



NEXT-GENERATION PH STAINLESS STEEL

A mission-ready combination of strength-toughness
and corrosion resistance for the defense industry

SUMMARY

Corrosion is one of the most pressing materials challenges facing the U.S. Defense industry. It is estimated that tens of billions of dollars are spent on corrosion challenges across the Department of Defense (DoD).¹ Therefore, there is demand in the Defense industry for resilient materials not only in terms of strength and toughness, but also with respect to environmental durability.

Traditionally, high-strength steels require coatings in the form of hard chromium (Cr) or cadmium (Cd), zinc-nickel (Zn-Ni), or paints to account for steel's lack of corrosion resistance. Not only are hard Cr and Cd coating lines toxic to the environment, but coatings require increased maintenance and life cycle demands. Further, the stress corrosion cracking (SCC) susceptibility of non-corrosion-resistant materials can lead to premature catastrophic failure with little to no underlying warning.

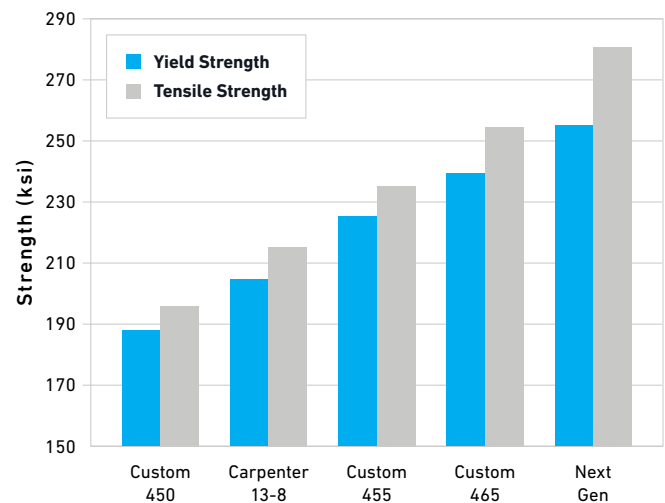
These challenges could be remedied by selecting a material with inherent corrosion resistance. However, current precipitation hardenable (PH) stainless grades do not offer the same strength and toughness levels required for structural components, and thus a debt in properties must be tolerated to substitute a PH stainless grade for a coated, high-strength steel.

The goal: Engineer a high-performance stainless steel alloy for demanding Defense industry structural components that reduces dependency on coated alloy steels prone to high maintenance costs and environmental hazards.

This white paper will discuss a patented² next-generation PH stainless steel from Carpenter Technology. This new alloy can offer the strength and toughness levels of high-strength alloy steels while supplying corrosion resistance. Additionally, this alloy features enhanced toughness at elevated strength levels compared to incumbent stainless grades, providing structural designers an opportunity to reduce dependence on toxic hard Cr or Cd coatings and reduce maintenance of coated parts such as landing gears, pins, axles, or other structurally demanding components.

The next-generation PH stainless steel from Carpenter Technology can achieve greater than 275 ksi tensile strength with greater than 55 ksi/in fracture toughness in mill section sizes up to 8.0 in. diameter while featuring no corrosion in ASTM B-117 salt spray after 1000 hours.

COMPARATIVE YIELD AND TENSILE STRENGTH IN STAINLESS STEELS



CHALLENGES AND OPPORTUNITIES

A history of strategic innovation

Carpenter Technology's Research & Development department has a long and storied history with delivering material solutions for the Defense industry. For example, 300M long served as the main alloy for naval aircraft landing gear. In the early 1990s, due to stress corrosion cracking concerns, an alternative structural steel capable of high strength and improved fracture toughness was sought by the U.S. Navy.

To meet these demands, Carpenter Technology R&D developed AerMet® 100, featuring an unprecedented level of strength and fracture toughness.³ The U.S. Navy has since relied upon AerMet® 100 for components used in harsh, no-fail operating conditions for high strength and high fracture toughness applications.



