Improving component wear performance through cryogenic treatment

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Controlling machine wear is a fundamental function of lubrication. By properly specifying lubricant viscosity, using appropriate modifying additives, and controlling contamination, wear rates can be minimized to extend equipment life. However, other influencing factors can still result in less than optimal component wear performance, including equipment loads, design issues, and environmental factors. Cryogenic treatment of tooling steels is a proven technology to increase wear resistance and extend intervals between component replacements for blades, bits, and machining mills. Recent work has also shed light on the effects of cryogenic treatment on bearings, gears and engine components to reduce wear and improve performance. Combining optimized lubrication, correct mechanical configuration, and cryogenic treatment of wearing parts results in the maximum performance of lubricated components, and can significantly extend component life.

Reliability of operating systems is influenced by 5 factors: component design, manufacture, specification, installation, and maintenance. Each of these stages can be influenced by separate individuals or teams, but ultimately the responsibility for performance of the assembled system falls to the plant maintenance team. It has been said that machines don't die, people kill them. In many cases this is true, and many of the contributing factors to premature failure can be controlled by the end user. However, if the equipment has been properly installed and maintained, exerting influence on the other factors may be difficult or impossible for the end-user. They may be "stuck", as it were, with a poorly specified, designed or manufactured machine. The poor design may also be a function of the available technology for the level of funding. In these cases, short time between failures may become accepted as the norm, in some cases at great cost.

If we address the important causal factors in premature failure from a wear perspective, we will see the most effective and dramatic extension of life of critical components such as bearings, gears, and engine components. However, when all reasonable steps have been taken to minimize lubricant contamination, utilize appropriate lubricant type and additives, and correct mechanical configuration issues such as balance and alignment, we may still be driven to other solutions to extend life. One solution that has shown great promise in achieving greater wear performance of components is cryogenic treatment of bearings, gears, and engine components.

Background on Cryogenic Processing

To understand the effects of cryogenic processing it is essential that one be acquainted with the heat treating of metals. The primary reason for heat treating steel is to improve its wear resistance through hardening. Gears, bearings, and tooling for example are hardened because they need excellent wear resistance for extended reliability and performance. The steps in heat-treating are frequently explained in a simplistic manner but it takes significant skill and experience to execute heat treatments successfully.

Steel will normally be raised in temperature to the austenizing temperature, usually 1600°F or higher. Austenite is a soft phase of steel and malleable – hence it is very easy to wear the structure down with repeated use, therefore the need for heat-treating. Gears and other tooling are often rough machined or formed in the austenitic state. After a predetermined period of time at the elevated temperature, that is

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determined by the phase diagram of the alloy in question, the material will be quenched in a bath that may be oil, water, brine or polymeric compounds. The rapid cooling (quenching) of the steel in the quenching medium will cause the atoms in the microstructure to rearrange in the atomic structure that is called martensite. Figure 1 shows a representation of the atomic structure of both the austenitic and martensitic phase. A close analogy to this is coal and diamond. They are both made up of primarily carbon atoms. In coal the carbon atoms are in a very loose arrangement and have very few cross-links to one another, this makes them readily available to be taken away by wear or some other reaction like heat. In a diamond the carbon atoms have a very different bonding arrangement making it the hardest substance known.

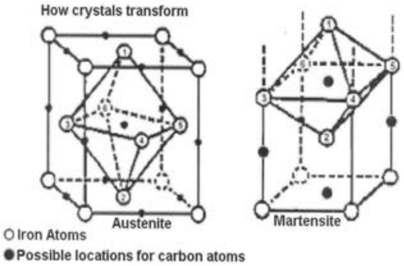

Figure 1: Austenite crystal (left) and Martensite crystal (right)

How it all Started

Cryogenic processing has been around for many years but is truly in its infancy when compared to heat-treating. For centuries the Swiss would take advantage of the extremely low temperatures of the Alps to improve the behavior of their steels. They would allow the steel to remain in the frigid regions of the Alps for long periods of time to improve its quality. Essentially, this was a crude aging process accelerated by the very low temperatures. What we now understand to have happened was the reduction of the retained austenite and the increase in martensite. By performing this once secret process the Swiss obtained the reputation for producing a superior grade of steel.

