International Symposium of Research Students on Material Science and Engineering
December 20-22, 2004, Chennai, India
Department of Metallurgical and Materials Engineering, Indian Institute of Technology Madras

ROLLING CONTACT FATIGUE STUDIES ON CASE CARBURIZED AND CRYOGENIC TREATED EN 353 GEAR MATERIAL

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ABSTRACT

This paper details the application of cryogenic treatment to gear material to improve the surface fatigue strength. Experimental studies were conducted to find the effect of cryogenic treatment on Rolling Contact Fatigue (RCF) strength of En 353 case carburized low alloy steel. Results showed improved contact fatigue life for the cryogenic treated steel when compared to the case carburized steel. This has been validated theoretically. The X-ray diffraction, micro hardness and microstructure studies showed the influence of retained austenite level on the surface fatigue life.

Key words: cryogenic treatment, retained austenite, rolling contact fatigue

1. INTRODUCTION

Over the years, researchers worldwide have reported lot of practical success by cryogenic treatment. One of the common claims in the research papers published on cryogenic treatment is the improved service life to tool and die steels[1-8]. The improved performance has been reported to be in wear resistance and dimensional stability. But there is no clear cut understanding about how cryogenic treatment improves the performance of the steels. However most researchers believe that the cryogenic treatment promotes the transformation of retained austenite to martensite[1-2]. Others claim that cryogenic treatment results in the precipitation of fine carbides in the martensite, which improves the wear resistance[3]. Still non-availability of metallurgical understanding, lack of accepted practices and scientific data made this treatment less popular It has been reported that the martensite conversion starts at M_s (martensite start) temperature and continues till the M_f (martensite finish) temperature, which is well below the room temperature[5]. The low temperature can be maintained at–80^0C (dry ice temperature) or deep treatment temperature also called cryogenic temperature of -196^0C (liquid nitrogen temperature). Liquid nitrogen is usually preferred as the cooling media due the slower cooling rate and hence reduces the problems associated with thermal stresses[1]. The cryogenic equipment preferred is of the heat exchanger type so that the liquid nitrogen is not in direct contact with the specimens. The treatment temperature, rate of cooling and soaking time can significantly affect the desired material properties[8]. The motivation for this paper is to study the effect of cryogenic treatment and the cryogenic mechanism in improving the surface fatigue strength of gears steels. For this, En 353 low alloy steel, which can be easily case hardened, is selected. RCF tests were conducted for both carburized and cryogenic treated specimens. The results of the test are presented and discussed here.

2. EXPERIMENTATION

Standard rods of En 353 low alloy nickel chromium steel readily available in the market are selected for the present study. En 353 is a case hardening steel, which on carburizing produces a tough, case with a soft core. The composition of En 353 steel in the as received condition was analyzed and is given in Table 1.The samples were subjected to

Table 1
Chemical composition of En353 (wt%)

C	Si	Mn	S	Ni	Mo	P	Cr
0.18	0.22	0.72	0.04	1.43	0.12	0.042	1.0

case carburizing and tempering. Case carburization of En 353 steel samples are carried out in gas carburizing furnace at temperature of 952°C for period of 6 hours (activation for 4 hours and diffusion for 2 hours). Treatment cycle is given in Fig.1. The heat treatment process is followed by a tempering cycle of 2 hours for relieving the stress induced during the heat treatment process as given in Fig. 2.

The cryogenic treatment was carried within 3 to 4 hours of completion of the heat treatment process. Heat exchanger type cryogenic treatment equipment with liquid nitrogen as the cooling media is used for the treatment. This was carried out by lowering the temperature to -195°C and held at this temperature for period of 24 hours. The cryogenic treatment cycle is given in Fig. 3. After the cryogenic treatment, tempering was performed to relieve any stresses induced during the cryogenic treatment. The tempering cycle is same as shown in shown in Fig. 2.
Test specimens were prepared for testing the mechanical and rolling contact fatigue properties of En 353 steel. The test specimens for mechanical testing were made as per ASTM standards. The impact, bending and compression tests were conducted for both carburized and cryogenic treated samples.. The specimen for RCF testing is made in the form of rollers with inner diameter 20mm; outer diameter 40mm and width 12mm. 30 samples each were tested for carburized and cryogenic treatment. The treated rollers were grinded to a surface roughness (R_a) value of 0.25-0.30 μm .

