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Correlation of Residual Stress to Bearing Condition[1]

Abstract

To determine whether there is a correlation between residual stress and bearing condition in reworked bearings, both properly ground and abusively ground bearings were analyzed. It was concluded that properly ground bearings could be distinguished from abusively ground bearings by their high compressive surface stresses. The abusively ground bearings had both compressive and tensile stresses, but the compressive stresses in the abusively ground bearing raceways were consistently lower than in the properly ground raceways. It was also determined as a result of the analyses that residual stresses, line broadening, and the linearity of d-spacing versus $\sin^2\Psi$ plots are directly related to the grinding parameters used on the reworked bearing raceways. These factors can be used in process control as well as to aid in the selection of properly ground bearings.

Bearing rings from a high performance jet engine were used to study the effects of regrinding on residual stress. Specifically, residual stresses (strains) were measured by x-ray diffraction on properly ground and abusively ground raceways made of M50 steel to determine if x-ray diffraction stress analysis could be used as an inspection tool to separate properly ground from abusively ground bearings.

History

Engines that come to the rework facility are disassembled and the components are carefully inspected. Bearings are nondestructively examined and are checked for correct dimensional tolerances. if the bearing passes inspection, small discontinuities on the surface may be removed by grinding or honing. The grinding operation may remove up to 0.005 to 0.008 cm (0.002 to 0.003 in) of material while the honing operation may remove up to 0.0008 cm (0.0003 in).

Grinding is done on a 40 to 60 grit Norton grinding wheel with about 0.00018 cm (0.00005 in) of material removed per pass. Standard grinding practice is employed; but, because many factors affect the quality of the grinding (wheel speed, abrasive media, coolant, coolant flow, coolant temperature, feed rates, etc.) variations in the reground part may occur.[1] For this study, three sets of bearing rings (Figure 1) were used. In each set, a bearing raceway that was carefully ground under controlled conditions (good) and a bearing raceway that had been intentionally abusively ground (bad) were supplied.

Measurements

The TEC Model 1610 Portable Stress Analysis System which uses the $\sin^2\Psi$ (multiple tilt) technique was used in performing these measurements. Both positive and negative Ψ angles were used to check for shear stresses in the raceways.[2] Measurements were first made on the surface at the point where the rolling elements contact the inner ring raceways. Residual stresses at various depths into the surface of one good inner ring raceway were then measured using standard depth profiling techniques. A chemical etchant, Tarasov's etch,* was used, not only to remove the surface layers, but also to show the areas of martensite versus over-tempered martensite. This etchant was also used on the bad bearing for the latter reason. Previous work performed by S.W. Shin and G.H. Walter[3] used this etchant on bearing rings to show clearly the areas

* 4% nitric acid in water for 15 seconds, hot water rinse, 4% hydrochloric acid in acetone for 15 seconds

[1] Reprinted from *Residual Stress in Design, Process, and Materials Selection*, 1988. Edited by William B. Young. Published by ASM International.

of grinding burn. They estimated that this etchant removed less than 0.003 cm (0.001 in) of material for every fifteen-second etch cycle. The geometry of the inner ring raceways (Figure 2) made it impractical to determine the amount of material removed.

The abusively ground (burned) raceways had periodic axial stains that were assumed to be related to areas of martensite alternated with areas of over-tempered martensite. A very small collimated beam was used to measure the stresses associated with each area. After completing the surface measurements, one of the burned raceways was etched to reveal the over-tempered martensite. A thin, light-colored circumferential strip at the bearing contact surface was accentuated by the etchant. Axial striations similar to the stains found before etching were visible within the circumferential strip.

The good rings exhibited uniform metallic coloration. Measurements were made on the surface of each good raceway, and then one of these raceways was selected for etching and depth profiling. The Tarasov's etch uniformly blackened the raceway surface in contrast to the light and dark regions found on the burned raceway.

Additional measurements were made on the mating surface between the split inner ring sections of the burned bearing to compare this surface with the raceway. This flat surface could be measured to help determine if the complex geometry of the raceway affected the d-spacing versus $\sin^2\Psi$ plots.

Results and Discussion

Surface stresses in the raceways of the inner rings from the good bearings were more compressive than those from the bad bearings. Results of the x-ray diffraction stress analysis are given in Table 1 and Figure 3. For one set of bearings, the good bearing had uniform compressive stresses in both the axial and circumferential directions, -774 to -887 MPa (-112 to -129 ksi). The bad bearing inner ring raceway of this set had all tensile stresses +476 to +777 MPa (+69 to +113 ksi). In the second set of bearings, stresses in the bad bearing inner ring raceway ranged from +30 to -461 MPa (+4 to -67 ksi), while those in the good bearing of the same set were -982 to -1172 MPa (-142 to -170 ksi). Similarly, in the third set of bearings, stresses in the bad bearing were -299 and +292 MPa (-43 and +42 ksi) compared to -966 and -1044 MPa (-140 and -152 ksi) for the good raceway. The compressive stress in the bad ring was measured near the edge of the raceway.

