Frozen Gears

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Durability is the most important criterion used to define the quality of a gear. The freezing of metals has been acknowledged for almost thirty years as an effective method for increasing durability, or "wear life," and decreasing residual stress in tool steels. The recent field of deep cryogenics (below -300°F) has brought us high-temperature superconductors, the superconducting super collider, cryo-biology, and magneto-hydrodynamic drive systems. It has also brought many additional durability benefits to metals.

The deep cryogenic tempering process for gears is an inexpensive, one-time, permanent treatment, affecting the entire part, not just the surface. Gears may be new or used, sharp or dull, and resharpening will not destroy the treatment. The process has a number of obvious benefits, including increases in tensile strength, toughness, and stability through the release of internal stresses. The exceptional increase in wear resistivity, generally exceeding 200%, is the greatest benefit.

Steel surfaces receiving wear, such as gears, shaper cutters, drill bits, end mills, taps, dies, surgical scissors, bearings, racing engines, slicers, and granulator knives, all benefit from this inexpensive treatment. New applications are being discovered regularly.

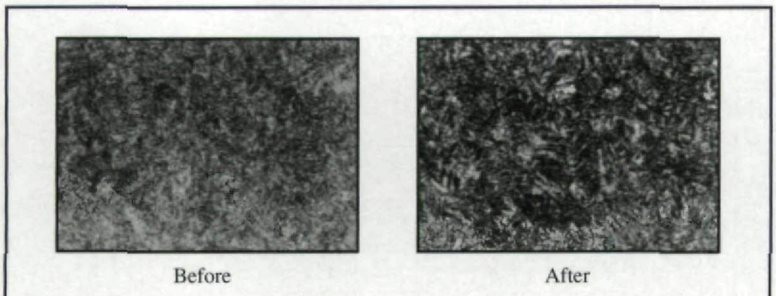

Fig. 1

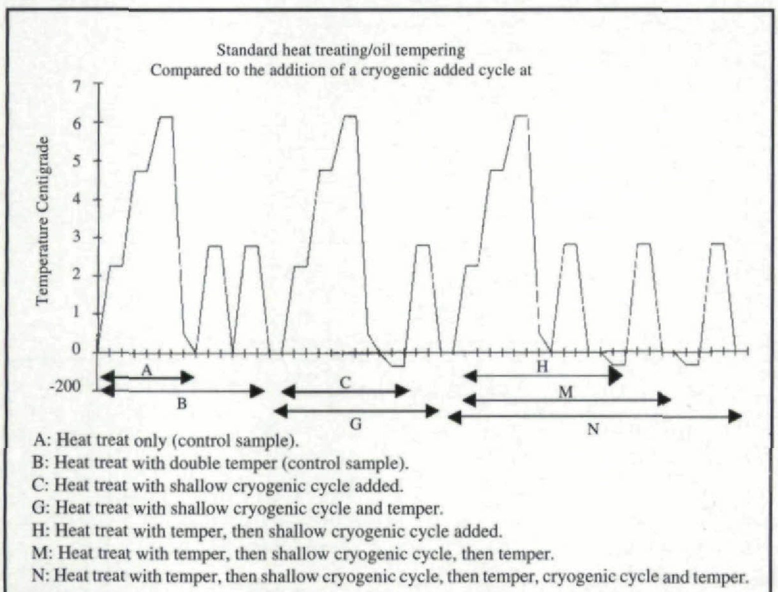

Fig. 2

Completing the Heat Treating Process - Martensitic Transformation

A research metallurgist at the National Bureau of Standards states, "When carbon precipitates form, the internal stress in the martensite is reduced, which minimizes the susceptibility to microcracking. The wide distribution of very hard, fine carbides from deep cryogenic treatment also increases wear resistance." The study concludes: "... fine carbon carbides and resultant tight lattice structures are precipitated from cryogenic treatment. These particles are responsible for the exceptional wear characteristics imparted by the process, due to a denser molecular structure and resulting larger surface area of contact, reducing friction, heat, and wear."

Metallurgists have been skeptical of the cryogenic process for some time, because it imparts no apparent visible changes to the metal. The thinking is that since proper heat treating changes 85% of the retained austenite to martensite, and the deep cryogenic process only transforms an additional 8 - 15%, deep cryogenic treatment is an inefficient process.

These are correct premises, but an inaccurate conclusion. Deep cryogenically cooled metals also develop a more uniform, refined microstructure with greater density. Microfine carbide "fillers" are formed, which take up the remaining space in the micro-voids, resulting in a much denser, coherent structure of the tool steel. The end result is increased wear resistance.

