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DRAGLINE ROLLER TRACK IMPROVEMENT

Evaluation of Low Hardness Dragline Track
Materials in Rolling Contact

Final Report
Contractor—The Franklin Research Center

Contract No. AC01-76ET-12502

U. S. Department of Energy
Assistant Secretary for Fossil Energy
Office of Coal Mining

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DRAGLINE ROLLER TRACK IMPROVEMENT

EVALUATION OF LOW HARDNESS DRAGLINE TRACK
MATERIALS IN ROLLING CONTACT

FINAL REPORT VOLUME I
FOR CONTRACT PERIOD
SEPTEMBER 30, 1976-JULY 30, 1980

J. DUNFEE
L. LEONARD
J. RUMBARGER

THE FRANKLIN RESEARCH CENTER
20TH STREET AND BENJAMIN FRANKLIN PARKWAY
PHILADELPHIA, PENNSYLVANIA 19103

PREPARED FOR THE
U. S. DEPARTMENT OF ENERGY
CARBONDALE MINING TECHNOLOGY CENTER
UNDER CONTRACT ET-77-C-01-9122

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ABSTRACT

The Franklin Research Center (FRC), a Division of the Franklin Institute, was contracted by the Bureau of Mines to improve walking dragline roller tracks. The contract was subsequently transferred to the Department of Energy.

The period from September 1977 to September 1978 covered laboratory rolling contact rig tests to evaluate typical low hardness dragline track materials. The results of this work are covered by DOE/ET/9121-1 Final Report, Volume I.

The period from September 1978 to July 1980 covered field measurements of dragline roller circle loadings. The results of this work are covered by DOE/ET/9121-2 Final Report, Volume II.

The laboratory rolling contact rig test results indicate that forged vacuum degassed air melt steel materials are recommended over air-melt cast materials for rollers and tracks. The steels tested exhibited good freedom from sensitivity to stress raisers like brinell marks and small holes or discontinuities (Volume I).

The largest unknown in a recommended method for life testing roller tracks is the condition of the upper rotating frame structure and the lower tub supporting structure.

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FRC appreciates the key contribution of the Bureau of Mines cognizant engineer Mr. Randall Conolly, Spokane Mining Research Center and later Mr. Howard Parkinson, Carbondale Mining Technology Center, Department of Energy.

Finally, FRC acknowledges the contributions and encouragement of Mr. Hamilton B. Reese, U. S. Department of Energy.

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1. INTRODUCTION

1.1 WALKING DRAGLINE ROLLER TRACK

One of the most critical mechanical components of a walking dragline, Figure 1-1, is the main thrust (slewing bearing). This bearing consists of a large lower roller track attached to the dragline base structure (tub), and an upper roller track bolted to the rotating frame with the boom, machinery house and associated supporting structure. Large cylindrical rollers along with pin cages form the rest of the bearing. Heavy, non-uniform loading on these roller tracks, as well as their massive size, dictates the use of low hardness materials for construction.

Prediction of bearing life for these tracks is difficult since peak loading and fatigue life data are not readily available. Repair of these bearings is a very expensive, time consuming process with corresponding losses of coal production.

The objective of this program was to obtain more of the information needed by bearing and walking dragline designers to extend the working life of the slewing bearing, with a subsequent decrease in maintenance cost and downtime.

1.2 ROLLER TRACK DESIGN

Roller tracks of walking draglines (Figure 1-1) are currently designed on the basis of past experience with little technology available regarding proper design considerations. Table 1-1 shows a few walking draglines (approximately 50 cubic yards) and describes the geometry, number of rollers, etc., in typical roller tracks. The roller load data of Table 1-1 shows ideal (no hard points) maximum roller loads. These loads would be the loads calculated by simple roller-bearing deflection calculations [4]^{*}, assuming that both the upper rotating structure and the lower supporting tub were flat, rigid supports.

^{*}[] - Bracketed numbers refer to numbered references in Section 6-6, page 6-15.

Figure 1-1. Typical Walking Dragline Configuration

Table 1-1. Walking Dragline - Roller Track Sizes

DRAGLINE	EXAMPLE A	EXAMPLE B	EXAMPLE C
Rotating weights, F_a , (lbs)	5.2×10^6	5.69×10^6	5.39×10^6
Max. overturning moment M (Ft-lbs)	0.38×10^8	0.43×10^8	0.42×10^8
Location of C.G. (% of pitch radius)	0.32	0.32	0.28
<u>ROLLER TRACK DATA</u>			
Pitch dia. of track (ft)	46	46.5	57
Upper rail track	120° FWD 90° AFT	180° FWD 150° AFT	360°
Track width (in.)	10.0	9.2	12.0
Track depth (in.)	5.0	3.5	6.0
Dia. of rolls (in.)	12.0	12.0	12.0
Length of contact (in.)	9.5	8.4	12.0
Number of rolls	120	120	140
<u>ROLLER LOADS</u>			
Ideal (no hard points)			
Max roll load	97 KIPS	82 KIPS	63 KIPS
Contact stress (mean)	72 KSI	70 KSI	52 KSI

Roller loads are calculated using flat rigid race bearing theory. [4]
Actual maximum roller loads may be higher due to structural design of rotating frames and tubs.

Rotating weight, F_a , (lbs) includes suspended load of filled bucket.
Max. overturning moment M, (ft-lbs) includes filled bucket suspended under boom point.

FRC has performed design analysis studies of a 55-cubic-yard dragline for a mine operator. The solid line of Figure 1-2 is a graph of calculated roller or wheel loadings in the roller track under maximum acceleration forces while slewing with a full bucket. The 1.5 revolutions per minute maximum machine rotational speed will develop significant inertial loads because of the extreme size and weight of the upper rotating structure and payload. The dotted line of Figure 1-2 shows calculated roller loads with idealized assumptions [4] of flat rigid roller track surfaces. An examination of the two curves shows a peak load of 140 kips compared to 63 kips under ideal structural support and static conditions. Maximum roller loads can therefore exceed simplified estimates by a factor of 2.25 (Figure 1-2) or more.

The determination of actual maximum track loadings is receiving additional attention by the dragline companies. Major manufacturers are using structural analysis computer programs to some extent (similar to Figure 1-2) to determine the effect of the roller track supporting structures and dynamic loadings.

An acceptable method for the life rating of a roller track is needed. No dragline manufacturer currently will supply a life estimate for roller track sections.

Normally accepted roller bearing fatigue life theory is based on experimentally determined material constants. These material constants have been obtained over many years for fully hardened (Rockwell C58 or harder) roller bearing steels. The roller tracks in walking draglines are much softer, as shown in Figure 1-3. The shaded area for a track section shows 302 to 331 BHN. This places the hardness in the Rockwell C32 to C36 range. This is a specification used on current dragline designs. Another manufacturer of draglines uses a specification of 330 to 340 BHN for the roller tracks.

The life factor or reduction of life due to reduced hardness is sometimes estimated by the ratio shown at the top of Figure 1-3 [6]. This reduction factor takes the ratio of the track hardness to the reference

Figure 1-2. Roller Loading with Dynamic Effects

Figure 1-3. Track Life Multiplier

Rockwell C58 hardness and raises this ratio to the 14.4 power. This large exponent causes many orders of magnitude of reduction in the life constant for the soft track materials. There is no supporting test information in the literature in the Rockwell C32 to C40 range. This then is a *gross extrapolation* at the low end of known data. Because of the reduction factor currently used (Figure 1-3) [6], one can calculate track life multipliers as shown on the graph. In this case the reference life at 302 BHN was taken as a factor of 1. The graph indicates that within the tolerance range 302 to 331 BHN the life of the track can vary by as much as 4.5 from one hardness to the other. It is difficult to accept this extreme change or reduction life due to 30 points difference in BHN. Track life data is needed for the typical roller track materials and typical roller track hardnesses. The design rating of the roller tracks cannot be improved without this knowledge. The knowledge is also necessary for the selection of proper roller track lubricants.

Failure of a roller track can be caused by a number of factors. Several types of conditions can compete to fail a track. Poor lubrication, excessive roller loads, static overload resulting in Brinell marks (plastic indentations) and rolling over foreign objects causing denting are some of the physical conditions that can be encountered. In any event, the roller track, if properly protected from all of the preceding conditions, will still have some finite life. Application of roller loads results in stresses in the roller track material below the surface. Cyclic application of these stresses that occurs during rolling will eventually cause fatigue spalls. Cracks form in the subsurfaces and propagate upwards to the surface and then allow small pieces of material to flake or spall out. All bodies in rolling contact have a limiting life in spalling fatigue. It is necessary to determine the actual design life limit for roller track materials. "Life" is a statistical quantity. There is a dispersion or scatter in the test data and actual field data in rolling contact bearings. It is common practice to talk in terms of a 10% failure, or 90% probability of survival rating life (defined in Section 6).

Testing of common commercial sizes of roller bearings has been accomplished by most roller bearing manufacturers. These tests have resulted over the years in catalog ratings based on the rating methods of the Anti-Friction Bearing Manufacturers Association [1]. It is, of course, physically impossible to laboratory test full roller tracks since they are approximately 60 feet in diameter. Also, because of the scatter in fatigue data, it is common practice to test a group of apparently identical bearings until at least 10 have failed. The literature accumulated over the years for the fatigue of rolling contacts is based primarily on Rockwell C58 minimum hardness bearing materials. There has been no documented data at the Rockwell C32 minimum hardness commonly used in roller tracks.

1.3 FRC ROLLING CONTACT TESTING MACHINE

The testing of different hardnesses and lubricants of the roller track materials was most practically accomplished by using an existing FRC rolling contact testing machine. The test rig is shown in Figure 1-4. The unit is completely instrumented and capable of automatic continuous operation. Occurrence of fatigue spall triggers an accelerometer and shuts down the testing machine. The details of the rolling contact test rig are shown in Figure 1-5 and in diagram form in Figure 1-6. Two wheels of 7-1/2 inch diameter are loaded against a cylindrical test specimen. This cylindrical test specimen is held in a collet attached to a precision high-speed spindle. Rotation of the spindle will result in rotation of the outer wheels. Each time the cylindrical specimen is rotated, it receives two stress applications or stress repetitions. The wheels are loaded by a hydraulic cylinder (not shown in the figure) below the center of the scissors arrangement. The photograph of Figure 1-5 shows timing belt drives for the external wheels; however, for the roller track specimen test, these belts are taken out and the center spindle belt-driven from below. The overall capability of the rolling contact testing machine is listed in Table 1-2.

