

Cryotreatment

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The Science of Deep Cryogenic Treatment (DCT)

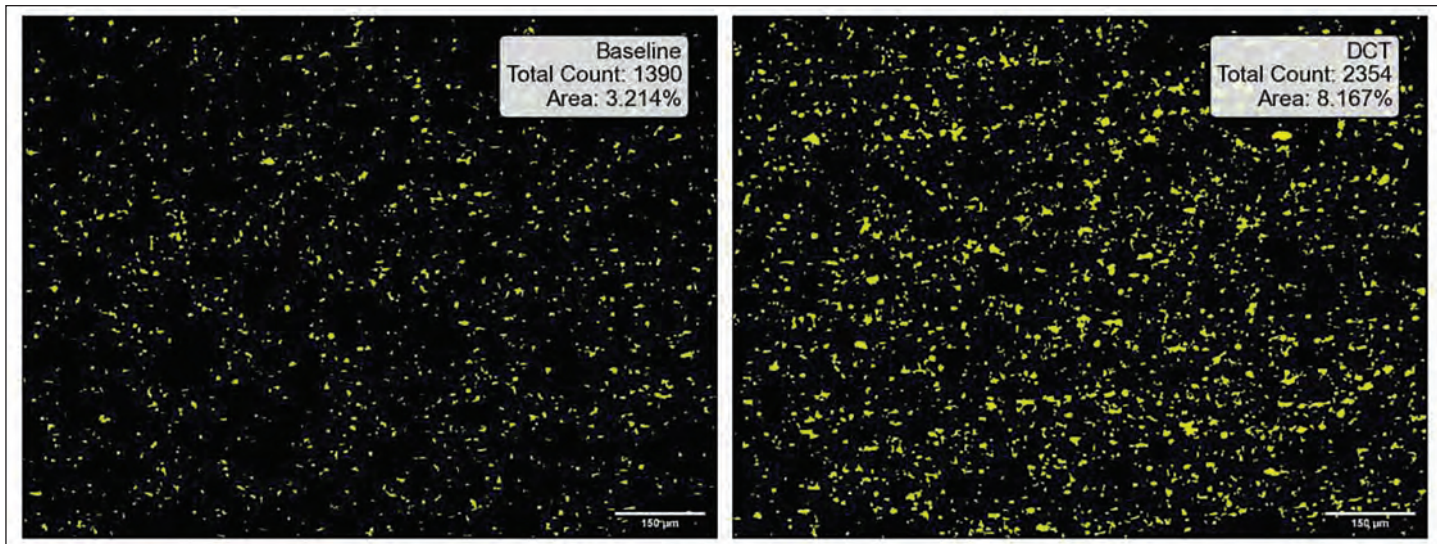


Figure 2: Carbide count in high-carbon steel. Credit: Jack Cahn

Let's dive in and explore the mechanisms and benefits of shallow cryogenic treatment (SCT: -60°F to -190°F) and deep cryogenic treatment (DCT: -190°F to -320°F). A quick refresher: generally, SCT occurs when the foundational heat treatment step of austenitizing is followed by quenching below ambient water or oil temperature, usually by quick exposure to dry ice or cold nitrogen gas vapor. DCT continues this process to even lower temperatures by using liquid nitrogen, a highly insulated chamber and a 24- to 36-hour PLC-controlled cycle. The boundary between SCT and DCT varies by metal and is dependent on material chemistry and prior heat treatment steps.

SCT is used to achieve:

Partial transformation of retained austenite. In steels—especially tool and high-carbon steels—SCT converts retained austenite, a softer, unstable phase, into martensite, a harder and more stable phase. Retained austenite forms during quenching and can reduce hardness and dimensional stability. However, because the