The RCF test set up consists of two standard rollers diametrically opposite to the test roller so that load is applied twice per cycle. The rig is designed for easy alignment of the shaft and to maintain identical test conditions for each assembling of the standard and test rollers. One of the standard rollers is fixed and the other is movable. Both the standard rollers are supported by roller bearings mounted in housing. The housing of the drive side standard roller is fixed to the base plate. The housing of the loading side roller is attached to the linear motion slides fixed to the bottom base plate. The test roller is supported on ball bearings mounted in bearing block. The bearing block is fixed on linear motion slide attached to the movable standard roller base plate. Since load is applied on the test roller from diametrically opposite sides, there is no load on the shaft and hence the shaft is made of small section. The top view of the roller assembly is given in Fig. 4.

The loading system consists of an actuator, load cell for measuring the load and a power pack to actuate the load. The power pack designed can develop a pressure of 210 bar with a flow rate of 3 lpm. The strain gauge based load cell is used is to estimate the load that is being applied by a 5 ton hydraulic cylinder. The force exerted by the cylinder is maintained within ±5% of the set value. The failure point is continuously monitored using sound vibration and temperature measurements. The piezo electric accelerometer of 11.23 mv/g fixed on the movable housing measures the vibration level in the loading direction. The sound level meter of B&K make kept at a distance of one meter from the sound source continuously monitors the sound level. The two infrared temperature sensors monitor the temperature at the bearing side of the drive roller and on the test roller so that machine is stopped if the temperature exceeds the permissible limits. All the sensors are connected to Labview data acquisition system.

Continuous lubrication is provided to the rollers at the contact region and all support bearings, using SAE 30 oil without any additives. The lubrication system used consists of a hydraulic circuit delivering 3lpm at 2bar pressure with 60 litre tank capacity. The oil flow is controlled by ball valves at the inlet to the jets.

The RCF test was conducted at four different stress levels keeping the speed constant at 4500 rpm. Five tests were conducted for each stress level. The average no of cycles for each stress level was calculated and S-N curve plotted for carburized and cryogenic treated En353 steel.
In the RCF test, failure of the specimens occurred mainly due to pitting. Single pit formation was established as the criteria for failure. For the tests conducted it was found that pit area of 2.2mm^2 point. The failure point was monitored using sound and vibration measurements. The sound level showed only a 1 to 2 dB increase up to the failure point. At the failure point the sound level increased drastically by 5-7 dB on the C scale. The maximum sound level observed was 93 dB at the load of 3028 MPa. The area of the pit formed varies from 2.2 to 15.2 mm^2 at the failure point. The increase in sound level with area of the pit and number of cycles are shown in Fig 5 and Fig.6 respectively. The octave level analysis of the sound signature showed that the sound level was at the maximum at contact frequency of 150Hz. This is shown in the 1/3 octave and 1/1 octave in Fig. 7 and Fig. 8. The roller bearing and ball bearing frequencies are also contributing to the sound level. The vibration level during normal running is 5.5m/sec^2. At the failure point, it was found that a vibration level increase from 10-50 m/sec^2 occurs. The increase in vibration level with area of pit formed and number of cycles is shown in Fig. 9 and Fig 10 respectively. At the failure point, vibration level reached a maximum value of 63m/sec^2. The maximum temperature on the test roller side is 48^{0}C. So the thermal effect on the rolling contact fatigue test results may be considered negligible.

3. RESULTS AND DISCUSSIONS

The mechanical test results showed that the bending strength and hardness of cryogenic treated specimen improved by 38% and 10.19% respectively. The impact strength decreased considerably. The test results are shown in Table 2.