Figure 1-4. FRC Rolling Contact (RC) Testing Machine

Figure 1-5. Closeup View of RC Testing Machine

Figure 1-6. RC Testing Machine Loading and Geometry

Table 1-2. FRC RC Testing Machine Capability

High-Speed Spindle Speed Regulation	100-10,000 rpm, Digital Readout $\pm 1\%$ No Load to Full Load 3 HP Variable Speed Drive
Low-Speed Spindle Speed Regulation	100-2500 rpm, Digital Readout $\pm 1\%$ No Load to Full Load 3 HP Variable Speed Drive
Test Load Load Cell Accuracy	0 to 3000 lb, Digital Readout 1/4 of 1%.
High-Speed Spindle, Torque Meter	54 inch-lb $\pm 1\%$
Low-Speed Spindle, Torque Meter	108 inch-lb $\pm 1\%$

Instrumented with Elapsed Time Meter, Piezoelectric Accelerometer, Tunable Filter and Automatic Shutoff Upon Test Specimen Failure

Note that the much larger stress volume of the wheels permit them to be used to test many specimens before redressing of the spherical wheel surfaces is necessary.

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2. SAE 52100 BASELINE TESTING

2.1 SAE 52100, A BASIS OF COMPARISON

As mentioned in Section 1.2, a large amount of fatigue life data is available for fully hardened (RC58 and up) SAE 52100 air melt vacuum degassed tool steel. It was desirable therefore to begin testing using this well characterized material.*

The spalling fatigue life of a rolling contact has considerable dispersion of results. The average life of a sample is usually five times the L-10 life. The L-10 life is the life where 10% of the samples fail. This L-10 life is also called the "minimum" life of the sample and is the number used for design life.

The method of testing with the rolling contact testing machine (RC rig) of Figure 1-4 is to test as many samples as possible to failure. An unfailed specimen will result in wider confidence bands or less exact results. Rolling or spalling fatigue life is inversely proportional to the fourth power of the contact load. Therefore, in order to keep test times to a reasonable amount of hours for this exploratory effort, the normal load, P , of Figure 1-6 applied was 2000 lbs. This load produces a mean Hertz contact stress of 225,000 psi [6].

The test samples were lubricated with a typical walking dragline track lubricant (Bel-Ray Number 0, Code 82905) by means of an automatic grease dispenser.

The baseline test results are given in Table 2-1 where all seven samples were run to a spalling type failure as shown in Figure 2-2. The statistical analysis [7] of the samples is given in Table 2-2 and the results plotted on special "Weibull" type plotting paper in Figure 2-1.

*Material certification is included in the Appendix of this report.

Table 2-1

<u>Spec. No.</u>	<u>Mean Hertz Stress (kpsi)</u>	<u>Hours Running</u>	<u>Stress Cycles*</u>
#1	225,000	96, Failed	58.8×10^6
#2	225,000	127, Failed	77.7×10^6
#7	225,000	245, Failed	149.9×10^6
#4 (rear)	225,000	141, Failed	86.3×10^6
#5	225,000	182, Failed	111.4×10^6
#6	225,000	246, Failed	150.6×10^6
#4 (front)	225,000	372, Failed	227.7×10^6

Test specimen speed (approx.) 5100 rpm

Wheel speed 680 rpm

Stress cycles per test revolution: 2

* $127 \text{ hours} \times 5100 \text{ rev/min} \times 60 \text{ min/hr} \times 2 \text{ cycles/rev} = 77.7 \times 10^6 \text{ stress cycles}$

The dragline examples of Table 1-1 with 120 rollers would experience 60 stress repetitions of a point on the track in a 180° swing and return. Thus 1×10^6 stress cycles would be equivalent to 16,667 dig, swing, dump and return cycles.

Table 2-2. Weibull Statistical Analysis of Rolling Contact Bearings
Life Based on Median Rank Plotting Positions

Franklin Research Center, Mechanical Engineering,
J. Rumbarger, June 1967

Weibull Statistical Analysis of Rolling Contact Bearings
Life Based on Median Rank Plotting Positions

BOM Rolling Tests with Hard Samples, March 1977

Number of Bearings Tested = 7, Failure Index = 7

<u>Order No.</u>	<u>Median Rank</u>	<u>Hours Life</u>
.100000+01	.942763-01	.960000+02
.200000+01	.229518+00	.127000+03
.300000+01	.364759+00	.141100+03
.400000+01	.500000+00	.182000+03
.500000+01	.635241+00	.245000+03
.600000+01	.770482+00	.246000+03
.700000+01	.905724+00	.372000+03

Bearing Life Values with 90 Percent Confidence Bands

	<u>Hours Life</u>	<u>Lower Band</u>	<u>Upper Band</u>
L(10) Life =	.885081+02	.387988+02	.171336+03
L(50) Life =	.194792+03	.139809+03	.262611+03

Weibull Slope = .238814+01
Order No. Ck. = .800000+01
Aver. Life, Hrs = .201306+03
Correlation Ck. = .950258+00

<u>Input Data</u>	<u>Index</u>	<u>Test Life Hrs.</u>	(0=Failed, 1=Not Failed)
	0	.960000+02	
	0	.127000+03	
	0	.141100+03	
	0	.182000+03	
	0	.245000+03	
	0	.246000+03	
	0	.372000+03

Figure 2-1. Statistical Plot of Individual Test Results

A

1X

B

2.5X

Figure 2-2. Macrographs of the Spalling in a 52100 Steel Test Specimen. This appearance is typical of spalling in rolling contact fatigue with line contact loading.

Results of this baseline testing are 88.5 L-10 hours life (54.2×10^6 stress cycles) at the 95% confidence level.

The loading wheels of the rolling contact testing machine, Figure 1-5, are also made from SAE 52100 air melt vacuum degassed steel and ground to the shape shown in Figure 1-6. These fully hardened (RC58 minimum) wheels were used for all of the testing described in this report.

3. CAST ALLOY STEEL TRACK MATERIAL TESTING

3.1 MATERIAL SPECIFICATION

At the onset of this program FRC knew that a cast track alloy steel material similar or equal to SAE 4340 was being used on some walking draglines. It was planned that samples with a range of hardnesses from RC30 to RC39 would be tested. Unfortunately, a supply of track material and specifications could not be obtained from dragline manufacturers since it was considered proprietary. However, through the cooperation of a mining company and the Bureau of Mines, a 30" section of used "Dragline Upper House Roller Rail" was obtained. The track was cut into sections and turned into samples as shown in the diagram, Figure 3-2. Note that no additional heat treatment was used on these specimens. The portion of the cross-section from which they were cut was sufficiently below the used surfaces of the track to avoid the cold working and spalling area present in the used track material. Table 3-1 gives the results of the chemical analysis for this steel, showing that it is similar in analysis to SAE 4340 steel.

3.2 TRACK MATERIAL TESTING

It was decided that the best comparison between the track material specimens and the 52100 baseline specimens would be obtained using the same conditions. Accordingly, the normal load applied was 2000 pounds, for an average Hertz stress of 225,000 psi. Also, the standard track lubricant was automatically applied.

The results of the tests on this track material are given in Tables 3-2, 3-3 and Figure 3-3. The L-10 life is 25.7 hours with the two non-failures (runouts) considered and 20.5 hours with those two data points omitted.

Note that the metallurgical aspects of these failures are discussed in Section 7.

Figure 3-1. Track Section

Figure 3-2. Sketch of Track Section
(all dimensions in inches)

Table 3-1. Steel Analysis

W. B. COLEMAN CO.
TESTING LABORATORIES

ESTABLISHED 1922

9TH ST. AND RISING SUN AVE.

PHILADELPHIA, PA. 19140

215-223-7751

DATE February 1, 1977

ANALYSIS OF Steel

RECEIVED FROM The Franklin Institute
 Research Lab Building Room 213
 20th and Race Sts.

Attn: Mr. H. Kelly Philadelphia, PA 19103
 P. O. No. 26213

NUMBER	953316			
No Mark MARKING	Track Material	SAE 4340		
COMB. CARBON, %				
GRAPH. CARBON, %				
TOTAL CARBON, %	.336	.38-.43		
MANGANESE, %	.89	.60-.80		
PHOSPHORUS, %	.021	.035		
SULFUR, %	.023	.040		
SILICON, %	.45	.20-.35		
NICKEL, %	1.40	1.65-2.0		
CHROMIUM, %	.75	.70-.90		
MOLYBDENUM, %	.32	.20-.30		
VANADIUM, %				
TITANIUM, %				
COPPER, %	.13	.35 max		

W. B. COLEMAN CO. am

FORM 4D F.P.

BY

S. J. Curran

Table 3-2

Results of testing of the cylindrical specimens made from the actual track material are given below for a mean Hertz stress of 225,000 psi.

Spec #21	424 hours	259×10^6 cycles	no failure
21 (opp. end)	124 hours	76×10^6	failed
22	625 hours	382×10^6 cycles	no failure
23	29 hours	17.7×10^6 cycles	failed
29	85 hours	52×10^6 cycles	failed
20	49 hours	29.9×10^6 cycles	failed
24	394 hours	241×10^6 cycles	failed
28	53 hours	32.4×10^6 cycles	failed

Table 3-3. Weibull Statistical Analysis of Rolling Contact Bearings
Life Based on Medial Rank Plotting Positions

Franklin Research Center, Mechanical Engineering,
J. Rumbarger, June 1967

Weibull Statistical Analysis of Rolling Contact Bearings
Life Based on Median Rank Plotting Positions

DOE Track Study, Actual Track Material

Number of Bearings Tested = 8, Failure Index = 6

<u>Order No.</u>	<u>Median Rank</u>	<u>Hours Life</u>
.100000E+01	0.829960E-01	0.290000E+02
.200000E+01	0.202140E+00	0.490000E+02
.300000E+01	0.321384E+00	0.530000E+02
.400000E+01	0.440428E+00	0.850000E+02
.500000E+01	0.559572E+00	0.124000E+03
.600000E+01	0.678716E+00	0.394000E+03

Bearing Life Values with 90 Percent Confidence Bands

	<u>Hours Life</u>	<u>Lower Band</u>	<u>Upper Band</u>
L(10) Life =	0.257380E+02	0.524336E+01	0.979635E+02
L(50) Life =	0.133056E+03	0.684969E+02	0.242909E+03

Weibull Slope = 0.114673E+01
Order No. Ck. = 0.900000E+01
Aver. Life, Hrs = 0.174465E+03
Correlation Ck. = 0.891641E+00

<u>Input Data</u>	<u>Index</u>	<u>Test Life Hrs.</u>	(0=Failed, 1=Not Failed)
	0	0.290000E+02	
	0	0.490000E+02	
	0	0.530000E+02	
	0	0.850000E+02	
	0	0.124000E+03	
	0	0.394000E+03	
	1	0.424000E+03	
	1	0.625000E+03

Figure 3-3. Weibull Plot of Actual Track Material Samples

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4. FORGED VACUUM DEGASSED 4140 TESTING

One dragline manufacturer furnishes forged vacuum degassed steel for rails. The wide scatter of FRC cast track material specimens as well as the results of the metallurgical examination, indicated that a cleaner steel should increase life. Therefore, a bar of air melt vacuum degassed forged 4140 steel* was used for the machining of the test specimen. They were heated to RC35 and ground. Three specimens were run 400 hours each, without a spalling fatigue failure. (There was insufficient test time available to run to failure.) This brief initial testing indicates the value of a cleaner steel for this application. Certainly the increased material cost should be well offset by the greater life expectancy, which is at least 400 hours L-10 life.

