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# Experimental study on the performance of superfinish hard turned surfaces in rolling contact☆

Salah R. Agha, C. Richard Liu*
*School of Industrial Engineering, Purdue University, 1287 Grissom Hall, West Lafayette, IN 47907-1287, USA*

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## Abstract

In this study, specimens of AISI 52100 with hardness of 62-63 Rc were hard turned using different cutting parameters. Surface roughness, residual stress, and micro-hardness were measured. The workpieces were then tested for the rolling contact fatigue life under several maximum Hertzian contact stresses. Results indicate that the choice of the cutting parameters greatly affects the surface integrity aspects of the hard turned parts and consequently, the fatigue life. For the range of experiments performed, it is found that varying the cutting parameters largely changes the fatigue life by a factor up to 40 times. The repeatability of the fatigue life of hard turned workpieces under the same loading is found to be much more consistent than that of ground workpieces. © 2000 Elsevier Science S.A. All rights reserved.

*Keywords:* Hard turning; Residual stress; Micro-hardness; Repeatability and rolling contact fatigue life

## 1. Introduction

Hard turning as a finish process has not been widely used by manufacturing industry even though it can potentially offer clear economic benefit by replacing grinding. Fig. 1 shows the benefits that can be achieved by using hard turning as an alternative [1]. The problem is thought to be related to the surface integrity as evidenced by earlier publications. It was shown that the residual stresses produced by hard turning were highly compressive, accompanied with a thin surface layer with a micro-structural change [16]. It was also shown that the tool flank wear could drastically affect the residual stress pattern [7–10,19].

The concept of using hard turning as a single step process for finishing bearing races demanded for a full understanding of the surface integrity aspects of hard turning [11]. Experimental studies showed that superior surface integrity could be obtained using selected cutting conditions [12,13]. Based on these experimental data, a residual stress model for superfinish hard turning was developed [17]. Based on this residual stress model, rolling contact fatigue lives were predicted using an analytical model. It was observed that the cutting conditions have significant effect on the fatigue life of the hard turned workpiece [15]. In the mean time, it was shown that hard turning had the capability to produce a wide range of compressive residual stresses under a broad range of cutting conditions [1,2,14]. In this paper, the effect of cutting conditions on fatigue life was studied experimentally. Within the range of the experiments, it was found that varying the cutting conditions could change the fatigue life by a factor of 40 times, consistent with the prediction found in [1,15].

## 2. Experimental details

### 2.1. Workpiece preparation and heat treatment

AISI 52100 rings of 3 cm outer diameter, 1.6 cm inner diameter and a thickness of 1.27 cm, were selected for the experimental work. The composition of AISI 52100 steel is given in Tables 1 and 2.

The workpieces were cut from the same annealed roll. Fig. 2 shows the selected workpiece. These workpieces were painted. To check for roundness, they were turned using a very small depth of cut. This procedure was repeated until the paint completely disappeared. Then, they were ground to improve perpendicualrity and parallelism. Finally, the workpieces were through hardened as follows. All parts were held at 843°C for 3 h in a 1% carbon potential atmosphere, then they were quenched in oil and kept at 60°C for 15 min. To

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☆ The concept behind this paper is covered by US Patent 5878496 [1].

* Corresponding author. Fax: +1-765-494-5448.

*E-mail addresses:* agha@ecn.purdue.edu (S.R. Agha), liuch@ecn.purdue.edu (C.R. Liu).

