

Effects of pulsed magnetic field on thrust bearing washer hardness

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Abstract

Magnetic treatment has been shown to be capable of altering mechanical properties of materials. Since the behavior of tribological systems depends on the mechanical characteristics of the interacting bodies, applying a magnetic field to an operating tribological system is a potential means for controlling system behavior. As a measure of the effects of applied magnetic fields on tribological processes the micro-hardness of ferromagnetic steel thrust bearing washers was measured for washers before and after being run under no-field and applied magnetic field conditions. Analyses of the data showed statistically significant effects. For the specific test conditions used, micro-hardness increased by approximately 5% for bearings run under no-field conditions. For bearings run under pulsed magnetic fields washer hardness decreased by approximately 9%.
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1. Introduction

While sparse, research has shown that the application of magnetic fields to materials can alter the material mechanical properties. This use of magnetic fields has been primarily in the study of the treatment of manufactured parts. For example, pulsed magnetic fields have been used to alter part hardness and residual stress state. The attractive features of this type of material treatment are that the field strength is low, the field is easy to produce and control, and the treatment is at room temperature. However, the reported effects are usually small, and a few studies show no effects.

If applied magnetic fields can alter material properties, and since tribological system behavior depends on material characteristics, the use of magnetic fields to alter and control system behavior becomes possible. If an applied field can be used to change tribological system behavior then an easy to apply process control scheme becomes available.

Also, some tribological systems operate in applied or induced magnetic fields, for example magnetic bearings and electrical generation machinery. Rational design and operation of such systems requires detailed understanding of the effects of magnetic fields on material properties and tribological processes.

The work reported here was directed toward ascertaining the existence of magnetic field effects and quantitatively characterizing the effects of pulsed magnetic fields on rolling contact bearings. Ferromagnetic steel thrust bearings were run under both no-field and applied magnetic field conditions. The micro-hardness of the thrust bearing washers before and after running was used as the measure of the magnetic field effect.

2. Background

Although it is an attractive possibility, there is only a limited amount of widely available research results describing the effects of magnetic fields on material properties and tribological processes.

2.1. Magnetic treatment of materials and manufactured parts

Prasad et al. [1] measured the hardness of steel workpieces that were rolled to different thicknesses and then subjected to a pulsating magnetic field. Hardness decreased by about 12% with magnetic treatment for the specimens rolled to the largest reduction of 80% and by about 7% for specimens rolled to 20% reduction. Increases in fatigue life of steel specimens treated with a pulsed magnetic field were reported by Fahmy et al. [2], and after both static and fluctuating magnetic field treatments by Lu et al. [3]. In related works, Tang et al. [4] and Lu et

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al. [5] subjected restrained tensile specimens and welded plate specimens to pulsed magnetic treatments. For tensile specimens, stress reductions of 4–30% were reported for pulsed magnetic field frequencies of 1–10 Hz. Residual stress reductions of 20–40% were measured for welded specimens. A few measurements show no difference or an increase in residual stress with magnetic treatment. Klamecki [6] measured micro-hardness of annealed and shot peened steel specimens before and after pulsed magnetic field treatment. A model relating indentation size to residual stress was put forward. The observed decreases in micro-hardness or residual stress with magnetic treatment were small, on the order of 5%. Based on Barkhausen effect, X-ray diffraction and magnetic force microscopy measurements of drawn steel bars, cold worked nickel bars and magnetic thin films before and after exposure to pulsed magnetic fields Johnson and co-workers [7,8] detected no effect of magnetic treatment.

2.2. Application of magnetic fields to tribological systems

Early work on the use of magnetic fields to control tribological processes centered on tool wear. Bagchi [9] and Bagchi and Ghosh [10] studied the effects of constant magnetic fields on wear of high speed steel tools when machining mild steel. They observed a decrease in tool wear that was dependent on both magnetic field intensity and cutting speed. Chakravarty [11] proposed a qualitative model to explain increased life of magnetized tools based on a physical reorientation of elemental magnets. Pal and Gupta [12] studied the effect of an alternating magnetic field on the wear behavior of high speed steel drills. In some drilling processes the field was applied using a solenoid that surrounded both the drill and workpiece. In other drilling tests the same solenoid was placed above the workpiece so that the magnetic field was applied mainly to the tool. Increases of tool life with applied magnetic field were obtained for both test configurations. No detailed theoretical explanations for the experimental observations were given. Muju and co-workers [13–16] performed extensive experimental work and proposed an explanation for some results obtained in machining and rubbing wear experiments. Magnetized high speed steel tools were used in turning mild steel, aluminium and brass. Increases in tool life of up to about 40% due to the magnetic field were reported [13]. El Mansori et al. [17,18] performed turning tests with a coil surrounding the tool providing a dc magnetic field around the tool–work contact region. High speed steel tools were used to cut stainless steel and carbon steel. Increasing the applied magnetic field intensity resulted in increased tool durability of up to about 40% for both tool–work material pairs. Bataineh et al. [19] magnetically treated high speed steel drills and steel workpieces with a pulsed field before drilling. For magnetically treated drills the number of holes drilled in untreated workpieces before drill failure was about 15% greater than for untreated drills. When both the drills and workpieces were magnetically treated increases in tool life of up to 35% were measured.

Muju and co-workers [14,15] observed decreases in wear rate for steel–brass pairs sliding in a magnetic field compared

to no-field sliding. A phenomenological explanation based on motion of dislocations in the junctions between asperities due to the magnetic field was proposed [14]. Muju and Radhakrishna [15] further developed a generalization of the model taking into account the influence of temperature and concluded that the application of a magnetic field reduces the activation energy of diffusion and wear. Kumagai et al. [20] produced wear rate decreases of up to 80% in sliding systems by the imposition of a pulsed magnetic field. The decrease in wear rate increased with increasing magnetic field strength, increasing normal load and increasing sliding speed.

