A Review on Cryogenic Treatment of Tungsten Carbide (WC-CO) Tool

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Abstract

Cryogenic treatment is a thermal treatment process in which parts are usually cooled to temperatures below −70 °C (< 203 K) to induce metallurgical changes in materials. The treatment showed a significant performance improvement in most ferrous materials and their alloys by transforming retained austenite to martensite and precipitating secondary carbides. However, the effect of such low-temperature treatment on highly stable super-hard materials such as tungsten carbide (commonly referred to as "cemented carbide") is uncertain. However, researchers have reported the precipitation of etaphase carbides, densification of cobalt binder, refinement of tungsten carbide grains, phase transformation of cobalt, and changes in residual stress in cryogenically treated tungsten carbide (WC-Co) materials, which resulted in increased hardness and wear resistance. Hence, this paper focuses on summarizing the cryogenic treatment parameters used in different studies, the rate of performance improvement in different applications, and the reported mechanical and metallurgical changes, which would serve as a pool of knowledge for further studies.

Introduction

Machining is a process of removing material from a workpiece in the form of chips. This involves turning, boring, milling, drilling, shaping, planning, and broaching. During turning, the chips slide on the rake face of the tool and are subjected to a high coefficient of friction. Most of the mechanical energy used to form chips is converted to heat, which reduces the wear resistance of the cutting tool. High cutting temperatures and their detrimental effects are generally reduced by proper selection of process parameters using heat- and wear-resistant cutting tool materials such as carbides, coated tools, and cryogenic treated tools. Instead of simply seeking new tool materials, researchers have shown interest in other areas such as the development of coatings for tools. Coating technology was introduced in the mid-1960. Currently, it has become an integral part of tool technology. Several researchers have established that hard coatings deposited on tool and machine parts using different physical vapor decomposition methods can improve the performance of the parts. These coated materials not only help reduce wear and increase tool life but also improve strength and chemical inertness, reduce friction, and make the parts more stable at high temperatures. Coatings used for tungsten carbide tools include titanium carbide, titanium nitride, aluminum oxide, or combinations of these. Although tool life is still less than that of extremely hard cutting tools such as diamond tools, coatings enable the tool life of carbide tools to be extended much longer than that of uncoated tools. Another possible method of improving wear resistance in tools is to subject them to cryogenic treatment. Cryogenic technology is not a new process, and has been used in several types of materials, including plastics and composites, to improve their performance in various applications. In cryogenic treatment, the inserts are cooled to cryogenic temperature, maintained at this temperature for a long time, and then brought back to room temperature to improve their wear resistance.Hard coatings have come a long way in improving the life of the tool. The coating of tools by physical vapor deposition is increasing considerably and is primarily used to prevent the separation of the coating from the base. TiAlN-based coatings are very popular because they reduce operating costs by eliminating the use of coolants, their disposal, and chip disposal.

When TiN was first applied by Physical Vapor Deposition(PVD) on cemented carbide cutting tools, it showed better performance in the milling of steels, prompting its use in other machining applications such as threading, grooving and parting, boring, and turning. This continuous success of PVD coated tools led to the commercial development of PVD-coated tools.

Nowadays, coating materials such as TiN, TiC, TiCN, TiAlN, ZrN, and Al2O3 and their combinations have been a great success. These coatings increase the tool performance and life of the tool by increasing its resistance to wear. TiCN is an excellent coating material for adhesion and basic cutting-edge strength. Coated carbides provide a better solution for the metal working industry and are an alternative solution for most milling operations. When these cutting tools continue to undergo cryogenic treatment, they exhibit a longer life, better surface finish, and resistance to wear. The surface finish is the key element affecting the machining characteristics. A good surface finish helps reduce friction and wear, premature fatigue failure, noise, etc. The surface finish was enhanced by cryogenic treatment.

Cryogenic treatment refers to the treatment of materials at approximately – -183°C using liquid nitrogen, which is less than that used in cold treatment, which is approximately – -96°C. Tungsten carbide is a hard wear-resistant refractory material that makes it exceptionally suitable for cutting tools, wear, metal forming, rock drilling, and mining applications. Cryogenically treated inserts show a longer life than non-treated inserts. It was found that the tool life of the cryogenically treated p-30 tungsten carbide insert improved by 21.8% in the deep cryogenically treated condition compared to that in the untreated condition. Islam concluded that the precipitation and distribution of the η phase after cryogenic treatment.