*Material certification is included in Appendix.

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5. SPECIAL CONFIGURATION TESTS

5.1 MECHANICAL DEFECT SPECIMEN TESTING

In the search for the causes of early failure in dragling roller tracks, the idea, that stress raisers such as a mechanical defect might be a factor, was briefly examined by preparing special test samples.

Several attempts were made to induce failure in actual track material test specimens by introducing mechanical defects.

Specimen #22 (opp. end) had standard depth Rockwell Indentor marks placed in the center of the track. It was removed after 118 hours of testing. Both Indentor marks were completely rolled out with no failure.

Specimen #28 (opp. end) was tested for 30 hours, with no failure. After a wheel failure stopped the test, a mechanical defect was again introduced in the middle of the track (0.047 in. diam. hole, 0.015 deep, flat bottom). This specimen failed after 21 hours, but the failure was outside of drilled area. Failure appeared to occur due to impact of load system from the mechanical defect, rather than the surface defect itself.

Therefore, it can be stated that small mechanical defects appear to be self-healing. Repeated impact loading on the same area can cause early failure.

5.2 TEST SAMPLES WITH EDGE EFFECTS

Another attempt to induce failure was to machine specimens from the actual track material as shown in Figure 5-1. Two test samples were used. Both exhibited heavy vibration, inducing small failures, but in the center of the wear path where stresses are highest. Results were inconclusive.

Figure 5-1. Test Samples with Edge Effects

5.3 CROWNING OF ROLLERS

Another question to be answered concerning the inducing of failures in the roller track was whether or not roller crowning is really necessary. In roller bearings constructed of fully hardened 52100 bearing steel, the rollers are usually crowned, to prevent high stresses at the edges of the rollers. A "crown" is a deviation from a true cylinder near the ends of the roller.

A true cylinder loaded into contact with another true cylinder or in contact with a flat plate will result in "stress increases" at the roller ends. This is often called "dogbonning" since the elastic contact area is a narrow rectangle with enlarged end areas. Many early roller or race failures can be identified with this "edge loading" condition.

Using the forged vac-degassed 4140 steel, some tests were run with the conditions as shown in Figure 5-2. Both the wheels and the roller were cylindrically ground with no crown radii. Three stress levels were tested; 225,000, 150,000 and 125,000 psi mean Hertz stress.

The 225,000 psi test had heavy vibration. In less than one minute crowning was achieved. The edges of the roller were changed from a true cylinder. For the 150,000 psi tests, the samples were run 24 hours. Figure 5-3 shows a typical "footprint" of the contact, before and after testing. The footprint is made by placing household aluminum foil in the wheel to roller contact and applying the 2000 lbs test load. The first foil "footprint" shows enlarged ends on the classical "dogbone" shape. The second "footprint" shows tapered ends indicating edge relief or crowning.

The results show that, for the conditions tested, the rollers are self-crowning. The edge stresses are relieved by rolling of a contour modification before spalling failure occurs.

Table 5-1 gives the results of micro hardness tests run on the test roller path. Values are given for the center, edges and a base value for the untouched portion of the specimens.

Figure 5-2. Roller Crowning Test

No. 38 New - No Crown
2200# Before ~4X

No. 38 Run in
2200# After 35-40 sec ~4X

Figure 5-3. Footprints of Roller Contact

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6. SUGGESTED ROLLER CIRCLE LIFE CALCULATIONS

6.1 THRUST CAPACITY

The test work on the rolling contact test rig of the actual roller track material established a base for rating roller tracks. These results, discussed previously, when compared with a control sample of similar tests under identical load speed and lubrication conditions gave us the thrust capacity of the present material. The Anti-Friction Bearing Manufacturers Association (AFBMA) [1] has established Standard No. 11 dated June 1972 for load ratings and fatigue life for roller bearings. The standard method for rating a roller thrust bearing will be described below and material properties will be suggested for use in these life rating equations.

The thrust capacity, C_a , is given by Equation (1). The hardness factor f_h comes from the present test work and indicates that the thrust capacity for the cast steel tracks which are representative of roll circle tracks in most existing machines will have a thrust capacity of approximately 69.3% of that recommended for fully hardened and ground roller thrust bearings.

The $f_H = 0.693$ hardness factor is obtained from the ratio of the B-10 life values of the actual track samples with the 52100 fully hardened test samples. The 52100 samples (see Appendix) were air-melt vacuum degassed steel. The 88 hours B-10 life on test theoretically should be reduced to one-third (29.3 hours) to make it comparable to an air melt only track steel. The increased life of the 52100 steel test samples due to vacuum degassing has not been demonstrated for the material used because of limited testing time. Conservative engineering dictates that we use the test results directly to establish the hardness de-rating factor, $f_H = 0.695$. Use of the one-third factor would give $f_H = 0.965$ which shows little difference between the baseline 52100 (reduced to 1/3) and the actual track samples.

$$C_a = f_H f_c l_{eff}^{7/9} Z^{3/4} D^{29/27} \text{ (lbs)} \quad (1)$$

$$f_H = \left(\frac{26}{88} \right)^{3/10} = (0.295)^{3/10} = 0.693 \text{ from present data}$$

f_c is a function of $\frac{D}{dm}$ geometry; Table 6-1 (1)

l_{eff} = Roller effective length of contact (in.)

Z = Total effective length of rollers

D = Roller diameter (in.)

dm = Pitch diameter of rollers (in.)

Table 6-1. Thrust Roller Bearing
Values of f_c (dimensionless)

$\frac{D}{dm}$	f_c $\alpha = 90^\circ$
0.01	9,500
0.02	11,000
0.03	12,100
0.04	12,800
0.05	13,200

The material factor f_c for Eq. (1) is a function of the geometry ratio of the bearing or the ratio of the roller diameter to the pitch diameter of the roller circle. Proper material factors are given in Table 1 for the range of interest of roll circles in most walking draglines.

The thrust capacity, C_a , is defined as the thrust load in pounds uniformly applied, which will result in one million revolutions of the deck with respect to the tub. This is with a 90% probability of survival. The basic life theory [2] defines failure as the first visible evidence of spalling of the surface. This is not a service failure in the sense that the roller circle would be incapable of operation. Spalling is a progressive phenomenon and some length of time will be required from the first evidence of spalling until a condition is reached, where, because of roughness of operation and induced vibrations, etc., the track is considered no longer serviceable. It is not possible to determine this length of time, however, for design purposes, the concept of rating life is valuable in comparing roll circle designs of various machines with known histories and for projecting for larger machines and newer designs. Spalling fatigue of the roll circle in rolling contact is the ultimate life of the material. Contaminants, dirt, stress raisers and many other extraneous items such as lack of lubrication, etc., can drastically shorten this service life. If all things are correctly observed and the bearing or roller circle is kept free of contaminants and is properly lubricated, etc., the rating life is a measure of the inherent life of the material under reversed cycles of rolling.

The rating life, L_{10} , of the roller circle as a complete thrust roller bearing is given by equations (2) and (3). The thrust load, P_a , used in these calculations will be discussed in Section 6.2. The life in millions of revolutions is a function of the ratio of the thrust capacity of equation (1) to the equivalent thrust load, this ratio raised to the 3.33 power. The AFBMA standard [1] also suggests the use of various life adjustment factors as indicated by a_1 through a_4 of equation (3).

Life adjustment factor a_1 accounts for increased reliability. Some applications require ratings for other than 90% reliability of survival, however, for surface mining equipment the L_{10} life is practical and life adjustment factor would be 1.0.

$$L_{10} = \left(\frac{C_a}{P_a} \right)^{10/3} \quad \text{millions of revolutions} \quad (2)$$

$$L'_{10} = a_1 a_2 a_3 a_4 \left(\frac{C_a}{P_a} \right)^{10/3} \quad \text{millions of revolutions} \quad (3)$$

a_1 = Life adjustment factor for increased reliability.

$a_1 = 1.0$ for 90% probability of survival

a_2 = Life adjustment factor for improved bearing steels.

$a_2 = 3.0$ for air melt, vacuum degassed, forged steel

$a_2 = 5.0$ for consumable electrode vacuum remelt steels (CEVM) also forged.

a_3 = Life adjustment factor for application conditions.

$a_3 = 0.1$ for most roller circles

$a_3 \ll 0.1$ for existing roller circles with many hard points in the upper deck structure or excessive frame or tub distortions

a_4 = Life adjustment factor for roller circle rotations of less than 180° and return

$a_4 = \left(\frac{180}{\theta} \right)$ θ = angle from dig to dump

$$H_{10} = \frac{L_{10} \times 10^6}{60 \times \text{rpm}} \quad (\text{hours}) \quad (4)$$

The life adjustment factor a_2 , for improved bearing steels, is to account for cleaner steels and improved methods of processing of the steels. In general, a forged air melt vacuum degassed or ladle degassed material which is used in the greatest majority of all ball and roller bearings, is considered to have a life adjustment factor of 3.0. Many demanding applications for high reliability and high speed, etc., will go to a consumable electrode vacuum remelt CEVM steel. This is a premium high cost, high quality steel and the life adjustment factor a_2 is generally conceded to be 5.0 for this material.

Life adjustment factor for application conditions, a_3 , is more difficult to define, however, for walking dragline use where the roller circle loadings will vary from loadings expected in bearings that are rigidly supported by flat surfaces, etc., we may expect some life reductions. The subject of method of determination of these will be covered in more detail in Section 6.3, however, a life adjustment factor of $a_3 = 0.1$ is reasonable for a well designed walking dragline roller circle. There are many existing machines with partial arc roller tracks on the upper deck with obvious hard points and soft points, etc., where the life adjustment factor a_3 may easily be much less than 0.1. Dragline structures distort crack and are field rewelded which can lead to reductions in life.

Life adjustment factor, a_4 , is for roller circle rotations of less than 0 to 180° and return. The calculation and theory used in oscillating roller bearing design [3] results in the expression given in $a_4 =$ ratio of 180° divided by θ . Thus, a dragline that moves 90° and returns would have a life of double that of one going a full 180° and return.

Finally, the rating life in hours, H_{10} , is given by equation (4). The speed of rotation is used here in revolutions per minute as indicated in equation or can be in terms of oscillations or cycles per minute. The usual rate is approximately 1 cycle per minute for large draglines.