The process of experimentation and understanding of the cryogenic treatment of steels really got under way during World War II at the Watertown Arsenal in Watertown, Mass. It was under the direction of Clarence Zener who would later go on to develop the Zener diode. At that time there were no computer controls so the steel tooling would be immersed in liquid nitrogen for a brief period of time, allowed to warm up, then placed into service. This method was crude and uncontrolled. Many of the tools would chip and break immediately upon use because the immersion process would create a very high thermal gradient in the tool and this would produce micro-cracks in the body. It was also later learned that the cryo-treatment would convert the retained austenite into un-tempered martensite. But the tools that would not break would experience a greatly enhanced service life.

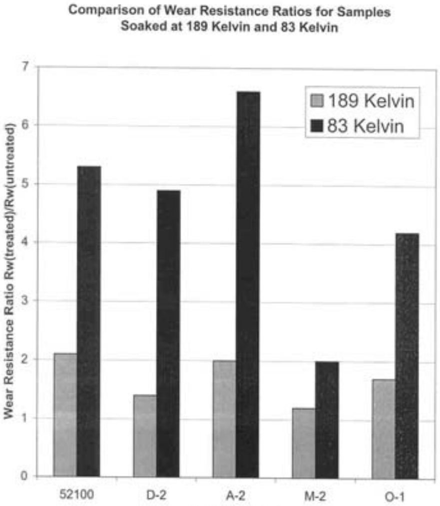

Figure 2: Wear Resistance comparisons of samples soaked at 189^{o}K and 83^{o}K

In the 1960's cryogenic processors would use multi-stage mechanical coolers along with insulated 'cold-boxes' to gently remove the latent heat from tooling thereby achieving a much slower cooling rate, concurrent with longer wear lives. Performing a standard wear test (pin-on-disk) showed that the wear resistance for these steels could be increased by more than 600%. At this time it was theorized that the increase in wear resistance was a direct result of the reduction in the amount of retained austenite. Figure 2 shows a comparison of wear resistance rates of the sample tool steels when soaked at 183^{o}K and 83^{o}K. Since the samples were both shown to have relatively the same amount of retained austenite before and after the soak periods another mechanism was at work for the greatly increased wear resistance of the sample treated at deep cryogenic temperatures (183^{o}K). A study in 1994 (6) showed that the reduction in retained austenite was only part of the reason for the increased

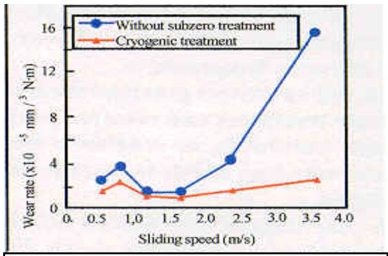

Figure 3: Wear rate vs. sliding speed both with and without cryo treatment

wear resistance. This research confirmed the precipitation of fine (eta) carbide particles. The deep cryogenic processing (soaking at liquid nitrogen temperatures (-320°F)) as compared to what is termed 'cold' treatment (soaking at dry ice temperatures (-120°F)) both reduced the amount of retained austenite. But the deep cryogenic processing increased the wear resistance of the materials 'dramatically, especially at high sliding speeds'. Figure 3 shows the comparison of wear resistance vs. sliding speeds on both treated and untreated samples. The greater wear at higher sliding speeds will correlate with a bearing. The conclusions of the research also state that 'the mechanism that the (deep) cryogenic treatment contributes to wear resistance is through the precipitation of fine (eta) carbides, which enhances strength and toughness of martensite matrix…"