A consistent result seen when comparing the inner ring raceways of the properly ground bearings to the abusively ground bearings was the difference in the diffraction peak full width at half the maximum intensity (FWHM). The FWHM is an indication of the amount of cold working in the surface of the material.[4] From these measurements, the FWHM was consistently lower (less cold working) in the properly ground bearings than in the abusively ground bearings. The FWHM ranged from 4.6 to 4.8° 2Θ for the good bearings and from 5.1 to 5.8° 2Θ for the bad bearings, indicating a higher amount of cold working in the abusively ground bearings.

Another noticeable difference between the measurements made on the good and bad inner ring raceways was the d-spacing versus $\sin^2\Psi$ plots. The plots for the good bearings were generally linear (Figure 4) while those for the bad bearings were nonlinear (Figures 5 and 6). The nonlinearity may be a result of measuring microstresses (short range stresses) rather than macrostresses (long range stresses). It is speculated that the abusive grinding process contributes to the nonlinearity of these plots.

Stress measurements made after etching differed from the surface measurements. Recall that only the first set of bearings was etched with the Tarasov's etchant. A stress measurement made in a dark axial striation in the light-colored circumferential strip of the bad raceway was -41 MPa (-6 ksi). This was the only compressive stress found in the inner ring raceway of this bearing with one exception. Measurements on the mating surface between the split inner ring sections were -1096, -1158, and -1227 MPa (-159, -168, and -178 ksi), suggesting that this surface was not representative of the raceway. Stresses in the light-colored etched areas, +372 and +510 MPa (+54 and +74 ksi), were similar to the surface stresses.

The stresses on the surface of the good bearing were consistently compressive, but this was not the case for the subsurface measurements. Etching with the Tarasov etchant for an unknown time (less than one minute) quickly discolored the surface and resulted in very low stresses, -69 to +28 MPa (-10 to +4 ksi). Considering that the etchant should only remove about 0.003 cm (0.001 in) of material, it was questioned that a stress gradient of this magnitude existed. The stress was then measured on the surface adjacent to the etched area. Once again the surface stress was compressive, -786 MPa (-114 ksi).

A series of etchings followed by stress measurements were performed in this adjacent area. This time the etching procedure was carefully controlled to insure that the etching time did not exceed ten seconds per etch. This procedure resulted in a linear decrease in the compressive stress measured for the first five etching cycles (Figure 7). The etching procedure was repeated a total of seven times until the stresses were -159 to -172 MPa (-23 to -25 ksi). A one-minute etch at a separate location resulted in a low stress of +28 MPa (+4 ksi). These results led to speculation that the etchant, at dwell times greater than ten seconds, may preferentially dissolve portions of the grain boundaries around the surface grains. The areas that had been etched longer than ten seconds at a time had a rougher texture than the other etched areas and lends credibility to this speculation. If portions of the grain boundaries were dissolved by the etchant, then the surface was left artificially stress free since the connective material necessary to support stresses was removed. Additionally, if high stress gradients really existed, then curved d-spacing versus $\sin^2$ psi plots of the unetched surface would be expected.[5] The d-spacing versus $\sin^2\Psi$ plots were linear for the unetched measurements.

A section (less than one inch) of the good bearing inner ring from the first set of bearings tested was removed for scanning electron microscopy (SEM) of the etched and unetched surfaces. The intent of this investigation was to determine if the etchant had preferentially attacked the grain boundaries resulting in an artificially induced stress-free surface. The bearing raceway geometry made the examination difficult. The 700X photographs (Figure 9) are clear enough to show that the etching did not occur only at grain boundaries. It was not possible to estimate the amount of material removed by etching. Based on the SEM and the ten-second etching cycles, it is assumed that stress gradients do exist in the raceway. The gradient cannot be quantified from these data since the amount of material removed could not be measured by means employed during this work.

The ten-second etching depth profiling was also performed on the mating surface of the bad bearing of the same set. Recall that the surface measurements on the area of the bad inner ring raceway were similar to the raceway measurements on the good bearing. The depth profile in Figure 8 follows the same trend as Figure 7. Again, this indicates that the split inner ring mating surface measurements cannot be used to distinguish good from bad bearings.

Data on raceways from a previous study[6] had suggested that shear stresses (indicated by $\sin^2\Psi$ splits) may be related to grinding burns. The current work indicates that tensile or low compressive stresses are found on the bad bearing raceways, and high compressive stresses are found on the good raceways. The d-spacing versus $\sin^2\Psi$ plots are linear or nonlinear and do not exhibit the $\sin^2\Psi$ split associated with shear stresses. The collimated x-ray beam was smaller for the current study. It was concluded that geometric effects from a large collimated x-ray beam and not shear stresses resulted in the $\sin^2\Psi$ splits seen in the previous work.

Conclusions

Abusively ground bearings can be distinguished from properly ground bearings by measuring the stresses on the inner ring raceways at the point of rolling element contact. The properly ground bearing raceways have high compressive stresses, linear d-spacing versus $\sin^2\Psi$ plots and a smaller FWHM. The abusively ground bearing raceways have tensile or low compressive stresses, nonlinear d-spacing versus $\sin^2\Psi$ plots and a larger FWHM. It was concluded that these differences were directly related to the increased cold working imparted to the surface during abusive grinding.

The shear stresses indicated by the $\sin^2\Psi$ splits observed during a previous study were not found on either the good or the bad bearings. Consequently, these splits were attributed to the geometric effects from the large collimator used.