6.2 EQUIVALENT THRUST LOAD

A walking dragline roller circle has axial thrust loads and large overturning moment loads in combination. The horizontal shear loads or radial loads are normally assumed to be taken by some type of pintle bearing. The rating life of a thrust roller bearing as given in equation (1) is for a flat surface roll circle with cylindrical rollers. Many walking draglines use a tapered roller which is capable of taking horizontal or shear loads. However, the majority of load is the actual thrust load and overturning moment loads, and equation (1) is applicable

to all roller circles including tapers because of the very slight amount of taper on the rollers. The roller diameter to be used in the calculations would be the average diameter or mid-diameter of the roller. The length of roller would be the horizontal projected length between corner radii or that length actually capable of carrying loads.

The equivalent thrust load, P_a , defined as that uniform applied or concentrically applied thrust load which will result in the same rating life as the actual distribution of roll circle loads. The calculation of the equivalent thrust load is covered in reference [4] for thrust roller bearings under these types of thrust and overturning moment conditions. The equivalent thrust load is given by equation (5) and the x-factor in this equation which comes from [4] is given in Table 6-2.

$$P_a = X F_a \quad \text{Equivalent Thrust Load (lbs)} \quad (5)$$

F_a = Thrust load on roller circle (lbs)

M = Overturning moment on roller circle (in-lbs)

P_a = Equivalent thrust load (lbs)

X = Factor from Table 6-2

It is significant to note that the eccentricity of the center of gravity of the thrust loading from the center line of rotation as explained in Table 6-2 and described by the ratio of the moment divided by the pitch circle radius and the thrust load, is an important parameter. As indicated on Table 6-2 this ratio is usually less than 0.5 which means that the center of loading is at 50% of the pitch radius or less near the center of rotation. In this case, according to the theory of flat rigid plates all the rollers would be loaded, however, the load would vary from directly under the boom at a maximum to a minimum roller load under the counter weight. If this ratio exceeds 0.524 some of the rollers towards the rear of the machine would be unloaded, assuming that overturning moment is with a loaded bucket towards the boom. In the extreme case this ratio should never exceed 0.75. In such a situation, the

Table 6-2. Equivalent Load Coefficient
For Roller Circle

$\frac{2M}{d_m F_a}$	X	e = eccentricity of CG of loading from ϕ rotation (in.)
1.000	∞	
0.961	4.14	$\frac{2e}{d_m} = \frac{2M}{d_m F_a} = \% \text{ of } \frac{d_m}{2} \text{ to CG.}$
0.922	3.14	
0.881	2.66	
0.838	2.36	
0.794	2.15	$\frac{2M}{d_m F_a} \leq 0.524$ All rollers loaded
0.748	1.98	
0.700	1.82	
0.649	1.72	
0.592	1.60	$\frac{2M}{d_m F_a} > 0.524$ Lift-off, some rollers unloaded
0.524	1.50	
0.360	1.29	
0.234	1.14	
0.137	1.05	$\frac{2M}{d_m F_a} > 0.748$ Unsafe - needs restraining hooks to carry uplift
0.061	1.01	
0.0	1.00	

bearing is becoming unstable, the machine is in danger of tipping over and lift hooks or restraints would be needed.

This equivalent thrust load as given by equation (5), however, is very idealized and depends on very uniform flat supports for both the upper and lower roller circles. The nonuniformity of the supports will be accounted for in the life adjustment factor a_3 discussed previously and a more detailed method of calculating equivalent load on the actual roll circle loads are given in Section 6.3.

Thus, the use of equations (1) through (4) and the use of an equivalent thrust load per equation (5) forms the basis of the life calculation methods for the roller circle.

6.3 EFFECTS OF NON-UNIFORM ROLLER LOADS

Calculations were made by the Franklin Institute (under industrial sponsorship) of predicted roll circle loadings on a 55 cu. yd machine. The results are shown in Figure 6-1. In this case, the entire upper deck supporting thrust members were modeled by finite element techniques and linear springs were used to represent the roller circle support between the upper revolving deck and the steel supporting tub. The dotted sinusoidal curve shown in Figure 6-1 is the ideal curve which would result if one assumed flat rigid supports. The predicted roll circle loads or individual roller loads, are shown by the solid line of Figure 6-1. All of the peaks of the solid curve are labeled and indicate the presence of known hard spots, such as boom points, centerline of supporting trusses, centerline of walking shoes and centerline of counterweight.

The dotted line or idealized curve of Figure 6-1 is the type of curve which would be calculated using equation (5) under idealized conditions. The maximum roller load is seen to be a little more than double that which would result from the idealized calculation.

The equivalent thrust load P_a may be computed in more detail per equation (6) when individual roller loads are known.

Figure 6-1. Calculated Roller Circle Loads 55 CYD Walking Dragline

$$P_a = P_E Z \quad (\text{lbs}) \quad (6)$$

$$\text{where } P_E = \left[\frac{1}{Z} \sum P_\phi^4 \right]^{1/4} \quad (\text{lbs})$$

P_ϕ = Roller load at location angle ϕ .

$a_3 = 1.0$ when using known roller loads in Equation 6

$$a_3 = \frac{P_a \text{ (Eq 5)}^{10/3}}{P_a \text{ (Eq 6)}} \quad (7)$$

The equivalent roller load P_E is the fourth root mean of the actual roller loads. Thus, in Figure 6-1 the mean equivalent roller load P_E for the predicted roll circle loadings is 83,000 lbs per roller. The equivalent roller load under idealized conditions in Figure 6-1 is 48,750 lbs per roller. The life adjustment factor, a_3 , is to account for application conditions. The effects of the supporting structures are the most significant effects in a walking dragline roller track. This factor, a_3 , may be estimated and a value of 0.1 is considered reasonable for a well-designed dragline. The factor, a_3 , can be calculated using the fourth root-mean roller load (Eq. 6, 7) when estimates of individual roller loads are known. Table 6-3 shows sample calculations for the three draglines illustrated in Table 1-1. No detailed calculated estimates are available for draglines A and B. The detailed calculations for dragline C, Figure 6-1, results in an application factor $a_3 = 0.17$ which is not inconsistent with a recommended value of $a_3 = 0.10$.

6.4 SAMPLE ROLLER CIRCLE CALCULATIONS

The typical dragline designs of Example C, Table 1-1 is used to illustrate the method of roller circle calculation. Figure 6-1 discussed previously, is the predicted roll circle load plot from case C using sophisticated finite element models. Table 6-3 shows the suggested numerical calculation of the application factor a_3 per equation (7).

Table 6-3. Calculation of Application Factor, a_3

Dragline (Table 1-1)

Maximum Roller Load (Ideal - No Structures Effects)	63,000 lbs
---	------------

Mean Effective Roller Load P_E (Equation 5) (Ideal - No Structures Effects)	48,750 lbs (Figure 6-1)
---	----------------------------

Maximum Roller Load (Predicted with Structural Hardpoints)	140,000 lbs
--	-------------

Mean Effective Roller Load, P_E (Equation 5) (Predicted with Structural Hardpoints)	83,000 lbs (Figure 6-1)
--	----------------------------

$$a_3 = \left[\frac{P_a \text{ (Equation 5)}}{P_a \text{ (Equation 6)}} \right]^{10/3} \quad \left[\frac{48,750 \times 140}{83,000 \times 140} \right]^{10/3}$$

$$a_3 = 0.170 \text{ (Calculated)}$$

Table 6-4. Sample Load Rating Calculations

Rotating Wt. (lbs)	5.39E6	
OTM ft-lbs	0.42E8	
Pitch Diam. Track (ft)	57	
Location CG $\left(\frac{2M}{d_m F_T} \right)$	0.273	
Table 6-2) X =	1.19	
$P_a = X F_T$ (lbs) (Eq. 5)	6.41E6	
Z (Number of Rollers)	140	
D (Diameter of Rollers, inch)	12	
l_e (Length of Roller Contact, inch)	12	
Pitch Diam. (in.)	684	
D/d_m (Ratio)	.0175	
<hr/>		
f_c (Table 6-1)	10,625	
f_H (Section 6.1)	0.693	
$l_e^{7/9}$	6.91	
$Z^{3/4}$	40.70	
$D^{29/27}$	14.43	
C_a (lbs) (Equation 1)	2.99E7	
<hr/>		
(C_a/P_a)	4.66	4.66
$L_{10} = (C_a/P_a)^{10/3}$ revs. x 10^6	169.0	169
Reliability a_1	1.0	1.0
Material a_2	1.0	1.0
Application a_3	0.17 calculated (Table 6-3)	0.10 Recommended Eq. (3)
Oscillation a_4	1.0	1.0
L_{10} Revolutions	28.73E6	16.9E6
L_{10} Years @ 400,000 cycles per year	71.8	42.25

The numerical example of Table 6-4 is calculated using equations (1) through (5). Thrust loads, overturning moments, equivalent loads and thrust rating capacity, C_a , are calculated. The resultant life numbers in terms of years of operation assuming 400,000 cycles per year result in approximately forty years to seventy years depending upon the method of determining the application factor, a_3 . The 400,000 cycles per year amounts to 1 swing per minute, 24 hours a day, 7 days a week, 75% utilization over a year's time. This is typical for draglines going round the clock for full shift work. The dragline design shows adequate life ratings for the roller circles. The fact that many roller circles experience much earlier failures can be attributed to an application factor $a_3 \ll 0.1$ in practice due to structural hard points in the upper rotating frame and structural distortions in the stationary supporting tub.

6.5 DISCUSSION OF RATINGS

The effect of roll track hardness upon life has been given in several bearing texts. Figure 1-3 uses the ratio of track hardness to Rockwell C58 hardness. This ratio taken to the 14.4 power on life or 3.6 power on dynamic capacity per reference [6]. One of the objectives of the present program was to determine the practical nature of this type of hardness reduction factor which corresponds to the f_H hardness adjustment factor discussed in Section 6.1.

If one uses the "as-furnished" hardness of the roll track the material is approximately Rockwell C35. This ratio to the 3.6 power would result in an f_H hardness factor equal to 0.162 which multiplies life by 0.0007. This is much too drastic to be considered practical.

If one uses the hardness of the roller track surface after a few cycles of operation in the expression the calculated f_H hardness factor becomes more realistic. The metallurgical work under this program

indicated that the test samples work hardened up into the mid-50's Rockwell C at least on the surface, or near surface, if one calculates with Rockwell C factor of 52.4 the f_H hardness factor would be equal to 0.693 (or 0.295 times life) as determined by the present tests. The role of work hardening in determining fatigue life is not well understood and these comments are not to suggest that a Rockwell C52.4 value should be used as a basis of calculation. Comments are only to emphasize that work hardening plays an appreciable role.

The other area of significance is the fact that the effect of the backup structures or hard points vs. soft points upon roll circle loading are much more significant than the effect of lowered capacity due to lower hardness materials. It is important and was necessary to establish a base for calculation for the low hardness materials. That has been done with the present rig work. A need now exists to gain actual field information regarding roll loads in dragline roller circles.