These particles are the same ones identified and counted in the accompanying study using a scanning electron microscope with field particle quantification. (An automatic particle counter.) It is now believed that these particles are largely responsible for the great gains in wear resistivity. Unlike the case of coatings, the change created is uniform throughout and will last the life of the tool, regardless of any subsequent finishing operations or regrinds. It is a permanent, irreversible molecular change.

The two 1000X micrographs shown in Fig. 1 represent samples from the same S-7 bar stock. The first is untreated S-7. The second was deep cryogenically treated. The martensitic transformation is readily apparent.

Field Testing Proves Deep Cryogenic Potential

The cryogenic cycle is an extension of standard heat treatment, and creates many outstanding increases in durability. For example, a major aircraft manufacturer testing deep cryogenics found that with only six different tools treated, the savings in tool purchases could exceed $5 million.

The deep cryogenic treatment of an 8% cobalt end mill has demonstrated dramatic improvements in two important ways. The number of milling cuts was increased from three before deep cryogenic processing to 78 after processing, 26 times the wear life. Resharpening the end mills after deep cryogenic treatment required only 1/3 the amount of stock removal to restore the tool geometry.

Rockwell, a major aircraft manufacturer running C-2 carbide inserts used to mill epoxy graphite, doubled its output after deep cryogenic treatment. In a second test used to mill 4340 stainless steel, it achieved a 400% improvement.

Other applications include leading national stock car auto racers, who previously raced only 4-8 races between teardowns, went to 40+ races after treating the block, crank, cam, pistons, and heads.

Lab Results Confirm the Field Testing

The latest research data on cryogenic tempering confirms the long standing theory that cryogenic treatment significantly enhances cutting tool life. Dr. Joan Alexandru and Dr. Constantin Picos of The Polytechnic Institute of Jassy, Romania, utilized the latest scientific equipment available, a JEOL IXA-5A Electron Probe, a DRON-1 X-ray Diffractometer, a Quantimet 720 Quantitative Microscope, and a Chevenard Differential Dilatometer to supply the following results from the extensive study.

The study involved 7 samples (A-N in Fig. 2), each subjected to a different tempering cycle as noted. Each sample was the equivalent of M2 steel; each sample had the carbide particles physically counted, both before and after the deep cryogenic treatment. The team then measured the samples with the equipment above, and with standard metallurgical evaluative testing. The results confirm with tangible evidence the carbide precipitation in cryogenic processing.

All the metal samples were taken from identical batch stock. The sample structure was comprised of .83%C, .38%Mn, .3%S, 4.1%Cr, 5.1%Mo, 1.92%V, and 6.3%W. Samples were all simultaneously standard heat treated at 1230°C, then oil-quenched. Four of the pieces were then subjected to the cryogenic cycle at -70°C with varying tempers added after cold soaking.

Findings

The results of the testing conclude with the following findings and analysis comparing standard heat treating to heat treating with the addition of a shallow cryogenic soak:

- Austenite decreased from 42.6% to 0.9%.
- Martensite increased from 66% to 81.7%.
- Carbides increased from 6.9% to 17.4%.
- Mean number of carbides counted @ 1 mm sq. increased from 31,358.17 to 83,529.73.
- Number of carbides less than 1 µm in size increased from 23,410.24 to 69,646.09.
- Rockwell increased from 60.10 to 66.10.
- Tensile strength increased from 86.0 to 244.46.
- Bending strength increased from 86.0 to 244.46.
- KCU (resiliency) increased from 0.668 to 1.18.
- HRC 675°C after 20 minutes keeping: 56.88 to 62.25.
- Durability of the cutting time increased from 20 minutes to 45 minutes with a *shallow* cryogenic cycle.

Fig. 2 illustrates the seven separate heat/cool cycles used to temper the lathe cutting tools. The lathe cutting tools were then used to cut a .5%