Hiratsuka and co-workers [21,22] explained decreases in wear rate when sliding was in a magnetic field as due to changes in the transition from severe to mild wear regimes. In sliding tests in an argon atmosphere the magnetic field effect was much less leading to the conclusion that the magnetic field plays a role in determining the rate of oxidation and hence wear rate. Zaidi et al. [23] reported decreases in wear rate with applied magnetic field for nickel–nickel and steel–steel sliding pairs for specific sliding conditions. Under other conditions Zaidi and Senouci [24] showed that in the presence of a magnetic field oxygen adsorption was increased by a factor of 4 and wear rate increased significantly. El Mansori and co-workers [17,25–28] observed changes in the severe-to-mild wear transition that depended not only on load and but also on applied magnetic field strength. For magnetic field intensities exceeding a critical level, decreases of wear rate of up to 90% were seen. Characterization of worn surfaces and wear debris from copper and steel pairs showed that the size of wear debris particles decreased when sliding was in a magnetic field. The extent of oxidation was measured for steel surfaces in air at room temperature with no field, at room temperature under various magnetic field strengths and at 100 °C with an applied field. Results showed the expected increase in oxidation rate with temperature and also an increase with applied field strength. A similar effect of the dependence of activation energy on applied dc magnetic field and temperature was reported by Paulmier et al. [29].

While there are tribological systems that normally operate in magnetic fields, only one, passing, reference to the effects of the field on tribological behavior has been seen. A photograph of a worn rolling element bearing appears in the Tribology Handbook [30]. The caption says that during running in a magnetic field “softening of the rotating track and rolling elements” led to premature fatigue.

2.3. Explanations of the effects of magnetic field on materials and processes

Explanations of experimental results and of the fundamental processes that cause changes in material properties due to magnetic fields have been mostly qualitative. The most common explanations are based on magnetostriction causing dislocation movement and dislocation structure rearrangement. Positron annihilation and X-ray diffraction studies of cold worked copper and nickel subjected to varying length of pulsed magnetic treatment were carried out by Su et al. [31]. They observed an initial magnetically induced recovery from, or

decrease in, cold working effects. Interpretation of the results led to the conclusions that low strength pulsed magnetic fields change dislocation and point defect concentrations and that the effects were localized in surface regions of the specimens. Alshits et al. [32] wrote an extensive review of their own and others' research on the magnetoplastic effect. There are several relevant results discussed with respect to the present concern of changing mechanical properties affecting tribological behavior. The primary, and most fundamental, result is that magnetic fields interact with the electronic structure of dislocations causing dislocation motion in metallic and nonmetallic crystalline materials. Also, these researchers observed a threshold field strength below which no effects were seen.

3. Problem considered and approach

The problem considered, and approach to it, were motivated by three observations about published research results. One is that simple magnetic treatments have been shown to be capable of changing material mechanical properties and influencing the operation of tribological processes. Another is that the reported effects were usually small and some inconsistencies in results were seen. The third observation is that apparently there are no detailed, fundamental, quantitative process models that explain observed effects. The limited state of understanding of the use of magnetic fields indicates a need to further demonstrate the existence and extent of effects of magnetic fields on tribological processes. To this end a strictly experimental project was formulated and executed.

The approach taken to demonstrating and specifying the effects of magnetic fields on tribological systems was to select a typical system and experimentally characterize the effects of a magnetic field on it. With the expectation of small effects, and so the need for multiple measurements, and the desire to relate effects to material properties directly related to material microstructure, micro-hardness measurement was chosen for specifying the effects of a magnetic field on tribological system components. Specifically, the effects of pulsed magnetic fields on rolling contact bearings were measured. Thrust bearing washer hardness was measured before and after bearings were run under no applied field and applied pulsed magnetic field conditions.

4. Tests and measurements, apparatus, and test specimens

The effects of applied magnetic field on rolling element thrust bearings were determined in two kinds of tests. In initial tests washer hardness was measured in the as-received condition and after washers were subjected to various numbers of pulsed magnetic field treatments. In other tests rolling element thrust bearings were run under no-field and applied magnetic field conditions and the effect of the field specified in terms of hardness of the bearing washers was measured. The running bearing tests were in air and unlubricated. Micro-hardness measurements were made using a Knoop indenter, applied loads of 100 g, 200 g, 300 g and 500 g, and a load application time of 5 s. Results

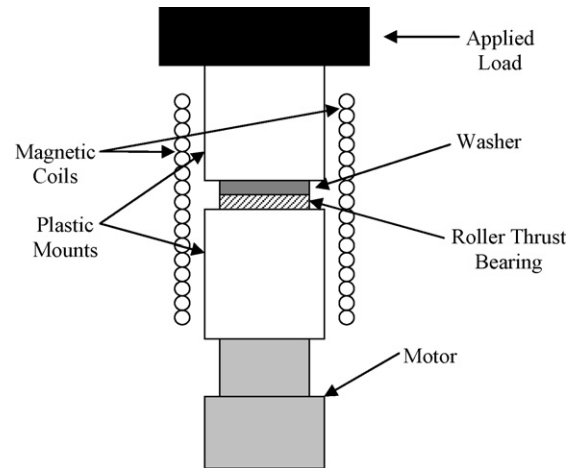


Fig. 1. Experimental apparatus in which rolling contact thrust bearings were run under no-field and applied pulsed magnetic field conditions.

are reported as the directly measured hardness test indentation length viewed at 400 \times magnification. The bearing washers used were in one of two general states of surface condition. Initial condition or as-received washers had the original manufactured surface state and some of these were magnetically treated but not used in running bearings. The hardness measurement locations on these washers were in four peripheral regions across the washer width with groups of measurements separated by about 90 $^\circ$ and on both sides of the washers. The other surface state was for washers that were run as loaded thrust bearings. In this case hardness measurements were in the rolling contact region, again across this region with measurement sites about 90 $^\circ$ apart.

The apparatus used for running bearings in the no-field and applied field tests is shown schematically in Fig. 1.

