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Effects of cryogenic treatment on the wear properties of brake discs

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Abstract. Disc brakes are invariably used in all the automobiles either to reduce the rotational speed of the wheel or to hold the vehicle stationary. During the braking action, the kinetic energy is converted into heat which can result in high temperatures resulting in fading of brake effects. Brake discs produced out of martensite stainless steel (SS410) are expected to exhibit high wear resistance properties with low value of coefficient of friction. These factors increase the useful life of the brake discs with minimal possibilities of brake fade. To study the effects of cryogenic treatment on the wear behaviour, two types of brake discs were cryotreated at 98K for 8 and 24 hours in a specially developed cryotreatment system using liquid nitrogen. Wear properties of the untreated and cryotreated test specimens were experimentally determined using the pin on disc type tribometer (ASTM G99-95). Similarly, the Rockwell hardness (HRC) of the specimens were tested in a hardness tester in accordance with ASTM E18. In this paper, the effects of cryotreatment on the wear and hardness properties of untreated and cryotreated brake discs are presented. Results indicate enhancement of wear properties and hardness after cryogenic treatment compared with the normal brakes discs.

1. Introduction

1.1 Brake discs

The dependability of any kind of vehicle or automobile mainly depends on the functional performance of disc brakes which is controlled by various critical factors. A disc brake assembly uses **calipers** to squeeze pairs of **pads** against a **disc** in order to create **friction** that retards the rotation of a shaft or to stop. During the braking action, the kinetic energy of the vehicle is converted into **waste heat** which can end up causing in brake fade. [1] The brake discs should possess stable coefficient of friction to avoid brake fade, high thermal resilience and consistent performance over the entire useful life. Failure of brakes can end up in fatal events if stringent requirements of material selection, fabrication, heat treatment processes, quality control, etc are not adhered to.

Brake discs are mounted on the automobile wheel assembly with pads produced out of composite materials impregnated with additives to strengthen their thermal characteristics. These additives are bound strongly within the composite material using a phenolic resin. [2] They are sometimes slotted on the surface with shallow channels to remove dust, water and gas. During the braking action, the pads strongly rub against the rotating disc with high friction resulting in very high temperatures in the contact region. The temperature rise is significantly determined by the kinetic energy of the vehicle



which is a function of both speed of the vehicle as well as the heat capacity and mass of the brake rotor. This heat absorbed by the brake discs should be rapidly dissipated to ambient air. The coefficient of friction between the brake discs and pads reduce significantly with increasing temperature, leading to reduced braking and hence prolonged distances before stopping.

Taking these factors into consideration, brakes are designed to optimise between the deformation, deflection and strength properties considering the braking forces, weight and thermal performance with very long expectant useful life of nearly 1,00,000 kilo meters.

1.2 Cryogenic treatment

The subzero treatment on metals has been extensively employed since many decades for various applications. However this treatment was restricted to about 193K (dry ice temperature). In the recent years, extensive research has been carried out in studying the effect of the cold treatment down to cryogenic temperatures. [3] Even though major application of cryogenic treatment has been in the field of tooling industry in improving the tool life of cutting tools, it has also other important applications like reduction of internal stresses in metals, imparting dimensional stability to gauges and precision machined parts, improvement in mechanical and physical properties of metals and alloys, etc. There is large scope to explore the applications of cryotreatment in other allied areas of engineering. A typical cryotreatment cycle is shown in figure 1.

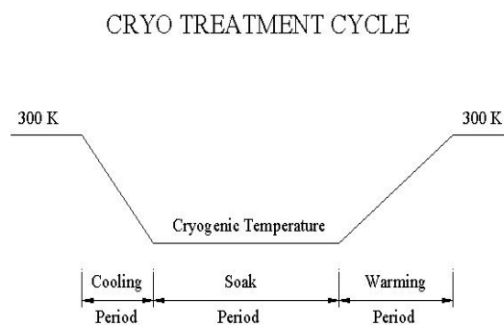


Figure 1. Cryotreatment cycle

Cryogenic treatment (cryotreatment) is a onetime add on process to the conventional heat treatment process and influences the entire cross section of the materials and components. The process involves broadly three stages viz. gradual lowering of the temperature to cryogenic zone, holding (soaking) for extended length of time and gradually warming to room temperature. A typical cryotreatment procedure takes around 38 hours to complete one complete cycle with 5 hours of cool down, 24 hours of soak and 9 hours of time to warm up to room temperature. During this entire period, permanent and invisible changes take place at the microstructure level imparting the desired properties to the material. The metallurgical changes are permanent and homogeneous over the entire volume and are irreversible. Cryotreatment can be followed by additional heat treatment processes like tempering which is based on individual cases.