FIGURE 1—F/A-18 AIRCRAFT

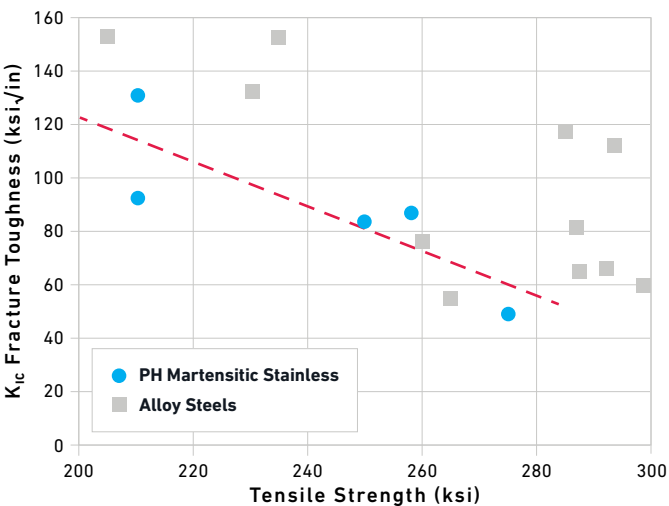


Novel alloy design didn't stop with AerMet 100. To address the ever-present challenge of corrosion, Carpenter Technology R&D got to work designing an alloy beyond the capabilities of 15Cr-5Ni, 13Cr-8Ni, and Custom 455. Custom 465 was created and has provided part designers a structural stainless steel with enhanced strength, fracture toughness, and SCC resistance. Due to this excellent balance of critical properties, Custom 465 has found numerous applications across the Defense industry.

R&D next set its sights on a stainless grade with even higher strength capabilities. Ideally, an alloy capable of achieving strength levels comparable to current structural steels while also providing corrosion resistance would be highly valuable. This alloy would provide structural designers the ability to lightweight existing stainless components in addition to replacing non-stainless components that currently require coatings.

This is best illustrated in Figure 2, which displays the current balance of strength and toughness achieved by PH stainless steels. Alloy steels offer a higher combination of strength and toughness. Therefore, the goal of the next-generation PH stainless steel was to be above the dashed line representing the current K_{IC} – tensile strength trade off for state-of-the-art PH stainless steels.

FIGURE 2 — PORTFOLIO OF STRUCTURAL STEELS BY FRACTURE TOUGHNESS AND TENSILE STRENGTH



Carpenter Technology R&D has developed a next generation of high-strength PH stainless steel. This patented alloy has been under development and mill scale-up for the past several years and is preparing to enter the marketplace.

Strength-toughness-stainless

In reference to Figure 2, the property objectives of this next-generation PH stainless steel were:

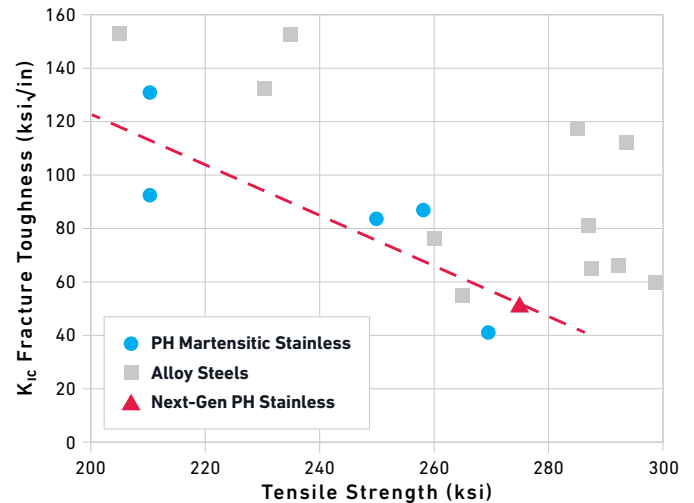
- > 240 ksi yield strength
- 280 ksi tensile strength
- > 55 ksi $\sqrt{\text{in}}$ plane-strain fracture toughness
- Corrosion resistance equivalent to 15Cr-5Ni

One of the main challenges with achieving these properties is delivering a careful balance of increased strength without sacrificing the functional fracture toughness of the alloy or the corrosion resistance. Traditionally, to achieve a gain in one aspect, such as strength and toughness, one must sacrifice corrosion resistance and vice versa.

The goal of Carpenter Technology R&D was to develop an alloy that pushed the limits and could retain excellent strength and corrosion resistance while providing enhanced toughness compared to existing similar high-strength stainless grades.

To demonstrate the capability of Carpenter Technology's next-generation PH stainless steel, Figure 3 presents mill scale properties of the new grade of steel compared to the incumbent grades. The next-gen PH stainless steel defies the current property trade-off of strength and toughness. Further, the alloy retains good general corrosion resistance compared to current grades of PH stainless steels.