Table 2
Mechanical test results

Specimen	Impact strength	Bending strength	Hardness
Carburized	18.5 joules	1233 MPa	726 HV
Cryogenic treated	7.5 joules	1701 MPa	800 HV

The RCF test was conducted on carburized and treated rollers. The S-N curve was plotted for the carburized and cryogenic treated rollers and extrapolated for 10^8 cycles. This is shown in Fig. 11 and Fig. 12. Most of the gears are made to run for long hours .So it would be relevant to estimate the contact fatigue life of gears for 10^8 cycles. The extrapolated results showed that the rolling contact fatigue strength for carburized specimen was 2450MPa while that for cryogenic treated specimen was 2710MPa. The cryogenic treated specimens were found to have improved contact fatigue strength of 10.6% over the carburized specimens. This is a considerable improvement and will enhance the service life of the gears significantly. The theoretical estimated of contact fatigue strength from hardness value using AGMA relations showed 5-6 %

improvement by cryogenic treatment. In order to substantiate the improvement in hardness, micro hardness studies were conducted on cut section of rollers of carburized and cryogenic treated specimens. Fig. 13 and Fig. 14 give the results.

The case depth for cryogenic and carburized specimens was found to vary from 0.6-1.0 mm. The hardness of the case varies from 726 to 650 HV for carburized and 800 to 650HV for cryogenic treated. The core hardness for both cryogenic treated and carburized specimens is in the range of 350-400HV thus maintaining a tough core. The carburizing of En 353 specimen increased the carbon content in the case to 0.82% by weight. Improvement in hardness by cryogenic treatment may be due to the conversion of the retained austenite present in the case to martensite. Microstructure studies were conducted on carburized and cryogenic treated specimens to find the distribution of retained austenite and tempered martensite. The microstructure of case and core for cryogenic treated specimen is shown in Fig. 15 and Fig. 16 and that of carburized specimen in Fig.17 and Fig.18. The case microstructure is predominately plate martensite and the core, which is not affected by carburizing, is also martensitic, but due to the low carbon content is predominately of lathe martensite. The case microstructure of carburized specimen showed distributed white region of retained austenite when compared to the case microstructure of cryogenic treated specimen. The dark dots of globular shape in the martensite are carbide deposits. In order to quantify the retained austenite level, X-ray diffraction was done on both the specimens. It was observed that the retained austenite level in the case for carburized specimen was 13.94% and that of cryogenic treated was 4.69%. The improvement in hardness and hence contact fatigue strength for cryogenic treated specimen may be due to the conversion of this retained austenite to martensite. Freshly formed martensite is brittle and so tempering was done after cryogenic treatment.
distribution for cryogenic treated

4. CONCLUSIONS

Cryogenic treatment was done on case carburized En 353 low alloy steel. It was found that the hardness and bending strength improved by 10.19% and 38% respectively. The retained austenite level has decreased by 66.35% for cryogenic treated steel. The RCF test on cryogenic treated En 353rollers showed that the surface fatigue strength improved by 10.16% when compared to the carburized rollers. Thus the service life of the En 353 gear material can be enhanced by the cryogenic treatment.