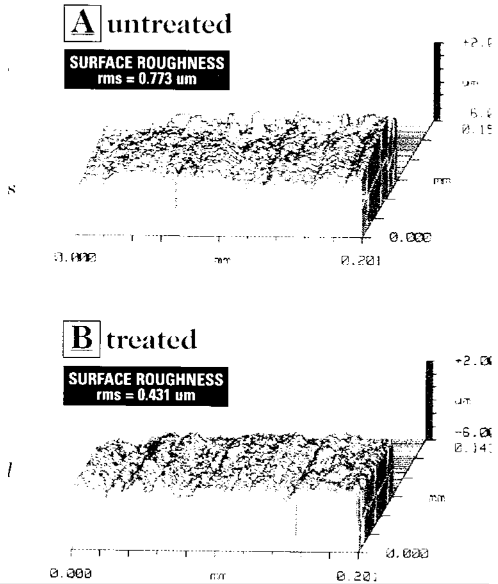

Figure 4: Surface roughness plots of treated and un-treated samples

State of the Science Today

Today there are an increasing number of studies that show the deep cryogenic process, when applied correctly and consistently to a host of materials, is effective in increasing wear resistance and stability in materials. A NASA report, "Cryogenic Treatment of Aluminum Alloys for Improved Crack Resistance & Fracture Toughness" (MFS-31629) shows a 50% reduction in residual stress in welded aluminum plates.

The effectiveness of the deep cryogenic process is well documented and is starting to become more widely accepted throughout industry. For years large companies have been selling a special line of cryogenically treated products. Browning, is currently selling cryo-treated barrels, many softball bat manufacturers offer cryo treatment as an add-on to their top-of-the-line bats, and Jack Nicklaus, has endorsed a line of cryo treated golf clubs. These are all examples of the sporting side of the cryo-industry but they are also good examples of the adage 'if one makes a better mouse trap…'.

The studies have shown that cryogenic treatment produces metallurgical changes in the microstructure of steel. These changes are the principal reasons for the dramatic improvement in wear resistance. As greater amounts of retained austenite are transformed, and the amount of martensite is increased, the material obtains a more uniform hardness. The studies have shown that hardness is not increased appreciably in the material being treated (1) but the consistency of the hardness is greatly improved. The surface energy of martensite is higher than that of austenite due to the differences in their atomic structures. (Austenite has a Face-Centered-Cubic crystalline structure and martensite has a Body-Centered-Tetragonal crystalline structure). In adhesive wear situations, the martensite is less likely to 'tear' out than is austenite. The probability of wear particles forming in steel in which the austenite has been transformed to martensite is less than for steel containing some retained austenite.

Gears—the effects of cryo-treating

A study by the IIT Research Institute published in November 1995 (5) for the Instrumented Factory for Gears sponsored by the US Army ManTech was conducted to 'study the effects of the carburizing process and cryogenics treatments in modifying the microstructure of the material'. The results of the tests as presented at the INFAC Industry briefing, June 13, 2000 were that the deep cryogenic treatment gave 50% extra pitting resistance, 5% more load carrying capacity, and a 40°F to 60°F higher tempering temperature. Although these experiments were performed on AISI 9310 material (standard helicopter transmission gear material) the conclusions show promising results which may be applicable to the general subject of mechanical and chemical wear resistance.

Bearings-can they be made to last forever?

An article published in Lubrication Engineering October 2002, investigates the effects of strain hardening and retained austenite transformation, both of which are triggered by rolling contact, on the fatigue life of 52100 bearing steel (11). The conclusion of the paper was that the origin of residual stress generated due to rolling contact is associated with phase transformation. The past assumptions were that strain hardening was the primary cause of the generation of residual stress. The fact that the amount of retained austenite correlates with the life of the bearing is one of the factors taken into consideration. The tie in here from a multitude of other research is that cryogenic processing converts retained austenite into martensite. Therefore, cryogenic processing eliminates the primary mechanism for the generation of residual stresses in ball bearings due to rolling contact. Of course, the majority of bearings never even reach their L_{10} life, because of factors such as contamination, improper lubrication, and incorrect installation. However, once we solve some of those man-made "bearing-killers", perhaps cryo-treating will present the next opportunity to extend life even further, beyond the typical expectations.