Technological Developments

Tool materials have rapidly improved over the last few decades. Development includes manufacturing carbon tool steels, high-speed steels, and cast alloys to carbides and ceramics. Until 1990, machining was performed using plain carbon steel, and shortly after 1990, high-speed steel was introduced. Ceramic tools exhibit extremely high hardness and wear resistance, facilitating the use of higher cutting speeds.

UCON, a new tool material consisting of columbium, tungsten, and titanium, permits a 60% increase in the cutting speed when compared with tungsten carbide. Cubic Boron Nitride with hardness similar to diamond, which is claimed to give speed 5 to 8 times that of carbide, can be used to cut hardened materials. Polycrystalline diamond bonded to a tungsten carbide substrate has been successfully employed for machining nonferrous materials.

Traditional materials such as high-speed steel continue to improve their properties by modifying their compositions and processing techniques. Owing to these technological advances, high-speed steel continues to compete with ceramics and carbides. Carbide, because of its ability to retain strength at high temperatures, more hardness, and economical price, is a logical choice for many industries. However, with some outer surface treatments, the life and surface properties can be enhanced to a new level.

Coated tools

Since 1970s many new developments have been made in tool coatings to improve the tool life and also to increase the cutting speed. Coatings on cemented carbide tools were developed initially using the chemical vapor deposition (CVD) technique. Currently, for HSS tools and cemented carbide tools, coatings involving physical vapor deposition (PVD) are used. The attraction of the PVD process is that it is a much cleaner process and the formation of brittle interface between the substrate of the tool and coatings which is responsible for the poor adhesion of the coatings with the tool substrate is eliminated to a certain extent, since the substrate temperatures are lower compared to those for the CVD process (450 ^{0}C instead of 1000 ^{0}C).

Today, coatings based on titanium nitride (TiN), titanium carbon nitride (TiCN), and titanium aluminium nitride (TiAlN), have been developed to withstand more severe operating conditions. Notably, TiAlN exhibits thermal stability up to 900 ^{0}C [4] reported that AlCrN coated tools are suitable for high speed cutting under dry conditions. investigated the performance of Coated and uncoated cutting tools turning nodular cast iron under dry conditions. They found that multilayer coated tools were the most suitable for turning nodular cast irons at high cutting speeds. Surfaces of cemented carbide cutting tools need to be abrasion resistant, hard and chemically inert to prevent the tool and the work material from interacting chemically with each other during machining. In order to accomplish these objectives, coated carbide tools were developed around 1970. This development was regarded as a significant advance in cutting tool technology. Coated carbides are basically a cemented carbide insert coated with one or more thin layers of wear resistant material, such as titanium carbide (TiC), titanium nitride (TiN) and/or aluminium oxide (Al2O3). It is well known that thin, hard coatings can reduce tool wear and improve tool life and productivity. Therefore, most of the carbide tools used in the metal cutting industry are coated though coating brings about an Extra cost.

2. Cryogenic treatment process

Cryogenic treatment is different from cryogenic machining in which conventional coolant is replaced with cryogens like liquid nitrogen to remove heat from the tool–chip interface. In general, cryo-treatment is a three-level technique in which, the tools are slowly cooled (stage 1) to the cryogenic temperature, soaked (stage 2) for a predefined duration, and finally heated (stage 3) back to the atmospheric temperature. Sometimes, additional tempering is performed to relieve the process stress. Heat-treatment acts as the foundation of cryogenic treatment. Atoms get displaced when metals are heated. This movement leads to the formation of a new structure that alters the properties of the metal. A similar movement of atoms at lower temperatures is believed to change the properties of metal when they are cryogenically treated. The various stages involved in the cryo-treatment process can be seen in Fig. 1. The technique uses cryogenic liquids like nitrogen, helium, hydrogen, argon, oxygen, methane, and carbon monoxide, which can be used to reach the cryogenic temperature. But as liquid nitrogen (LN2) is non-hazardous and comparatively economic it remains as the most favored cryogen among the researchers.