High stress gradients probably exist in the surface of the inner ring raceways. The stress gradients could not be quantified; however, the stresses decreased linearly when the sample was etched under controlled conditions.

Acknowledgments

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References

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2. H. Dolle, J. Appl. Cryst. (1979), 12, pp. 489-501.
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4. Paul Prevey, Diffraction Notes, Vol. 1, No. 1, Winter 1987, Lambda Research, Inc., Cincinnati, Ohio.
5. H. Dolle, loc. cit.
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Table 1
Surface Stress on Inner Ring Raceway

Bearing	Direction	Stress, MPa	Stress, ksi	FWHM, °2θ
1st Set				
Good	Circumferential	−825.3±150.3	−119.7 ±21.8	4.6
	Circumferential	−887.3±161.3	−128.7 ±23.4	4.6
	Circumferential	−773.6 ±78.6	−112.2 ±11.4	4.8
	Axial	−808.1±119.3	−117.2 ±17.3	4.8
	Axial	−787.4 ±69.6	−114.2 ±10.1	4.7
Bad	Circumferential	+482.6±193.1	+70.0 ±28.0	5.4
	Circumferential	+777.0±223.4	+112.7 ±32.4	5.3
	Axial	+476.4±170.3	+69.1 ±24.7	5.3
	Axial	+529.5±160.6	+76.8 ±23.3	5.6
2nd Set				
Good	Circumferential	−981.8 ±62.1	−142.4 ±9.2	4.8
	Axial	−1172.1 ±84.1	−170.0 ±12.2	4.8
Bad	Circumferential	−311.0±115.8	−45.1 ±16.8	5.2
	Circumferential	−313.7±115.1	−45.5 ±16.7	5.1
	Circumferential	−268.9±126.2	−39.0 ±18.3	5.2
	Circumferential	+29.6±160.0	+4.3 ±23.2	5.7
	Circumferential	−33.8±144.1	−4.9 ±20.9	5.5
	Axial	−461.3 ±89.6	−66.9 ±13.0	5.2
	Axial	−49.0±122.7	−7.1 ±17.8	5.8
3rd Set				
Good	Circumferential	−1044.5 ±62.1	−151.5 ±9.0	4.8
	Circumferential	−965.9 ±91.0	−140.1 ±13.2*	4.8
Bad	Circumferential	+291.6±183.4	+42.3 ±26.6	5.7
	Circumferential	−299.2±115.1	−43.4 ±16.7*	5.5

*Measurement made near edge of inner ring raceway.