Bearings and washers were mounted on shoulders of cylindrical plastics supports that maintained alignment as the bearing part of the system was driven. The upper support held the washer and was free to move in the vertical direction but was restrained from rotating. Bearing loading was applied by placing dead weights on top of the upper, floating, non-rotating support. Running speed was constant at 1175 rpm and applied load and field strength were experimental variables.

The applied pulsed magnetic field was composed of a relatively low frequency, lower strength component with a superposed higher frequency, higher level component. The lower frequency component was of the order of 10 Hz with a magnitude of the order of 100 G. The higher frequency component was of the order of 100 Hz. Two pulsed magnetic fields were used. In one the peak value of the total, composite, applied field was 360 G. The other field had the same pattern and a peak value of 480 G. The pulsed magnetic fields are referred to in the text in terms of the peak values as 360 G and 480 G fields. The length of the applied pulsed field in washer magnetic treatment and the length of bearing running tests were both 42 s. This time was based on preliminary tests that showed measurable, but small, effects for this length of magnetic treatment and length of bearing running.

Commercially available needle roller thrust bearings were used. The washers were steel with 25.4 mm inside diameter,

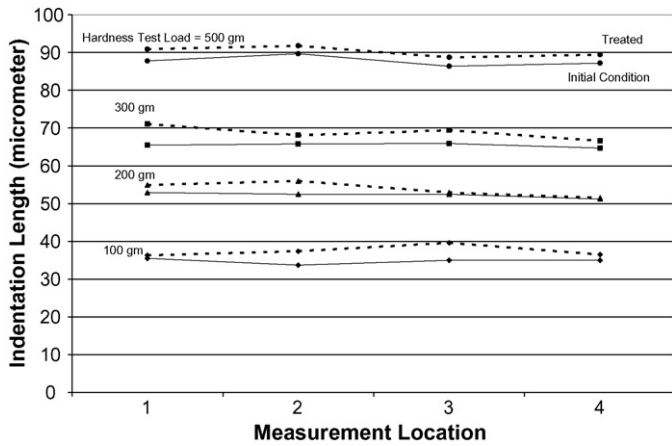


Fig. 2. Average micro-hardness test indentation length at various locations around washer and for various hardness test loads for washers in the as-received condition and after pulsed magnetic treatment.

39.7 mm outside diameter and 4 mm thickness. Initial hardness measurements on 320 bearing washers gave an average hardness measurement of 977 Knoop Hardness Number with standard deviation 34. The thrust bearing cage was steel with 25.4 mm inside diameter, 39.7 mm outside diameter and contained 30 hardened AISI 52100 steel, 2 mm diameter, 8.6 mm long rollers.

5. Typical effects of magnetic field on bearing washers and running bearings

The data points in Fig. 2 show average values of 20 micro-hardness test indentation lengths for washers before and after one 42 s, 480 G magnetic treatment. The measurement loca-

tions were around the washer periphery separated by about 90° and hardness tests were run with 100 g, 200 g, 300 g and 500 g applied load at each location. That is, 80 hardness measurements were made at each applied load before and after magnetic treatment. These results are typical of results from a large number of similar tests. In initial work [33] temperature changes were calculated and also measured using thermocouples mounted on surfaces for various size and shape specimens. Over a range of pulsed magnetic treatment times from seconds to tens of minutes the maximum temperature increase measured was 17 °C. This small temperature rise indicates no important thermal effects in the material hardness measurements reported here.

The pulsed magnetic treatment resulted in an increase of hardness test indentation length of 2.5–6%. A decrease in hardness with magnetic treatment was measured at all locations on the washer and for all hardness test loads. There is no apparent difference with micro-hardness test load and so either there is no difference in material structure with depth below the surface or the micro-hardness test is unable to resolve any differences. While there are differences in hardness with measurement location around the washer there is no consistent variation to indicate a dependence of hardness on measurement location. The spread in the data in terms of standard deviation indicated a small effect and the statistical analyses necessary to establish the existence of the effect of magnetic field was done using data generated in a large number of running bearing tests and are described below.

Fig. 3 shows average values of 80 micro-hardness test indentation lengths for washers run in no-field condition and for washers run in the 480 G pulsed magnetic field, along with data for washers in the initial, as-received condition and after being magnetically treated in the non-operating condition, i.e., in the test apparatus but with no motion and no applied load. The initial

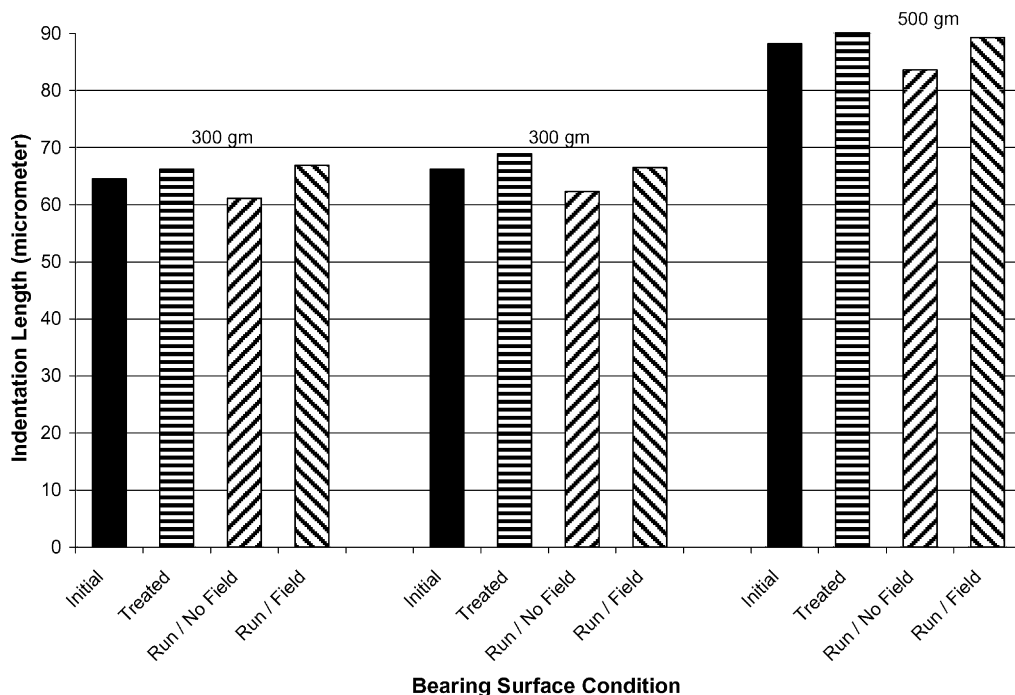


Fig. 3. Average indentation length measured for washers in initial condition, after magnetic treatment and after running under no-field and pulsed magnetic field conditions.

