Friction → Abrasion → Corrosion Testing

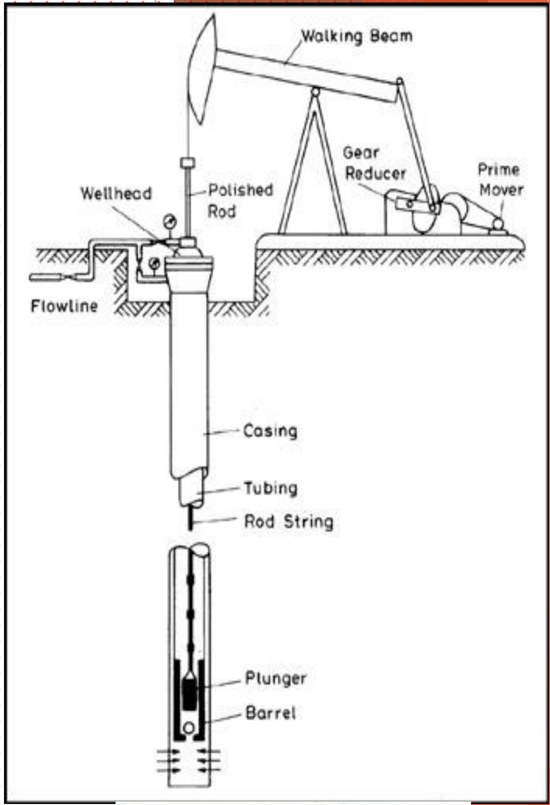
Task → **Tribological behavior of the boronized steels produced by Endurance Technologies Inc. and its comparison with some other materials**

Focused to reduce potential damage of the production equipment at the friction, abrasion and corrosion situations with the service cycle extension of the components

Conducted in collaboration with NRC-EME Canada, Vancouver (Dec. 2014 – Feb. 2015)

Materials

- Carbon steel A36/44W (CS)
- Carbon steel with electroless nickel coating - hardened (ENC-CS) – 60-70 µm (~0.0025”)
- Carbon steel with chromium electroplated coating (Cr-CS) - 200-225 µm (~0.008-0.009”)
- Carbon steel boronized (B-CS) with case depth of ~200 µm (~0.008”)



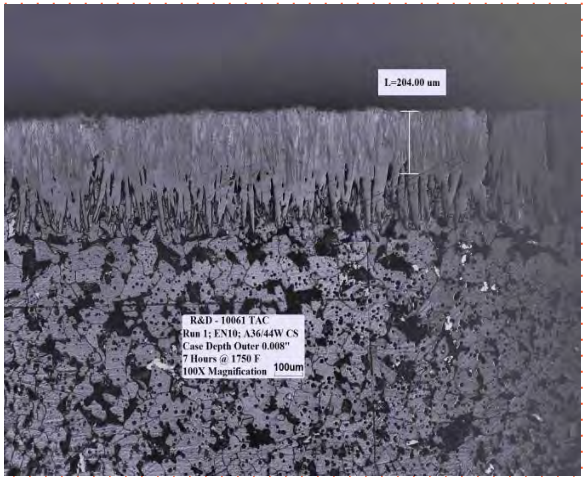
Materials→Structure→Properties

Boronize Samples

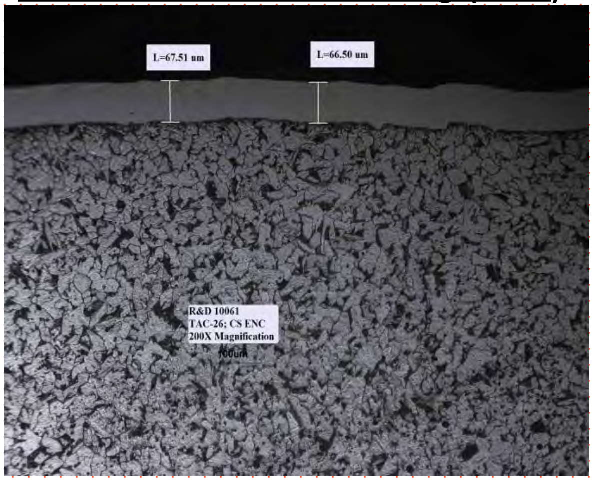
"Saw-tooth" dense structure; consists of iron borides Fe_2B and FeB with high hardness; no mechanical interface between boride coating and steel substrate

ENC and Cr Coatings Smooth coating structure with visible interface between the coating and the substrate

Boronized Steel



Electroless Nickel Coating (ENC)