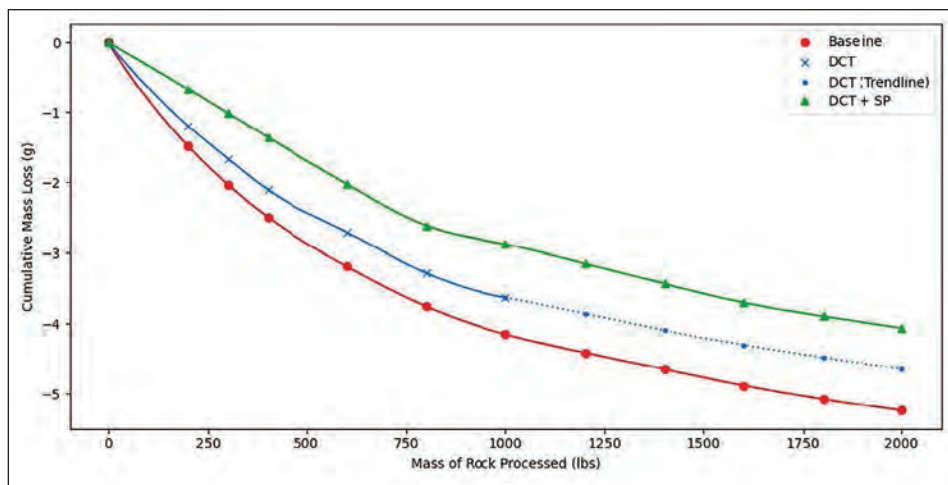


Figure 3: ASTM G81-97(a) wear test of Mn steel after crushing 2,000 lbs. Credit: Jack Cahn

martensite start temperature (M_s) of 4340 high-carbon steel begins at approximately 314°F and the martensite finish (M_f) is generally below -212°F , SCT does not complete the transformation like DCT does.

Austenite decay begins immediately after newly formed, heat-treated steel begins to cool (the decomposition of austenite from FCC crystal phase into ferrite, bainite, martensite, etc.). Heat

treaters often report greater benefit from SCT or DCT conducted immediately on-site, rather than DCT done later at remote facilities, where parts may have cooled for a greater period of time.

Reduced distortion and improvement of dimensional stability. SCT can reduce internal tensile stresses created during machining or heat treatment.

Improved (moderate) wear resistance. Due to the partial phase transformation (retained austenite to martensite) and microstructural refinement, SCT can increase surface hardness and improve wear resistance. SCT is more effective on single-phase rather than dual-phase materials, in less demanding applications when exposed to moderate wear or cyclic loading.

Cost-effectiveness. SCT is more cost-effective and accessible than DCT and predates computer-controlled systems. Unlike DCT, it maintains or slightly improves surface hardness—a key durability metric for most heat treaters.

DCT is used to achieve:

Precipitation of fine carbides. DCT promotes the formation of fine eta-carbides in steels (Figure 2), which strengthen the material via precipitation hardening by pinning dislocations at grain boundaries. Unlike heat treating that requires precise thermal control, these carbides remain stable at ambient temperatures, making DCT especially effective at reducing two- and three-body wear (Figure 3).

Reduction in residual stress. Deep cryogenic temperatures relieve tensile residual stresses caused by machining, fabrication, heat treatment and welding (Figure 4). DCT achieves greater microstructural stress balance than SCT by reducing atomic-level vacancies. More pronounced than SCT, DCT also induces beneficial compressive stress, helping to heal fatigue cracks that nucleate at grain boundaries, reduce MnS and oxide inclusions and disrupt transgranular or carbide-precipitated crack initiation or propagation (Figure 5).

Increase in ultimate tensile strength (UTS). DCT's extreme cold reduces grain size in most metals—a phenomenon known as the Hall-Petch effect, which states that as grain size decreases, a material's strength increases. This happens because grain boundaries resist the movement of dislocations

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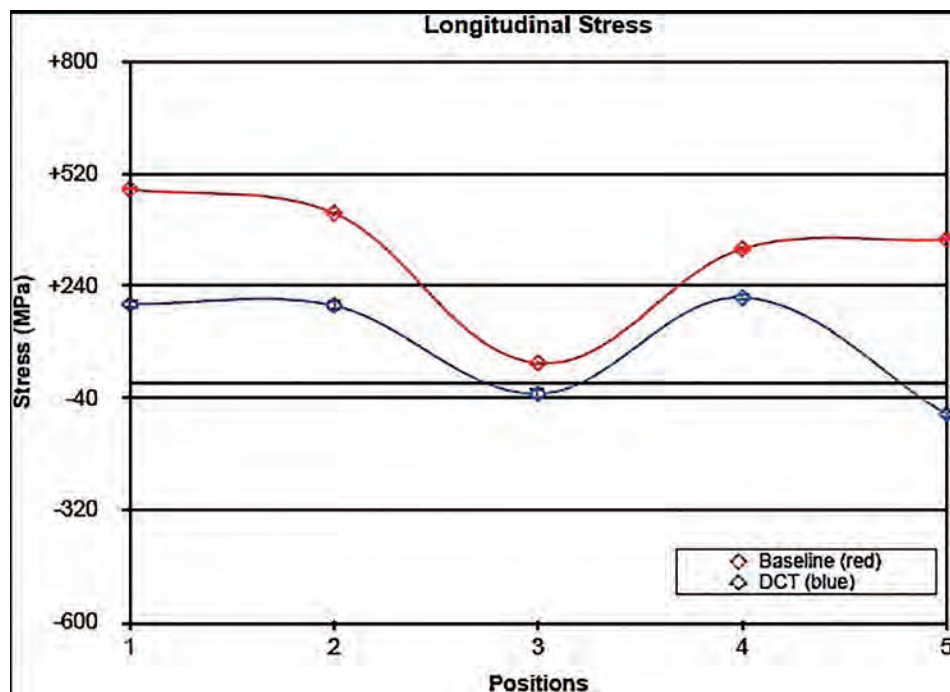