Shallow and deep cryo-treatment (SCT and DCT)

The cryo-treatment process is broadly categorized into two types based on the soaking temperature. Early researchers used the SCT process, wherein the materials were usually soaked at temperatures between −70 C to −140 C and significant performance improvement in softer materials like steel and its alloys were achieved. Later, to get further improvement in the performance, a deep cryogenic treatment (DCT) technique evolved in which temperature between −140 C to −196 C was used and super-hard materials like WC-Co and CBN were treated and tested. Gill et al. investigated the variations in mechanical and material properties of shallow (−110 C) and deep (−196 C) cryo-treated P25 turning inserts (uncoated WC-Co). They found a substantial improvement in the wear resistance of tools treated by both the processes which were attributed to the refinement of tungsten carbide grains, decrease in population of binder phase, and precipitation of η-phase. They have also reported that although cryogenic treatment increases the hardness, the difference in hardness between SCT and DCT tools is negligible.

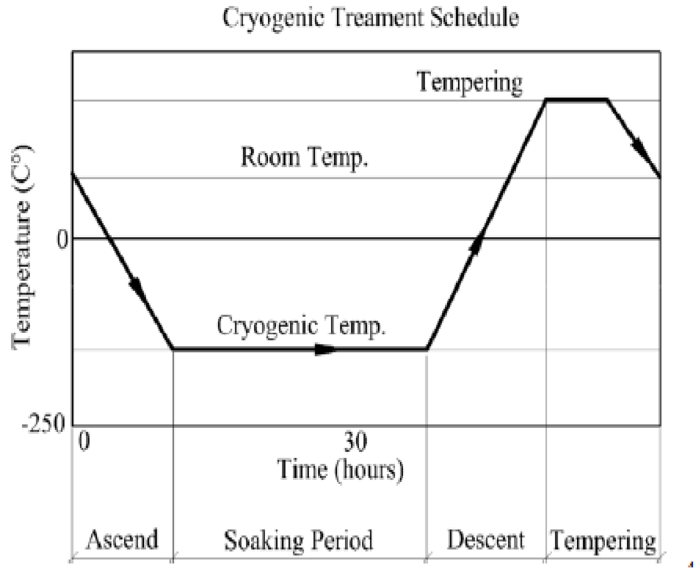

Figure a: Variations of temperatures during Cryogenic Treatment

imilarly, Arun et al. noticed a performance improvement in the SCT (−80 C) and DCT (−196 C) tungsten carbide drills. They have observed that the hardness of the drills increased to 79 HRC and 85 HRC in the SCT and DCT, respectively, from the initial hardness of 62 HRC. Shallow cryo-treated (−110 C) P-30 tungsten carbide turning inserts showed around 21% reduction in the flank wear rate and an overall tool life improvement of around 11% was seen. Similar improvement in tool life and an increase in the electrical onductivity and Rockwell hardness was reported on the deep cryo-treated (−176 C) tools as well. Apart from shallow (−110 C) and deep (−175 C) cryotreatment, Vardhan et al. researched the influence of medium cryo-treatment (−150 C) on tungsten carbide end mills. From the study, they have concluded that deep cryogenictreated tools showed higher life than the shallow and medium treated tools. SEM analysis proved that the precipitation of eta phase and improved thermal conductivity enhanced the performance of the tools. There is a lot of comprehensive research that compares the performance of shallow and deep cryogenic-treated steel material and its alloys. But studies that compare the performance of WC-Co material are limited. However, researchers agree that soaking temperature, duration of soaking, and the rate of cooling and warming are the three most critical parameters, in the same order that affects the performance of cryogenically treated materials. So, the different cryogenic treatment parameters selected by various researchers are discussed in detail in the following sections.

Soaking temperature

Soaking temperature is the temperature at which the materials are treated. Usually, the temperature depends on the type of cryogen used for the study and this single factor contributes around 72% for performance improvement. Researchers have varied the soaking temperature between −30 C to −196 C and studied the behavior of treated tools.