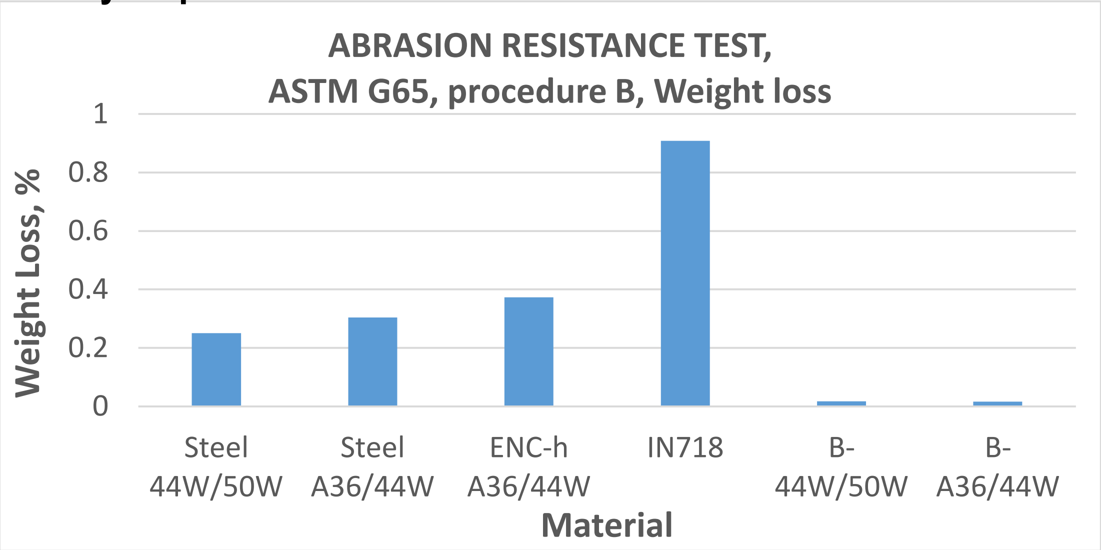


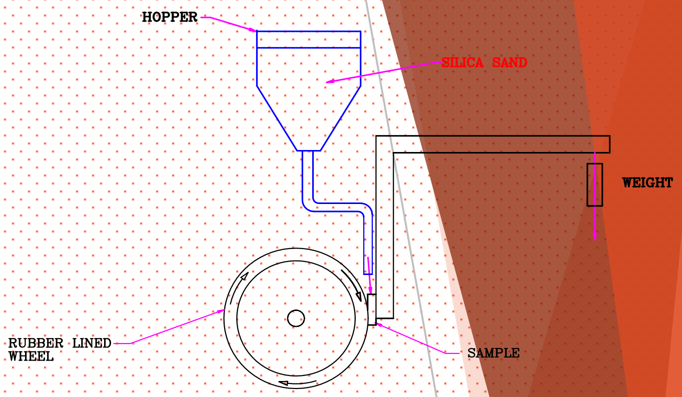
Electroplated Cr Coating

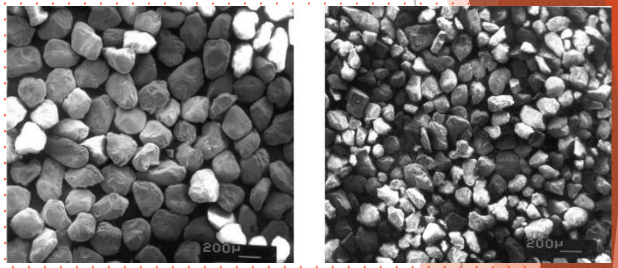
Material	Coating Thickness	Hardness HK0.1	Roughness
CS	-	175-185	2.6-4.0 µm blasted
ENC-hardened	~67 µm	700-800	3.0-3.4 µm
Cr	~225 µm	900-1050	3.4-4.1 µm
B-CS-200	~200 µm	1750-1850	3.9-4.3 µm

Wear Resistance

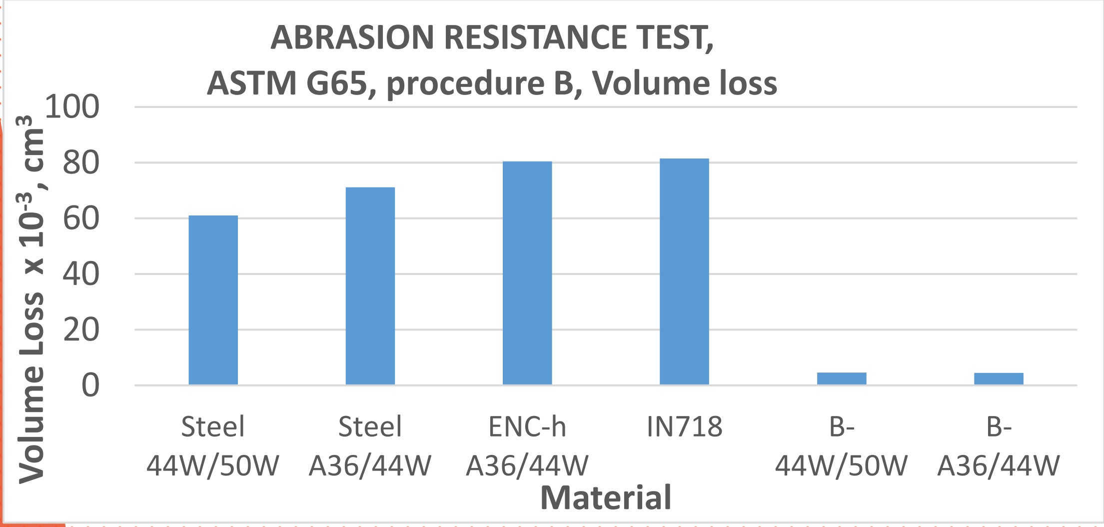
Sliding abrasion is often situation of the service of piping systems and engineering components in heavy oil production