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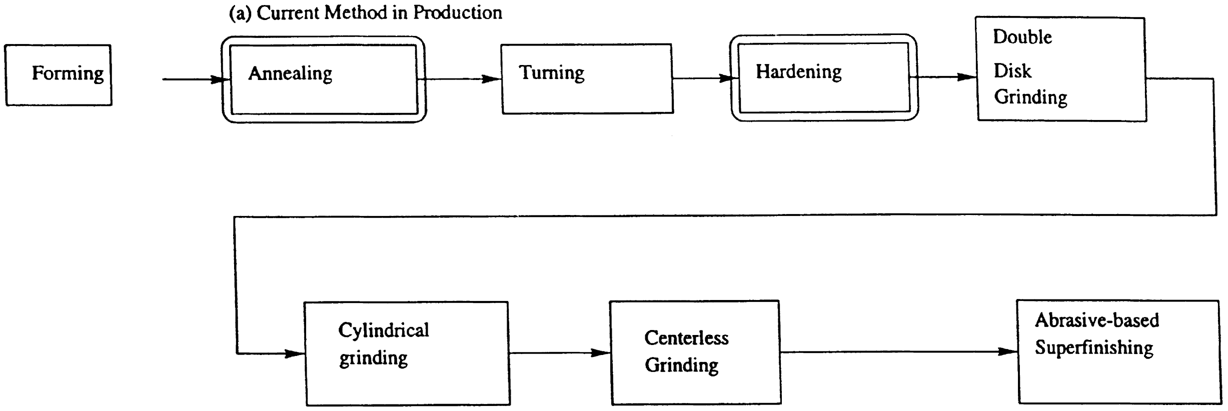
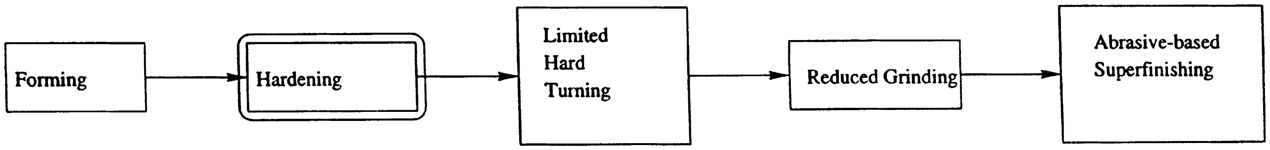
(a) Current Method in Production



(b) Advanced Method Being Pursued by Industry
(Matsumoto, Barash, Liu, 1984and others)



(c) The proposed Method Will Enable This major Improvement (Liu, 90; Liu and Mittal, 92,95]

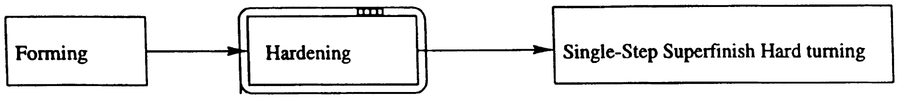


Fig. 1. Evolution of superfinish hard turning for producing bearing races, gear, cams, etc.

Table 1
Composition (%) of workpiece material

| Specimens | C | Mn | $P_{max}$ | $S_{max}$ | $Si_{max}$ | Cr |
|---|---|---|---|---|---|---|
| AISI 52100 | 0.98–1.1 | 0.25–0.4 | 0.025 | 0.025 | 0.15–0.3 | 1.3–1.6 |

reduce brittlness and residual stress, and increase ductility and toughness, tempering was performed at 173°C for 1.5 h, then the workpieces were cooled to room temperature. The hardness of each specimen was checked, and only the specimens with hardness of 62-63 RC were accepted.

## 2.2. Machining setup

| | |
|---|---|
| Type of cut | facing |
| Workpiece | AISI 52100 through-hardened steel (62-63 RC) |
| Machine tool | Cinturn 8 u-40, series 1208 (by Cincinnati Milacron) |
| Tool material | BZN 8100 (by GE Super-abrasives) |
| Cutting tool geometry | BRNG-42, round tool with 1.27 cm diameter, 0.318 cm thickness, lead angle=90°, clearance angle=0° |
| Coolant | none |

## 2.3. Surface roughness, residual stresses and micro-hardness

Surface roughness of the workpieces was measured using the Talysurf. Three parameters were used to measure the surface roughness. These parameters include $R_a$, (the arithmetic average), $R_t$, (maximum peak-to-valley) and $R_q$ (root-mean-square). Measurements of the surface roughness were taken in a direction parallel to the feed direction. As

Table 2
Properties of the workpiece material

| Young’s modulus (MPa) | Yield strength (MPa) | Thermal expansion coefficient (°F) | Thermal condition (BTU(ft.F/m)) | Specific heat (BTU/Lb.F) |
|---|---|---|---|---|
| 205 620 | 1725 | 7.6e−6 | 0.58 | 109.5 |