TiAlN PVD coated turning inserts were cryo-treated at two different soaking temperatures of −110 C and −196 C and the wear behavior was compared by Gill et al.[62] They have reported that tools treated at lower temperature enhanced the life by around 25%, whereas the tools treated at −196 C degraded the performance by weakening the bond between the coating and tungsten carbide substrate. But other researchers who have selected −196 C as soaking temperature have reported a good performance improvement. Thakur et al. have observed thermally induced stresses in the cryogenically treated WC-Co alloy at −196 C. A slight increase in microhardness, formation of eta carbides, densification of cobalt binder, and uniform distribution of tungsten carbide particles were also observed. Better machinability in terms of increased life, lower forces, and reduction in surface roughness were seen in cryogenically treated tungsten carbide turning tools treated at −176 C. Tungsten carbide inserts treated at −196 C were tested at four different cutting speeds by Gill et al.in turning hot rolled annealed steel and they have reported that cryo-treatment improved the performance at wet conditions in both continuous and interrupted machining. Past studies show that around −196 C (the boiling point of LN2) is the frequently used and the lowest temperature at which the materials were soaked. As liquid nitrogen is the most frequently used industrial cryogenic fluid and is non hazardous, the majority of the studies have used it as the cryogen.

Further reduction in soaking temperature of around −269 C (close to absolute zero) is possible by using liquid helium. But it would invariably increase the soaking time as the movement of atoms or molecules would be low at such temperatures, which is required for metallurgical changes to occur. Hence, a constant temperature of −196 C or lesser and a variable soaking period would be the preferred combination for future investigations.

Soaking period

The duration for which the materials are treated is the soaking period and it is the second significant factor with around 16 to 30% contribution to the performance improvement. It is assumed that a higher soaking period is required to allow complete metallurgical transformation to occur. In line with the assumption, literature studies show that the soaking period was varied between 2 and 180 hours by different researchers. However, a duration of around 24 hours was the commonly used time period. Dhande et al. have investigated the performance of mixed (alloyed) tungsten carbide inserts with 11.3% Co treated for 8, 16, 24, and 30 hours. Wear experiments conducted on Pin-on-disc wear tester confirmed that 8 hours is the optimum soaking period which showed a significant reduction in weight loss. They have attributed the improvement in wear resistance to the precipitation of fine η-phase carbide on the surface and grain refinement. However, another study conducted at 24, 48, and 72 h soaking period showed that an increase in the soaking period increased the rate of tool wear and subsequently affected the surface finish.

A linear increase in eta-carbide precipitation was observed by Özbek et al. in the tools soaked for 12 and 24 hours, whereas increasing the soaking period beyond 24 hours showed a decreasing trend. Wear results from turning experiments conducted with tools soaked for 12, 24, 36, 48 and 60 hours (DCT-12 to DCT-60) aligned with the trend observed in eta-carbide precipitation and showed that tools soaked for 24 hours (DCT-24) exhibited higher wear resistance followed by DCT-12, as shown in Table 2. Reduction in flank wear was attributed to higher eta carbide precipitation in DCT-24 as shown in Fig. 2. An increase in eta carbides led to the rise in microhardness, which influenced the performance improvement.

Similarly, by conducting turning experiments with uncoated tungsten carbide inserts (WC-10 wt.% Co) soaked for 18, 24, and 32 hours, Varghese et al.[74] have concluded that 24 hours is the optimum soaking period to achieve higher machinability. Yong and Ding[73] declared that cryogenic treatment increases the micro-hardness and compressive strength of WC–8 wt.% Co carbide without affecting the bending strength and toughness. But they have also noted that an increase in soaking time did not increase the mechanical properties of tungsten carbide

Cooling and warming rate

The pace at which the material is cooled down to cryogenic temperature is the cooling rate, whereas the pace at which the samples are brought back to ambient temperature is the warming rate. It is the third most influential variable in the cryo-treatment technique with a significance of around 10%, next to soaking temperature and soaking period. Early researchers followed the dipping-technique to treat the tool materials. In the process, the material to be treated was dipped into liquid nitrogen tank for a predefined amount of time and taken out to allow warming to happen at room temperature naturally. Experience from such studies has taught that selecting appropriate cooling and warming rates are vital, as a sudden change in temperature could induce thermal shock and cracks. Singh and Singh have determined that the cooling rate must be in the range of 20–30 C/h to avoid cooling stress which could rupture the material. Bal probed the consequence of varying cooling rates on the behavior of WC-Co turning tools. Their report shows that tools treated at 0.5 C/min precipitated fine eta-carbides which increased the hardness and toughness, whereas the tools treated at 1 C/min showed lesser carbide precipitation, higher wear rate, and lower surface quality.