Reducing friction and wear

It has been shown by Dr. Sudarshan of Materials Modification Inc. and Dr. Levine of Applied Cryogenics in an unpublished study that the surface finish of cryo-treated material versus non-cryo-treated material will be reduced by approximately one half when the same means of polishing has been applied. A smoother surface finish is characterized by a reduction in the number of microscopic peaks and valleys. Fewer peaks and valleys mean a reduction in the number of asperity contacts, therefore contributing to a reduction in wear. Figure 4 shows Plots A and B which are which are surface roughness plots of the area near the cutting edges of two H.S.S. drills. Prior to making the measurement, both drills had been super polished to obtain the minimum roughness. The drill represented in plot B had been cryogenically treated prior to polishing and attained a significantly better finish (rms= .431μm) than the non-treated drill (rms= .773μm).

A second effect is the precipitation of fine eta (η) carbide particles. Research (6) has shown that these fine eta carbide particles are precipitated during the long cryogenic soak. These are in addition to the larger carbide particles present before cryogenic treatment. These fine particles or "fillers", along with the larger particles, form a denser, more coherent and tougher matrix in the material. The adhesive wear coefficient is decreased, and the wear rate is decreased as measured by standard pin-on-disk wear tests. In abrasive wear situations, both the martensite formation and the fine carbide formation work together to reduce wear. The additional fine carbide particles help support the martensite matrix, making it more difficult to abrade 'lumps' of material. When a foreign particle is squeezed onto the surface, the carbide matrix resists plowing, thereby reducing wear.

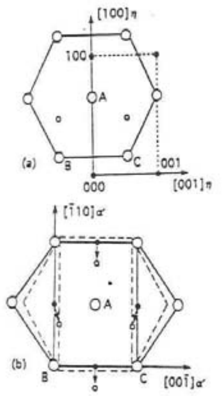

Figure 5: Formation of eta carbide from Martensite

Examples of improved wear in components

While improvements in the wear performance of blades and tooling are the most common and well-documented use of cryogenic processing, extending the life of components that are not designed to wear in normal service has also been demonstrated.

A paper mill was experiencing extremely low operating life of a water pump impeller. Because of head conditions in the system, the impeller was subjected to significant cavitation forces, which rendered the it unusable after only 3 months in service. The mill was forced to shut down the pump and swap out the impellers every 3 months. (Fig. 6)

With system redesign not cost-feasible, the only option seemed to be the purchase of expensive stainless-steel impellers. As an alternative, the existing silicate bronze alloy impellers were prepared with a combination of surface treatment and cryo-treating. The result was an increase in hardness and wear resistance of the alloy, and an indefinite increase in the life of the impeller in the same conditions.

Figure 6: Severe cavitation of silicate bronze alloy impeller.