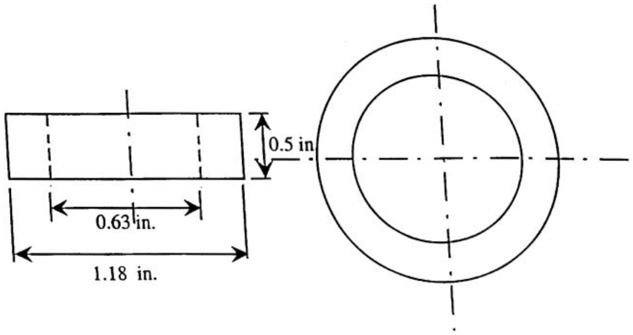


Fig. 2. Dimensions of the specimen used for experinentation.

many as six readings were taken along randomly selected lines of the produced surface. The cut-off length used for measuring the surface roughness was selected as 0.762 mm according to the cut-off length that is, normally used to evaluate the surface roughness of bearing surfaces. For the sake of brevity, only $R_a$ values are given in this paper. Residual stress measurements were performed using the X-ray diffraction method. The $\sin^2\psi$ method was used [18]. Four $\psi$ angles were used for calculating the residual stresses in both feed and cutting directions. Fig. 3 shows the cutting configuration and the directions along which the residual stress was measured. Results of residual stresses measurements on three workpieces for each of the cutting conditions used in this study were averaged. In addition to surface roughness and residual stresses, micro-hardness distributions produced by the different cutting conditions were measured using the Knoop indenter a load of 200 g. About 4–6 readings were taken along the same depth and the average was taken to plot the results given in this study.

### 2.4. Test rig and fatigue testing

A simple test rig was designed for rolling contact fatigue testing. These tests were run at a shaft speed of 1840 rpm with different axial loads that produced maximum Hertzian stresses ranging from 2815 to 5686 MPa. Grade 25 balls of 0.397 cm diameter were used in testing. The lubricant used in the test was SAE-30 circulating through a 10 μm filtered-pump feed system at a rate of 56.8 cm$^3$/min. The rolling contact fatigue tests were automatically stopped, once a certain level of vibration is exceeded, using an accelerometer that is attached to the housing of the test rig and connected to a vibration monitor. The vibration level was kept fixed for all the experiments to enable comparison between fatigue lives for different conditions. The balls and retainer were replaced after each test. The diameters of the balls were checked using the zygo-laser bench. Care was taken in the assembly and disassembly of the test rig so that results might not be invalidated. The test rig was thoroughly cleaned by flooding it with pressured lubricant and then dried using pressured air after each test. Fig. 4 shows a schematic of the designed test rig. The experiments were run in a controlled-room temperature that was kept at 25°C. The axial run out was about 1.27 mm. Finally, the film thickness parameter was calculated to be around 4.5 [6].

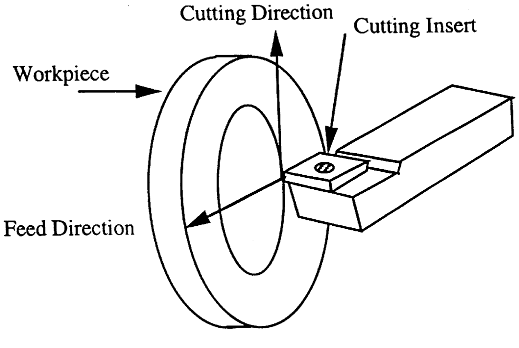


Fig. 3. Cutting configuration.

