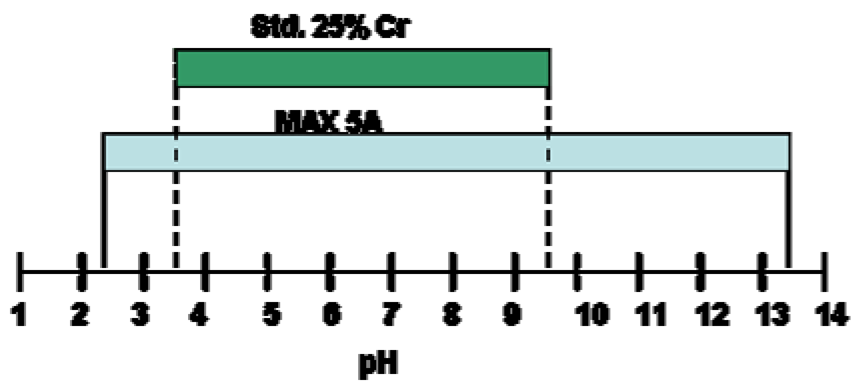


Figure 2. Operational pH range of Max5A and 25% Cr Industry Standard hard iron

During the corrosion tests the stoichiometric calculations used sulfuric acid at the acidic side and sodium hydroxide at the alkaline end. All corrosion tests were accomplished per ASTM G1 “Standard practice for preparing, cleaning and evaluation corrosion tests specimens” [3].
The following microstructural features increased the corrosion resistance of Max5A:

- Small and randomized chromium carbides reduced chromium migration into chromium carbides and diminished the “depleted zone” width, therefore improving passivation conditions;

- The small cuboidal shaped, unconnected and evenly distributed secondary carbides provided uniform chromium distribution within the matrix and also avoided the harmful formation of microscopic galvanic cells.

Mechanical properties

Fracture toughness

The fracture toughness established by K_{IVM} per ASTM E1304 “Standard test method for plane-strain (Chevron-notch) fracture toughness of metallic materials” is a relatively slow advancing, steady crack initiated at the very sharp Chevron point, and propagating as seen with Arrow “G” in Photo 7 [4].
Arrow “H” in Photo 8 points to the grip slot in which closed grips are fit simultaneously.
Subscript “I” indicates mode one opening, “V” indicates Chevron notch, while “M” indicates that maximum force occurs at critical length.

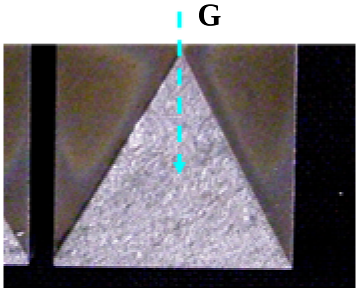


Photo 7.

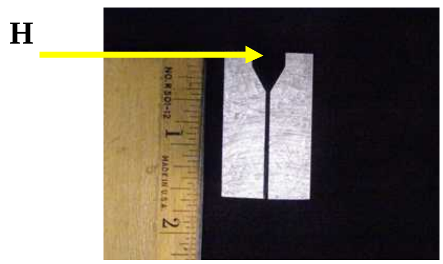


Photo 8.

Photo 7 and Photo 8 view the Max5A Chevron-notch fracture toughness tested sample

The fracture toughness of Max5A with 780 HBN was 27.2 KSIx(inch)$^{1/2}$, an excellent value, and close to Aluminum 7075 – see Table 2 listed by ASTM E1304.

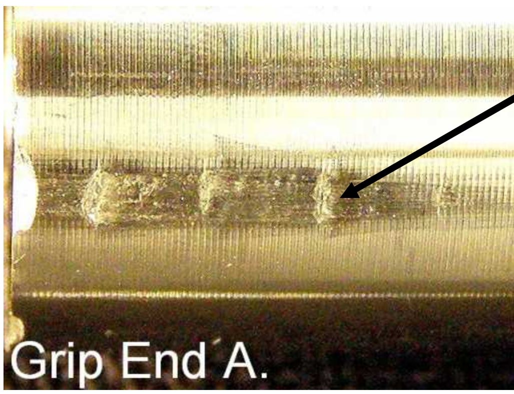
Table 2. Fracture toughness values listed by ASTM E1304