FIGURE 3— K_{IC} -TENSILE STRENGTH VS. INCUMBENT GRADES



A novel alloy design approach

The nominal chemistry of Carpenter Technology's next-generation PH stainless steel is provided in Table 1.

TABLE 1—TYPE ANALYSIS OF NEXT-GEN PH STAINLESS STEEL

Iron	Balance	Nickel	11.0–12.0 %	Chromium	9.0–10.0 %
Cobalt	2.5–5.0 %	Molybdenum	2.0–3.0 %	Titanium	1.6–1.8 %
Aluminum	Max 0.25 %				

The design of the composition was based on an optimization approach leveraging proprietary empirical modeling with thermodynamic computer modeling. Deliberate selection of a novel set of strengthening phases permits elevated strength to be achieved without sacrificing toughness and corrosion.²

Ease of processability

Concurrent with the design of the chemical composition was focusing on producing a scalable composition with processing pathways similar to those of state-of-the-art PH stainless steels.

To meet the stringent corrosion resistance and mechanical property requirements, Carpenter Technology's next-gen alloy is premium vacuum melted and vacuum arc remelted. Heat treatment schedules and workability are equivalent to Custom 465. The novel alloy has been vacuum melted without deleterious segregation or melt defects. The alloy is readily hot-workable, can be cold-worked, and has been also produced via powder atomization.

Current wrought billet has been produced up to 8.0 in. (203 mm) in diameter and can meet the strength, toughness, and corrosion resistance required for demanding structural requirements. Bar and strip products have been manufactured with excellent mechanical properties exceeding 290 ksi yield strength with no cold work.

Mill scale properties

Average properties for mill processed 5.5 in. diameter bar are shown in Table 2. These values are derived from mill solution annealed and lab capability aging. They represent both longitudinal and transverse tensile properties, alongside longitudinal plane-strain fracture toughness values. From Table 2, the next-generation PH stainless steel can achieve 280 ksi tensile strength while preserving fracture toughness on average of over 70 ksi√in.

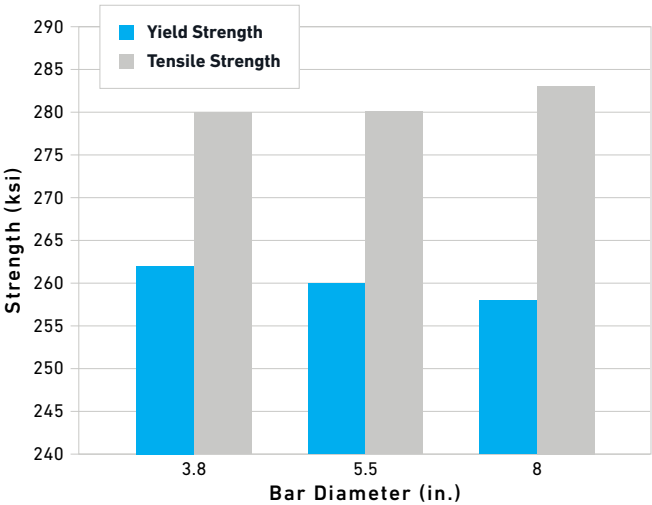
TABLE 2

TYPICAL MECHANICAL PROPERTIES OF FORGED NEXT-GEN PH STAINLESS AT 5.5 IN. DIAMETER	
PROPERTY	TYPICAL VALUE
0.2% yield strength (ksi)	260
Tensile strength (ksi)	280
EL in 4D (%)	10
RA (%)	40
K _{IC} (ksi √in)	55

Value range derived from longitudinal and transverse properties from bars > 7 in. diameter at peak age heat treatment.

Forged bar products have been produced in a range of finish sizes from 3.5– 8.0 in. diameter bars. These bars have been solution-annealed at full section size and capability aged for testing. From Figure 4 below, longitudinal testing of samples from mid-radius and capability heat treated to peak aging condition can achieve 280 ksi across the size range produced.