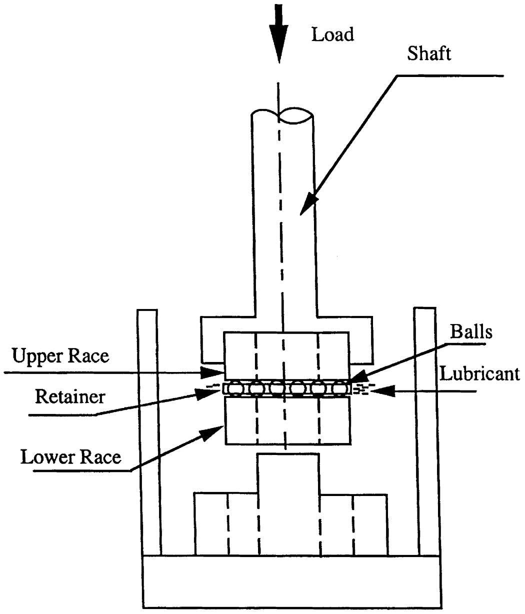


Fig. 4. Schematic of the test rig.

## 3. Experimental results and discussion

### 3.1. Residual stresses and micro-hardness

Since the cutting tool is progressively worn out in production and due to the impracticality of having a sharp tool all the time when cutting, several conditions were developed so that the effect of flank wear on rolling contact fatigue life might be studied. From Table 3, it is seen that the surface roughness produced by these different cutting conditions is very close so its effect on the rolling contact fatigue is the same when comparing the lives under different conditions.

Fig. 5 shows the residual stress distribution in both cutting and feed directions as produced by one cutting condi-

Table 3
Cutting conditions and surface roughness

| Condition | Speed (m/min) | Feed rate (mm/r) | Depth of cut (mm) | Flank wear (mm) | Surface roughness $R_\mathrm{a}$ (μm) | Surface roughness stress in cutting direction (MPa) | Surface roughness stress in feed direction (MPa) |
|---|---|---|---|---|---|---|---|
| 03sL | 106.7 | 0.051 | 0.762 | Sharp | 0.15 | −312.57 | 74.8 |
| 01sL | 106.7 | 0.051 | 0.254 | Sharp | 0.15 | −800.4 | −121.45 |
| 0104L | 106.7 | 0.051 | 0.254 | 0.4 | 0.1875 | 56.58 | 451.26 |
| 0107L | 106.7 | 0.051 | 0.254 | 0.7 | 0.2 | −92.46 | 367.77 |
| 0304L | 106.7 | 0.051 | 0.762 | 0.4 | 0.1875 | −32.43 | 247.71 |

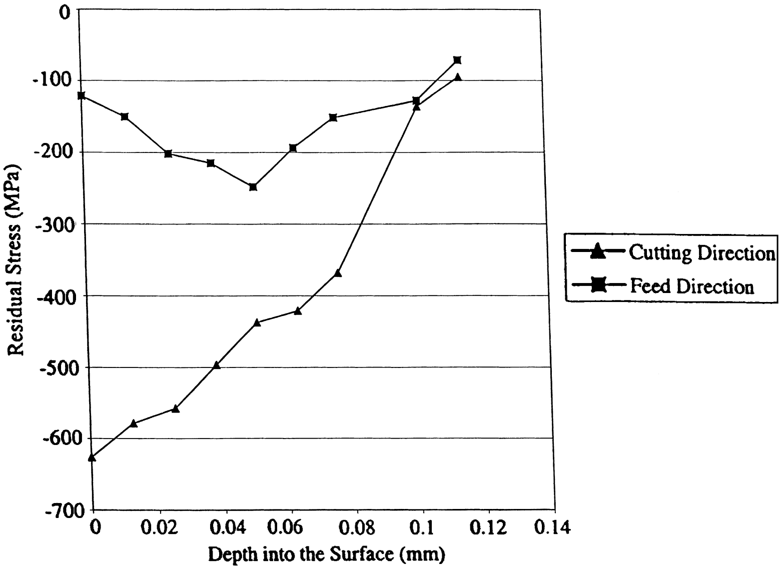


Fig. 5. Residual stress distribution.

tion. This cutting condition is where a sharp tool was used. As expected for this cutting condition, the residual stress is compressive in both directions. As for the other conditions, where a worn tool was used, the residual stress was tensile in the feed direction as seen from Figs. 6 and 7. Moreover, it is noticed from these figures that for the large flank wear, the residual stress penetrates deeper into the work piece as compared with that produced using a sharp tool. This is