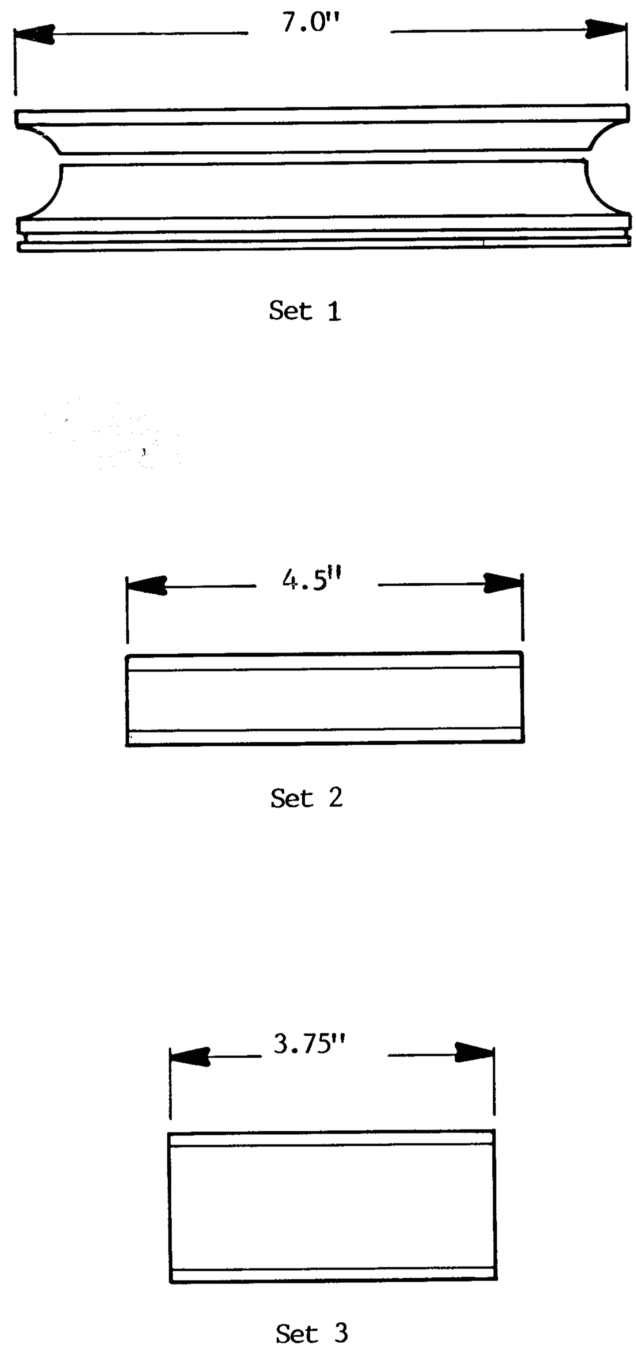

Figure 1. Drawing of Three Bearings Used for Study

Correlation of Residual Stress to Bearing Condition

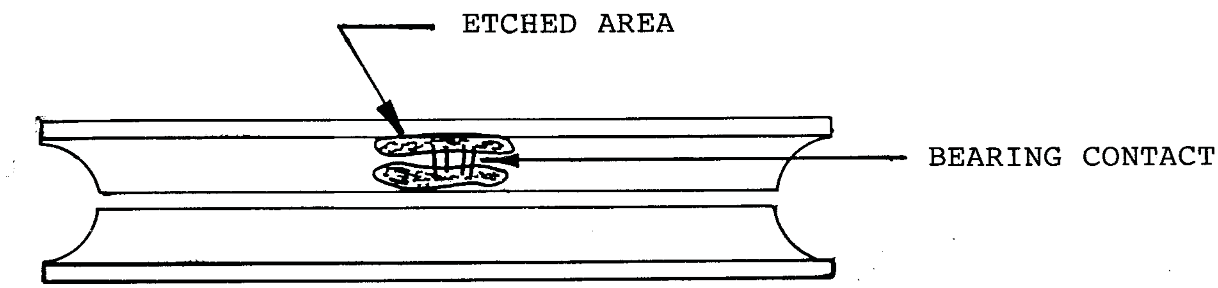

Figure 2. Geometry of the Bearing Ring Inner Raceway

Correlation of Residual Stress to Bearing Condition

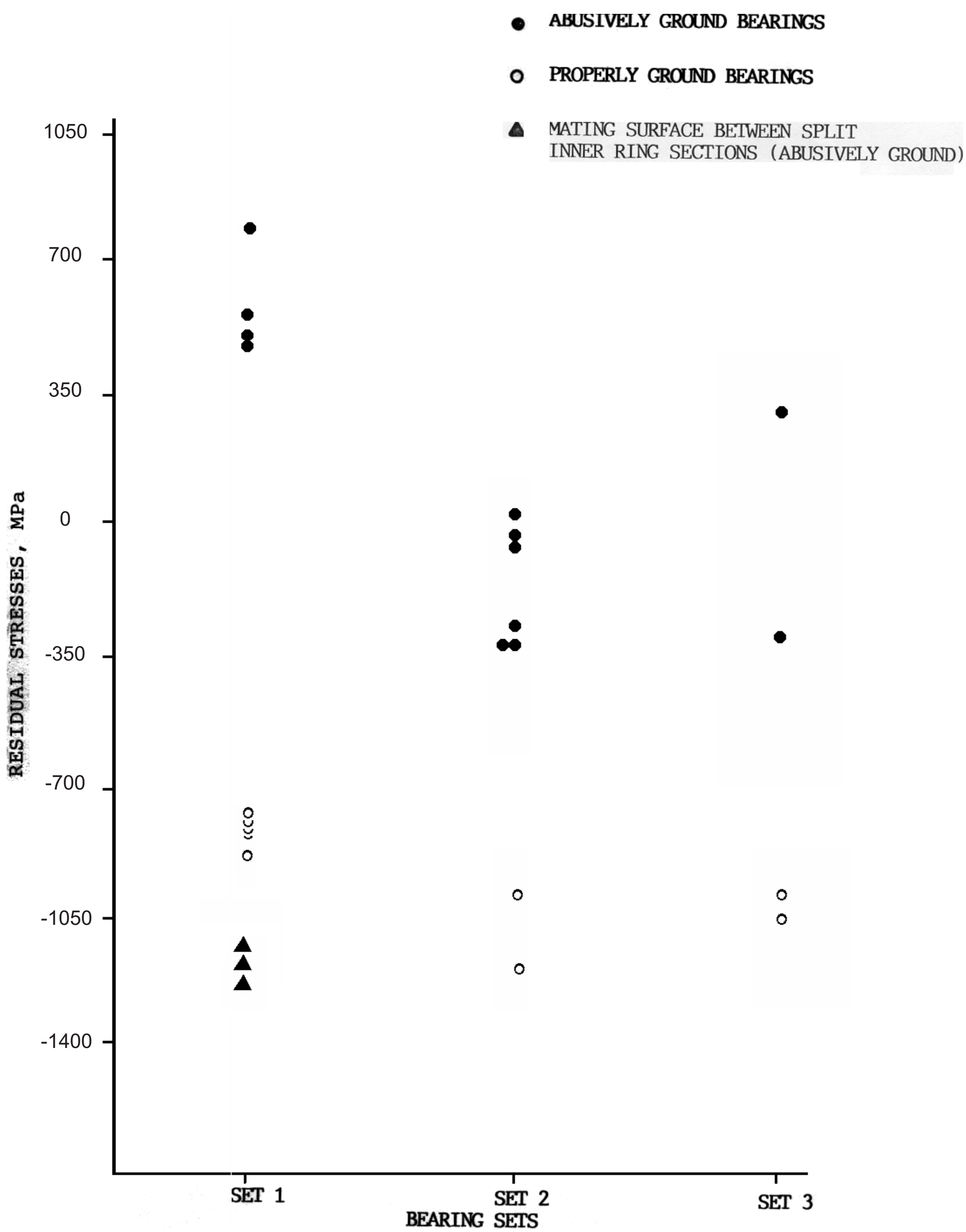

Figure 3. Results of X-Ray Diffraction Stress Analysis on Abusively and Properly Ground Bearing Raceways.

