the big chill

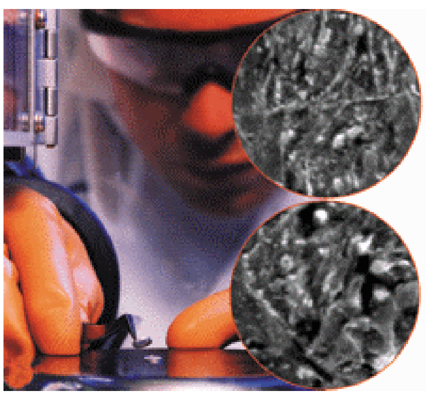
Post-heat treatment involving cryogenics may greatly extend the wear life of mechanical components.

By John DeGaspari, Associate Editor

Improving the wear resistance of steel can amount to found money, particularly in industrial uses such as stamping dies, cutting blades and machine tools.

In the operation known as quenching, steel is heated and then brought back to room temperature, either gradually or abruptly (using air free or forced, water, or oil). Quenching makes steel harder, improves mechanical properties, and increases wear resistance. Yet some tool and die makers believe that the proven benefit of extended wear life of conventionally heat-treated steel parts can be further enhanced by tempering at cryogenic temperatures.

Prior to quenching, steel is relatively softer, allowing it to be wrought and drilled easily. Cold-worked steel is in the austenitic phase, in which the microstructure is characterized by large, coarse, and irregular grains. (According to information published by the American Iron and Steel Institute, about 70 percent of stainless steels produced are austenitic.) Quenching converts most of the austenitic microstructure to the martensitic phase, which is finer and denser. Martensite, the chief component of quenched steel, consists of hardened carbides that provide the higher hardness and wear resistance.



The grain structure of steel alloy before and after cryogenic tempering. Lab tests demonstrated that cryogenic tempering completed the transition from austenite to martensite, improving the alloy's wear resistance.

Although conventional heat treatment results in harder steel, it still leaves room for improvement. For one thing, quenching does not quite completely transform the austenite to martensite, leaving a residue of the softer, coarser microstructure. Also, martensite, although much harder, is also more brittle than austenite.

Some tooling experts believe that an additional treatment involving cryogenics can help complete the transformation to martensite and dramatically improve wear resistance in a range of steel alloys. The idea of treating steel cryogenically to improve wear life has been around at least since the 1940s, according to Randall Barron, an ASME Fellow and professor emeritus in the Department of Mechanical Engineering at Louisiana Tech University in Ruston, who is also a consultant on cryogenics.

Cryogenics came to prominence during the latter half of World War II, although first attempts were primitive and led to disappointing results, he said. Parts were basically dipped in liquid nitrogen and taken out, but brittleness in the treated parts soon ended most interest in the process.

Better results were obtained in the mid-1970s by cooling slowly with cold nitrogen gas, followed by a mild tempering, which avoided thermal stresses and brittleness, Barron noted. Some aerospace companies have used cryogenics to treat steel parts that are subject to high wear, he added.

Controlled Cooling

Cryogenics has attracted the interest of others who want to improve wear resistance in wider applications. Les Davey, the owner of Silver Bullet Machine & Tool Inc., a tool and die maker in Windsor, Ontario, became intrigued with the idea of using cryogenics to boost wear life when he noticed that cutting tools cryogenically treated in a local machine shop lasted three to four times longer than normally expected.

Together with his brother, Brian, Davey investigated the process. He eventually teamed up with a partner in the United States to develop a process called Dynamic Thermal Tempering, which his company now offers as a service. Silver Bullet Machine, with assistance from the Canadian Industrial Research Assistance Program, tested various formulas through statistical analysis and experimentation.

For the last two years, the process has had good results treating steel parts in a broad range of categories, including stamping dies, drill bits, golf club heads, and even guitar strings, Davey said. Davey describes his process as a tempering operation that incorporates cryogenics, with some differences from previous deep-cold treatments of steel. Hardware consists of a combination of oven and freezer, and includes a tower of liquid nitrogen. The process itself is automated, with temperatures and duration programmed into a computer. The DTT process subjects parts, all of which have already been heat-treated, to temperatures generally ranging from about 600°F to -300°F.