AFS 50-70 mesh sand vs. oilsand tailing solids



Boronized coating (B) – cased depth of ~200 μm (0.008")

ASTM G65 (Procedure B) – dry sand rubber wheel test

Continuous action of abrasive media (AFS 50-70 mesh sand) supplied between the sample and a rubber lined wheel.

Test duration – 2000 revolutions

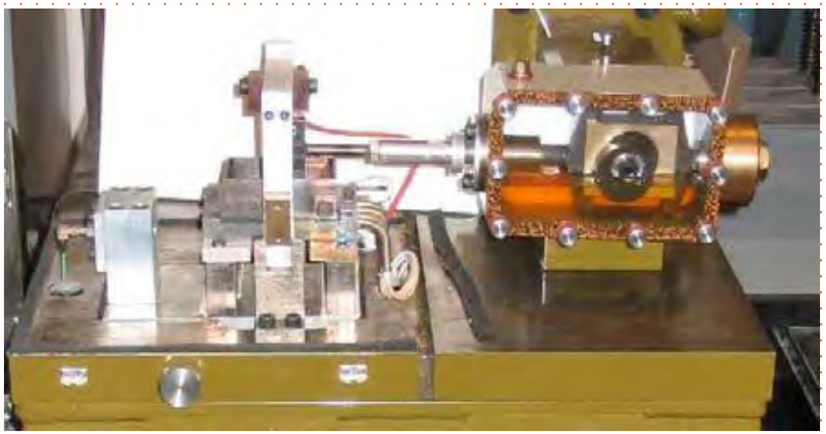
Crack formation in hard Boronized coating is reduced by the support of ductile steel through "saw-tooth" grain structure and strong adhesion

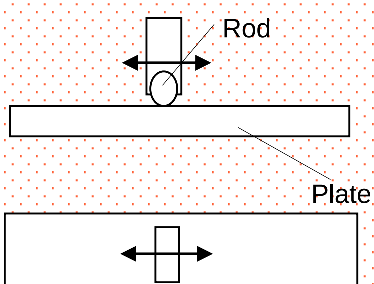
Friction Test

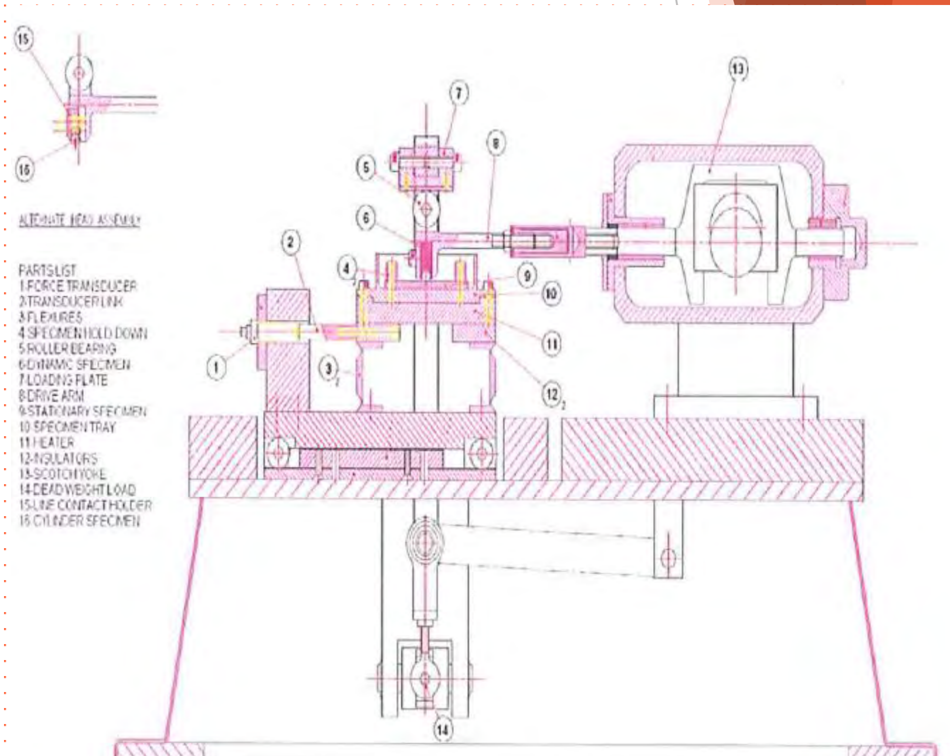
Friction Test Principle – rod-on-flat reciprocating sliding conditions