Figure 4: Residual stress test of 13% Mn using XRD. Credit: Jack Cahn

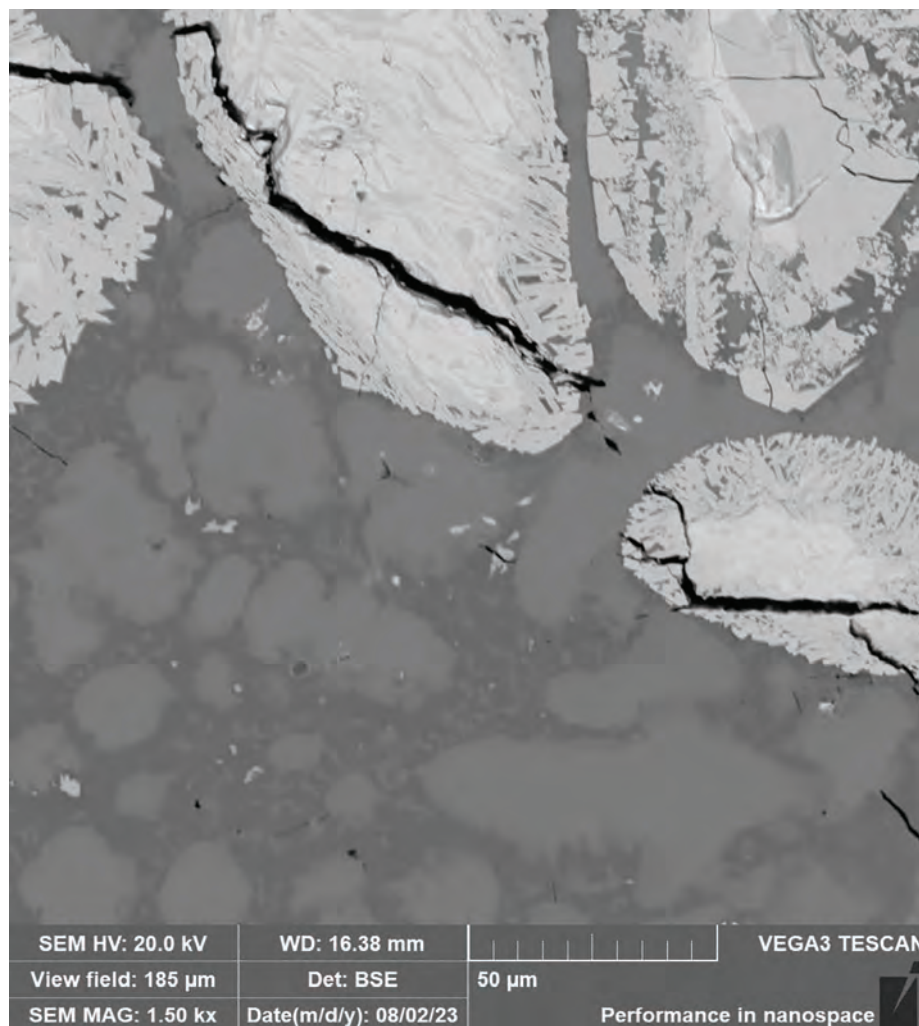


Figure 5: Crack healing between two carbides. Credit: University of Alberta

(the atomic-level defects in a crystal responsible for plastic deformation). More grain boundaries by volume means more resistance to dislocation movement, thus higher strength under stress (Figure 6). Admittedly, this may qualify as “TMI” for non-metallurgists!

Most of the benefits listed above are textbook responses to SCT and DCT on tool steels (440C, H13, S7, D2, M2), carbon steels (4140, 4340, 1018, 1020), and gear steels (52100, 8620, 440C, 1045)—and even titanium, which has a martensitic phase. These materials also demonstrate improved resistance to corrosion after DCT (Figure 7).

Other metals

What about nonferrous materials like aluminum or copper that don’t have martensite phases? Most aluminum alloys show added stress relief and fatigue resistance after DCT but no added corrosion protection. Copper, while showing no improvement in wear life, UTS or corrosion, consistently exhibits a 1 to 1.5% increase in permanent conductivity post-DCT—even outside a superconductive state.