condition indentation length shown is the average value of 80 measurements made on each of the two washers used in the running bearing tests. That is, the average indentation length for the washers in the as-received, initial condition, that were then run under no applied field conditions. The results labelled treated are for washers received from the same lot as all the other washers tested in this research. The results from three typical tests are shown, two tests with washer hardness measured using a 300 g load and one using a 500 g hardness test load. The load applied to the running bearings was 27 N and this produced a calculated maximum Hertz contact stress of 273 MPa between the rollers and washer.

Micro-hardness test indentation lengths were 1.3–3.7% longer for the bearing washers run in a magnetic field than for the initial condition state of the washers. The indentation lengths are similar for the washers treated under no load, no motion conditions and washers run under pulsed magnetic fields. These small changes are comparable in size to results seen in other studies on other type of systems, primarily changes in hardness of manufactured parts. In contrast to the decrease in hardness of washers from bearings run in a magnetic field, washers from bearings operated under no-field condition showed an increase in hardness. The bearings were run in the test apparatus with the coil not energized, and washer hardness increased by about 5.5%. Comparing hardness of washers run in the magnetic field to those run under no-field conditions shows a net effect of about 7–9% lower hardness for the washers run in the pulsed magnetic field.

6. Statistical analysis of experimental results from running bearing tests

Convincing arguments as to the existence and size of the measured effects of magnetic fields on material properties and tribological processes call for rigorous statistical analyses of the data. A large number of tests were run with operating thrust bearings and the data analyzed to establish whether or not the effects seen in initial experiments were real and to determine the size of real effects.

6.1. Experiment design

This study was based on a modified two factor experiment. The dependent variable was the measured micro-hardness test indentation length and the independent variables were load applied to the bearings and magnetic field strength, referred to as LOAD and FIELD in this paper. Applied load and magnetic field each had three levels. The applied bearing load levels were 0 N, 45 N, and 90 N. The peak values of the applied pulsed magnetic fields were 0 G, 360 G, and 480 G. This factorial design results in nine experimental levels.

The typical two factor design described above was modified for the statistical analysis. Before and after different bearings being run in no-field and applied field conditions, 10 hardness measurements were made on each washer to account for variability in the micro-hardness measurement procedure and in the washers. So, bearing washer was included as a random effect.

The 10 measurements per washer resulted in a separate variance for each washer. To account for this additional variability, the experimental model was modified from a standard two-way fixed effects factorial model to a three-way mixed model. While different than the typical two factor model, and not as commonly used, three-way mixed models are available and used, e.g., Kirk [34] and Devore [35].

A power analysis was used to determine the number of specimens required to detect an effect for the experiment design and specified significance level. The power gives a measure of the probability that the experiment will detect a true effect when it is present. Power is equal to $1 - \beta$, where β is the probability of a Type II error, a false negative. Standard results, e.g., Kirk [34], specify that for a two-way three-level factorial analysis, with significance level (defined below) of $\alpha = 0.05$, and $1 - \beta = 0.80$, the useful sample sizes are: $n = 7$ for a large effect; $n = 18$ for a medium effect; and $n = 106$ for a small effect. A large effect is typically defined to mean that 13.8% of the variance in the overall mean can be attributed to the given effect. This study was focused on testing for the presence of an effect that initial testing and prior published results show exists at some measurable level. Therefore, it was assumed that a large effect criterion was appropriate and a sample size of $n = 7$ was chosen for each of the nine treatment levels.

The three-way mixed model incorporated two fixed effects, LOAD and FIELD, and one random effect, WASHER. The final model is

$$X_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijkl} \quad (1)$$

where X_{ijkl} is the dependent variable, indentation length, μ the grand population mean, α the effect of independent variable, Factor 1—load applied to bearing, β the effect of independent variable, Factor 2—applied magnetic field, γ the effect of independent variable, Factor 3—washer, $(\alpha\beta)$, $(\alpha\gamma)$, $(\beta\gamma)$ the two-way interaction effects, $(\alpha\beta\gamma)$ the three-way interaction effect, ε the error term, $i = 1-3$ levels of applied load, $j = 1-3$ levels of applied magnetic field, $k = 1-7$ levels of washer per each factor combination, and $l = 1-10$ measurements per washer.

It was expected that the random washer effect would prove to be insignificant and so eventually could be dropped from the model, but only after quantitative justification. The initial post-experiment analysis described below showed that the washer effect was indeed insignificant and so after establishing this result the final results are reported using a true two-way fixed effects model. This model assumes random assignment of treatment levels among the specimens and a balanced design. Random assignment was accomplished by randomly assigning washers to treatment levels and a balanced design was maintained by assigning an equal number of specimens to each treatment level. Additionally, the model assumes independent and normally distributed residuals, as well as homogeneity of variance. These assumptions are described and validated using standard statistical measures in the statistical analysis presented in Section 7.