(testing sample against hard SS rod)

- Cameron-Plint machine TE77
- Lubricating (water-oil) conditions simulated oil production (e.g. at sucker rod)
- Tribo-abrasion (TA) – silica particles added
- Tribo-corrosion (TC) – sulphuric acid and sodium chloride added
- Tribo-abrasion-corrosion (TAC) – silica particles, sulphuric acid and sodium chloride added

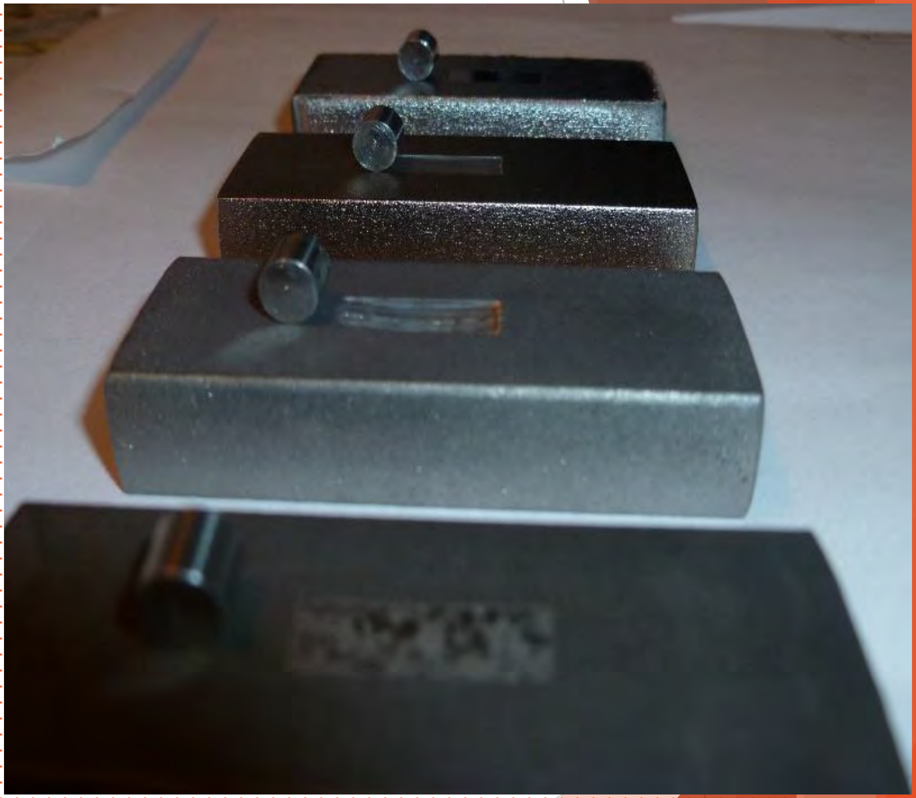