6.6 References

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7. METALLURGICAL ANALYSES

Samples of track material and test rollers were subjected to macroscopic, scanning electron microscope, metallographic, and hardness analyses in order to characterize the materials and their response to test loading and to correlate the time to failure data with particular aspects of the various steels. In order to facilitate comparisons among the different materials, each particular analysis or characteristic of the steels is discussed in a common subsection below.

7.1 PRE-TEST MATERIAL CHARACTERIZATION

7.1.1 Chemical Composition

The composition of the track material closely resembles that of standard SAE 4340 as shown in Table 3-1. The composition of the 52100 and 4140 test steels are given in the Appendix to this report. Both of these test steels were air melted and vacuum degassed. The 4340 steel (actual track) has a higher hardenability, i.e., a greater depth to which maximum hardness can be achieved by heat treatment, than does the 4140 steel. However, since, as discussed in Section 7.1.3 below, the track is relatively soft, hardenability does not appear to be a major consideration in the choice of the alloy.

In general, when different composition steels are quenched to martensite and tempered to the same hardness below $R_c 50$ they develop the same tensile properties. However, elements do influence the ductility and notch toughness of the steel. Thus, the higher silicon and lower nickel content of the track material compared to standard 4340 steel would be expected to result in a somewhat lower notch toughness. Although 4140 contains no nickel and thus would be less tough than standard 4340, particularly at low temperatures, the effectiveness of nickel in enhancing toughness may be more than offset by the cast condition of the track, since cast materials in general exhibit lower notch toughness than wrought materials. A further consideration is the fact that the higher the alloying content the higher the tempering temperature that can be used after quenching to achieve a given hardness. This can reduce residual stresses and thus increase service life.

7.1.2 Microstructure

All the steels are in the quenched and tempered condition and thus the primary constituent is tempered martensite as shown in Figures 7-1 and 7-2. 52100 differs from the other two steels in that it contains primary carbides and is tempered to a lesser degree, consistent with its being in the "full hard" bearing condition. The 4340 track material is cast, as shown by the coarse dendritic structure, Figure 7-3, whereas the 52100 and 4140 steels are wrought. The cast microstructure exhibited a range of grain sizes and some coarse martensite which is generally felt to be detrimental to rolling contact life.

All the steels contained sulfide inclusions. In the vacuum processed 52100 and 4140 steels they were small, Figure 7-4, and although non-uniformly distributed on a microscale, there were no gross differences in size as a function of location. In contrast, in the track steel the sulfides were larger, more numerous, less uniformly distributed, and associated with harder aluminum containing inclusions, Figures 7-5 and 7-6. Also, in the track material the sulfides were irregularly shaped, consistent with the fact that the material was cast. In the wrought 4140 and 52100 steels, the process of forming the material into bars had strung out the inclusions and, thus, in the transverse cross sections of Figure 7-4 the sulfides appear circular.

In polished cross sections of the track material, examples of cracking associated with inclusions, Figure 7-6B, were found. Since the section of track analyzed had experienced extensive spalling and deformation it is not clear if excessive stresses induced by an inhomogeneous, spalled track surface initiated these cracks or if similar cracks had formed prior to, and were responsible for, the original surface spalling. It has been clearly demonstrated in many rolling contact studies that hard oxide inclusions initiate subsurface cracking.

7.1.3 Hardness

The hardness of the steel in the pre-testing condition was as follows:

A 52100

500X

B 4140

1000X

Figure 7-1. Micrographs showing tempered martensite plus primary carbide structure of the 52100 steel and the tempered martensite structure of the 4140 steel. A few larger carbides and a sulfide inclusion are also evident in B.

A

225X

B

1200X

Figure 7-2. Micrographs of a polished and etched cross section of track material. Tempered martensite is the primary constituent in the microstructure.

A

5X

B

5X

Figure 7-3. Macrographs of a macroetched section of track material. A coarse dendritic casting pattern is evident.

A 52100 1000X

B 4140 1000X

Figure 7-4. Micrographs of transverse, unetched cross section of 52100 and 4140 steel rollers showing sulfide inclusions. The sulfides were non-uniformly distributed on a microscale with many areas free of inclusion. The micrographs illustrate the highest inclusion densities in the sections scanned.

A

200X

B

500X

Figure 7-5. Micrographs of unetched sections of the 4340 track material showing examples of sulfide and mixed sulfide and oxide inclusions. Note the differences in the magnifications in the micrographs in this figure and those in the preceding figure.

A

1200X

B

1200X

Figure 7-6. Micrographs of an unetched polished cross section showing a high concentration of inclusions in A and cracking associated with an inclusion in B. The inclusions are a combination of manganese sulfides and harder aluminum oxides.

4340 track material : 35 - 38R_c

52100 : 57R_c

4140 : 32 - 33R_c

As pointed out in Section 1.2 of this report, rolling contact bearing life theory predicts a life reduction for a material whose hardness is below 58R_c. However, the data obtained in this test program clearly show a significantly longer life for the softer 4140 steel than for the base line 52100 steel. An explanation of this behavior may lie in the fact that previous testing which showed that bearing life increased with the hardness of the steel was conducted with loads which did not induce macroscopic plastic deformation. In the present series of tests, the track and 4140 material experienced pronounced metal flow, as will be discussed below.

7.2 POST TEST ANALYSES

7.2.1 Macroscopic Evaluation

7.2.1.1 Unspalled Areas

As reported in Section 2, all the 52100 steel test rollers experienced fatigue spalls, similar to that in Figure 2-2. Also evident in Figure 2-2 is a striped appearance in the unspalled areas of the wear band. This was typical of all the 52100 rollers and was the result of the more highly elevated regions having been smoothed over and polished by the running, leaving the deeper finishing lines to appear darker in contrast. The transition from the wear path to the unrun surface was gradual, and there was no evidence of plastic deformation of metal out of the load zone on to the unrun areas.

The first two test rollers of track material, #21 and 22, did not fail after running times of 424 and 624 hours. The wear surfaces of these rollers had a dull appearance, Figures 7-7 and 7-8, in contrast to the shiny, striped bands of contact on the 52100 rollers. In addition, the roller which ran for 424 hours exhibited a distinctive "herringbone" pattern on the contact surface, Figure 7-7. This regular corrugation of the surface was not apparent on the roller which ran for 624 hours, but on this latter roller there were discrete circumferential wear bands within the wear path, Figure 7-8. On both of these unfailed rollers the surface at the boundary of the wear path and the unrun surface was uniformly elevated as a result of the stress induced flow of metal out of the contact zone. On subsequent test rollers, all of which failed, the boundaries of the wear path and the unrun areas exhibited varying degrees of "scalloping" resulting from a non-uniform flow of metal out of the wear path, Figures 7-9, 7-10 and 7-11. Although not clearly evident in these figures, herringbone patterns were present to varying degrees on the surfaces of these test rollers.

The non-uniform metal flow, or scalloping, may influence roller life. Roller 24 which had the longest life of the 4 failed rollers in Figure 7-9 exhibited relatively little of this scalloping effect compared to rollers 23 and 29. Roller 20 which had the shortest life of the standard configuration track rollers also had experienced very little scalloping. However, as will be discussed later, there were other specific reasons for its early failure.

~ 4X

Figure 7-7. Macrograph showing the wear band on a 4340 track steel test roller which had not failed after 424 hours. There is a "herringbone" pattern on the smooth, dull wear surface and there is no pronounced transition from the wear path to the unrun surface.

~4X

Figure 7-8. Macrograph of the contact surface of a 4340 track steel test roller which had not failed after 624 hours. There are distinct wear lines but the herringbone pattern noted on the roller in the previous Figure is not evident. There is a gradual transition from the wear path to the unrun surface.

A. #23

29 Hrs.

B. #20

49 Hrs.

C. #29

85 Hrs.

D. #24

394 Hrs.

Figure 7-9. Macrographs at 3.5X showing the details of spalling and the general nature of the wear paths. The spalls and the unspalled wear surfaces are shown at higher magnification in subsequent figures.

1.1X

Figure 7-10. Macrograph showing different widths of wear paths on track roller 21. The narrow right hand test path is the one previously shown in Figure 7-7. It had experienced 424 hours without failure. The spall on the wider left hand wear path occurred after 124 hours run under nominally identical conditions. This latter wear path is also "scalloped" in contrast to the right hand track.

A

4.5X

B

4.5X

Figure 7-11. Macrographs of wear paths at opposite ends of track roller 28. The spall in A occurred after 53 hours of running under standard test conditions while that in B formed after 51 hours total running and 21 hours of running after the hole below the spall was introduced by drilling (see Section 5.1). Note the differences in path width and the appearance of boundaries of the wear path, particularly the high concentration of scalloping on the left hand side of the wear path in B and the absence of any scalloping in A.

Factors which could have contributed to the scalloping effect include such test conditions as axial movement of the test roller relative to the test wheels, the relative geometry between test wheels and rollers, the degree and effectiveness of lubrication, and differences in the plastic deformation characteristics of the metal. Since it was beyond the scope of the present investigation, a definitive study of this phenomenon could not be conducted, but, as far as could be determined, no systematic differences in test conditions were introduced from test to test. The test wheels were always reground to the same profile and the alignment of samples appeared to be reproducible. Furthermore, the pronounced differences in wear path widths and degree of scalloping of opposite ends of individual rollers, Figures 7-10 and 7-11, suggest that inherent differences in test samples were not responsible for the variation of the edge effects. On the few tests which were run on rollers on which the edges of the wear path were relieved by machining, Section 5.2 and Figure 5-1, unexplained heavy vibration was encountered. This again is an indication that metal deformation is an important parameter and that a more detailed study of deformation and its role in failure is merited.

Three 4140 steel test rollers ran for 400 hours without experiencing any failures. On all these rollers, the boundaries of the wear paths were raised but not scalloped and appeared similar to the unfailed and longer lived rollers made from the track steel, Figure 7-12. This again indicates that longer running time is dependent upon the uniform plastic deformation of the surface. To a varying extent herringbone patterns were present, primarily near the center of the wear paths, Figure 7-12.

7.2.1.2 Spalls

The spalls on the 52100 steel rollers were typical of rolling contact failures, with each spall being comprised of a series of individual regions where small fragments had exfoliated as cracking progressed, Figure 2-2. There were no obvious surface defects responsible for spall initiation.

The general appearance of the spalls on the failed track rollers, Figures 7-9, 7-10 and 7-11 was similar in nature to that on the 52100 steels, with the exception that the spalls extended across the entire wear path on the 52100 steel but were limited to the center of the wear path on the track rollers. Factors which may have contributed to this difference include hardness, crack propagation characteristics and the surface geometry changes

Figure 7-12. Macrograph of a 4140 steel roller which had not failed after 400 test hours. The boundaries of the wear path are uniform and a herringbone pattern is evident, particularly at the center of the wear path.

induced by the plastic deformation of the softer track steel. As on the 52100 rollers, no initiating defects were evident.