Material	Specimen orientation	Yield strength KSI (MPa)	K_{IVM} KSI(inch)$^{1/2}$
2024	L – T	52.4 (361)	50.8 (55.9)
Aluminum	S – L	42.7 (294)	35.3 (38.8)
7075-T651	L – T	78.7 (543)	31.3 (34.4)
Aluminum	S – L	67.8 (468)	20.7 (22.8)
Grade 250	L – T	230.8 (1592)	90.6 (99.7)
Maraging steel	S - L	229.6 (1583)	79.1 (87.0)
Grade 300	L – T	274.0 (1890)	49.9 (53.9)
Maraging steel	S – L	288.0 (1986)	47.3 (52.0)
6A1 – 4V	L – T	131.5 (907)	103.9 (114.3)
Titanium	S - L	122.8 (847)	95.2 (104.7)

The specimen configuration is S-L which stipulates pulling the sample in the short transverse direction, while the crack grows longitudinally.

Tensile strength and hardness

The 780 HBN hardness of the machined test sample is higher than the commonly grip hardness of tensile testing machines, thus the sample could not by tighten – (see Arrow “I” in Photo 8 which points to sliding grip marks).
Using axial tension testing of bolts per ASTM A370 “Standard test method and definitions for mechanical testing of steel products”, the tensile strength of Max5A was 111,000 PSI, a particularly high value when compared to martensitic, semi-austenitic, duplex, and super duplex Stainless Steels.[5]



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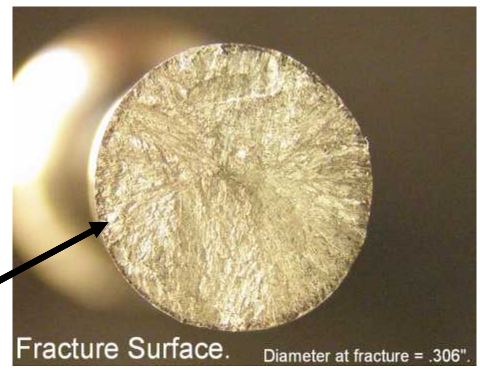

Photo 8. **Photo 9.**

Photo 8 and Photo 9. Max5A tensile tested specimen

Photo 9 shows the fractured surface of the tension tested sample at X5.7 magnification. Arrow “H” indicate the strain hardened skin which strengthens without any deformation. Fracture occurred under cleavage conditions breaking atomic bonds along preferred crystallographic planes.

A Knoop hardness tester was used to establish the microhardness of the Max5A matrix. The Max5A casting hardness was checked with Rockwell C and Brinell per ASTM A370, however, reliable results were obtained with the Brinell tester using 10-mm diameter carbide ball.

Max5A service performance

Fertilizer Plant in Louisiana

Photos 10 and 11 show the Max5A “impeller”, “pump case” and “intake cover” of the EMW 150 pump, which run successfully 24/7 for 10 months. The operation had 66% phosphate rocks with SG = 1.78 and 1,000 RPM.

Photo 10. **Photo 11.**

Photo 10 and Photo 11. The Photos show the excellent appearance of Max5A castings after ten continuous months of service in a Louisiana Fertilizer Plant

Arrow “J” points to small material displacements which were previously seen on the pin-on-disk tested sample.

Mining operation in South America

Photo 12 is a view of the backside of the old impeller after 40 days of service in a heavy mining operation. The hardness range was 620-660 HBN taken at the “impeller” OD the most wear exposed area.

Photo 13 shows the Max5A “impeller” after 97 days. The total service life was 135 days. The service life of the Max5A “impeller” increased 260% over the previously used material and by 450% over the hard iron manufactured by local suppliers.

Photo 12. **Photo 13.**

Photo 12 and 13 show the old “impeller” compared to the Max5A “impeller

Second mining operation in South America
Photo 14 and 15 show two used, old “impellers”. The first “impeller” pumped 96,978 T during its 316.5 operation hours. The second “impeller” pumped 182,561 T and had 645.25 operation hours.
The arrows show the worn out “impeller” shrouds.