Friction Test Results

Samples After Friction-Abrasion-Corrosion Testing



Sample dimensions

63.5 mm L, 25.4 mm W, 12.7 mm H

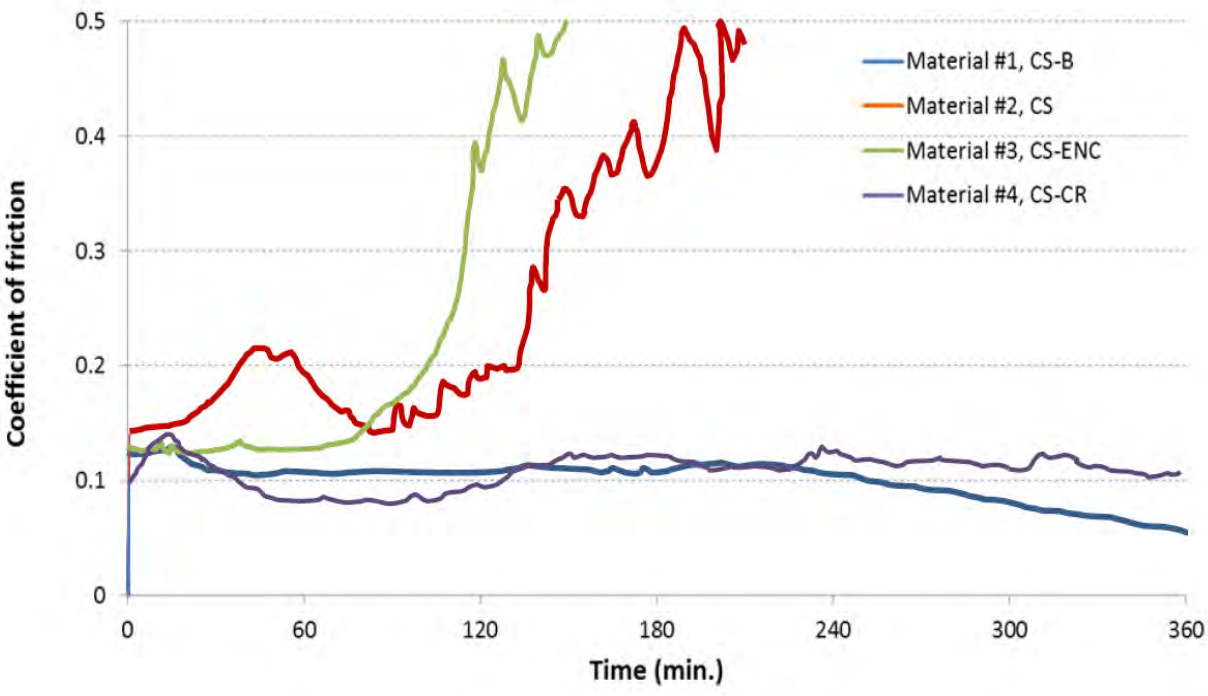
Rod – 440C grade SS HRC54

6.35 mm Dia. x 6.35 mm L

Friction → Abrasion → Test Results

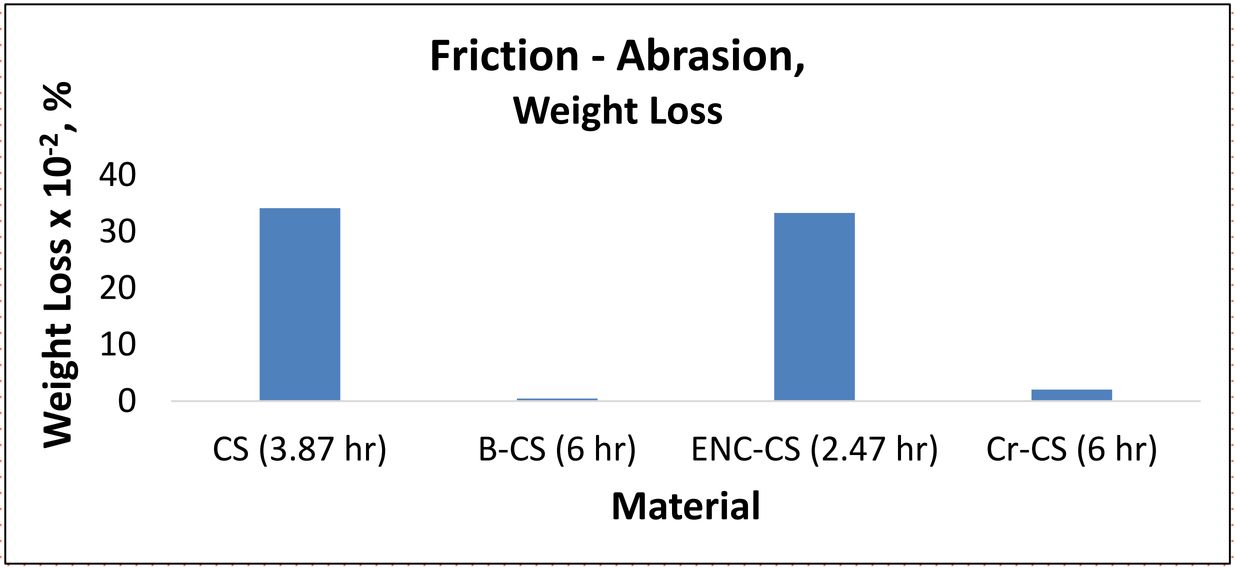
Test parameters: Load 200 N, friction force conversion factor 20 N/V