The two-way fixed effects model that resulted after quantitatively identifying the washer effect as insignificant and the model used for summarizing the main results of the investigation is

$$X_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ijk} \quad (2)$$

where X is the dependent variable—measured indentation length, μ the grand population mean, α the effect of independent variable—Factor 1, peak value of pulsed magnetic field, β the effect of independent variable—Factor 2, load applied to bearing, $\alpha\beta$ the effect of Factor 3, interaction effect Factor 1 \times Factor 2, ε the error term, $i = 1\text{--}3$ levels of magnetic treatment (no-field, 360 G, 480 G), $j = 1\text{--}3$ levels of applied load (0 N, 44.5 N, 90 N), and $k = 1\text{--}7$ observations per cell.

6.2. Hypotheses tested

The null hypothesis claims that all deviations from the overall mean will be zero. This experiment tested three null hypotheses.

- Ho1: all $L_{\text{LOAD}} = 0$ against Ha1: all $L_{\text{LOAD}} \neq 0$
- Ho2: all $L_{\text{FIELD}} = 0$ against Ha2: all $L_{\text{FIELD}} \neq 0$
- Ho3: all $L_{\text{LOAD} \times \text{FIELD}} = 0$ against Ha3: all $L_{\text{LOAD} \times \text{FIELD}} \neq 0$

Contrasts, denoted by L , are comparisons involving two or more factor level means. Null hypothesis Ho1 states that all possible contrasts involving the effects of the load will equal zero, i.e., that the experiment will reveal no effects of load on the measured hardness. Similarly, null hypothesis Ho2 implies that the experiment will reveal no effects of the magnetic treatment on the measured hardness. Null hypothesis Ho3 describes the interaction effect and states that there will be no measured effect as a result of the combined influence of magnetic field and applied load.

These hypotheses were tested using a significance level of $\alpha = 0.05$ which is the probability of a Type I error (or false positive). That is, a null hypothesis was rejected only if the results provide 95% confidence that there is a measured effect. The two-way factorial analysis of variance (ANOVA) uses an F statistic to determine whether to reject the null hypothesis and this approach was adopted. The F distribution is commonly used as the null distribution of a test statistic in analysis of variance tests, e.g., Filliben [36].

7. Analysis and findings

The total experiment consisted of nine levels with seven specimens per level and 10 measurements per specimen for a total of 630 measurements. All test runs, with or without applied field, were 42 s long. Micro-hardness measurements were with a 300 g applied load and 5 s load time. The statistical software package SPSS version 11.5 was used to perform the bulk of the analyses.

7.1. General findings

The mean values for the seven washers at each experiment level are shown in Fig. 4 and the data listed in Table 1.

It is apparent in Fig. 4 that patterns do exist in the data. When the three treatment levels with no applied magnetic field are compared, the average indentation length decreases with increasing applied load. The seven washers run under 0 N load had an average indentation length of 65.9 μm ; for washers run under 45 N load the average was 63.1 μm ; and the 90 N load the average was 62.7 μm . An increase in washer hardness with larger applied load due to strain hardening, and so a decrease in average indentation length, was expected and observed.

For constant applied load tests, all three magnetic field cases show an increase in indentation length when bearings were run in

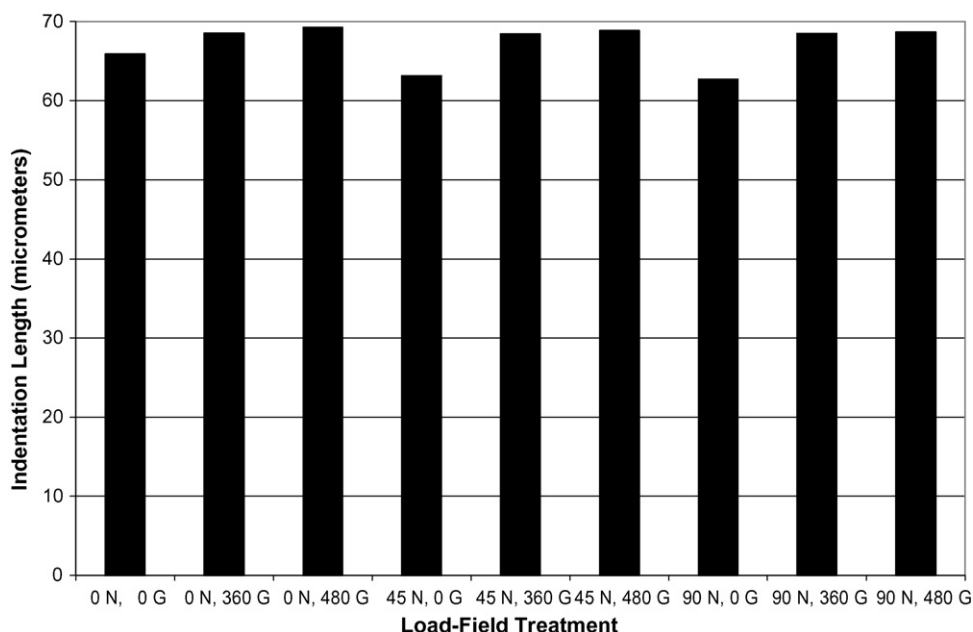


Fig. 4. Average micro-hardness test indentation lengths for thrust bearing washers at each experiment design level.

Table 1
Micro-hardness test data

Experiment level	Average washer micro-hardness indentation length (μm)							Mean
	Washer 1	Washer 2	Washer 3	Washer 4	Washer 5	Washer 6	Washer 7	
0 G field, 0 N load	66.00	65.80	66.00	65.70	66.15	65.70	65.90	65.89
360 G field, 0 N load	68.30	68.75	68.80	68.10	68.65	68.80	68.50	68.56
480 G field, 0 N load	69.15	68.85	69.00	69.60	68.85	69.95	69.20	69.23
0 G field, 45 N load	63.05	63.20	62.45	63.25	63.85	62.70	63.35	63.12
360 G field, 45 N load	67.80	68.65	68.45	67.80	68.55	68.90	68.85	68.43
480 G field, 45 N load	68.90	69.00	68.85	68.70	68.70	68.70	69.10	68.85
0 G field, 90 N load	62.35	63.45	63.05	62.20	63.05	62.60	62.25	62.71
360 G field, 90 N load	68.20	68.15	68.90	68.55	68.05	69.25	68.35	68.49
480 G field, 90 N load	69.05	68.60	68.60	68.45	68.35	68.75	69.00	68.69

the presence of a magnetic field. For example, for the 45 N load, the average indentation length increased 8.4%, from 63.1 μm with no field to 68.4 μm in the presence of the 360 G field. For the 480 G field the increase was 9.1% from 63.1 μm to 68.85 μm . This pattern is consistent for all three load levels. To further understand these results a statistical analysis was performed to quantify the significance of the findings.