Steel parts are exposed to precise temperatures for specific periods of time. The program regulates the temperatures in a controlled, step-wise fashion. Davey said that he developed specific recipes after observing how different steel alloys were affected by various temperature exposures. He believes that the tightly controlled recipes are what differentiate his process from standard cryogenics, which may involve simply lowering the temperature gradually to -300°F or so and holding it there for a time before letting the steel warm to room temperature. The key, he said, is "the temperatures we go to, how long we stay there, and how quickly we get there."


A technician polishes discs of 4340 and 9310 steel alloy, comparing conventional quenching results and quenching followed by cryogenic tempering.

Davey noted that Dynamic Thermal Tempering involves "deep cryogenics" for extended soak periods. "We have data from a number of studies that indicate a significant difference between -120°F and -300°F treatments," he said. The evidence favours deep-temperature treatments, he added. He also added that the treatment penetrates through the steel. He has tested the process on various blocks of steel to see how long it takes for the temperature to penetrate from the surface to the core. One treatment lasts for the life of the part. "Once tools are sharpened, the treatment is always there, because we are actually changing the properties of the steel, rather than solely its surface," he said.

"The entire process, from start to finish, requires that we have the tool for three days," Davey said. "Once we get the temperature down to deep freeze, it has to sit there and soak for a long time. Achieving the proper temperature and holding it for a prescribed period of time results in the benefits of the process being imparted to the steel tool."

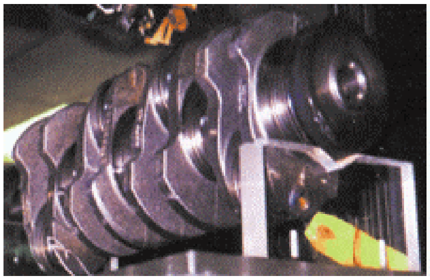
The temperature is then brought back very slowly to ambient. Some materials require tempering; parts are heated to the required temperature and then cooled to ambient. In many cases, such heating and cooling cycles are repeated once or twice. Temperature is rigidly controlled during the tempering cycle as well.

Promising Results

The process can be applied to any steel alloy that is heat-treatable, including cobalt, carbide, and carbon steels, Davey said. He claimed good results with D2, A2, 52100, S7, and M2 steel alloys, which are widely used in stamping dies. "We can enhance the life of a stamping die anywhere from 40,000 hits to 250,000 hits before maintenance is required," he said. He admitted that is among the most dramatic results.

According to Davey, Dynamic Thermal Tempering has improved the longevity of high-speed carbide drill bits by 40 to 300 percent, and has tripled the wear life of carbide tooth woodcutting saw blades.

Davey claims that the tempering process provides stress relief, in addition to increasing wear resistance. This is important for precision parts, such as aircraft components, which must keep their dimensions after machining, he said.



X-ray mapping measures residual stress in a crankshaft at Windsor Lab. Dynamometer tests will be done on parts with and without cryogenic treatment.

Less obvious applications include guitar strings, which local musicians claim have four to five times the life of untreated strings with no need for tuning. Davey said that treating golf club heads improves accuracy and distance.

He has also treated racing car components, such as crankshafts, camshafts, and transmission gears. Treated transmission components have lasted up to three NASCAR races; normally, the parts must be replaced after each race, he said. One company that has submitted parts for treatment is Worthington Cylinders, a manufacturer of pressure cylinders. According to Larry Hartley, operations analyst at the company's Tilbury, Ontario, facility, the company has seen improvements in the wear life of bandsaw blades, inserts, and cutters used for trimming and drilling holes.

The bandsaw blades are used to cut 4133 steel. Before tempering, each blade cut about 625 pieces. After treatment, blades were averaging 1,500 to 1,600 pieces. "We were using 36 blades a month, and we cut it down to 14 to 16 blades a month, maintaining the same productivity," said Hartley.

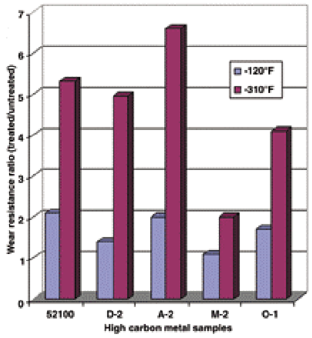
Drill inserts improved to 210 pieces off each insert, from 131, after cryogenic tempering. The biggest improvement was seen with cutting inserts. Prior to tempering, cutting inserts were averaging 720 pieces per cutter. After tempering, the life increased fivefold, to 3,500 to 4,000 pieces per cutter, said Hartley. He is now tempering thread mills, used to produce threads on cylinders, although it is too early to quantify results.