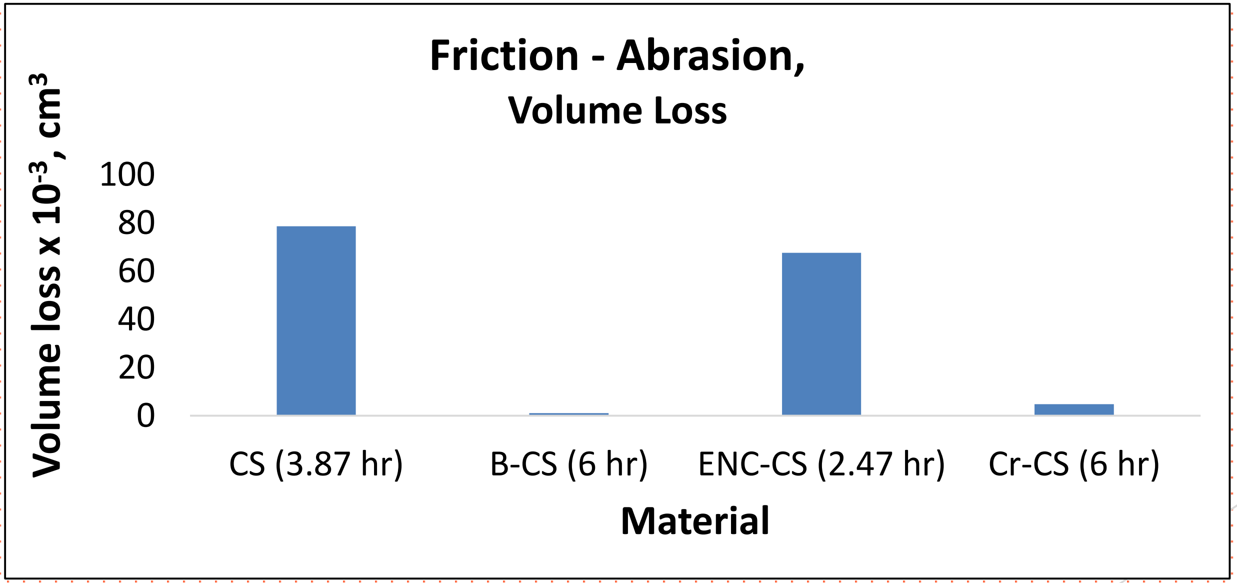
- Stroke peak to peak 15 mm
- Speed 10 Hz (sliding speed 300 mm/sec)
- Sliding time 360 min for B-CS and Cr-CS, 232 min. for CS and 148 min. for ENC
- Water : Oil = 75 : 25; silica sand (5%) with particles of 38-53 µm (-270/+400 mesh)
- Coefficient of friction (COF) variation



Boronized steel – *COF is low and steady (does not change during testing) → minimal degradation at friction-abrasion*

Friction → Abrasion → Test Results





Boronized steel lost only <0.05x10^{-2} % of weight or ~1x10^{-3} cm^3 of volume after 6 hrs vs. 38x10^{-2} % or 79x10^{-3} cm^3 for CS after 3.87 hrs. Boronized surface roughness is removed – no wear loss

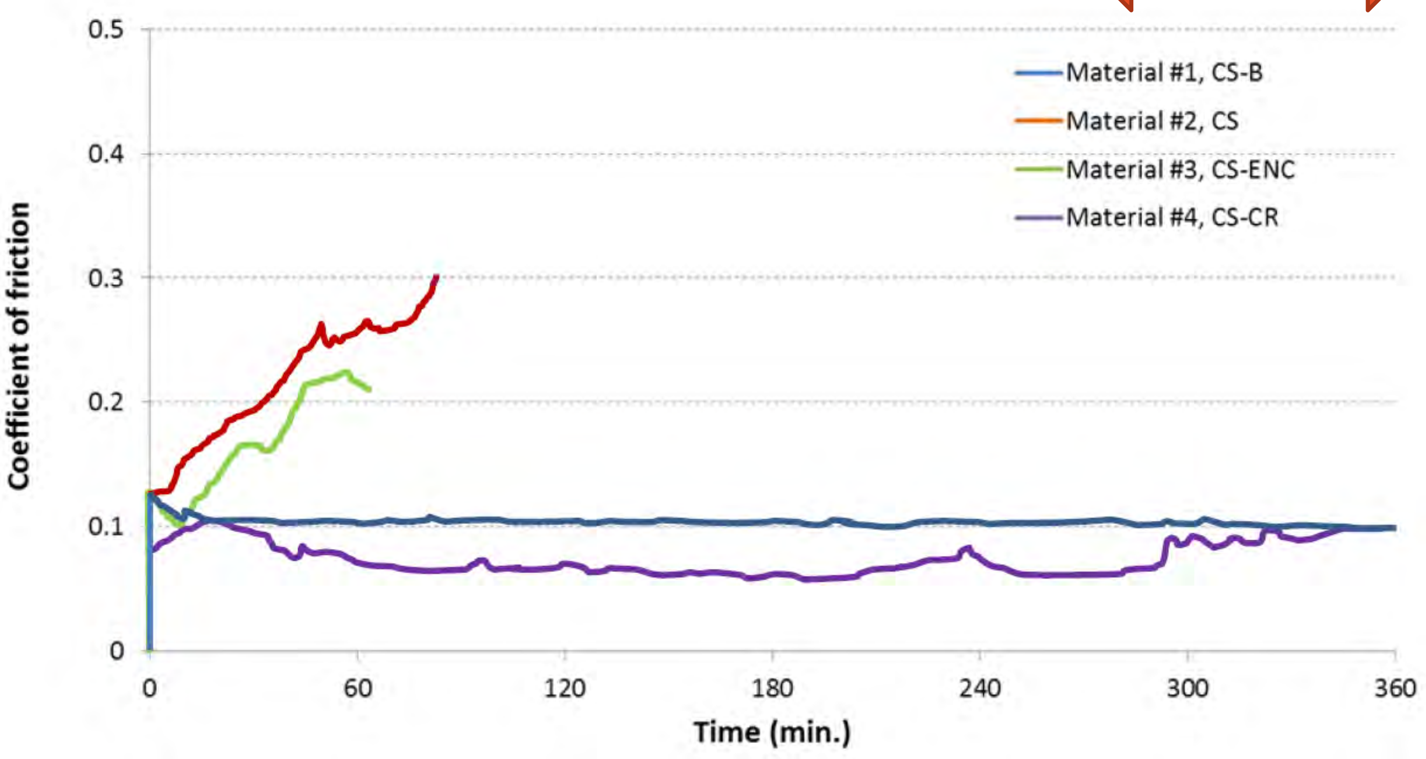
Friction → Abrasion → Corrosion Test Results