7.2. Statistical analysis of full model and significance of effects

To determine the significance of each of the effects in the mixed model, SPSS was used to calculate F statistics for a univariate general linear model with two fixed effects (LOAD and FIELD) and one random effect (WASHER). To determine significance the F statistics were compared to a critical F value using the F distribution.

F statistics are typically calculated by dividing the mean square of a treatment effect by the mean square of error. The mean square (MS) of a treatment is an estimate of the variance in the grand population mean that results from the treatment effect. For the mixed model, the random factor must be considered and the mean square error term in the typical F test is replaced by the mean square interaction term containing the random effect. For example, the F test for load is performed using the mean square description of the load effect and the random LOAD \times WASHER effect and is

$$F_{\text{LOAD}} = \frac{MS_{\text{LOAD}}}{MS_{\text{LOAD} \times \text{WASHER}}} \quad (3)$$

Table 2
SPSS mixed model analysis output

Source	Sum of squares	d.f.	Mean square	F	p -Value
Intercept	2837122.232	1	2837122.232	2364789.865	0.000
FIELD	3244.886	2	1622.443	720.853	0.000
LOAD	197.550	2	98.775	107.159	0.000
WASHER	7.198	6	1.200	0.588	0.733
FIELD \times LOAD	233.907	4	58.477	51.727	0.000
FIELD \times WASHER	27.009	12	2.251	1.991	0.073
LOAD \times WASHER	11.061	12	.922	0.815	0.634
FIELD \times LOAD \times WASHER	27.132	24	1.130	0.633	0.912

In practice significance is assessed by comparing the calculated F value to a critical F value using the p -value which is the ratio of the F statistic to the experiment significance set in the experiment formulation. In this study the experiment significance level was set at $\alpha = 0.05$. Therefore, a significant F test will have

$$p\text{-value} < 0.05 \quad (4)$$

If the F statistic (ratio of MS treatment to MS error) is large enough, it suggests that the variance due to the treatment effect cannot be explained by simple error, the null hypothesis can be rejected and the effect is significant. The results of the significance analysis describing the relationships between LOAD, FIELD, and WASHER are presented in Table 2.

Sum of squares provides a measure of variance for the experiment sample and is computed by summing the squared deviations of each observation from the sample mean. d.f. refers to the degrees of freedom and it characterizes the number of independent pieces of information contained in a statistic.

For WASHER, the calculated F value is 0.588 with a p -value (significance) of 0.733. Since the p -value is much greater than the experiment significance level of $\alpha = 0.05$, the null hypothesis must be accepted, meaning that WASHER did not produce a main effect, i.e., did not influence indentation length.

The interaction effects FIELD \times WASHER, LOAD \times WASHER, and FIELD \times LOAD \times WASHER have p -values of 0.073, 0.634, and 0.912, respectively. Each of these is greater than $\alpha = 0.05$. Since all of the effects that contain the WASHER independent variable were found to be insignificant,

the WASHER effect can be safely removed from the full model. The reduced model is the two-factor fixed effects model which includes applied load, applied magnetic field, and the interaction effect, Eq. (2). It is used in subsequent analyses.

FIELD, LOAD, and FIELD × LOAD listed in Table 2 all have *p*-values of 0.00 providing strong evidence that each of these effects is significant.

7.3. Size of significant effects

To estimate the size of the significant effects the $\hat{\omega}^2$ statistic, also known as effect size, was used, e.g., Kirk [34]. The effect size is an estimate of the percentage of total variation in the dependent variable caused by a given effect. For example, $\hat{\omega}^2_{LOAD}$ is the portion of total variation in indentation length as a result of the effect of applied load. It is

$$\hat{\omega}^2_{LOAD} = \frac{SS_{LOAD} - (a - 1)MS_{LOAD \times WASHER}}{SS_{TOTAL} + MS_{LOAD \times WASHER}} \quad (5)$$

SS_{LOAD} is the sum of squares for the load effect, $MS_{LOAD \times WASHER}$ is the mean square for the LOAD × WASHER interaction effect, SS_{TOTAL} is the sum of squares for the total model, *a* is the number of levels of the load effect (3 for 0 N, 45 N, and 90 N) and *b* is the number of levels of magnetic field effect (3 for 0 G, 360 G, and 480 G). Using the results in Table 2 gives the effect sizes listed in Table 3.

The estimate of the applied load effect is 0.052 implying that 5.2% of the observed variation in the indentation length is due to the applied load. The applied magnetic field was responsible for 86% of the observed variation in indentation length and the interaction effect was responsible for 6.1%. While all effects proved to be significant, the large value of the estimate of effect size for the applied magnetic field variable provides additional support for the claim that an applied pulsed magnetic field does affect washer hardness.

As stated above, the model and analysis assume normality and homogeneity of the residuals. To validate the normality assumption a quantile–quantile (Q–Q) plot of the residuals was generated, e.g., Filliben [36]. The Q–Q plot, Fig. 5, shows the expected normal values of the residuals versus the observed values. The plotted residuals fall on the 45° line indicating that the normality assumption is satisfied.