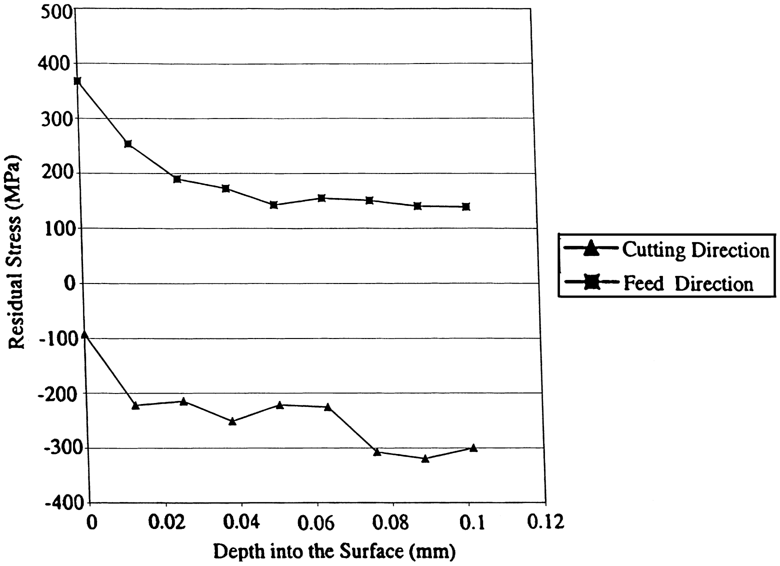


Fig. 6. Residual stress distribution.

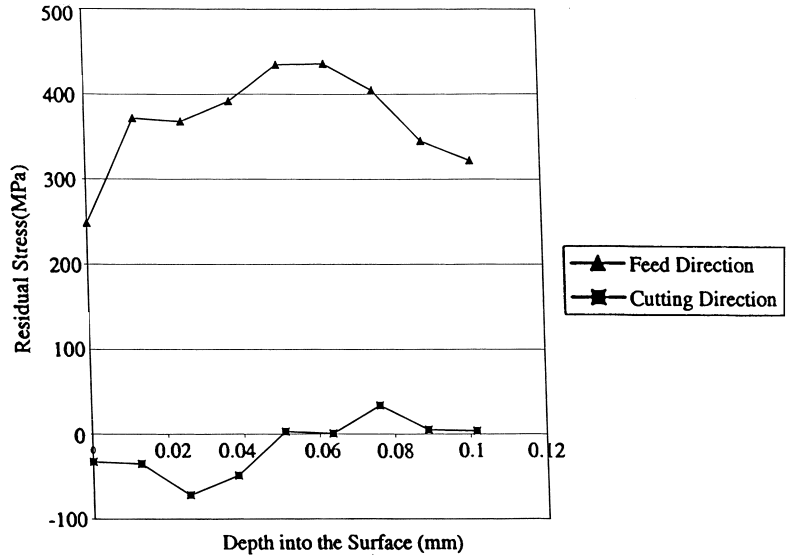


Fig. 7. Residual stress distribution.

consistent with the findings of [1,8,10]. Examples of the micro-hardness distributions produced by some cutting conditions are given in Figs. 8–10. It is clear that the standard deviation of the measurements is maximum for the condition where the maximum flank wear was used. Moreover, a reduction of the micro-hardness of the workpiece as compared with the parent material is noticed for all the conditions. However, it is seen from the figures that the maximum reduction of micro-hardness occurs in the subsurface for the condition in which the maximum flank wear was used. While, it occurs on the surface for the other two conditions.