Since no spalling occurred on the 4140 rollers, the possible role of hardness in limiting the spall width on the soft track steel relative to that on the hard 52100 steel could not be evaluated.

7.2.2 Microscopic Surface Characteristics

7.2.2.1 Unspalled Surfaces

Several of the 52100 samples were analyzed in the scanning electron microscope (SEM). Consistent with the macroscopic appearance, there was a general smoothing over of the higher areas of the original finishing lines on the unspalled surface.

None of the original surface characteristics, Figure 7-13, remained on the wear paths of either the track or 4140 rollers. At low magnification in the SEM, Figure 7-14, the herringbone pattern on track roller #21 was clearly a periodic arrangement of elevated and depressed surface areas. The mechanism by which this occurred is not readily explained. When observed at higher magnifications, Figure 7-15, the wear surface was a complex arrangement of dents and heavily deformed and flattened individual patches of metal, which may have first exfoliated from the surface and then rewelded. A similar surface was present on all unfailed surfaces on both track and 4140 steels. The flattening or smearing over of elevated areas was less pronounced at the transition from the unrun to the run surface, Figure 7-16.

As mentioned previously, there were distinct circumferential bands within the wear paths of roller 22 which ran for 624 hours and other track test rollers. The general surface appearance between these bands was similar in detail to that on roller 21, indicating a similar mechanism of surface accommodation to the contact stresses. Each circumferential band was found to be a regular series of dents, Figure 7-17. Based upon a common dent shape in any given band, and the presence of elevated bands of metal on the surfaces of the test wheels, Figure 7-18, it appears that the dents were produced by material which had welded to the test wheels after exfoliating

A

60X

B

1000X

Figure 7-13. SEM backscatter micrographs of the unrun, ground surface of a track steel roller. The unrun surfaces of the 4140 steel rollers were similar.

60X

Figure 7-14. SEM backscatter micrograph of the rolling contact wear band on roller #21 (424 hrs.) showing a well defined "herringbone" pattern of raised and depressed metal. The rolling direction is indicated by lines at left and right. The original finishing lines were at 90° to the rolling direction.

A. Backscatter 1000X

B. Secondary Electron 1000X

C. Secondary Electron 3000X

Figure 7-15. Higher magnification SEM micrographs of the region of the previous figure. Finer details of the heavily deformed surface are evident in the secondary electron images. The rolling direction is almost vertical in these micrographs (90° rotation compared to the previous figure).

A 300X

B 1000X

Figure 7-16. SEM secondary electron micrographs of the transition region from the unrun surface on the right to wear path on the left on roller #21. The "herringbone" pattern is absent at the edge of the run region and the flattening of the surface on a microscale is less pronounced. Note the contrast between this transition region and the heavily scalloped transition between run and unrun surface on roller #23, Figure 7-19.

A

300X

B

1000X

C

3000X

Figure 7-17. SEM micrographs of the 624 hour roller #22 (624 hrs.) showing circumferential bands of dents. These bands are the wear lines which are evident in Figure 7-8.. In any given band the shape of the dents is similar, indicating they were caused by a common raised area on one of the test wheels. Metal pickup from the test roller is the most likely source for such a raised area.

3.5X

Figure 7-18. Macrograph of the surface of one of the test wheels following the running of a series of test track rollers, some of which had spalled. Elevated bands of metal which had been picked up from the test samples are evident.

from the test rollers. Such denting generally causes spalling in fully hardened steels, since lubricant escaping into the dents leads to higher stresses around them. However, the relatively soft track material was resistant to spalling from these defects even though it did not meet the cleanliness standards of the vacuum treated steels commonly used in rolling contact applications. The ability of the material to deform and to exfoliate thin layers also appeared to reduce the effect of or to eliminate such artificial stress raising surface defects as the hardness indentations which were introduced on rollers 22 and 28 in an attempt to induce specific failures. (See Section 5.1).

The microscopic surface morphology of the scalloped boundaries was the same on all the track rollers. There was a fine scale mixture of denting and plastic deformation, Figure 7-19, similar to that present at the boundaries of the wear paths on the long lived unfailed rollers, Figure 7-16. In fact, the surface morphology of all unspalled wear surfaces differed only in the degree to which the elevated regions had been flattened or smeared over by the rolling contact process. Thus, the center of all unspalled wear paths experienced the greatest degree of flattening and the edges of the wear path, whether uniform or scalloped, had been deformed to a lesser degree owing to less contact between the roller and the radius profile of the test wheels (see Figure 1-6).

An attempt was made to evaluate the effect of restraint imposed upon metal flowing out of the wear path by the non-contacting surface adjacent to it. Tests were conducted on a special grooved configuration roller, Figure 5-1. Although scalloping occurred at both edges, Figure 7-20, indicating the width of the roller was slightly wider than that of the wheels, nevertheless there were significant differences between the surface morphology of the main central portion of the wear path on this roller and the same regions on standard configuration rollers. Likely owing to the escape of lubricant at the edges of the wear path on the grooved roller, the surface of the wear path was more highly smoothed over, Figure 7-21, indicating greater metal to metal contact between the test wheels and the roller. The scalloped metal appeared similar to that on the standard configuration rollers indicating a similar history, i.e., contact with the radius profile of each wheel.

A

100X

B

1000X

Figure 7-19. SEM micrographs of track roller #23 showing the fine details in heavily "scalloped" edge of the wear path. Patches of metal which had plastically flowed out over the original surface have a complex, dented and smeared surface.

3.5X

Figure 7-20. Macrograph of a grooved track roller (#26) showing the highly polished nature of the wear track. An incipient spall is present as indicated by the arrow. The test wheels were not centered perfectly, resulting in more scalloping of the wear track boundary on the right.

A

100X

B

3000X

Figure 7-21. SEM micrographs showing several surface cracks on track roller #26. These cracks which are perpendicular to the running direction do not appear to be associated with metal exfoliation as were all incipient spalls on this and other rollers. Furthermore, the smoothness of the wear track in B is consistent with the shiny surface in Figure 7-20 and in contrast with the dull, dented surfaces, on other rollers, Figures 7-7 and 7-17, for example.

This lack of constraint at the edges of the wear path appears to approximate the service conditions of the roller track, as evidenced by the fact that the non-spalled surface of the track received by FIRL was highly polished and glazed similar to the grooved roller. Thus, it is felt that future testing should use this configuration roller.

7.2.2.2 Spalls

No specific inclusion or surface crack initiating defects were evident when the spalls on the 52100 rollers were analyzed in the SEM. However, spall initiating defects are often removed in the spalling process. The fracture details within the spalls were smeared over indicating the spall fragments had been cyclically pressed into the surface as cracking progressed prior to exfoliation. Extensive secondary cracking was present around most of the spalls, with the cracks, like the spalls, running almost across the entire wear path.

A typical example of the spalls on the track rollers is presented in Figure 7-22. These spalls, as discussed in 7.2.1.2, were primarily confined to the central portion of the wear path in contrast to those on the 52100 steel. Secondary cracking was present on the surfaces of the track rollers, but, similar to the spalls, these cracks were more limited in extent across the wear path than those on the 52100 rollers. Furthermore, the individual small segments of each spall appeared to be smaller in magnitude than those on the 52100 steel indicating that crack propagation had occurred with smaller pieces exfoliating than in the case of the hardened 52100 steel. Consistent with the hardness, the fracture segments within the spalls appeared somewhat more deformed and smeared over than those in the harder 52100 steel.

In most cases, a single incidence of significant spalling was noted around the circumference of each track roller. However, on roller 29, which failed after 85 hrs., a second small spall was in the process of forming, Figure 7-23, and on roller 20 (49 hrs.) there was a series of small spalls in the initiation stage, one of which is shown in Figure 7-24. Incipient spalling appeared somewhat different on the grooved roller, Figure 7-25.

A

100X

B

500X

Figure 7-22. SEM micrographs showing regions within the large spall on roller #23 (29 hrs.). A lower magnification view is in Figure 7-9. Multiple cracks are evident in A and a smearing over of the fracture details is particularly evident in B.

Figure 7-23. SEM micrographs of roller #29 (85 hrs.) showing a spall in the early stages of formation. B and C are higher magnification views of the left and right hand regions of A. The surface details within this small spall are similar to those within the larger spalls, in Figure 7-22.

A

55X

B

300X

Figure 7-24. SEM micrographs of track roller #20 (49 hrs.) showing in A the largest of a series of small spalls present in a circumferential band on the surface. In B the early stages of exfoliation in one of the smallest spalls are evident.

A

100X

B

1000X

Figure 7-25. SEM micrographs showing incipient spalling on roller #26 (21.8 hrs.). In contrast to spalling on other test rollers, this defect is not perpendicular to the running direction which is vertical in the micrographs. The white outlines are the results of thin layers of exfoliating metal elevated above the primary surface.

7.2.3 Metallographic Cross Sections

In order to evaluate the effect of running upon the microstructure of the material and the possible influence of this microstructure, including inclusions, on crack initiation, transverse cross sections of representative rollers were studied. The rollers were cut at the central region of a spall or the center of the wear path and, after nickel plating the surfaces in order to minimize the rounding-off of the contact surface during polishing, they were metallographically prepared. Analyses were conducted under the light microscope and in the SEM on samples in the unetched and etched conditions.

In the 52100 steel rollers crack branching associated with spalling was apparent but no initiating factors could be identified. No evidence of microstructural alterations or of any modification of the original sulfide inclusion morphology was detected.

On the cross sections of the track steel no microstructural alterations to the original tempered martensite were noted. There was a series of cracks associated with each large spall, similar to the 52100 steel, Figure 7-26. In no case was a specific inclusion or other defect found associated with any of the large spalls, nor did the cracks follow specific paths such as grain boundaries. However, the relatively large amount of material removed in the spalling process makes it unreasonable to rule out the possibility that a specific inclusion had contributed to and then been removed by the spalling. One example of a sulfide inclusion in a region of subsurface cracking is shown in Figure 7-27. It was not clear whether this cracking was connected to an actual spall or if this was a location of incipient spalling.

Significant alteration of the near surface sulfides had occurred in most of the track rollers. The original blocky or equiaxed shape, Figures 7-5 and 7-6, was changed to a stringer configuration, Figures 7-27b and 7-28. When present, the stringers were always oriented at a shallow angle to the surface, indicating that a specific deformation mode had been operative. In the extreme case, some of these sulfides were thinned out to such an extent that they appeared to be cracks rather than inclusions. However, energy dispersive x-ray analysis (EDXA) in the SEM proved the presence of high manganese and sulfur.

A

100X

B

300X

Figure 7-26. SEM micrograph of a polished transverse cross section of roller #23 (29 hrs.) Cracking emanating from the major spall is at the lower left in A. B is a higher magnification view of the central region of A and shows additional cracking which may connect with the primary cracks on another cross sectional plane of polish. Also, in B, there is an elongated sulfide inclusion, indicated by the arrow near the contact surface.