Levene’s test for homogeneity tests the null hypothesis that the error variance of the dependent variable is equal across groups and so specifies homogeneity if the assumption for equal variances is valid. Based on a given variable with a given sam-

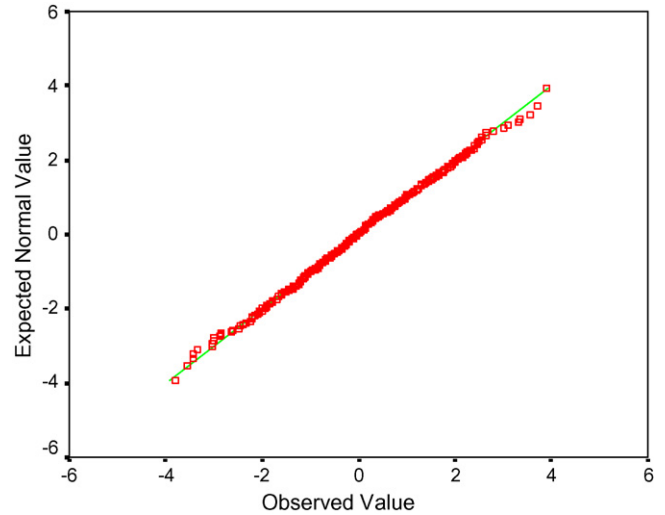


Fig. 5. Q–Q plot showing expected values of residuals vs. observed values.

Table 4
Test of equality of error variances

<i>F</i>	1.144
d.f.1	62
d.f.2	567
<i>p</i> -Value	0.219

ple size, the test calculates an *F* statistic. The null hypothesis is rejected if the statistic is significant as denoted by the *p*-value.

Results from the SPSS Levene’s test function are shown in Table 4. In the determination of the *p*-value the degrees of freedom for the numerator (d.f.1) is equal to one less than the number of subgroups (63 – 1 = 62). The degrees of freedom for the denominator (d.f.2) is equal to the number of total observations minus the number of subgroups (630 – 63 = 567).

The *p*-value or significance from the Levene’s test is 0.219 and therefore the null hypothesis cannot be rejected supporting the assumption of equal variances across samples and justifying the model homogeneity assumption.

7.4. Interpretation of results

With apparently significant main effects and interaction effect, each effect can be evaluated separately both to assure that the results are not confounded and to specify final results. Variables are considered to be confounded when the effect of each variable cannot be distinguished from any other, i.e., when

Table 3
Effect size

$\hat{\omega}^2$	Value
$\hat{\omega}^2_{LOAD} = \frac{SS_{LOAD} - (a - 1)MS_{LOAD \times WASHER}}{SS_{TOTAL} + MS_{LOAD \times WASHER}}$	0.052 = 5.2%
$\hat{\omega}^2_{FIELD} = \frac{SS_{FIELD} - (b - 1)MS_{FIELD \times WASHER}}{SS_{TOTAL} + MS_{FIELD \times WASHER}}$	0.860 = 86%
$\hat{\omega}^2_{LOAD \times FIELD} = \frac{SS_{LOAD \times FIELD} - (a - 1)(b - 1)MS_{LOAD \times FIELD \times WASHER}}{SS_{TOTAL} + MS_{LOAD \times FIELD \times WASHER}}$	0.061 = 6.1%

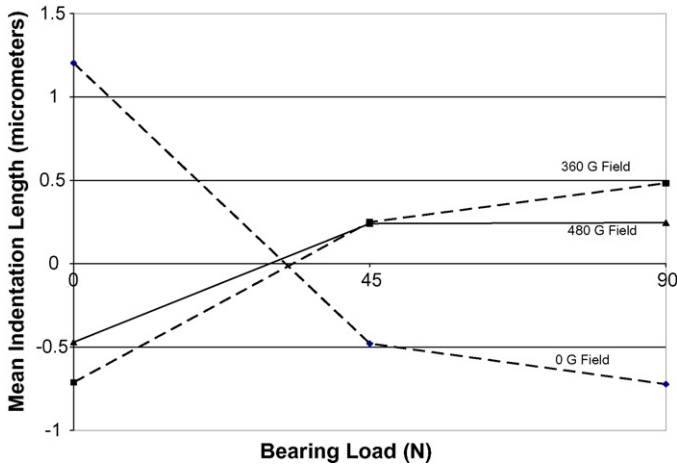


Fig. 6. Interaction effects with main effect removed.

two variables are varied simultaneously and their effects cannot be separated.

7.4.1. Interaction effect

To be certain a true LOAD–FIELD interaction effect exists, the main effects were removed and the true interaction effects plotted giving Fig. 6. The mean indentation length has been normalized as a result of removing the main effects.

Fig. 6 interaction plot shows that for no applied field, the mean indentation length decreased with applied load while, when the bearings were run in the presence of the magnetic treatment, the mean indentation length increased with applied load. This indicates that the effect of the applied load on the measured indentation length depends on the presence of an applied magnetic field.

The interaction plot also suggests that there is only a small difference between the 360 G field and the 480 G field effects. To examine this relationship a comparison of the confidence intervals was performed for the mean indentation lengths for: 45 N load with 360 G field; 45 N load with 480 G field; 90 N load with 360 G field; and 90 N load with 480 G field experiment levels.

Confidence intervals were derived for all treatment levels by first calculating the standard error for each mean by dividing

the standard deviation of each mean by the square root of the number of observations:

$$S.E. = \frac{S.D.}{\sqrt{n}} \tag{6}$$

The confidence interval for each mean for the $\alpha = 0.5$ significance level is

$$C.I. = \bar{X} \pm 1.96 \times S.E. \tag{7}$$

The confidence intervals of all nine treatment levels and are displayed in Table 5.

The 95% confidence interval for the 360 G, 45 N treatment level is {67.22, 69.64} and for the 480 G, 45 N treatment level is {67.86, 69.84}. The overlap of these confidence intervals implied that there is no significant difference in the effect of the 360 G and 480 G fields on indentation length for 45 N load. Similarly, there is overlap for the 90 N load. The confidence intervals for the 360 G, 90 N level and 480 G, 90 N level are {67.48, 69.51} and {67.63, 69.74}, respectively.