The cryotreatment procedure is carried keeping the materials inside a closed insulated chamber normally produced out of stainless steel. The materials are gradually cooled to cryogenic temperature using circulating liquid nitrogen. Gradual cooling is very critical since direct immersion of materials into liquid nitrogen bath can produce thermal shock on the external surfaces, a situation of cold embrittlement. The popular choice of cooling is by closed loop circulation of cold nitrogen gas within the chamber. The process parameters like soak time and temperature can be varied by regulating the supply of liquid nitrogen with the help of PID controller operated cryogenic solenoid valve. Generally cryotreatment is classified based on the soak temperature as cold treatment (CT) in the range of 273-193K, shallow cryogenic treatment (SHT) in the range of 193-113K and deep cryogenic treatment (DCT) in the range of 113-77K.

In the case of carbon based steels three important changes take place at the soaked temperature.

1. The lattice parameters of the atoms change due to stresses being relieved during cryogenic treatment.
2. Soft, tough and ductile Face Centred Cubic (FCC) lattice structured retained austenite of the steel gets converted to strong and hard Body Centred Tetragonal (BCT) structured martensite.
3. Micron sized carbide particles are precipitated which evenly disperse within the entire material. They fill up the voids and gaps between the existing larger atoms in the atomic structure. This results in more uniform, dense and compact arrangement of the atomic structure.

Cryotreatment imparts no visible changes in the metal after treatment. Even though it is not possible to observe external physical changes in the metal, a more uniform, refined microstructure can be observed through metallurgical microscopes. [4] [5] These irreversible metallurgical changes are permanent and homogeneous over the entire volume. The soak temperature and its duration are largely responsible for changes in the properties after cryotreatment. After the cryotreatment cycle, the samples are normally tempered which further stabilizes the crystal structure due to precipitation of nano sized carbide fillers. The selection of tempering temperature and time mainly depends on the samples selected for cryotreatment.

2. Experimental details

To study the effects of cryotreatment on the wear and the hardness properties of brake discs, two types of commercially available brake discs were procured. After preparing the test specimens from these brake discs, the wear and hardness values were experimentally determined (untreated specimens). These specimens were divided to two equal batches. Specimens of the first batch were cryotreated for 8 hours and the remaining specimens of the second batch for 24 hours at 98K. After the completion of cryotreatment, the specimens were subjected to wear and hardness tests again to observe the changes. The results of wear and hardness values of untreated and cryotreated specimens were compared and studied. The plan of action is shown in the figure 2.