A

300X

B

1000X

Figure 7-27. SEM micrographs of a transverse cross section of roller #24 (394 hrs.) showing subsurface cracking. The region indicated by an arrow in B is manganese sulfide. It is not known if this cracking started with the sulfide or if it is a continuation of cracking associated with a spall which intersects the surface on another cross sectional plane.

A

600X

B

600X

Figure 7-28. SEM micrograph showing examples of elongated sulfide inclusions near and at the running surface on the polished transverse cross section of roller #29 (85 hrs.). A layer of nickel plating prevented rounding of the contact surface edge.

In roller 20, in which a series of small spalls had been identified in the macrographic and SEM surface analyses, it was found that these spalls were associated with the stringer sulfide inclusions, Figure 7-29. Stringer sulfides were absent, Figure 7-30, in roller 24 which had the longest life of any failed track roller. This latter roller also exhibited little scalloping but it should not be concluded that there is a direct relationship between scalloping and the formation of sulfide stringers. For example, in roller 20, which had a short life of 49 hours, there was pronounced sulfide elongation but scalloping was very limited. Thus, there may be two competing failure modes both of which could lead to spalling. Roller 24, which had very little scalloping and no alterations of the sulfides, exhibited a long life. On the other hand the shorter lived rollers had pronounced scalloping and/or sulfide stringers present.

Roller 21 which had not failed in 424 hours of running was similar to roller 24 in that neither scalloped wear path boundaries on the surface nor elongated inclusions on a polished transverse cross section were present. There was some indication of a tendency of the sulfides to elongate but even those very close to the surface, Figure 7-31, were still relatively blocky compared to the pronounced elongation of those in other rollers, for example, Figure 7-28.

There was little or no scalloping on the unfailed 4140 test rollers, but on a transverse cross section elongation and alignment of near surface sulfides was noted. However, since the average original sulfide cross section, Figure 7-4B, was much smaller than that in the track steel, Figures 7-5 and 7-6, the elongated length of the sulfides, Figure 7-32, was very limited. Furthermore, since the processing of the steel into the bar caused the sulfides to be elongated along the axis of the bar (and thus normal to the test running direction), elongation normal to the bar's axis during testing would produce short sheets of sulfide rather than thin stringers.

Based on the above, it appears that the original sulfide shape and orientation may be important with regard to crack initiation. A forged steel in which the inclusions and flow lines would all run parallel to the rolling direction might be expected to have a longer life than a steel in which flow lines and inclusions are normal to the rolling direction. However,

A

150X

B

600X

Figure 7-29. SEM micrographs of a polished transverse cross section of roller #20 (49 hr.) showing minor spalling associated with an elongated sulfide inclusion.

A

500X

B

1000X

Figure 7-30. SEM micrographs of a polished transverse cross section of roller #24, showing sulfides near the nickel plated surface. In spite of the long running time - 394 hours - little or no elongation of these near surface sulfides was noted.

A 500X

B 500X

Figure 7-31. SEM micrographs of a transverse cross section of track roller #21 (424 hrs., no failure) showing sulfides near the contact surface in the process of elongation. Most near surface sulfides on this roller experienced little or no elongation.

A 1000X

B 3000X

Figure 7-32. SEM micrographs of a transverse cross section of an unfailed 4140 roller (400 hrs.) showing elongated near surface sulfides. Compare the length of these sulfides at 1000 and 2000X with those in Figure 7-29 at 150 and 600X.

further elongation of an already long inclusion could then lead to defects whose lengths are critical with regard to crack initiation. Further testing of 4140 steel with sulfides elongated in the rolling direction would help to resolve this question.

On polished cross sections of the track from which the roller samples were prepared, an analysis was made to determine if near surface sulfides had been strung out in a manner similar to that in the test rollers. No examples of elongated sulfides were found. However, the surface of the track had undergone extensive spalling, and once this spalling had occurred the non-uniform surface in conjunction with the existing cracks may have accelerated further spalling. Thus the surface may not have experienced a sufficient number of loading cycles to induce sulfide stringer formation.

7.2.4 Hardness

Hardness measurements were taken directly on the contact and unrun surfaces as well as on cross-sections of the test rollers in order to determine the degree to which the surface deformation increased the hardness of the different materials. By conducting R_C , R_A and superficial surface hardness tests, information about the depth to which the hardness increased was obtained since the respective test loads of 150, 60 and 15 Kg cause different indentation depths and hence sample different surface layer thicknesses. Microhardness testing on cross sections of the rollers further defined the hardness alterations as a function of depth below the surface.

The surface hardness data, which are presented in Table 7-1, indicate that all rollers, including the 52100 fully hardened steel, experienced significant wear path hardness increases. It is also evident from the differences among the R_C , R_A and superficial data that the hardened layer is relatively shallow. The surface hardness of the track and 4140 steels approached the initial hardness of the 52100 steel while the latter, although nominally fully hardened by heat treatment, was further hardened by the running.

The scatter in the data, and the likelihood that spalling may have influenced the hardness increase in failed rollers made it impossible to correlate hardness increases with running time. Thus, it is not clear whether any significance can be attributed to the fact that the hardness

TABLE 7-1

Surface Hardness Data *

52100 Steel

Specimen

	Edge		Center		Edge		Unrun	
	Rc	15N	Rc	15N	Rc	15N	Rc	15N
1(96 hrs.)	60		60		59		56	
	(64)	92	(64)	92	(63)	91	(56)	88
4 (372 hrs.)	60		61		60		56	
	(65)	92	(66)	93	(62)	91	(56)	89
4 opposite end (141 hrs.)	60		61		60		56	
	(65)	92	(66)	93	(61)	91	(56)	89
5 (182 hrs.)	61		61		59		57	
	(66)	92	(66)	92	(64)	92	(60)	90

Track Steel

23(29 hrs.)	48		49.5		41.5		37	
	(43)	82	(57)	89	(50)	85.5	(36)	78.3
20(49 hrs.)	47.5		50.2		45			
	(51)	86.0	(53.5)	87.2	(53)	87.0	(40)	80.5
29(85 hrs.)	44		50		43.5		37.5	
	(47)	84	(49)	85	(49)	85	(38)	79.3
24(394 hrs.)	44		50		43.5		36	
	(49)	85	(53)	87	(43)	82	(38)	79.5
21(424 hrs.)			(50)	85.6			38	
	(43)	72R _A	(50)	76.2R _A	(43)	72R _A	(38)	79.2
21 opposite end (124 hrs.)			(56)	88.6			38	
	(46)	73.5R _A	(52)	77R _A	(46)	73.5R _A	(38)	79.2

TABLE 7-1 - continued

Surface Hardness Data*

4140 Steel

Specimen

	Edge		Center		Edge		Unrun	
	Rc	15N	Rc	15N	Rc	15N	Rc	15N
400 hrs.	44		52		39		33	
	(52)	86.5	(59)	89.5	(50)	85.3	(36)	78.6
400 hrs.	50		52		52		32.5	
	(51)	86	(55)	88	(52)	86.5		

*150 Kg load for R_C , 60 Kg load for R_A and 15 Kg load for 15 N.

Readings in () are R_C converted from 15N or R_A .

of the 4140 unfailed rollers exceeded that of the 394 hour unfailed track roller. Also, it is not clear if there is a limit to the deformation or degree of hardening which a steel can experience, dependent upon the material, its initial microstructure and the test conditions. If such a limiting hardness is a consequence of a material's inability to undergo further plastic deformation and thus accommodate contact stresses, it may reflect the onset of spalling. In addition, if inclusions or other stress raising defects are present, localized hardening may lead to cracking prior to the bulk of the material's having deformed to this saturation limit.

A hardening and failure mechanism such as this can help to explain why the softer 4140 steel exhibited longer life than the initially hardened 52100 steel. Also, the softer track material which had more stress raising defects, i.e., inclusions, would thus be expected to have a shorter life than the 4140 steel. The track steel's life relative to that of the 52100 steel could be longer or shorter depending upon the relative effectiveness of the inclusions and the steel's ability to deform. Since the rate of work hardening in a material is dependent upon initial microstructure as well as its initial hardness, there may be an optimum combination of these parameters which could be achieved by heat treatment. Further testing would help to define this hardening phenomenon and its influence on rolling contact life.

The microhardness data, Table 7-2, indicate that the depth of hardening in the 52100 steel was very limited, consistent with the absence of appreciable surface deformation. In contrast, the hardening of the softer track and 4140 steels extended to about .005" below the surface. It also appears that running time influenced the depth of hardening in the track steel. The 624 hour unfailed roller hardened to a greater depth than the 29 hour failed roller, while the depth of hardening for the unfailed 624 hour track steel and the 400 hour unfailed 4140 steel was very similar. This supports the theory that the bulk steels behaved similarly with regard to deforming and resisting cracking, and that inclusions in the track steel were a major factor in initiating spalling failures.

The hardness data at the contact surface region on the track from which the roller test samples were machined are also included in Table 7-2. Except for a reading which appears to have been influenced by the presence of a crack, the maximum hardness very near to the surface appears to be less than that on

TABLE 7-2
Cross Section Microhardness Data

52100 Steel

Specimen	Depth Below Surface (in.)	Knoop Hardness Number (KHN)	R _C (converted)
6(246 hrs.)	.003	650	56
	.013	616	54
	.023	606	53.5
	.033	634	55
	.043	666	57
	.053	646	56

Track Steel

22 (625 hrs.)	.0045	545	50
	.0145	471	45
	.0245	449	44
	.0345	440	43
	.0445	426	42
	.0545	420	41.5
23 (29 hrs.)	.004	562	51
	.014	510	48
	.024	453	44
	.034	479	46
	.044	373	37
	.054	340	34
Actual Track Surface	.0025	409	40.5
	.0125	416	41
	.0325	471	52
	.0425	454	44
	.0525	460	44.5
	.0625	416	41

crack

TABLE 7-2 continued
Cross Section Microhardness Data

4140 Steel			
Specimen	Depth Below Surface (in)	Knoop Hardness Number (KHN)	R _c (converted)
624 hrs.	.003	445	43.5
	.013	445	43.5
	.023	481	46
	.033	423	42
	.043	389	39
	.053	390	39

the test rollers. However, there is a hardened layer which is similar in depth to that on the roller which ran for 625 hrs. Since the surface of the track was highly irregular owing to the presence of spalling, the actual location of a cross section must strongly influence the hardness readings. Also, there is no way to determine how long this particular layer had been undergoing stresses after spalling in this region had occurred. Thus, there may be regions where a maximum hardness equivalent to that on the rollers was developed.

7.3 GENERAL DISCUSSION

As a result of the rolling contact testing and the analyses of the test samples several variables which have an influence on rolling contact life have been identified. Some of these have been partially defined, while the effect of others upon life have only been indicated to a certain extent.