ecipitation, higher wear rate, and lower surface quality. From the literature study, it can be inferred that 0.25 and 0.5 C/min are the most commonly used cooling rates. But, Li et al. have reported that cooling rate is the second most critical factor that affects the microhardness of cryogenically treated tools, whereas soaking temperature occupies the first position. Unlike other researchers, they have selected a very high cooling rate of 2, 3.5, 5, 6.5, and 8 C/min. Independent studies conducted at both low and high cooling rates have given a significant performance improvement in tungsten carbide material. However, slow cooling and warming rate increases the overall process time which in turn increases the cost. So, to avoid thermal shocks and get the maximum benefit out of the treatment, it is suggested to maintain a minimal rate of cooling and warming.

Tempering

Tempering is one of the important metallurgical technique that is in existence since the time humans started using fire and iron. In heat treatment of steel, tempering is an additional step performed by heating the material below its lower critical temperature and holding it for a certain amount of time to remove the inner stress and thereby improve the toughness. However, in regards to cryo-treatment of tungsten carbide, most of the researchers have selected tempering temperatures between 150 and 200 C for about 1.5 to 2 hours . Few reports show that either tempering was not performed or the process details are not reported. But the scientific reason behind the selection of tempering temperature, duration, and the number of tempering cycles was not clarified. Darwin et al. have proven that tempering has a negligible effect on performance improvement with a significance of less than 2%.

In line with their findings, many researchers have either performed one tempering or no tempering at all and have considered tempering as the least preferred step in the cryo-treatment process. However, Kalsi et al. have observed that tempering stabilizes the tungsten carbide material by releasing the internal stress that was formed during cryogenic treatment. The compressive and tensile stresses from the carbide and cobalt phases that are formed because of the large variance in the thermal expansion coefficient of the two materials were reduced by exposing the samples to repeated tempering cycles. By studying the metallurgical and mechanical properties, they have concluded that increasing the number of tempering cycles decreases the micro-hardness, whereas the highest wear resistance was achieved for the inserts treated with double and triple tempering.

The influence of tempering on micro-hardness has reported that precipitation of fine, homogeneously distributed carbide particles occurs only when tempering is performed after cryogenic treatment. However, Padmakumar et al.have reported no change in the metallurgical properties in the samples that have undergone an additional tempering cycle. The literature study shows that tempering is one of the key stages that was given the least importance in most studies and hence must be adequately clarified and optimized to get the maximum benefit out of cryo-treatment.

3. Application of cryogenic treatment

Cryogenic treatment is a one-time, permanent process that subjects materials to very low temperatures to enhance their physical and mechanical properties . This treatment is applicable to a diverse range of materials, including metals, alloys, polymers, carbides, ceramics, and composites, and has industrial applications in manufacturing, automotive, aerospace, and even medical fields such as cryosurgery and cryobiology . Interestingly, while cryogenic processing has been in use since the early twentieth century, its widespread adoption has been hindered by a lack of understanding of the microstructural changes involved and a consensus on optimized processes for different applications or materials . However, advancements in microstructural analysis tools are now allowing for a more satisfactory explanation of these processes . Moreover, the application of deep cryogenic treatment (DCT) has been shown to improve the mechanical properties of high-speed steels, doubling their service life and altering their microstructure in a way that challenges conventional views of cold treatment . In summary, cryogenic treatment is a versatile technology that improves the durability and performance of various materials, with significant implications for industrial applications. Its effectiveness has been demonstrated in enhancing the hardness and surface roughness of age-hardenable aluminum alloys , increasing the wear resistance and fatigue life of steels Senthilkumar & Rajendran, , and supporting the development of space science and technology through its role in infrared detection (Han & Zhang,) . Despite historical challenges in its adoption, recent research and technological advances are facilitating a deeper understanding and broader application of cryogenic treatment in various sectors (Slatter & Thornton, Yun et al.).