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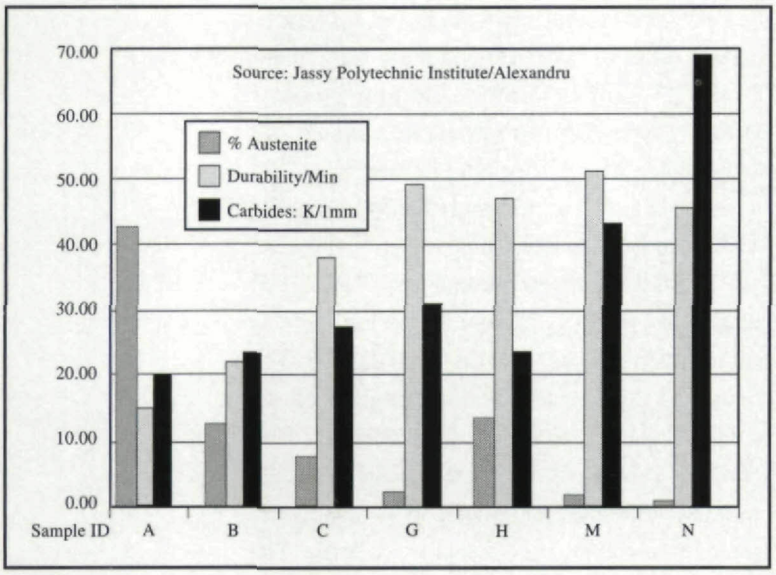

Fig. 3

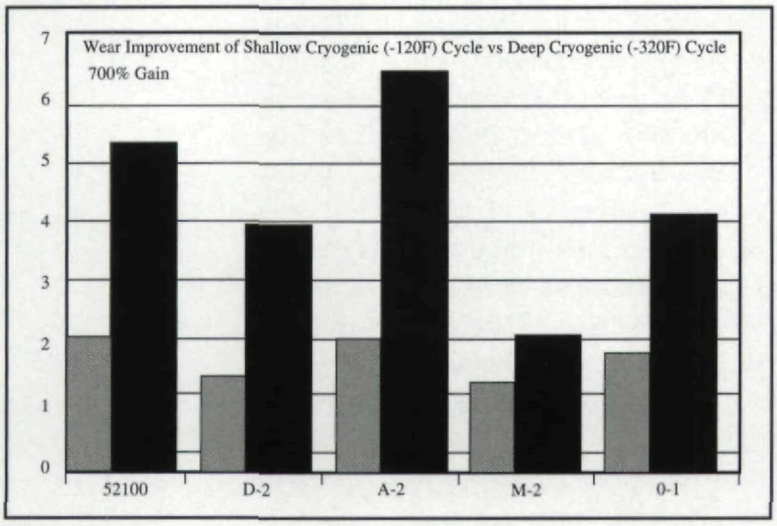

Fig. 4

Table I
TEST RESULTS: Percent of Increase in Wear Resistance After Cryogenic Tempering

AISI#	Description	At -110°F	At -310°F
Materials that showed significant Improvement			
D-2	High carbon/chromium die steel	316%	817%
S-7	Silicon tool steel	241%	503%
52100	Standard steel	195%	420%
0-1	Oil hardening cold work die steel	221%	418%
A-10	Graphite tool steel	230%	264%
M-1	Molybdenum high-speed steel	145%	225%
H-13	Chromium/moly hot die steel	164%	209%
M-2	Tungsten/moly high-speed steel	117%	203%
T-1	Tungsten high-speed tool steel	141%	176%
CPM-10V	Alloy steel	94%	131%
P-20	Mold steel	123%	130%
440	Martensitic stainless	128%	121%
Materials that did not show significant improvement.			
430	Ferritic stainless	116%	119%
303	Austenitic stainless	105%	110%
8620	Nickel-chromium-moly alloy steel	112%	104%
C-1020	Carbon steel	97%	98%
AQS	Graphitic cast iron	96%	97%
T-2	Tungsten high-speed steel	72%	92%

R. F. Barron study results. Louisiana Polytechnic Institute.

structural carbon steel. Durability was established by measuring the radial component of wear. Intensive Speed: @33.6m/min.; Depth: 5mm; Feed: 0.62mm per rev. Relief angle: 8°; Hake angle: 5°; Plan angle: 45°.

Deep Cryogenic Cycle Doubles the Results of the Shallow Cryogenic Cycle

Separate laboratory testing has been performed by Dr. Randall F. Barron at Louisiana Tech University, Ruston, LA. The results by Dr. Baron confirm the Jassy study even further. In one series of tests Dr. Barron compared five common steel alloys. First he tested them as procured. Then he chilled them to -120°F, tested them again, and then treated them at -317°F. In all cases the cold treatment improved wear resistance. The colder the treatment, the better. The -120°F (dry ice) treatment improved ratios ranging from 1.2 to 2 times, depending on the alloy. This is consistent with the Jassy findings. However, the deep cryogenic treatment at 317°F improved wear resistance by even greater ratios ranging from 20 to 6.6 times.

Process Developments

The deep cryogenic process has had an Achilles heel. It has been inconsistent. In the past, improvements to gears would vary from little improvement to over a 1,000% increase in useful life. The trick is in the processing. Temperature changes must be controlled exactly for consistent results. If a gear or tool is dropped in liquid nitrogen, it could shatter.