These results suggest that there is not a significant difference between the effects of the 360 G field and 480 G fields.

The 95% confidence intervals for the 0 N, 45 N, and 90 N loads with no magnetic treatment are {65.00, 66.78}, {62.10, 64.14}, and {61.76, 63.66}, respectively. These confidence intervals do not overlap with the confidence intervals of either the 360 G or the 480 G treatment levels. The conclusion is that in the presence of an applied load, a pulsed magnetic field does have an effect on washer hardness. However, there is not a significant difference in effect between the 360 G and 480 G magnetic fields.

7.4.2. Magnetic treatment main effects

The final step of the analysis was the quantification of the effects of magnetic field in terms of micro-hardness test indentation length by comparing means from specific treatment levels and testing for significance. Four tests were performed.

In the first test, the mean indentation lengths of the 45 N load–no magnetic field group and of the 45 N load–360 G field group were compared. The difference in the mean indentation lengths for these treatment levels was 5.31 μm (8.4%). To validate this finding the statistical significance of the difference in means was evaluated. The Bonferroni multiple comparison

Table 5
Confidence intervals

Magnetic field (G)	Load (N)	Mean	S.D.	n	S.E.	95% confidence interval	
						Lower bound	Upper bound
0	0	65.89	1.204	7	0.4551	65.00	66.78
	45	63.12	1.376	7	0.5201	62.10	64.14
	90	62.71	1.284	7	0.4853	61.76	63.66
360	0	68.56	1.128	7	0.4263	67.72	69.39
	45	68.43	1.634	7	0.6176	67.22	69.64
	90	68.49	1.371	7	0.5182	67.48	69.51
480	0	69.23	1.062	7	0.4014	68.44	70.02
	45	68.85	1.331	7	0.5031	67.86	69.84
	90	68.69	1.420	7	0.5367	67.63	69.74

Table 6
Comparison of means

Test	Load (N)	Magnetic field (G)	Mean indentation length	Mean difference	Calculated <i>t</i> statistic	Significant
1	45	0	63.121	5.308	7.431	Yes
		360	68.429			
2	45	0	63.121	5.729	8.020	Yes
		480	68.85			
3	90	0	62.707	5.786	8.099	Yes
		360	68.493			
4	90	0	62.707	5.979	8.370	Yes
		480	68.686			

procedure was used to evaluate the differences for four means because the comparisons were planned a priori. The Bonferroni multiple comparison procedure performs simultaneous estimations using the Bonferroni inequality to adjust the significance level, e.g., Kutner et al. [37]. This procedure uses a standard *t* statistic that is adjusted for the Bonferroni inequality. Four comparisons were performed; therefore the significance level will be divided by four to account for the simultaneous estimations. In this case the critical *t* value = 2.50 was found in a standard *t*-distribution table for a significance level of $\alpha = 0.05/4 = 0.0125$ and degrees of freedom $(n_T + r) = (63 - 9) = 54$. n_T is the total number of specimens tested and *r* is the number of factor levels:

$$t = \frac{(\bar{x}_{\text{no field}} - \bar{x}_{360\text{G}})_{45\text{N}} - 0}{\frac{\sigma_{(\bar{x}_{\text{no field}} - \bar{x}_{360\text{G}})_{45\text{N}}}}{\sqrt{\text{MSE}((1/n_1) + (1/n_2))}}} = \frac{(\bar{x}_{\text{no field}} - \bar{x}_{360\text{G}})_{45\text{N}} - 0}{\sqrt{\text{MSE}((1/n_1) + (1/n_2))}}$$

$$= \frac{63.12 - 68.43}{\sqrt{((1.786/7) + (1.786/7))}} = -7.433 \quad (8)$$

This *t* value is clearly greater in magnitude than the critical *t* value of 2.50. MSE is the estimate for the variance of the population ($E\{\sigma^2\} = \text{MSE}$). This can be used because the assumption for homogeneity of variance was satisfied. The results of the multiple comparisons are displayed in Table 6.

In all four cases, the difference in the mean indentation length in the presence of a pulsed magnetic field is significantly higher than in the no-field condition. Although the previous analysis of the interaction effect revealed that there is not a significant difference between the effects of the 360 G field and the 480 G field, the above data provides strong support that the presence of either magnetic field does in fact influence the hardness of the thrust bearing washers.

8. Discussion

Presently the state of understanding of magnetic treatment processes is progressing primarily through experimental studies. There are some results describing possible fundamental material processes and furthering such basic understanding is needed if magnetic treatment is to be rationally and consistently developed. However, since previous research showed only small effects and some contradictory results, the research described here was experimental and intended to show the existence of

effects of pulsed magnetic treatment and to rigorously, quantitatively describe any effects.

The experimental data and statistical analyses of it strongly indicate that pulsed magnetic fields affect material mechanical properties and hence the behavior of mechanical processes. For the particular rolling contact bearings and test conditions used micro-hardness decreased by about 8% when the bearings were run in a magnetic field compared to running under no-field conditions. Statistical analyses showed that the observed increases in hardness test indentation length were statistically significant. Additionally, there was no significant evidence to discern a difference in magnetic field effect between the 360 G and the 480 G pulsed magnetic fields used in this investigation.

While, these results are limited to specific load and magnetic field characteristics, they do suggest that using magnetic fields may be an effective, inexpensive and easy technique for manufactured part treatment and tribological process control. Initial applications will probably be limited to situations in which small changes in material mechanical characteristics can have relatively larger effects on manufactured part performance or process behavior. For example, the dynamic behavior of parts with thin sections such as thin wall tubes depends critically on the mechanical state of the material and this material state can be manipulated by magnetic treatment. Also, an imposed magnetic field may be useful for controlling nonlinear processes operating near qualitative changes in behavior as in the mild-to-severe wear transition in tribological processes.

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