Large castings used in mining, energy and transportation—typically gray, ductile, high-chrome white iron or manganese steel—rely on work hardening, where impact or deformation boosts surface hardness and fatigue resistance. DCT is especially valuable to end users of hard rock mining items like shovel teeth and cone crushers because it induces compressive stress (crack healing) deep in the material and accelerates work hardening by forcing increased dislocation density from the reduction in austenite grain size and from the TRIP/TWIP effect.

Weldments benefit from DCT as the heat-affected zone (HAZ) surrounding the weld shrinks significantly following cryogenic treatment. The HAZ is subject to weld-induced residual stresses that often lead to premature cracking and failure. DCT has proven effective across an array of welded items from stainless steel and refractory alloys to additive manufactured items. Because strain at the bond interface is significantly reduced—by up to 70%—additive manufacturing could achieve breakthrough improvements in weight, geometry

52100 BEARING AND 4340 HIGH CARBON STEEL					
SUMMARY RESULTS:	Yield Strength	Peak Strength	% Stress	Strain Elong	Reduction @ Break
	KSI	KSI	%	%	%
No Cryo 52100, Baseline	268	359	2.5	3.9	6
Cryo 52100, Cryo then Tempered	317	382	1.6	3.5	1
Cryo 52100, Tempered then Cryo	320	376	1.8	3.8	4.5
No Cryo 4340, Baseline	221	295	15.3	12.5	51.7
Cryo 4340, Cryo then Tempered	240	300	14.2	11.6	51.3
Cryo 4340, Tempered then Cryo	221	287	15.9	12.3	51.6

20% improvement to 52100 yield strength
10% improvement to 4340 yield strength

Figure 6: UTS of 4340 and 52100 steel in baseline and DCT states. Credit: Jack Cahn

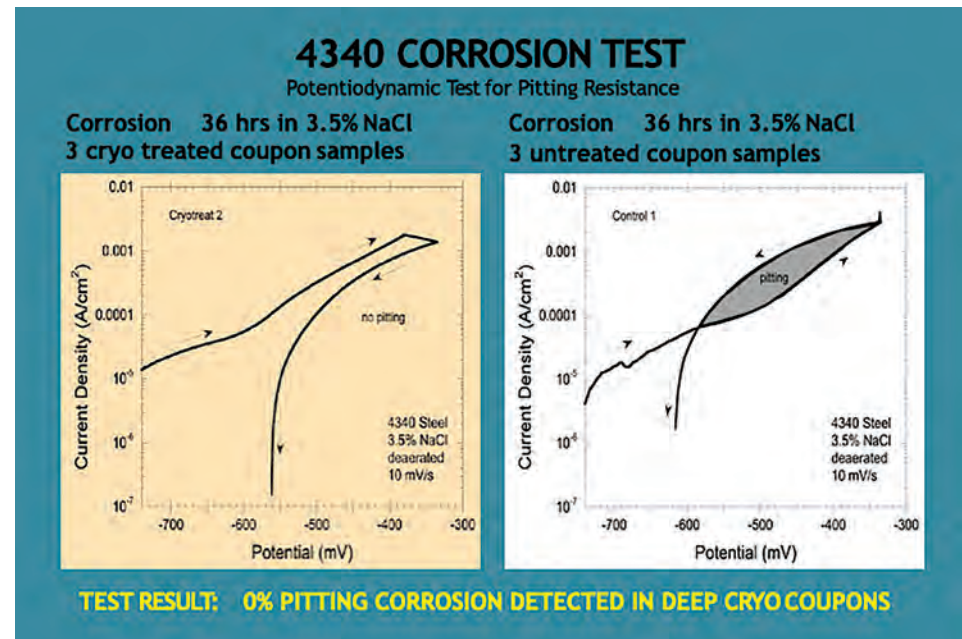


Figure 7: Corrosion in 4340 steel. Credit: Jack Cahn

and tensile strength when dissimilar metals are combined in a monostructure.

Conclusion

Shallow cryogenic treatment offers low-cost and readily available benefits for high and low carbon steels and many non-ferrous materials used in low to moderate wear applications. Deep cryogenic treatment is most effective for ferrous alloys, particularly high carbon tool steels, white iron and manganese castings, due to its ability to transform retained austenite and

enhance carbide precipitation in high-wear applications—far beyond SCT. Cryogenic treatment of aluminum and titanium is typically limited to stress relief, with minimal gains in hardness or wear resistance. DCT’s effectiveness depends on material type, prior heat treatment and application-specific needs.

In the next issue, we’ll explore the range of equipment available to perform cryogenic treatment in commercial and industrial settings. 🧊