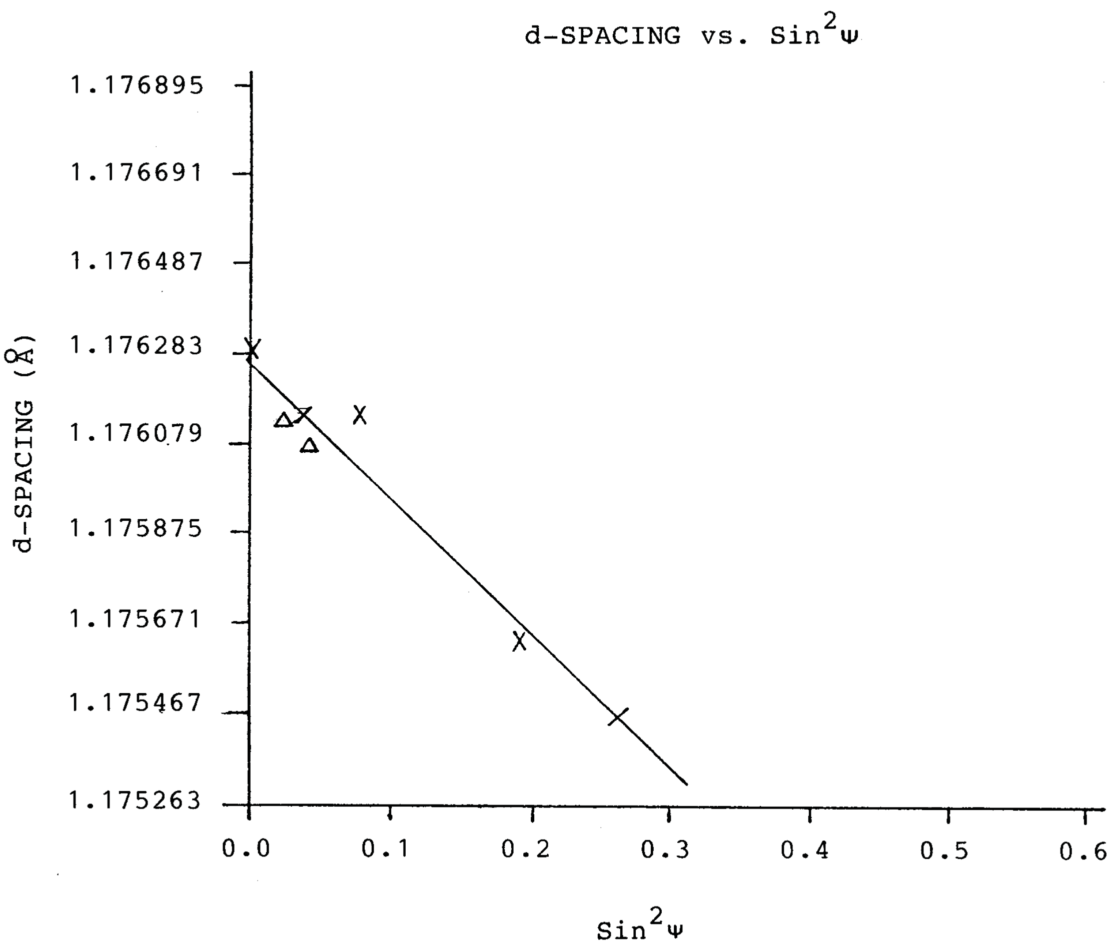

Figure 4. Linear Plot for Properly Ground Bearing.