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FIGURES

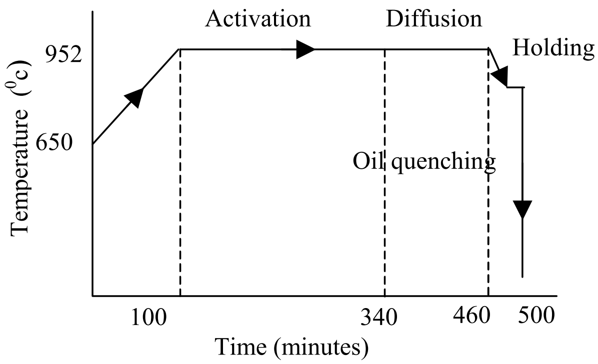


Fig. 1. Gas carburizing cycle

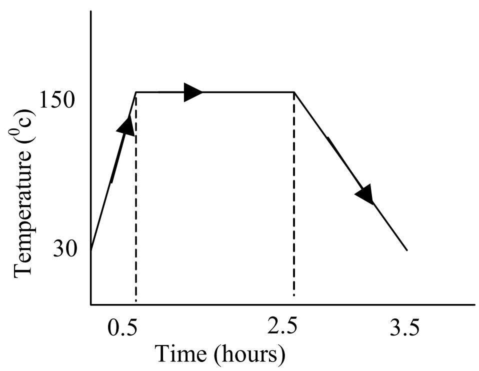


Fig. 2. Tempering cycle after carburizing

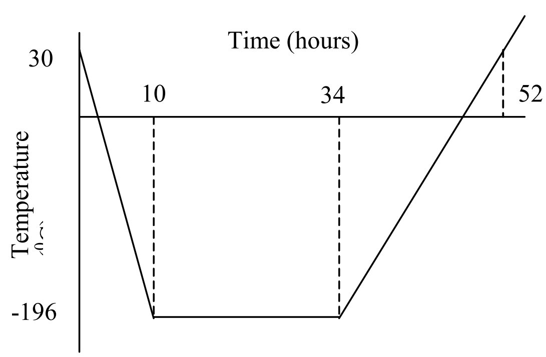


Fig 3. Cryogenic treatment cycle

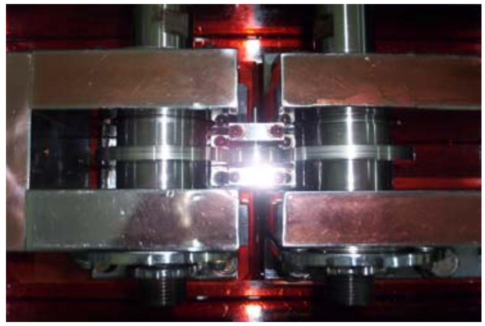


Fig. 4.Top view of the roller assembly of RCR test rig

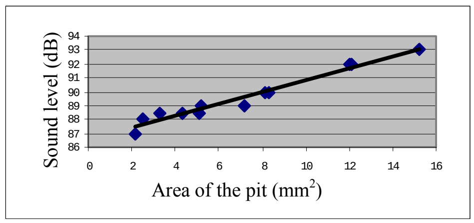


Fig 5. Variation in sound level with area of pit

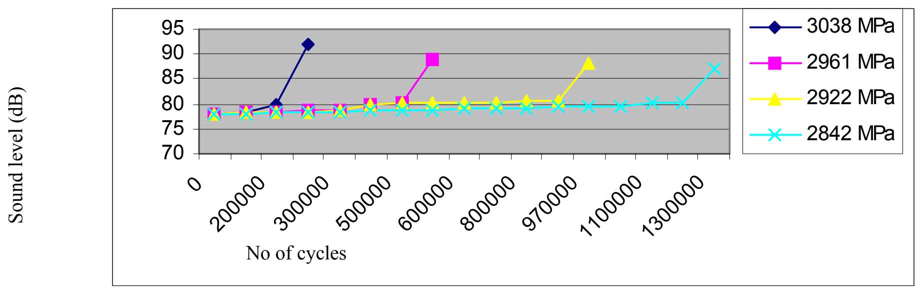


Fig 6 Variation in sound level with no of cycles