Test parameters: Load 200 N, friction force conversion factor 20 N/V

- Stroke peak to peak 15 mm
- Speed 10 Hz (sliding speed 300 mm/sec)
- Sliding time 360 min for B-CS and Cr-CS, 232 min. for CS and 148 min. for ENC
- Water : Oil = 75 : 25 with addition of 0.02M NaCl and 0.001M H2SO4 (pH 2.7);

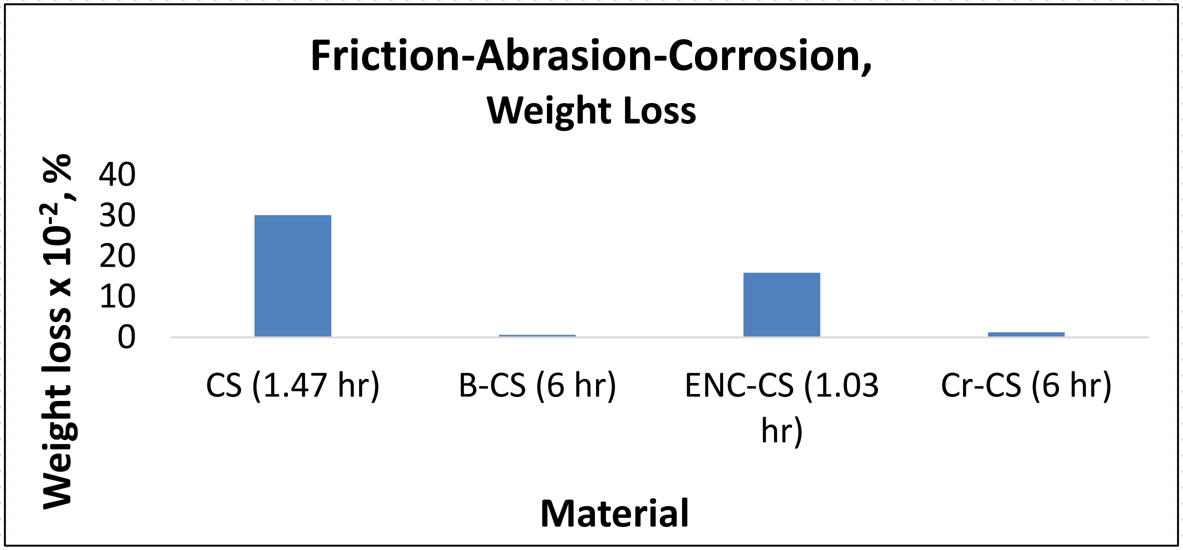
  silica sand (5%) with particles of 38-53 µm (-270/+400 mesh)