### 3.2. Cutting conditions and rolling contact fatigue life

Fig. 11 shows the effect of cutting parameters on the rolling contact fatigue life. Form that figure, it is interest-

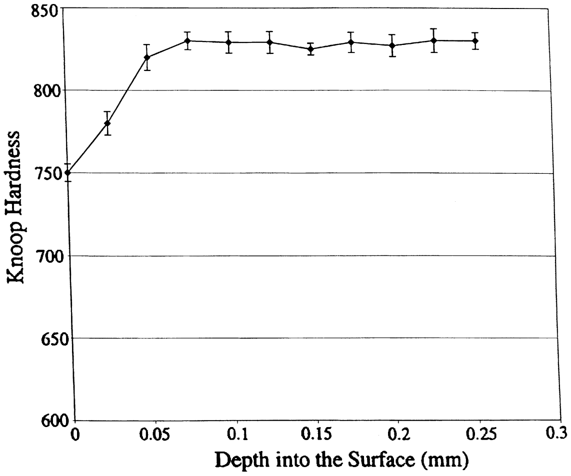


Fig. 9. Micro-hardness distribution.

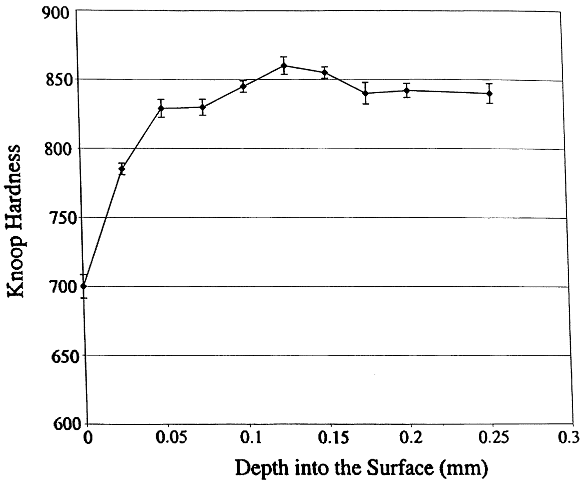


Fig. 8. Micro-hardness distribution.

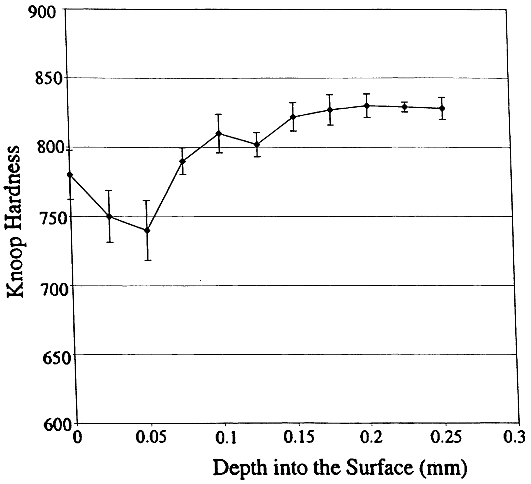


Fig. 10. Micro-hardness distribution.