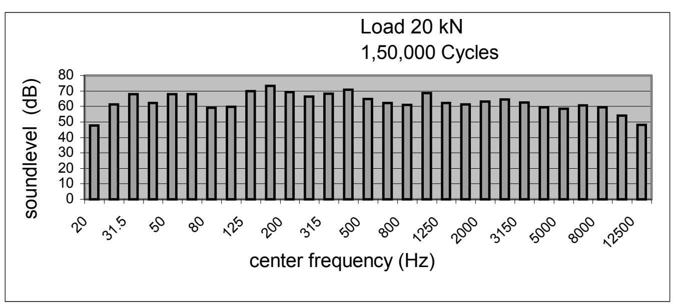


Fig 7. 1/3 octave sound level for cryogenic treated steel

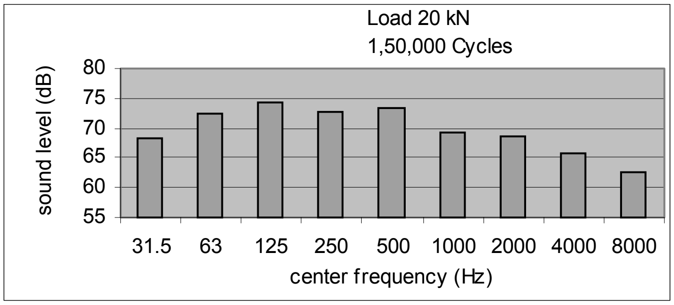


Fig 8. 1/1 octave sound level for cryogenic treated steel

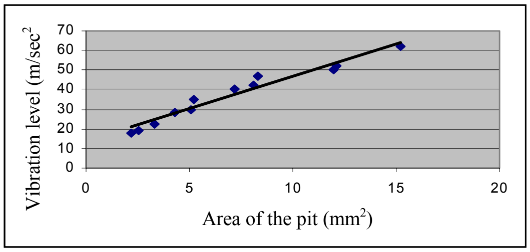


Fig 9. Variation in vibration level with area of pit

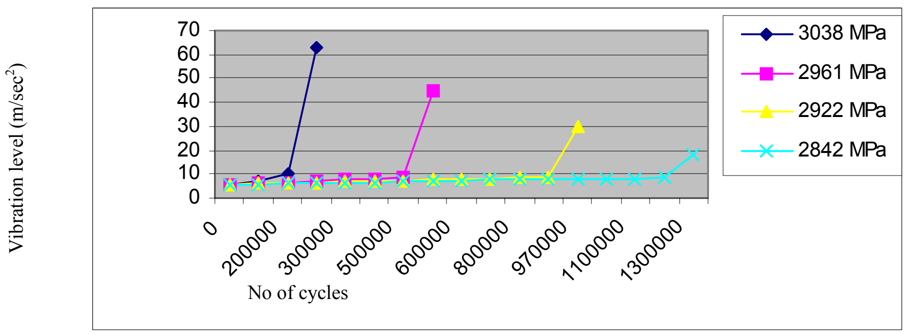


Fig 10. Variation in vibration level with no of cycles

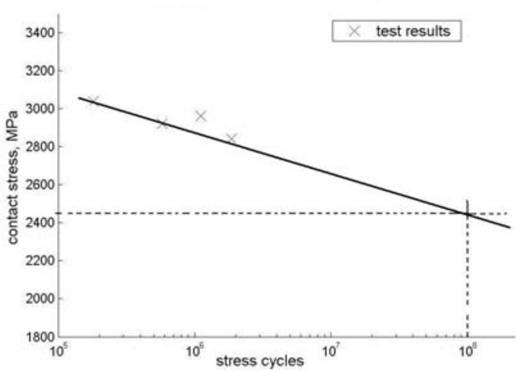


Fig 11. S-N curve for case carburized

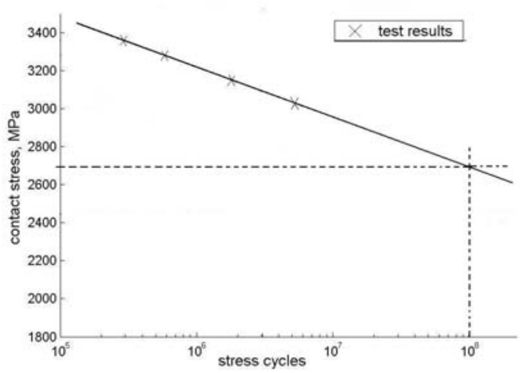
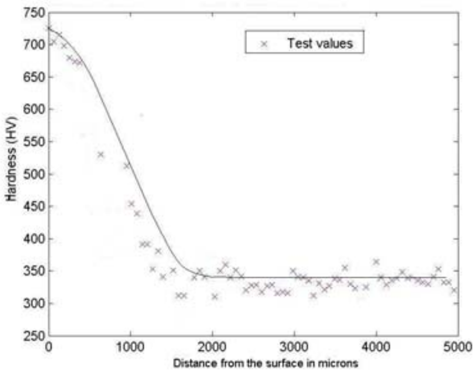