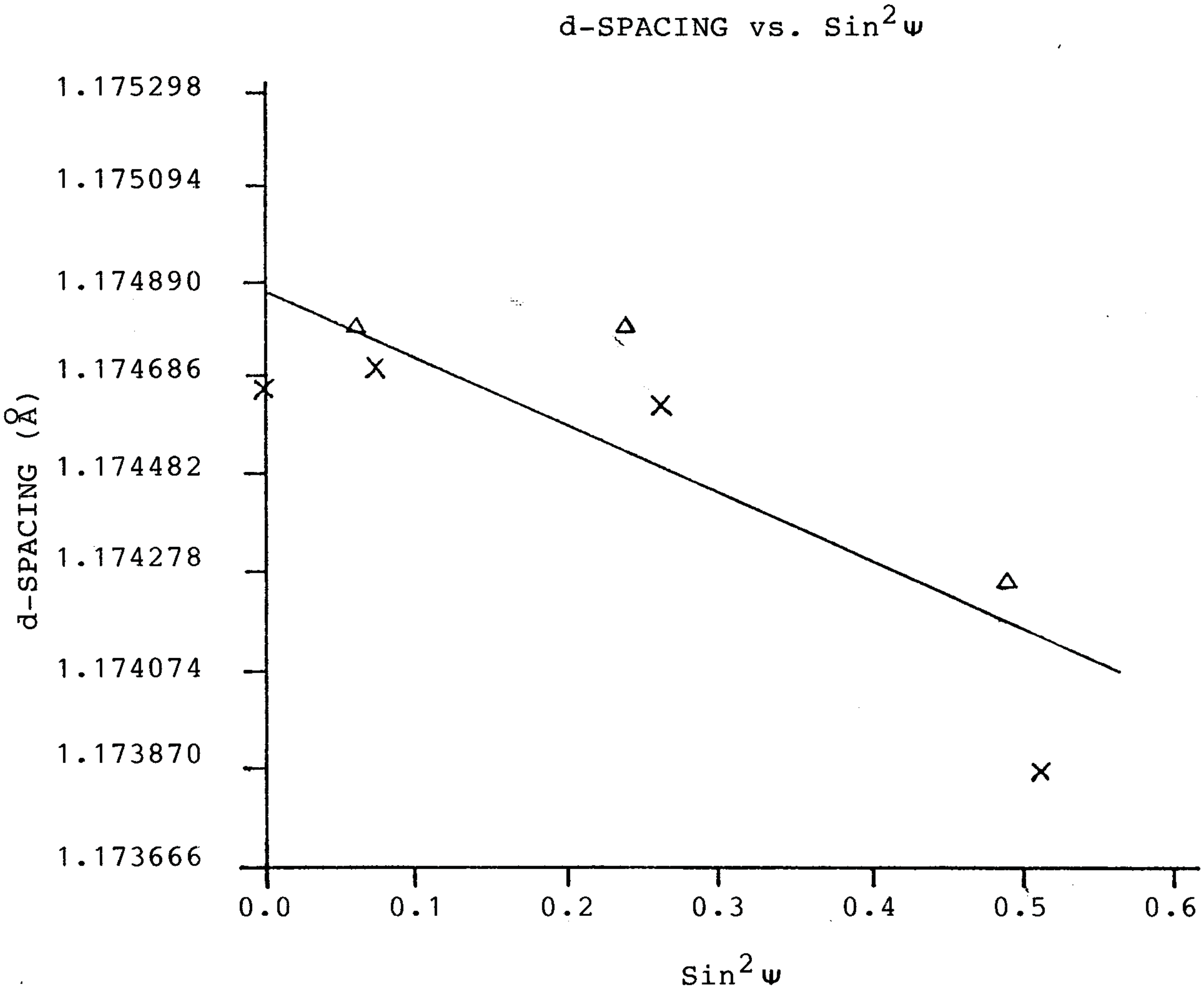

Figure 5. Nonlinear Plot for Abusively Ground Bearing (Compressive Stress).