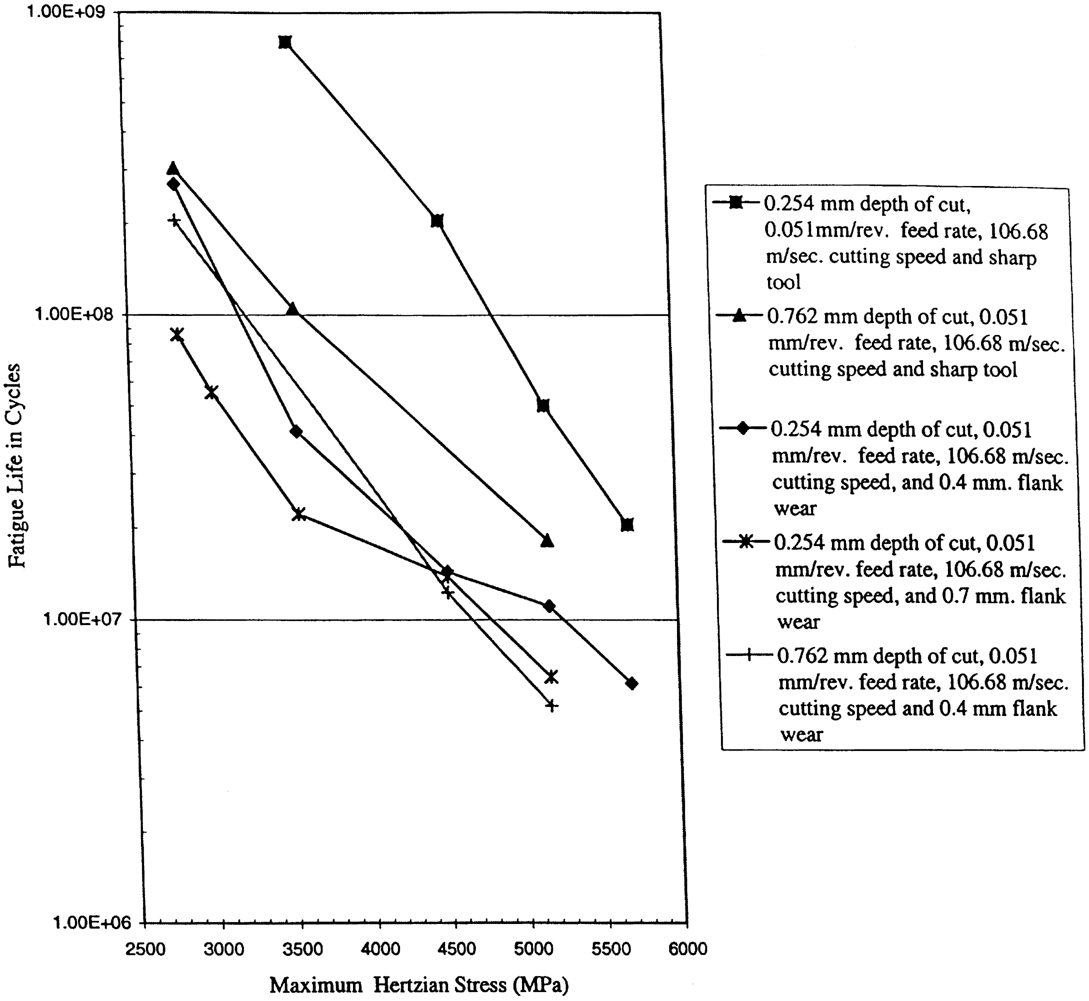


Fig. 11. Effect of cutting parameters on the rolling contact fatigue life of superfinish hard turned surfaces as a function of maximum Hertzian stress.

ing to note that there is a certain range for which the rolling contact fatigue life is insensitive to the applied load. A similar trend was obtained by [20] in their study on the effect of component hardness on rolling contact fatigue life. In other words, they found that the rolling contact fatigue life has a maximum for a specific hardness difference between the rings and the rollers. These hardness differentials were obtained using different tempering temperatures. Therefore, it is expected that tempering not only change the hardness but also the residual stress distribution which is the case in this study. It is noted that this 'insensitive range' is clear for the tool with flank wear as compared with that of a sharp tool. This behavior is can be attributed to the fact that sharp and worn tools produce different residual stress distributions. It is known for example that a sharp tool produces a narrow peak of compressive stress under the surface, whereas a worn tool produces a broader and deeper peak of compressive residual stress under the surface (for the effect of tool flank wear on the residual stress, see [8]). As for the worn tool, where the residual stress at and close to the surface where the maximum critical stress occurs is mostly tensile and thus the decrease in the actual fatigue life under low loadings versus the one obtained by extrapolation of the fatigue life under high loads. Similar results were obtained using the sharp tool and a large depth of cut (03sL condition) which produced a tensile residual stress on the surface as opposed to the compressive residual stress produced at the surface when a small depth of cut was used (01sL condition). It is clear from the figure that at the relatively high cycle fatigue (low loading), the difference in fatigue life is about 40 times compared with only 3 to 4 times for the low cycle fatigue. Finally, the reduction in fatigue life due to different cutting conditions indicates a deterioration of the surface condition. Thus, it is essential that the flank wear be monitored such that the surface integrity aspects don't deteriorate. The above is being under study by the authors. That includes modeling the rolling contact fatigue life as a function of the most important surface integrity aspects of the superfinish hard turned workpieces.

### *3.3. Repeatability of the results*

As mentioned earlier, the hard turned surfaces showed a very good repeatability under identical loading conditions.