FIGURE 4 — TENSILE PROPERTIES OF NEXT-GEN PH STAINLESS STEEL AT 3.8, 5.5, AND 8 IN. DIAMETER FORGED BAR



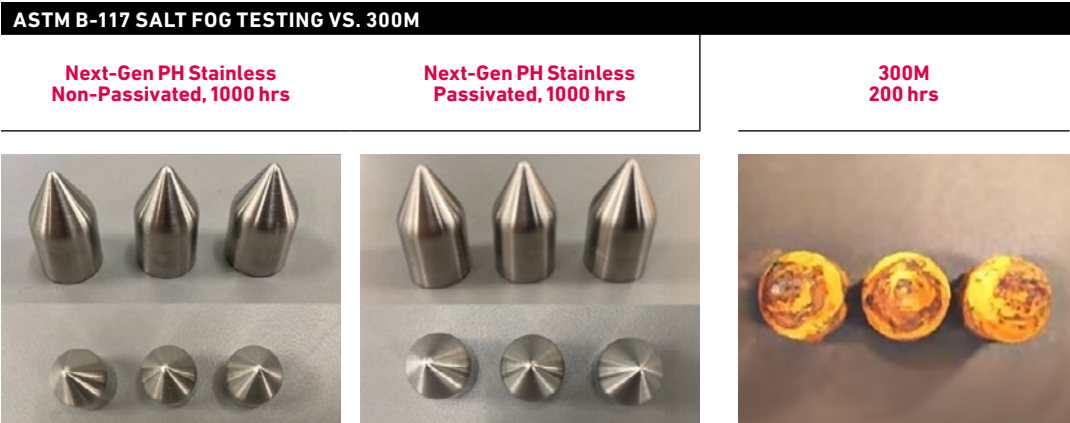
Corrosion resistance

One of the most important properties of the next-generation PH stainless steel is corrosion resistance. Combining premium melt quality and leveraging the matrix Cr and Mo content after aging, the next-generation PH stainless steel can provide equivalency in general corrosion resistance to incumbent stainless grades such as 15Cr-5Ni and Custom 465.

The most common test for validating general corrosion performance is the salt spray test detailed in ASTM B-117.⁴ Aged samples are prepared and placed in a 95°F humid fog cabinet continuously spraying 5 m % NaCl solution on specimens for a prolonged duration.

Salt spray performance of the next-generation PH stainless steel is presented in Figure 6. Samples were prepared with and without AMS 2700 Type 2 passivation.⁵ From Figure 6, both sets of samples were corrosion-free after 1000 hours, showcasing the material's corrosion resistance. Comparatively, on the far-right of Figure 6 is a common structural alloy steel, 300M, after 200 hours of salt fog testing. Heavy general corrosion is evident.

FIGURE 6



Left: Next-Gen PH Stainless Steel after 1000 hours in the unpassivated and passivated conditions.
Right: 300M alloy steel after 200 hours.

Beyond general corrosion testing of the next-generation PH stainless steel, the Corrosion Lab at Carpenter Technology is investigating rising step load (RSL) per ASTM F1624 at open-circuit and potentiostatic conditions to quantify the SCC resistance of the alloy.

CONCLUSION

The ambition of Carpenter Technology's next-generation PH stainless steel is to provide a stainless solution for structural applications in the Defense industry without requiring a compromise in strength or toughness.

Based on the data shown here from mill properties of the next-generation PH stainless steel, this alloy is poised to serve as a valuable material for numerous structural applications that can take advantage of the alloy's unique strength and corrosion resistance, plus excellent fracture toughness.

Carpenter Technology's next-gen PH stainless steel gives end users a corrosion-resistant alternative to many current grades of non-corrosion-resistant high-strength steels to:

- Reduce dependence on toxic coatings
- Decrease life cycle costs
- Reduce maintenance
- Serve on next-generation Defense platforms
- Upgrade existing components and solve for corrosion or reliability challenges

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²Roth, Wesley T. *High fracture toughness, high strength, precipitation hardenable stainless steel*. US20210371945A, United States Patent and Trademark Office, 2 December 2021.

³Thomas, J., and Mc Caffrey. "Combined Strength and Toughness Characterize New Aircraft Alloy [J]." *Adv. Mater. Process* 2.3 (1992): 47-53.

⁴ASTM Standard ASTM B117-19, 2024, "Standard Practice for Operating Salt Spray (Fog) Apparatus," ASTM International, West Conshohocken, PA, 2024, DOI: 10.1520/B0117-19

⁵SAE International Material Specification, *Passivation of Corrosion Resistant Steels*, SAE Standard AMS2700F, Revised March 2018, Issued March 2000, <https://doi.org/10.4271/AMS2700F>.

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