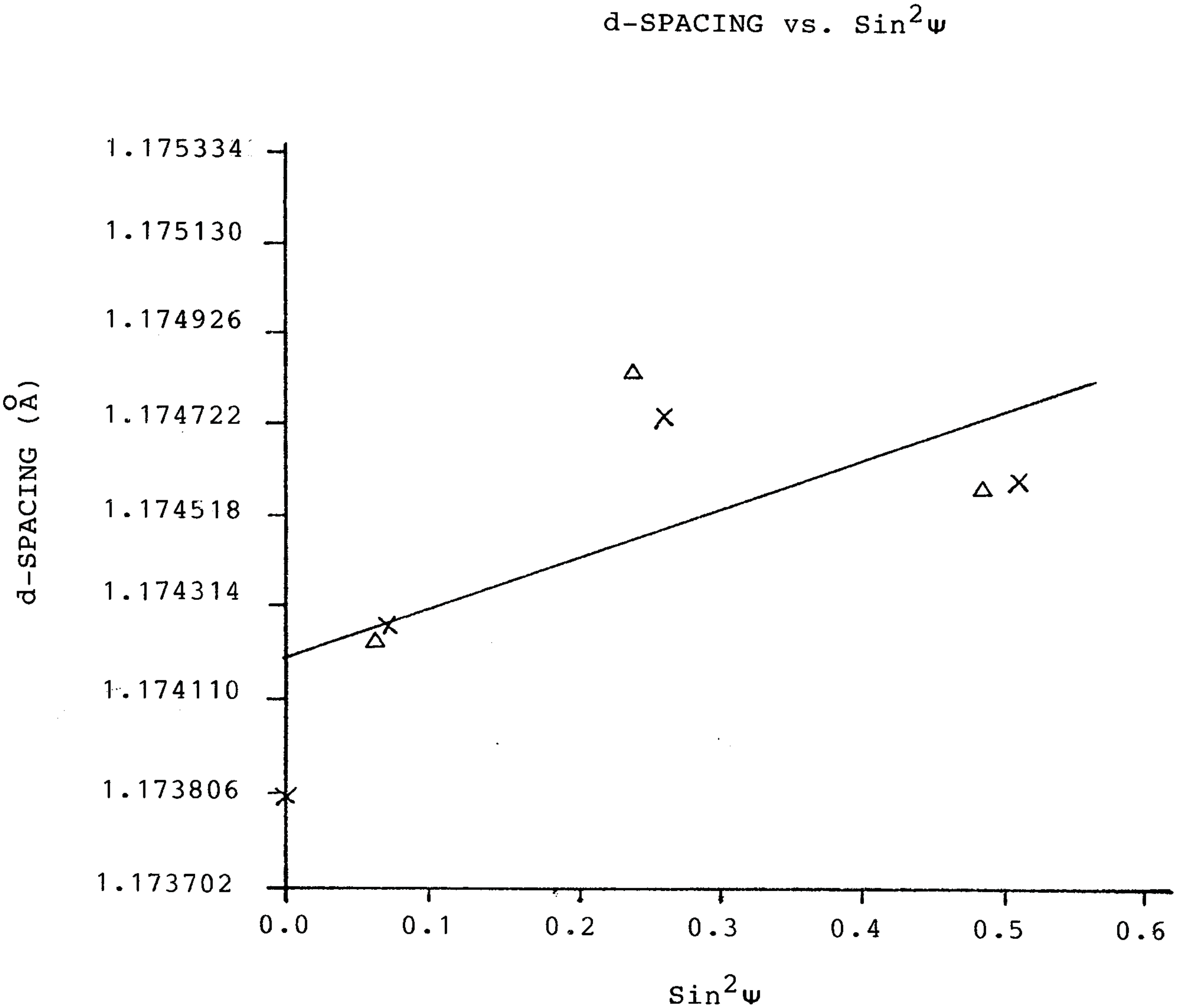

Figure 6. Nonlinear Plot for Abusively Ground Bearing (Tensile Stress).

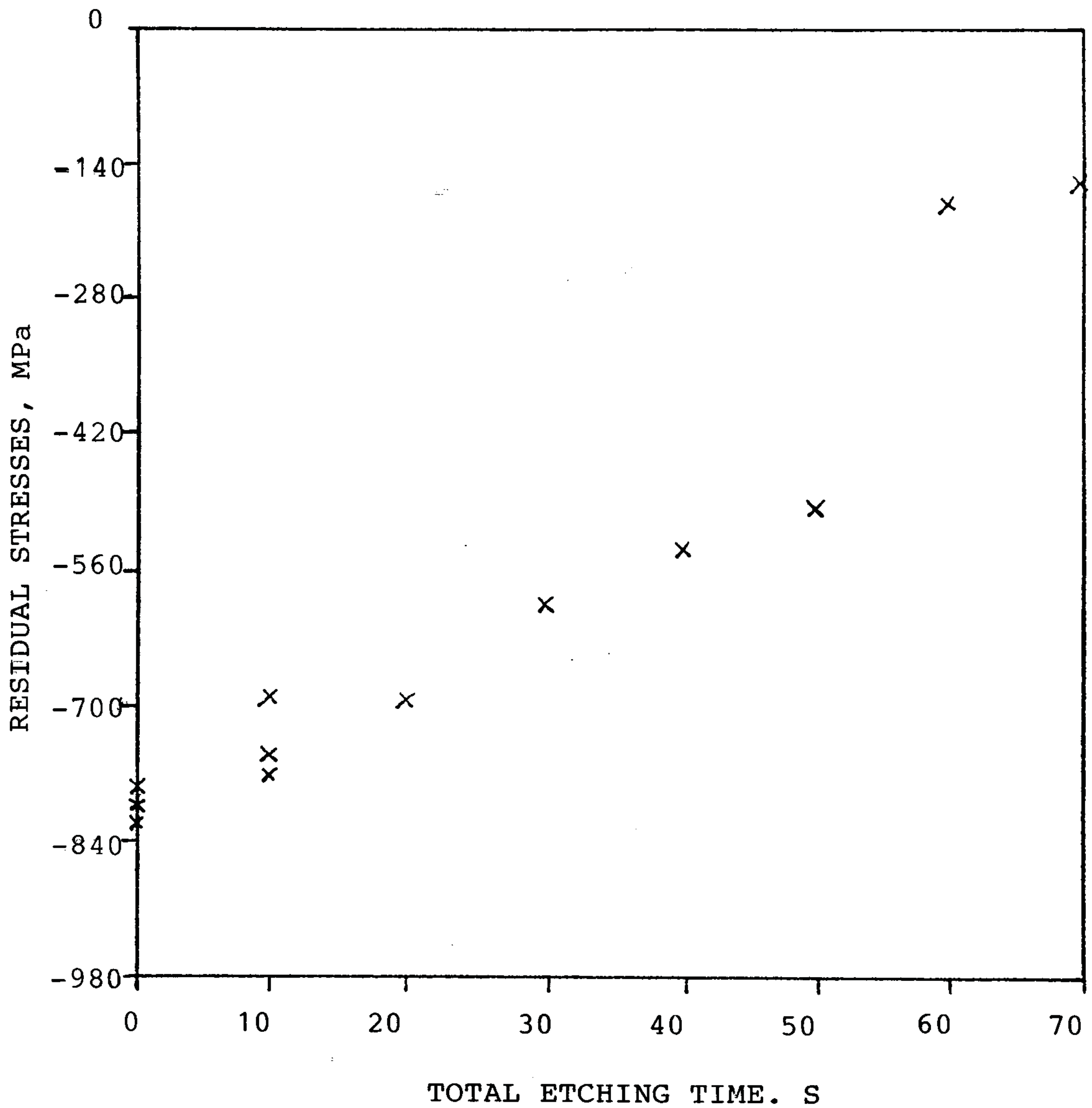

Figure 7. Residual Stress Versus Etching Time for Bearing Raceway (Good).