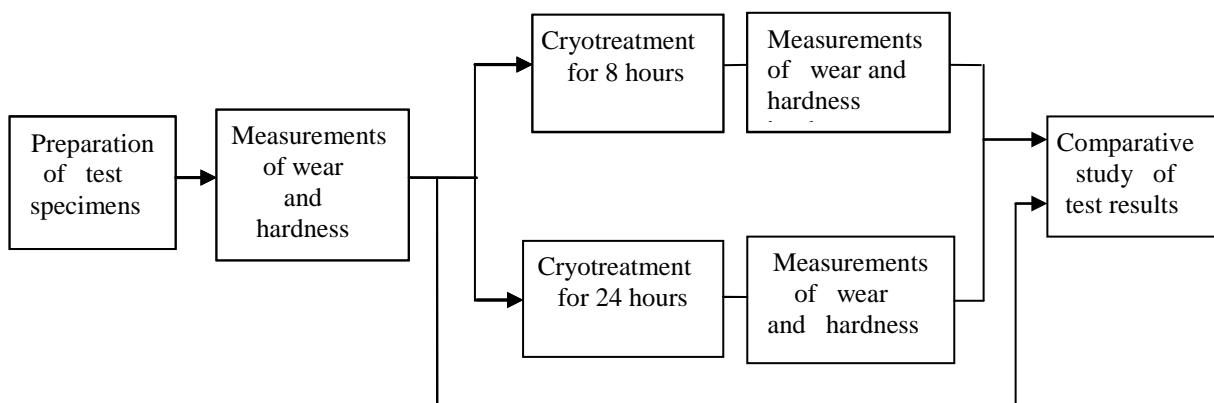


Figure 2. Schematic of the plan of action

2.1 Source material

The test specimens were prepared to determine the hardness and wear resistance properties using two types of commercially available brake discs. The discs are made of SS410 with the following composition as shown in table 1.

Table 1. Composition of SS410

Element	Chromium	Manganese	Silicon	Nickel	Carbon	Phosphorous	Iron
Percentage	13.5	1.0	1.0	0.75	0.15	0.04	Balance

Two brake discs were procured from different manufacturers and the specimens for the tests were produced with these discs as source material. These discs produced out of SS410, have a large circular hole at the centre which is mounted on the hub of the shaft of the wheels. At the outer circumference, there is an integral circular flat portion with many through holes in a symmetric manner. When brake is applied, brake pads press hard against this flat circular surface and retard the speed of the automobile. The drilled holes on this surface have a positive effect in wet conditions because they prevent a film of water building up between the disc and the pads. The photographs of the brake discs are shown in the figure 3.



Figure 3. Brake discs

2.2 Preparation of test specimens

The wear of the disc takes place in the circumferential flat region where the brake pads rub against the contact area with high friction and force. Hence the test specimens were produced from the material in this region. A total of sixteen test specimens were produced for each type of discs (A and B) for both the cryotreatment runs for 8 and 24 hours respectively. A water jet machine (WJM) was used for cutting. Circular discs of 8 mm diameter and 5 mm thickness (equal to thickness of disc) were produced by cutting the brake discs with high pressure water jet coming out through the nozzle of the water jet machine.

2.3 Wear tests

The test specimens in the form of circular discs were subjected to sliding wear test using the pin on disc type tribometer. This tribometer works on the guidelines of ASTM standards (ASTM G99-95). The test specimen was made to slide over the rotating abrasive disc under the load for the fixed time duration. During this test period, the pin continuously wears and the total wear during the test period is indicated by either reduction in length or loss of weight with respect to the original length / weight. In the present study, total wear is determined based on the total wear measured in microns. Wear is a function of the applied load, rotating speed of the disc, track radius of the pin (with respect to centre of the disc) and the friction between the contacting surfaces. [6] The schematic of the same is shown in the figure 4. Wear trials were conducted by sliding the test specimens against the abrasive disc rotating at 300 rpm under the load of 98N with track radius of 150mm. Test duration was confined to 1200 seconds. Test results of wear and coefficient of friction were determined for all the untreated and cryotreated specimens. The schematic diagram of the pin on disc tribometer is shown in figure 4.