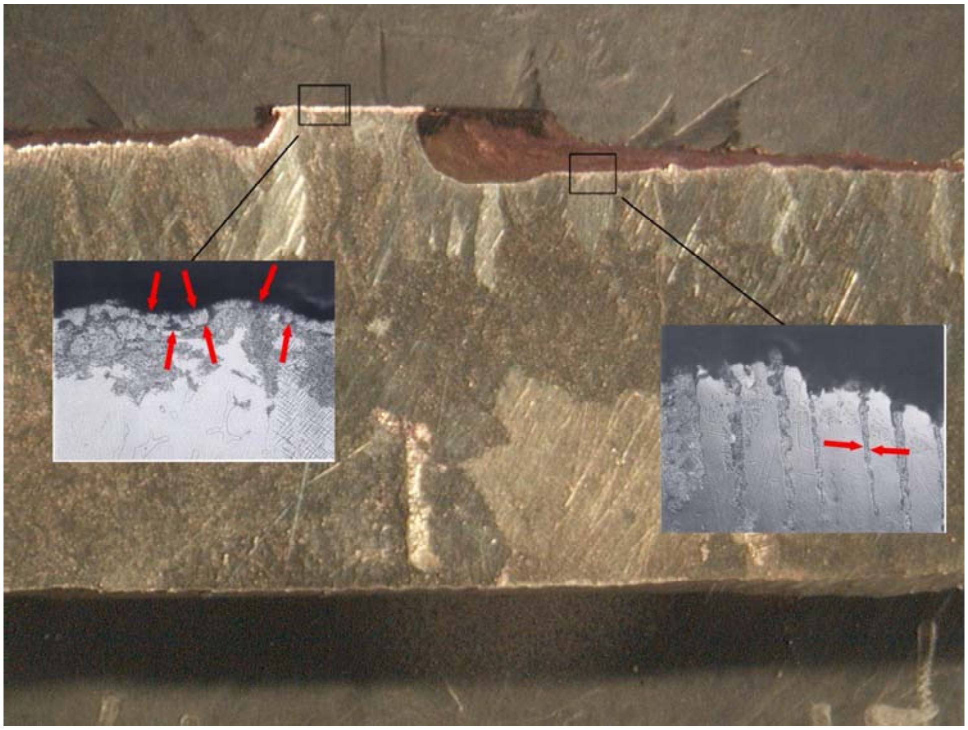

Figure 7: Cross-section of treated and untreated bronze alloy impeller.

Figure 7 shows the detail seen on two distinct areas of the silicate bronze impeller. The left callout shows a 400X etched micrograph of the profile of the treated portion of the impeller. Note in the macrograph, the raised portion of this treated area that showed little erosion in the cavitation environment. The 400X micrograph shows a significantly altered metallurgy to a depth of approximately 100 microns, with a very defined copper-rich region at the surface indicated between the red arrows. The features of altered metallurgy run parallel to the surface of the impeller. In the callout on the right, also a 400X etched micrograph but from the untreated area, a very different structure is seen. Tendrils run perpendicular to the surface, and appear as porosities in the material.

Ultimately, the extremely low MTBF for these impellers was increased by a factor of at least 6, and may be higher, since there has yet to be a failure with the fully surface prepared and cryo-treated impellers. This approach has promising indications in the application of bronze and brass bushings. Often these bushings provide a load-bearing function, but are not subject to the same options present with grease or oil lubricated bearings. Such dry or water-lubricated bearings may have a finite or unacceptably short wear life, and in those cases, the application of surface prepared cryo-treatment may provide an opportunity for life extension.

Using cryo-treating at the plant level to address problems

With the background and science in place, what can a maintenance or engineering department do to address wear issues or look to improve wear performance? As is stated in this paper, the first steps must always be to address or rule out the affects of improper lubrication, incorrect mechanical configuration, or design issues. When reasonable efforts have been exhausted, or when a less-expensive alternative course of action is needed, cryo-treating may provide the needed results.

Bearings can be cryo-treated, still in the box wrapped in cosmolene, for a very economical rate. Because of the relative small size, and the lack of handling required in the cryo-treating process, the bearings can be loaded efficiently into a cryo-processor. New bearings must be used, of course, and once the treatment is complete, they can be placed in service without any additional or extraordinary steps in the installation. By converting the residual austenite to martensite, the wear performance of the bearings in improved, and the life can be extended.

Gears can also be treated following normal heat-treating and surface hardening processes. Like bearings, new gears can be taken right off the shelf and placed into a cryo-processor for treatment, although providing a protective coating will be necessary to prevent the condensation of ambient moisture on the gear surfaces. This is easily preventable through water displacement sprays.

Engines, transmissions and other larger components can be treated as well, and typically are handled as an assembled unit and placed into the cryo-processor in their entirety. When components of different materials are treated, the cool-down and heat-up rates can be sufficiently controlled to prevent differential expansion/contraction rates and the stresses that would otherwise be imparted.

The bronze impeller example cited in this paper is a great example of finding a low-cost alternative to a system redesign, or upgrade to expensive replacement parts. Understanding the benefits of cryo-processing and utilizing it in conjunction with proper lubrication, contamination control, and machine configuration, can result in optimal equipment wear performance, and minimal instance of breakdown.

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