Correlation of Residual Stress to Bearing Condition

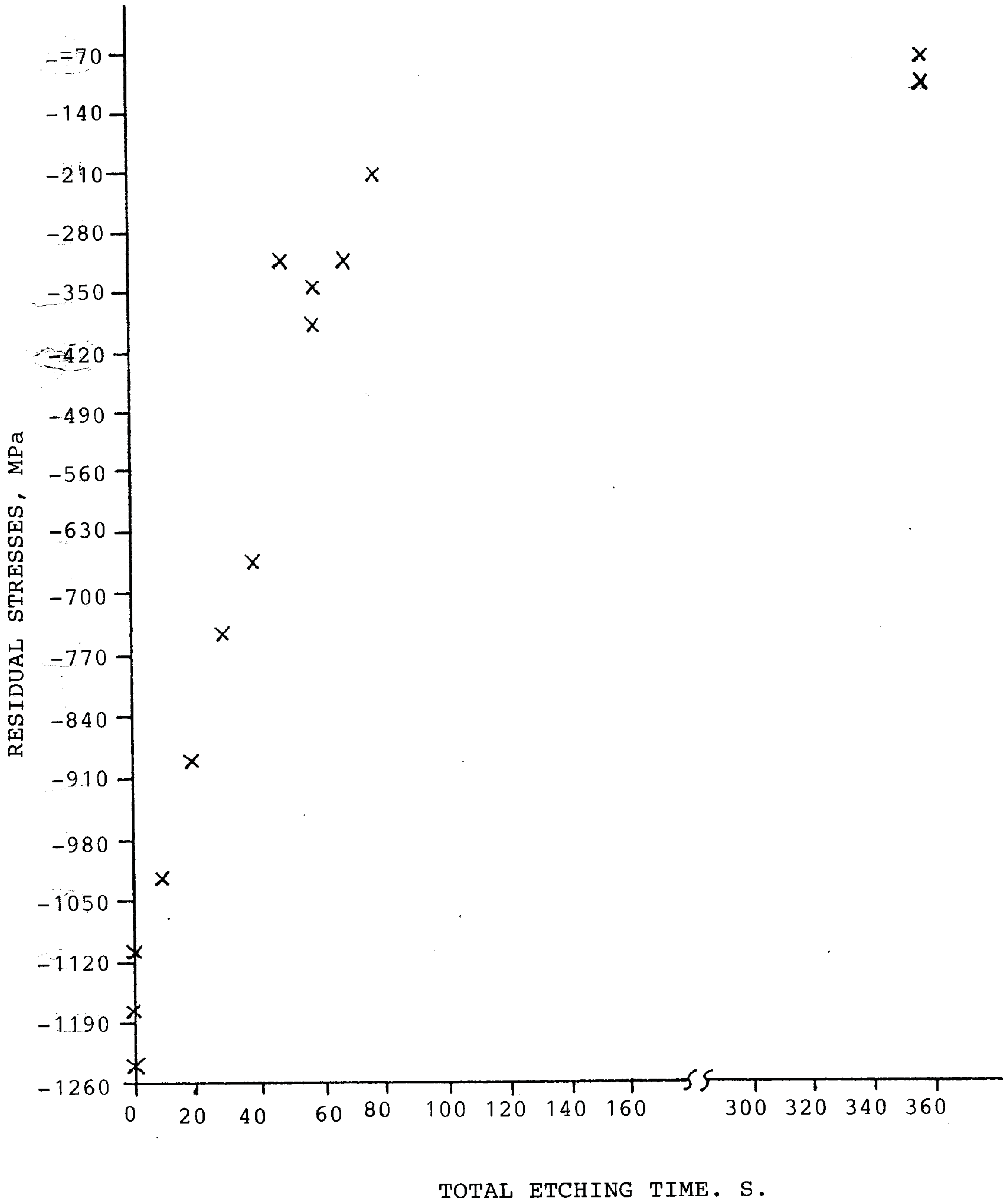

Figure 8. Residual Stress Versus Etching Time for Inner Split Ring (Bad) Mating Surface.

UNETCHED

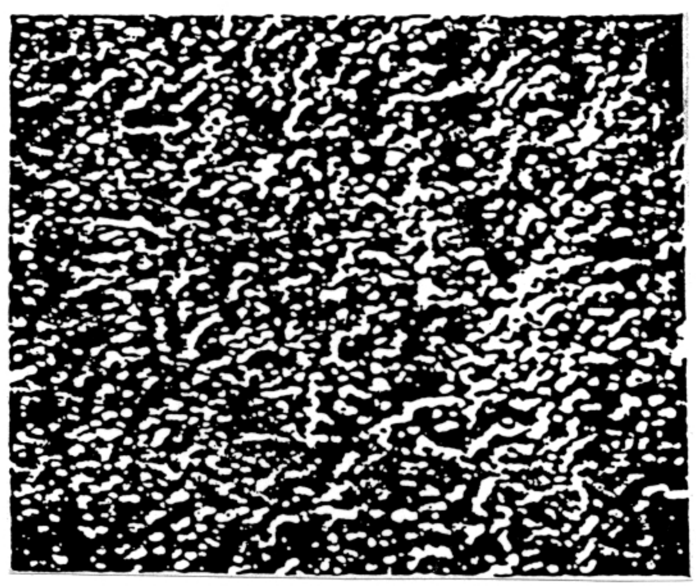

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Figure 9. Scanning Electron Microscopy Photographs of Raceway