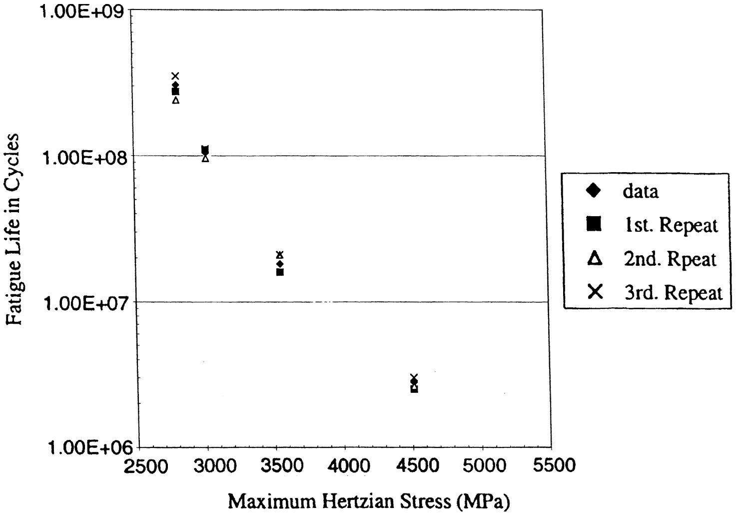


Fig. 12. Repeatability of the experimental results.

The repeatability of fatigue lives of similar workpieces under similar loadings was between 5 and 20%. Reported variations for ground and lapped bearings can be as much as 50 times. This might be due to the random nature of the grinding process [1]. Moreover, the difference in fatigue lives between the results obtained from the designed set-up and those obtained by using the Fallex-multi-specimen rolling fatigue tester didn't exceed 10–17% [3–5]. Fig. 12 shows the repeatability of one condition under different loadings. The consistency of the obtained repeatability is another advantage of hard turned surfaces over ground surfaces. In other words, the fatigue life of the bearing can be obtained in a more deterministic way than that of the ground surfaces. And thus meet the quest of industry for more reliable and economical products.

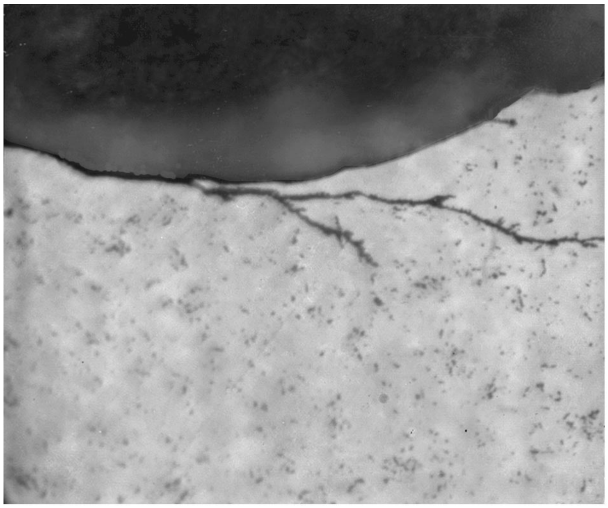


Fig. 13. Crack initiation and propagation for the condition (0304) under 3605 MPa.

### 3.4. Preliminary analysis of the failed specimens

In order to check the origin of the cracks in the tested workpieces, several of these workpieces were sectioned, mounted, and polished. Photos were taken using an optical microscope. Most of the tested specimens showed that the crack started at the subsurface. Fig. 13 is an example where it is seen that two cracks started at different locations in the subsurface. Those cracks continued propagation until they formed one crack and reached the surface just under the balls track.

## 4. Conclusions

1. It is shown experimentally that in this paper that the effect of cutting conditions is very significant on the fatigue life of the hard turned workpieces. The differences in fatigue life can be 40 times for the range of the cutting conditions used.
2. It is shown that the repeatability of the fatigue lives of the workpieces produced by the same cutting condition in hard turning is much better than that for ground workpieces. The range of the fatigue lives of the hard turned parts, using the same conditions and under various loading conditions is found to be 5–20%. A typical deviation in the fatigue lives of ground parts using the same grinding conditions is about 50 times [6].

## Acknowledgements

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