Fig 12. S-N curve for cryogenic



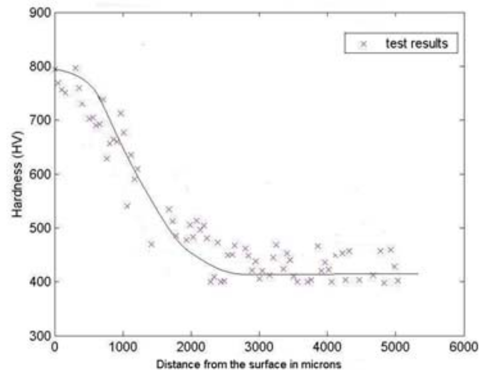
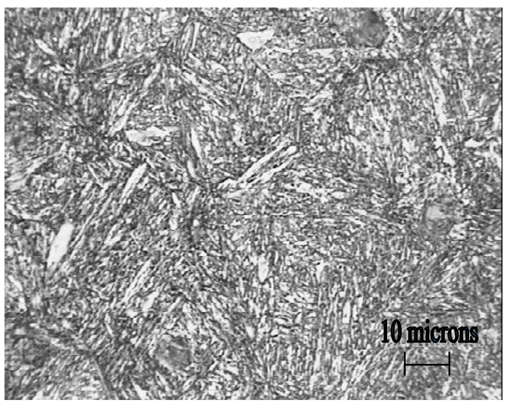


Fig 13 Micro hardness distribution for case carburized Fig 14 Micro hardness



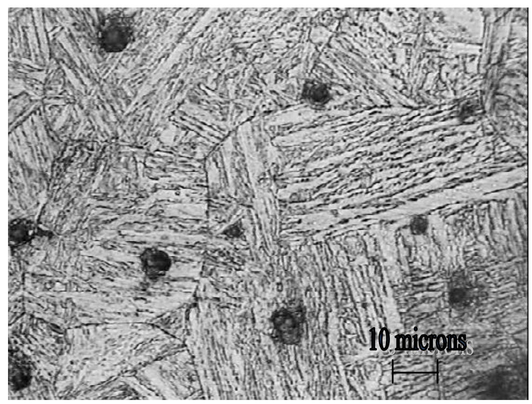
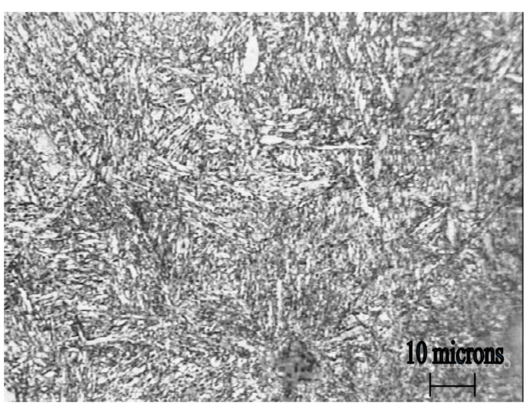


Fig. 15 case structure of cryogenic treated steel Fig. 16 core structure of cryogenic treated steel



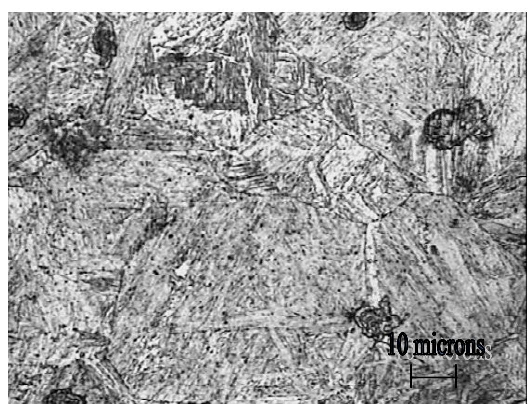


Fig. 17 case structure of carburized specimen Fig. 18 core structure of carburized specimen