Milling tools

The application of cryogenic treatment in milling tools is primarily focused on enhancing tool performance by improving wear resistance and extending tool life. Deep cryogenic treatment (DCT) has been shown to be effective in refining the microstructure of cutting tools, which in turn improves their mechanical properties such as hardness and wear resistance (Li et al., Li et al., Liu et al.). Specifically, the treatment has been reported to result in the precipitation of fine carbides and the transformation of cobalt phases, leading to increased hardness and reduced tool wear during milling operations (Li et al., Li et al.,). However, there are some contradictions in the findings. While most studies report improvements in tool life and performance after cryogenic treatment, one study found that deep cryogenic treated and nitrided high-speed steel (HSS) inserts performed worse than classically heat-treated inserts in certain conditions (Šolić et al.). This suggests that the effectiveness of cryogenic treatment may vary depending on the type of cutting tool material and the specific machining application. In summary, deep cryogenic treatment is a valuable process for enhancing the performance of milling tools by improving their wear resistance and hardness, which can lead to significant economic benefits in manufacturing (Akincioğlu et al., Kumar et al.). However, the treatment's effectiveness can be influenced by the type of tool material and the parameters of the treatment process, indicating the need for careful optimization to achieve the desired improvements in tool performance (Li et al. Podgornik et al.).

4. Effect of Cryogenic Treatment on Mechanical Properties of Materials

Hardness

Deep Cryogenic Treatment (DCT) increases hardness in materials. Amini et al. found that DCT samples had 4.6% higher hardness compared to Conventional Heat Treatment (CHT) samples. Das et al. reported a smaller increase of 4.2% in the hardness of D2 tool steel after subzero treatment. Harish et al. observed a 14% improvement in the hardness of EN31 bearing steel with DCT compared to CHT samples. This increase in hardness is linked to the conversion of retained austenite into martensite and the formation of fine submicroscopic carbides . Gogte et al. noted that cryogenic treatment with soaking times of 18 to 21 hours can triple the hardness of AA 6061 alloy. However, some studies suggest that cryogenic treatment may have little or no effect on hardness.

Wear Resistance

Several researchers have found that cryogenic treatment significantly improves the wear resistance of materials. This improvement is mainly due to the conversion of retained austenite into martensite and the formation of fine secondary carbides . Darwin et al. reported a 43.8% increase in the wear resistance of DCT SR34 piston rings. Bensely et al. noted that shallow cryogenically treated (SCT) EN353 steel showed an 85% increase in wear resistance, while deep cryogenically treated (DCT) EN353 steel had a 372% increase. Leskovšek et al. found that deep cryogenically treated M2 HSS samples had better wear resistance than those treated with vacuum heat, and this resistance improved with higher tempering temperatures. Additionally, the tool life of coated cryotreated carbide inserts was improved by 16-23% compared to untreated inserts due to better wear resistance.

Toughness

Cryogenic treatment can increase strength and hardness, but may also reduce toughness. Yan et al. demonstrated that subzero treatment and subsequent tempering led to a 29% improvement in impact toughness for W9 HSS (DCT1 sample) compared to conventional heat treatment. This enhancement was more pronounced when subzero treatment was performed prior to tempering. The improved impact toughness was attributed to a more uniform distribution of fine secondary spherical carbides, which can effectively divert and block cracks. Jaswin et al. also observed a 23% increase in impact energy for deep cryogenically treated En52 samples. However, several studies have reported a reduction in fracture toughness in DCT samples.

Dimensional Stability

Residual stresses and retained austenite, often introduced during manufacturing, can cause dimensional distortion in materials. Bensley et al. found that case carburized gears treated with subzero treatment or deep cryogenic treatment (SCT and DCT) exhibited superior dimensional stability compared to those subjected to conventional heat treatment (CHT). Lomte argued that deep cryogenic treatment and tempering are essential for reducing residual stresses and improving the dimensional stability of tool steel. Leskovšek and Ule concluded that deep cryogenic treatment following vacuum treatment enhanced the dimensional stability of HSS after subsequent tempering. Diekman suggested that cryogenic treatment prior to heat treatment can minimize distortion during the heat treatment process, thereby reducing the need for grinding to achieve desired dimensions.