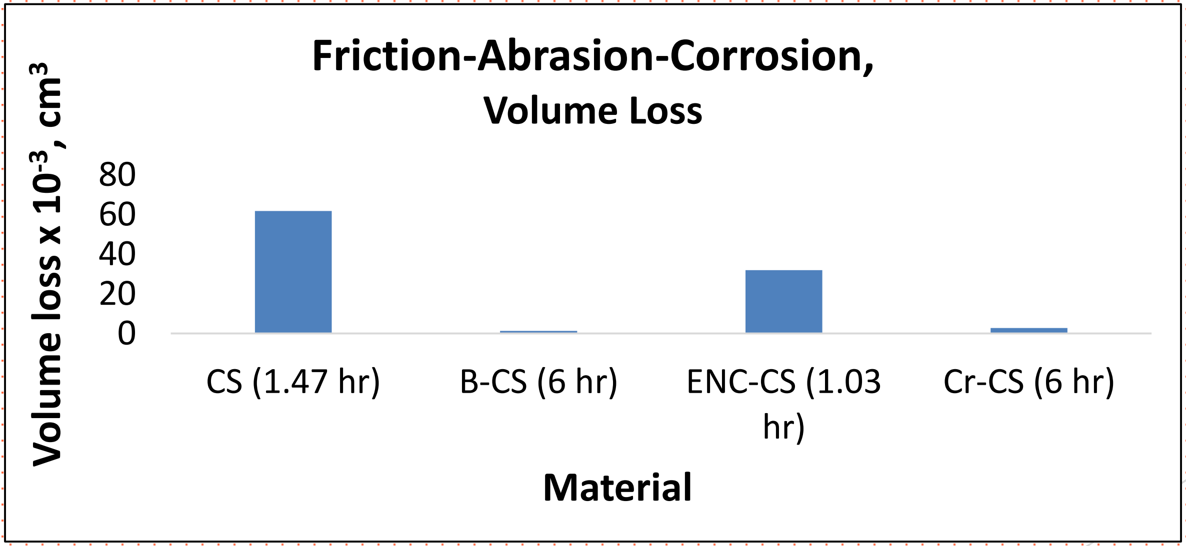
Coefficient of friction (COF) variation



Boronized steel – COF is low and steady (does not change during testing) → minimal degradation at friction-abrasion-corrosion

Friction → Abrasion → Corrosion Test Results

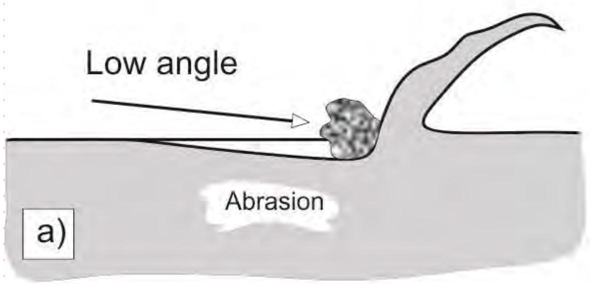


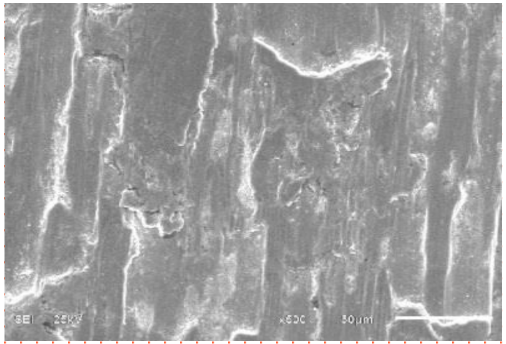


Boronized steel lost only $<0.06\times10^{-2}$ % of weight or $\sim1.3\times10^{-3}$ cm^3 of volume after 6 hrs vs. $\sim30\times10^{-2}$ % or 62×10^{-3} cm^3 for CS after ~1.5 hrs. Boronized surface roughness is removed – no wear loss

Wear Mechanism → (in Abrasion and Friction)

- Steel – plastic deformation and "ploughing" of soft material
  - worn steel particles between counterparts increase destruction and wear of steel





How does boronizing prevent this fast wear?

- Boronized steel – micro-indentation but no plastic deformation
- Saw-tooth morphology – hard Fe-B teeth perpendicular to friction mode – preventing crack propagation
- Hard coating is supported by ductile steel
- Surface oxidation and thin "nano"-tribofilm $(FeB)_xO_y$ formation → reduction of COF → tribological equilibrium → adaptation to existing tribological conditions → delay friction wear
- High chemical inertness of iron boride

! Combination of high hardness + well-consolidated structure + self-lubricating tribofilm + minimal micro-cracks + no spalling → *improved abrasion and friction resistance*

Friction Test Results

- Boronized coatings obtained through the ETI thermal diffusion process demonstrated superior friction – abrasion – corrosion resistance in simulating oil production testing conditions –
- Wear loss is only $1.3x10^{-3}$ cm^3 (after 6 hrs.) that is **about 50 times lower** than of carbon steel, while boronized steel tested ~ 4 times longer than bare carbon steel
- No delamination and flaking the boronized coatings observed
- Steady COF (very minimal growth) indicating high integrity and very minimal wear
- Crack formation and wear in hard boronized coating (~10 times harder than bare steels) are reduced by the support of ductile steel through the “saw-tooth” grain structure and strong diffusion bonding
- The synergistic effect (friction + abrasion + corrosion) enhances the wear process; abrasion has the major effect on the wear
- The benefit of boronizing for friction-abrasion-corrosion applications is in a good correlation with the data of the dry sliding abrasion test (ASTM G65)