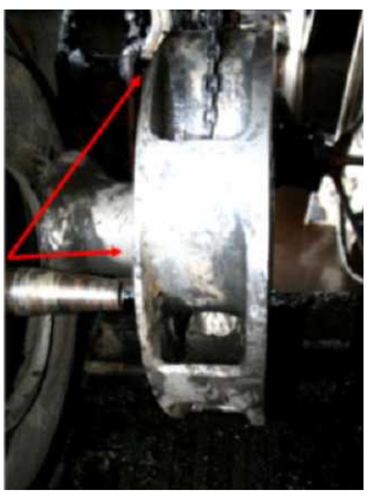

Photo 14. **Photo 15.** **Photo 16.**

Photo 14, Photo 15 and Photo 16. The first two “impellers” are poured from the old material and show severe wear. The third “impeller” is poured in Max5A and has significantly longer service life

Photo 16 shows the Max5A "impeller" which pumped 314,480 T, during its 1,109.25 operation hours.
Considering the average performance of the old two "impellers", the Max5A "impeller" increased production by 225% T and 231% in operating hours.

Fracking operation
Photo 17 views a fully machined Max5A "impeller" with double pumping veins and cleaning veins.
Despite the increased hardness and the discontinuous cut machining was successfully completed.
The Max5A "impeller" pumped 120 Millions lb of sand.

Photo 17.
Photo 17. The fully machined Max5A "impeller" has excellent appearance

Basic review of wear in centrifugal pumps

Impacting particle erosion
The material volume loss [W] through impacting particle erosion of brittle materials was developed by the National Institute of Standard and Technology: [6]

$$W \alpha \ V^{19/6} r^{11/3} \rho^{19/12} K^{-4/3} H^{-1/4} \qquad [1]$$

V = particle velocity;
r = particle radius;
ρ = particle density;
K = material fracture toughness;
H = material hardness

Fracture toughness is more important than hardness in diminishing the material loss through impacting particles.
Max5A's combination of increased hardness and elevated toughness ensured excellent service life.

Sliding abrasion
The published formula of volume loss [W] through sliding abrasion is: [7]

$$W \alpha K.C.L.\sigma / H \qquad [2]$$

K = proportion of abrasive particles contacting the material surface;
C = coefficient;
L = sliding distance;
σ = particle load on the contacting surface;
The validity of this formula was practical established by monitoring the hardness influence on the service life of the Max5A "wetted end" castings – see Fig.3. When hardness exceeded 670 HBN the service life increased exponentially.

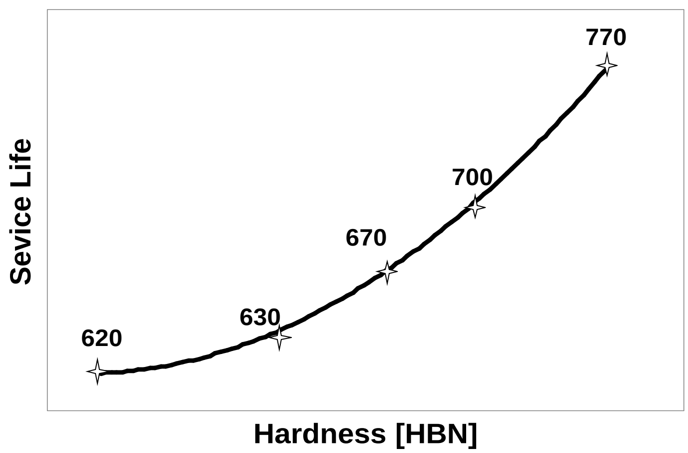

Figure 3.

Figure 3. Service life increases exponentially for materials with high hardness.

Final remarks

The combined 770 HBN hardness and 27.2 KSI.(inch)$^{1/2}$ fracture toughness increased the service life of Max5A "wetted end" pump parts between 2 - 4 times over the 25% Cr Industry Standard hard iron.
The operational pH range of Max5A is 2.35 – 13.6, a remarkably higher value than the 25% Cr Industry Standard of pH = 3.5 – 9.5.

The increased wear and corrosion resistance of Max5A is obtained through the optimized microstructure of primary and secondary chromium carbides, which controls the size, shape, distribution and chromium depleted zone width.

[References

[1] ASTM A532 “Standard specification for abrasion-resistant cast irons.
[2] ASTM A439 “Standard specification for austenitic ductile iron.
[3] ASTM G99 “Standard test method for wear testing with pin-on-disk apparatus”.
[4]ASTM G1 “Standard practice for preparing, cleaning and evaluation corrosion test specimens”.
[5] ASTM E1304 “Standard test method for plane-strain (Chevron-notch) fracture toughness of metallic materials”.
[6] ASTM A370 “Standard test method and definitions for mechanical testing of steel products”.
[7] Treatise on material science and technology, Volume 16 EROSION published by Academic Press.
[8] Treatise on material science and technology, Volume 13 WEAR published by Academic Press.