Hartley noted that Worthington Cylinders had been trying to get its operators to work consistently by eliminating variables that might affect outputs, such as differing feed rates and coolant concentrations. Getting operators to run more consistently has enabled the company to accurately evaluate outputs with regard to tempering, he said.

Grain Size Changes

To characterize what was going on with the Dynamic Thermal Tempering process, Davey contacted Windsor Industrial Development Laboratory Inc., a materials testing lab based in Windsor, Ontario. The lab tested samples of two "workhorse" steel grades, 4340 and 9310, supplied by Silver Bullet Machine. Both grades are used in racing cars.

The lab analysed and compared the mechanical properties and microstructures of samples that were left untreated, had undergone conventional quenching, and had been tempered with the DTT process using various recipes.



Changes in the steel samples' microstructure became apparent when viewed under a scanning electron microscope, according to Ben Chouchaoui, president of Windsor Lab. Chouchaoui noted that two major changes take place in tool steel after treatment. The first is conversion from austenite to martensite. The second is that the ultracold temperature promotes the formation of fine carbides, such as tungsten and chromium, depending on the alloying elements in the original grain structure.

Randall Barron of Louisiana Tech found large improvements in wear resistance of five high-carbon metals that had "deep cryogenic" treatment at -310°F versus samples that were soaked at -120°F.

Microstructure photographs that Chouchaoui's team took under a scanning electron microscope at the University of Windsor revealed the differences in carbide formation before and after treatment. The microstructure of the virgin material was rather coarse. Samples that had gone through conventional quenching showed a finer microstructure, in which the material appeared denser, eliminating voids. Heat-treated samples that had undergone the additional DTT process exhibited additional carbides, but resulted in a slightly coarser microstructure than that of conventionally heat-treated samples.

Chouchaoui compared his results to the structure of concrete. The virgin material is coarse concrete that is not reinforced; conventionally quenched samples are a denser concrete that is somewhat reinforced; cryogenically treated steel increases the "reinforcing rods" or carbides, in a slightly looser structure as the rods multiply to strengthen the material.

The next step, after cryogenic treatment, is stress relief, said Chouchaoui. Tempering in an oven following cryogenic treatment is critical, because the converted martensite is brittle, he explained. Windsor Lab conducted tensile tests on untreated coupons machined out of 4340 alloy as well as on coupons quenched in the traditional manner and other samples treated cryogenically. The data showed more than a 10 percent increase in mechanical properties, yield, stress, and hardening, between quenching and DTT treatments.

So far, Windsor Lab has completed a series of materials tests, including Izod impact, slide wear with heat and lubrication, and pin-on-disc (dry at room temperature). The lab is also conducting X-ray diffraction tests to measure residual stresses on heat-treated and cryogenically treated samples. In the future, Chouchaoui plans to conduct dynamometer tests on parts with and without cryogenic treatment. He believes that cryogenic treatment can be beneficial to a much broader range of materials than tool steels, including many steel alloys and aluminium.

Not a Cure-all

As a follow-on treatment to conventional heat treating, cryogenics should be seen as the very last step in the process, remarked Randall Barron of Louisiana Tech. This is good, because it doesn't change the heat-treated hardness significantly, he said. All it does is improve the wear hardness of the part. On the other hand, in order for cryogenics to do its stuff, it is important for the part to be heat treated correctly in the first place. "Cryogenics won't fix a screwed-up heat treatment," he said.

Barron performed several studies in cryogenic treatment for improved wear resistance on high-speed tool steels. Much of what he said bore out Davey's experience. Among the important factors, in his view, is slow cooling—at a rate of about 1°F to 2°F per minute, from room temperature to -320°F.

Following the cryogenic treatment with a mild temper was important for relaxing the martensite and eliminating brittleness from the part, he added.

After wear tests, in which cryogenically treated parts were run against an abrasion wheel, Barron found that weight loss on several steel grades improved by factors of two to five.

Barron found that the overall hardness of the treated steel did not change noticeably. He explained that, because the stronger martensite is much less likely to be ripped out on a microscopic level during abrasion, wear resistance increases.

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The Treatments quoted in this article refer to Deep Cryogenic Treatment as described by Dr. R. Barron, the COLDfire process is dramatically different and improved on this treatment first used in the 1960's. The results with the COLDfire treatment have proven far more reliable and repeatable.

This article is provided for a general background and an appreciation of the possibilities available to industry.