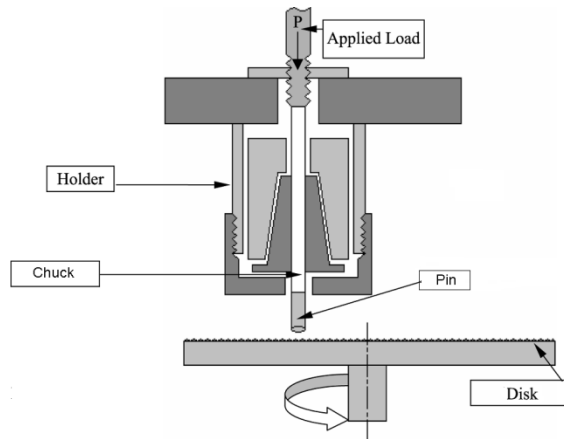


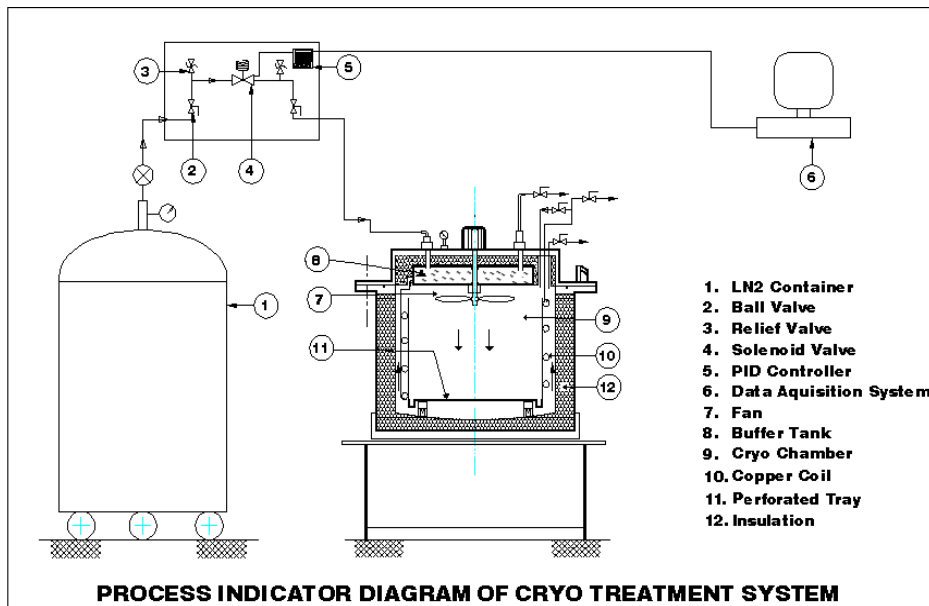
Figure 4. Schematic of the pin on disc tribometer

2.4 Hardness

Hardness values of the specimens were determined with the help of Rockwell hardness tester using the C scale (HRC). The test procedures were carried in accordance with guidelines of ASTM E 18. [7] The Rockwell scale measures hardness based on the indentation of the harder material on the test material. In Rockwell test, hardness is evaluated by measuring the depth of penetration of an indenter under a large load compared to the penetration made by a preload. Rockwell hardness has a distinct advantage over the other hardness tests since calculations, measurements, etc are not needed. In the present study, a 120° diamond spheroconical diamond indenter was used for indentation with major load of 1500 N and minor load of 98 N.

2.5 Cryotreatment system

A dedicated cryotreatment unit has been designed and developed to operate for various combinations of temperature and time parameters. In this system, cooling of the samples is carried out indirectly by producing forced convection heat transfer closed loops within the cryotreatment chamber. The schematic diagram of the developed system is shown in figure 5.



PROCESS INDICATOR DIAGRAM OF CRYO TREATMENT SYSTEM

Figure 5. Process indicator diagram for cryotreatment system

The cryotreatment unit is a double walled cylindrical stainless steel container produced out of SS 316L with the annular space filled with polyurethane foam insulation to minimize heat inleak from the atmosphere. The top cover also made out of stainless steel has a double end shaft fan-motor assembly mounted centrally. The liquid nitrogen connecting valves, pressure gauges, feed through and outlet connections are all mounted on the top cover. Below the top cover has a cylindrical buffer tank underneath where the supplied liquid nitrogen gets collected and the evaporated vapours are vented through a vent pipe. The shaft of the fan motor assembly passes through this buffer tank with its blades inside the cryotreatment unit.

The specimens kept in the meshed stainless steel tray are cooled by two ways.

i. The circulating fan housed below the buffer tank, induces forced convection currents picking up cold from stored liquid nitrogen in the buffer tank downwards over the specimens. The cold gas moving down to the bottom of the chamber cools the specimens and moves radially side ways and travels upwards between the SS shroud and inner vessel. This cold gas re-enters into the back side of the rotating fan and is force pushed over the specimens by the fan. This sets up a closed loop forced convection current loop inside the unit.

ii. Part of the liquid nitrogen stored in the buffer tank is made to circulate over the shroud by thermo-syphon effect. To facilitate this, a copper tube is connected to the buffer tank and this tube is brazed on the outer wall of the shroud over its entire length. The return stream is vented to the atmosphere.