The computer processor solves this problem. The computer can duplicate the optimal cooling curve exactly time after time after time.

Older cryogenic tanks did not have adequate control. Using them was like trying to bake a cake in a wood-fired stove. The newest cryogenic tempering systems achieve consistent results. Furthermore, the price enables the gear manufacturer to improve his profit margin, improve his product, and increase market share with a superior product.

The Cryogenic Tempering Process

The new machines operate with controlled dry thermal treatment. "Controlled" simply means that the process is performed according to a precise prescribed time table. A 386 PC is utilized as the process controller operating the descent, soak, and ascent modes. The material is cooled slowly to -317°F, held for 20-60 hours, then raised to +375°F, and slowly returned to room temperature. It is a "dry" process in that, unlike other deep cryogenic processes, it does not bathe the materials in liquid nitrogen, which is more likely to cause damage from thermal shock.

How It Works

The Barron study looked at how the changes brought about by cryogenic treatment affected steel's ability to resist abrasive wear. It found that the martensite and fine carbide formed by deep cryogenic treatment work together to reduce abrasive wear. The fine carbide particles support the martensite matrix, making it less likely that lumps will be dug out of the cutting tool material during a cutting operation and cause abrasion. When a hard asperity or foreign particle is pressed onto the tool's surface, the carbides further resist wear by preventing the particle from plowing into the surface.

Some of these benefits may be achieved through standard tempering, which also transforms austenite into martensite. But standard tempering may not bring about a complete transformation in some tool steels. For example, 8.5% of an O-1 steel remains austenite after it is oil-quenched to 68°F. If M-1 is quenched from 222°F to 212°F, then tempered at 1049°F, the retained austenite is 11%.

Additional improvements in tool performance can be achieved if this retained austenite can be transformed to martensite. As Barron's study has confirmed, adding a cryogenic step to the treatment process does just that.

In Table I, data drawn from another study of treated metals by Barron indicates which samples exhibited improved abrasive wear after cryogenic treatment. In addition to results obtained from samples treated at liquid-nitrogen temperature (-310°F), the chart also lists results of treatment at dry-ice temperature (-110°F).

How Effective Is It?

Knowing how deep cryogenic tempering works, we can predict which materials will benefit most from treatment. Generally, if an alloy contains austenite, and this austenite responds in some degree to heat treatment, further improvements will be seen after deep cryogenic tempering. For instance, ferritic and austenitic (430 and 303) stainless steels generally cannot be hardened by heat treatment. Martensitic (440) stainless steels, on the other hand, can be hardened by heat treatment; therefore, the effect of deep cryogenic treatment should be more pronounced for 440 stainless steel than for the other stainless steels.

C-1020 carbon steel and QS Meehanite iron also show no significant improvements in performance after cryogenic treatment. Because these materials contain no austenite, sub-zero temperatures can cause no further metallurgical changes in them.

Financial Potential

Liquid nitrogen is the largest processing cost in cryogenically cooling gears. The newest systems are designed to more efficiently transfer cold from the liquid nitrogen to the metal parts being treated without losing the cold to the outside. They have reduced processing costs by half, making it economical to process all types of steel items, not just gears and tooling. Gears now cost pennies instead of dollars to treat with this method.

Potentially every gear which is heat treated is a candidate for the additional service of cryogenic tempering. Most customers are pleased to pay for the additional improvement of any gear, especially at a nominal additional cost (less than $1 per pound!).

There are more than a handful of large tooling manufacturers quietly utilizing the process today for manufacturing a premium line of cutting tools. They manufacture a "premium" tool which lasts 2-5 times longer for pennies and charge dollars more for it - a great boost in a competitive market place where profit margins have been squeezed.

Some heat treaters offer "cold cryogenic services" utilizing -120°F (dry ice) systems, but deep cryogenic treatment (below -300°F) is where most of the benefits occur. Ultra low temperature treatments below -300°F show much more impressive results.

Conclusion

While not a magic wand which will extend the life of every product, over 100 items, such as gears, reamers, taps, dies, broaches, drills, endmills, slicers, and cutting knives do respond to the process. It can create a "premium" more profitable tool gear for a manufacturer and save a lot of tool expense dollars for end users. The process is effective throughout the tool, unlike a coating, so tools can be resharpened and receive the benefits until completely worn out. The process also works with TiN coatings.

Among the properties which define the qualities of a gear steel, durability is the highest importance. These results are decisive in establishing the benefits of cryogenic treatment in increasing durability. ■