1. Advantages of wrought versus cast material

The wrought 4140 steel had a significantly longer life than did the cast steel in the rolling contact tests which simulated the loading in dragline roller track applications. The inherent differences between the cast and wrought material which are responsible for the life differences include the smaller density and size of inclusions, the specific directionality of the inclusions and the finer and more homogeneous microstructure in the wrought material. By vacuum processing a molten steel and then working the ingot into a final shape, solidification defects and inclusions can be minimized and their morphology controlled. In this manner the discontinuities which act as stress raisers when a steel experiences service loads are also minimized. If a steel were cast in such a manner that inclusions and porosity were kept below a certain critical size, which would have to be defined empirically, then the service life of a cast steel would be expected to improve. However, it is not clear if the life would approach that of a vacuum degassed, wrought steel.

2. The role of sulfide inclusions in initiation failure.

Although sulfides, owing to their ability to deform, are generally thought to be more innocuous with regard to initiating cracking than hard oxides, it appears that the sulfides which were elongated by the rolling contact tests acted as wedges or cracks to initiate spalling. Furthermore, since the unidirectional rolling contact loading introduced a specific directionality of elongation, reversal of the running direction may have a very strong influence upon how these inclusions would be altered and in turn what effect this would then have upon contact life. The original inclusion morphology also appears to be important, since elongation along the direction of spall cracking, i.e., downward from the surface, would be

more limited in the case of sulfides originally elongated normal to the rolling direction rather than parallel with it. Accordingly, testing is recommended in order to define the influence of sulfide size, shape and orientation in conjunction with the rolling direction upon life.

3. The role of a steel's hardness and its ability to accommodate the loading stresses

A fully hardened 52100 bearing steel was used in this study in order to establish a base line of data in accordance with rolling contact bearing theory and not to evaluate its potential for use in dragline roller track applications. However, the results do indicate that such a fully hardened steel should not be considered for roller track use. The major reason for this appears to be the inability of the fully hardened steel to accommodate high stresses by means of plastic deformation. On the other hand, contrary to rolling contact theory, the relatively soft 4140 steel, which is equivalent to the 52100 steel in its cleanliness and its processing into the bar stock from which the test samples were machined, experienced extensive localized deformation and yet no failures occurred within the limits of testing time available. The question, therefore, arises as to whether there is some optimum hardness for a clean steel which will lead to a maximum life. At a hardness greater than the $35 R_c$ the rate of deformation and work hardening may be reduced and this in turn may be a factor in initiating a crack initiation. However, as the hardness approaches $R_c 60$ the steel may be so hard that insufficient deformation can occur to permit accommodation and relaxation of highly localized stress concentration. Accordingly, further evaluation of this aspect is strongly recommended.

Another factor which should not be overlooked is the role of the microstructure of the steel in the deformation and accommodation process. Since the rate of work hardening and the uniformity of deformation is dependent upon the initial microstructure, and since a range of microstructures and processing treatments can all result in a particular final hardness for a steel, it may not be appropriate to consider hardness alone without characterizing and controlling the microstructure. Thus, such factors as grain size, size of carbides and the presence of retained austenite

or bainitic transformation products may all play a significant role along with the hardness in controlling the rolling contact life.

4. Uniformity of surface deformation

The presence of scalloped boundaries at the edges of the wear paths on the test rollers appeared to preclude long life. Accordingly, this indicates that non-uniform deformation at the contact boundaries should be avoided. Factors which can contribute to the non-uniform deformation include: the microstructure and mechanical and metallurgical anisotropy in steel; the contact loading, including geometry, particularly track width; and the lubrication. Since plastic deformation generates heat the effect of this heat upon localized dimensional changes and upon the lubricant is also of importance. Furthermore, surface coatings may offer potential means of controlling the overall surface deformation as well as its uniformity, particularly at the boundaries of the contact zone. Since there are so many interacting parameters which can influence this deformation, it appears that a well defined program to evaluate the individual parameters would be justified.

5. Steel composition

Since many of the variables discussed above are dependent upon alloy composition, there may be certain steels which are better suited for drag line roller track applications. For example, the transformation characteristics of a steel are a function of composition and, thus, if a particular microstructure-hardness combination leads to long track life, this may define the alloy of choice. Similarly, if crack propagation proves to be a critical parameter, there could be a specific choice of microstructure, hardness and alloy. Comparison of published data will help to narrow the list of potential steels and avoid excessive testing.

It is not surprising that 4340 steel has been used for roller track since there exists such a large background of application experience for it. 4340, as well as 4140 steel, can be heat treated to achieve a wide range of microstructure-hardness (mechanical property) combinations and therefore both are reasonable alloy choices for further studies aimed at defining the critical parameters controlling track life.

7.4 CONCLUSIONS

1. The test results indicate that a vacuum degassed wrought steel at a hardness of about $35R_c$ should have a significantly longer life in drag line roller track applications than the cast 4340 track steel tested in this program.
2. Sulfide inclusions were elongated by rolling contact. These elongated sulfides appeared to act as cracks in the initiation of spalls in the track steel. The elongated size of the sulfides in the 4140 was much smaller than in the track steel, owing to an originally smaller cross section. The longer life of the 4140 steel likely is due in part to this factor. Additional work is required to define whether the original direction of alignment, relative to rolling direction, of inclusions in a forged steel can play a significant role in controlling the initiation of cracking.
3. The expected life of a cast steel should be increased if casting defects and inclusions can be controlled to specific limits. Such limits would have to be defined by further testing.
4. In the testing, long life was fostered by the ability of a steel to deform under the rolling contact loads typical of dragline roller track. When the deformation of the edges of the wear path was non-uniform or scalloped, early failures resulted. Deformation leads to self-crowning and to the reduction of localized high stresses caused by service and artificially introduced defects. There may be an optimum hardness for track steel which balances the deformation accommodation with retention of dimensional configuration.

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8. GENERAL CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

1. Forged vacuum degassed tool-alloy steel (4140) exhibits superior fatigue life, compared to a cast tool-alloy steel (4340 , cut from used roller track), at similar hardnesses (RC35 to RC38). The limited testing done does not permit a multiplication factor to be used for comparison.

2. Work hardening and the rate at which the surface hardness changes can greatly affect the fatigue life of these softer tool-alloy steels.

3. These alloy steels (in the RC 35-38 range), exhibit good freedom from sensitivity to stress raisers like brinell marks and small holes.

8.2 RECOMMENDATIONS

1. Where possible use forged vacuum-degassed tool-alloy steel for roller track and rollers.

2. The testing time required to get fatigue life ratings at lower stress levels (150,000 mean Hertz) demands more knowledge of actual load levels occurring in running machines. Armed with this information it may then be possible to more easily recommend stress and hardness levels appropriate for further testing. Such testing would be desirable for optimization of design procedures for roller track bearings.

3. In the absence of more complete data, the suggested roller track calculation method discussed in detail in Section 6 is recommended. The design method and life ratios to hardness given should be a more realistic calculation of anticipated roller track life.

4. The largest unknown in the recommended rating method of Section 6.0 is the application factor a_3 . More field information is needed to accurately describe actual roller load in operating draglines. A finite element analysis of the complete dragline structure can also be used to calculate actual roller loads.

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Appendix

MATERIAL SPECIFICATIONS

THE FRANKLIN INSTITUTE RESEARCH LABORATORIES
THE BENJAMIN FRANKLIN PARKWAY • PHILADELPHIA, PENNSYLVANIA 19103

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AISI 4140 ANN. VACUUM DEGAUSS

SYMBOL BDAH

SIZE

COLOR IDENT. BLACK & YELLOW

SOURCE

REPUBLIC STEEL

HEAT No. 8076998

CUST. ORDER No.

DATE

CUR. ORDER No.

HEAT ANALYSIS	C	Mn	P	S	Si	Ni	Cr	Mo	Pb	Grain Size
	.425	.92	.013	.024	.31	.23	.94	.21		7
WORKING TEMPS.	Oil Quench 1550/1600 °F.			Anneal 1450/1550 °F.			Forge 1950/2250 °F.			Norm. 1000/1700 °F.

Mechanical Properties as Interpreted from End-Quench Tests

Quenched in OIL at 1550 °F. and tempered as shown.

Size of Round	Tempering Temperature	Rock "C" Hardness	Tensile Strength (X1000 PSI)	Yield Point (X1000 PSI)	% Elong. (2 inches)	% Red. Area	Size of Round	Tempering Temperature	Rock "C" Hardness	Tensile Strength (X1000 PSI)	Yield Point (X1000 PSI)	% Elong. (2 inches)	% Red. Area
1-inch	800	43	198	189	12.6	46.5	4-inch	800	37	170	159	16.0	52.3
Center	1000	36	166	155	16.4	54.0	1/2 Radius	1000	32	149	136	18.4	57.4
	1200	27	131	115	20.4	61.4		1200	22	117	99	22.0	63.0

NOTE: This data is believed accurate within normal testing limits, but is applicable only to material marked with the symbol shown at top of page. Check your shipment to be sure it is stamped or tagged with this certificate.

THIS CERTIFICATE NOTARIZED ONLY WHEN REQUIRED

I, _____, a Notary Public do hereby certify that this affidavit was subscribed and sworn to before me by a duly authorized agent of Joseph T. Ryerson & Son, Inc., this _____ day of _____.

We hereby certify that the foregoing is a true copy of the data furnished us by the producing mill or the data obtained from tests performed in the Ryerson Laboratory.

JOSEPH T. RYERSON & SON, INC.

MY COMMISSION EXPIRES

NOTARY PUBLIC

C-16-74

material certification

Franklin Institute
20th & Parkway
Phila., PA 19103

Attn: Purchasing

DATE

2/28/1977

OUR ORDER NO.

09-666549

YOUR ORDER NO.

24942

ITEM DESCRIPTION

HEAT NUMBER

1 pc. Alloy HR 4140 Ann.
1-1/8"RD x 12'0"

8076998
Republic

This document certifies that the material described
above was shipped on your order and that the attached
data is a true copy of the test report furnished by
the producer with said material.

JOSEPH T. RYERSON & SON, INC.

By

(Authorized Agent)

PETERSON STEELS, INC.
 SPRINGFIELD ROAD, P. O. BOX 157, UNION, NEW JERSEY 07083

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	DIR. PAY.	☐										
	SERV. OCC	☐										

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52100 BQ CD SA VD STEEL BARS
 1 R/L 1.125" Rd
 40#

CERTIFICATE OF ANALYSIS ATTACHED ☐ VENDOR NO. _____

We certify that the following information is true and correct in regard to the above steel as contained in the records of the company.

Heat No.	Carbon	Manganese	Phosphorus	Sulphur	Silicon	Chromium	Nickel	Molybdenum	Copper
113945	1.05	.38	.006	.008	.30	1.45	.18	.03	.13

DATE 10/25/76

PETERSON STEELS, INC.

BY: _____
 AUTHORIZED SIGNATURE

CERTIFICATE OF ANALYSIS