A solenoid valve operated by a PID controller with predetermined set points regulates the liquid nitrogen supply to the unit. Various cycles of cooling, soaking and warming can be programmed to suit the requirements. The temperatures of the specimens are measured using temperature sensors (Pt 100). The temperature data of the specimens are read by PID at various stages of the cryotreatment cycle and recorded continuously using a Data Acquisition System. In the present study, the specimens were exposed to cryogenic environment of 98K for 8 and 24 hours respectively. In both the cases, the specimens were gradually cooled for 5 hours and warmed to room temperature in 9 hours after the soak period.

3. Results

3.1 Hardness

The results of hardness (HRC) of the untreated and cryotreated test specimens are shown in the table 2.

Table 2. Results of hardness test

Brake disc	Test specimen	Hardness (HRC)
A	Untreated	35.93
	CT (8 hours)	38.05
	CT (24 hours)	39.27
B	Untreated	36.23
	CT (8 hours)	38.05
	CT (24 hours)	38.67

Cryotreatment process has increased the hardness values for both the types of brake discs. Hardness is an indirect measure of resistance to scratch or penetration of the indenter. During the cryotreatment process, micro sized hard carbide particles are released which fill up the voids, gaps and vacancies present within the atomic structure of the material. [8] Filling of these carbide particles causes the atomic structure to be more dense, strong and hard. For both the types of brake discs,

increasing the duration of soak during cryotreatment has resulted in increased hardness, which indicates that enhancement in hardness depends on the duration of cryotreatment.

3.1 Wear

The pin on disc wear tests indicate enhancement of wear resistance properties of both the brake discs. The test results are shown in table 3. Even though the tests were conducted under similar conditions, brake disc A has rendered more convincing results as compared with B. In both the cases, cryotreatment (CT) for 24 hours has been more effective as compared with cryotreatment for 8 hours. This trend can be attributed to the increase in hardness values of the test specimens as discussed earlier. Even though the wear resistance in brake disc B has increased with duration of cryotreatment process, the enhancement has not been very significant. This can be attributed to various factors like variation in percentage composition of alloying elements, heat treatment process followed post production, etc.

Table 3. Results of pin on disc wear tests

Brake disc	Test specimen	Wear (microns)	Percentage improvement
A	Untreated	175	-
	CT (8 hours)	68	61.14
	CT (24 hours)	45	77.14
B	Untreated	135	-
	CT (8 hours)	110	18.51
	CT (24 hours)	102	24.44

4. Conclusions

Experiments were conducted to study the wear properties of brake discs of automobiles. Two types of brake discs from different manufacturers produced from SS410 were procured. The test specimens machined from these discs were subjected to wear and hardness tests. Sliding wear properties were determined using the pin on disc tribometer. Hardness values were determined using the Rockwell hardness tester (HRC). After cryotreating the test specimens at 98K for 8 and 24 hours, wear and hardness values were determined again. The test results of untreated and cryotreated specimens were compared and analysed. The conclusions of the experimental study are as follows:

Cryogenic treatment has enhanced the hardness and wear resistance properties of both brake discs. This is due to the precipitation of hard carbide particles filling up the voids and vacant spaces and conversion of soft and ductile retained austenite to martensite during the cryotreatment process.

Brake disc A has indicated better response to cryotreatment as compared with brake disc B. This is because the hardness values of brakes B are comparatively higher. This increased hardness could be due to various factors like composition of alloying elements, method of heat treatment post production, etc.

Duration of the soak time during cryotreatment process has direct effect on the wear resistance and hardness properties of both the brake discs. Increasing the soak time enhances the wear resistance and hardness properties which in turn improve the useful life of brakes. Soak temperature is also an important factor which can influence the effects of cryotreatment. Hence, the results call for an extended study to optimise the experimental parameters with regard to soak time and temperature during the cryotreatment process.

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