Surface integrity

Surface integrity encompasses both surface roughness and subsurface microstructure. It plays a crucial role in determining the functional performance of a material, including fatigue strength, corrosion resistance, fracture toughness, wear resistance, and dimensional accuracy. Gill et al. reported a 39.8% improvement in surface finish for deep cryogenically treated OHNS die steel.

5. Applications of Cryogenic Treatment

Aerospace

Cryogenic treatment is utilized to improve the dimensional stability of precision components, such as helicopter gears. This process significantly enhances tensile strength in aluminum alloys commonly used in aerospace and aeronautical applications, including 2XXX and 8XXX series alloys. Chen et al. discovered that cryogenic treatment reduced residual stresses by up to 82.73 N/mm² in the heat-affected zone (HAZ) of welded specimens and by up to 62.052 N/mm² in the parent metal. Moreover, the study demonstrated a significant improvement in stress corrosion cracking (SCC) performance.

Automotive

"Cryogenic treatment is widely used in the automotive industry to enhance the fatigue strength, wear resistance, and functional performance of engines and their components. Connecting rods made of 300 M alloy steel, used in V8 racing engines, were deep cryogenically treated to increase their hardness. Cryogenic treatment has extended the replacement interval for brake rotors from 8000 miles to 24000 miles. Thornton et al. reported a 9.1-81.4% improvement in the wear rate of grey cast iron brake discs due to deep cryogenic treatment. Cryogenically treated brake pads, clutches, valve springs, gears, bearings, connecting rods, crankshafts, and assemblies have demonstrated significant improvements in wear resistance and fatigue life. Cryogenic treatment of engine blocks has resulted in a 15% increase in engine power.

Manufacturing

"The emergence of new high-strength and super-hard materials necessitates improvements in the functional performance of cutting tools and dies. Cryogenic treatment is now being applied to drills, cutting tools, dies, end mills, punches, and other tools to enhance their hardness, wear resistance, and tool life. Yong et al. found that cryogenically treated tools exhibit superior tool wear resistance compared to untreated tools. Diekman et al. reported that deep cryogenic treatment increased the life of end mills and punches by three times and 82 times, respectively. Cryogenic treatment stabilizes the microstructure of castings, maintains uniform thickness during the machining of thin-walled materials, improves the dimensional stability of machined parts, and reduces the scrap rate of aluminum alloy castings.

Conclusion

Cryogenic treatment is a sequential process that follows conventional heat treatment. It is most effective when performed immediately after quenching and is succeeded by progressive tempering. The low-temperature conditioning of martensite during successive tempering promotes increased precipitation and a uniform distribution of fine secondary carbides. However, cryogenic treatment applied to fully heat-treated material is not effective, as this condition results in tempered martensite and a relatively stable distribution of secondary carbides within the martensitic matrix.

The major parameters involved in cryogenic treatment include cooling and heating rates, soaking periods, cryogenic temperatures, and the sequence of treatment. These parameters must be optimized for both performance and cost, depending on the type of material and the desired properties, while considering the mechanical, metallurgical, and manufacturing history of the material. This optimization will facilitate the efficient use of cryogenic treatment, leading to reduced time and energy consumption.

Cryogenic treatment significantly enhances the mechanical properties of materials, thereby extending the life of mechanical components. The improvement in mechanical properties of ferrous materials, such as tool steel, is attributed to the maximum conversion of retained austenite into martensite and the precipitation of fine secondary carbides. The low-temperature conditioning of martensite is primarily responsible for these enhanced mechanical properties, as it increases the population density and uniform distribution of small secondary carbides (SSCs).

For nonferrous materials, only second-phase precipitation has been found responsible for improvements in mechanical properties. Further research is needed to uncover the true potential of cryogenic treatment in aluminum and magnesium alloys. Additionally, more investigation into cryogenic treatment is essential to minimize distortion in heat-treated components, ultimately reducing scrap rates.

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