R-586

FINAL REPORT

GYRO BEARING IMPROVEMENT PROGRAM

TASKS 1 TO 6 - NAS 9-3079

by

Steven Allen

June 1970

CHARLES STARK DRAPER LABORATORY

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

R-586

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NAS 9-3079

ABSTRACT

The Gyro Bearing Improvement Program bettered the technological base for the manufacture, test, and application of very precise spin-axis ball bearings. The tasks covered include exploration of novel hardening techniques and matching manufacturing techniques on a limited range of stainless steels, as well as bearing surface evaluation techniques. The program final bearings demonstrated the improvements through their excellent geometry and finish.

Steel lots of 440C and 440B as well as a 14% Cr, 4% Mo, 1% V martensitic grade were selected on the basis of standard and specially developed inclusion ratings, primary carbide conditions, response to conventional heat treatment, and other quality indices. Variations in conventional heat treatment, and ausforming, strain aging, and a nitriding treatment were investigated, leading to the strengthening of the steel matrices. The manufacturing techniques developed include direct extrusion ausforming, special dimensional control to allow surface hardening, and means for forming bearing rings from fully hardened bar stock.

Race-groove manufacturing techniques were investigated, especially finish grinding and honing, resulting in greatly improved race-groove geometry and finish. The manufacturing approach of establishing final race-groove geometry by grinding and following this by finishing with minimal stock removal was validated. Critical manufacturing stages, requiring close engineering control, were identified. It was also shown that the manufacturing and finishing techniques exert a greater influence than the range of material parameters explored.

Race grooves of bearing parts were investigated and rated by specially developed quantitative visual, pseudo-functional, and other means. These included taper section, near-surface metallurgy, running electrical resistance, lubricant-degradation analysis, local running-temperature measurement, and surface finish by coherent light reflection.

Of the three steels with various hardening treatments, 440C conventionally hardened was found best, with the 14-4-1 ausformed next. In fixture tests the final bearings, before rehabilitation, inadvertently demonstrated the major effect that race-groove surface chemistry can play.

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SECTION 1

PROGRAM DESCRIPTION AND SUMMARY

1.1 Introduction

The Gyro Bearing Improvement Program was designed to better the technological base for design, manufacture, test, and application of spin-axis ball bearings, simultaneously probing some concepts for step-function improvements in the technology. The vehicle chosen for the main thrust was that of exploring novel hardening techniques and matching manufacturing techniques on a limited range of stainless steels. These were coupled in part because prior work* showed that inconsistent manufacturing technology might vitiate the range of materials explored for potential use in spin-axis ball bearings.

There were several reasons for expecting improvements in hardening and manufacturing to further the geometry, finish, and surface condition of the ball bearing. As-manufactured geometry evidently hinges on the manufacturing technique and because normal 440C stainless steel contains relatively hard, large carbides in a considerably softer matrix, treatments increasing the hardness of the latter would make 440C more homogeneous, leading to a better finish. Similarly, improved mechanical properties should lead to improved surface conditions in the race grooves. The combination of these were then expected to enhance the reliability and performance of these bearings in gyroscopes. The main avenue of the program was therefore aimed at providing fixture and gyro test-verified bearings to demonstrate the improvements.

1.2 Participants and Areas of Work

MIT, acting through the Instrumentation Laboratory of the Department of Aeronautics and Astronautics, was the prime contractor. The Barden Corporation and ManLabs Inc. were the two principal subcontractors, acting in the capacities of bearing manufacturer and metallurgical agency respectively.

It should be noted that on January 1, 1970, the Instrumentation Laboratory was renamed the Charles Stark Draper Laboratory after its founder but will be

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* AF33(616)-6664.

referred to throughout this report by the name then current, or MIT/IL. MIT/IL has a semiautonomous group substructure and the work being reported here, i.e., Tasks 1 through 6, is that of the Inertial Gyro Group with some in-house support from the Gyro Research Group. These groups, in turn, are distinct from the FBM-B Group which had designed and holds design responsibility for the Apollo Guidance System gyroscopes. As explained in Section 2.6.1 and reported on separately,[(1)*] under Task 7 FBM-B gyro tested some of this program's final bearings in refurbished units of the early Apollo I design, referred to here as Modified Apollo I IRIG's.

Except for Task 7, the Inertial Gyro Group provided overall management and coordination to the program, and made the program decisions in cases of conflicts of ideas or interests. Using the support of the Gyro Research Group Metallurgy Section, program personnel supplemented, verified, and in some instances extended the subcontracted and other outside metallurgical effort. This included participating in on-the-manufacturing-floor supervision during critical phases. MIT/IL also played the major role in the mechanical and surface chemistry aspects including assembly and test of various types of bearings both for mainline program and ancillary efforts.

Program coordination was obtained by meetings held monthly through most of the program reported on. These, on a rotating basis, were at MIT/IL and at each of the two subcontractors and were informally chaired by MIT/IL using a "modified family plan" to obtain interaction from a broad range (technician to director of research) of individuals participating in the program. In addition to obtaining and interjecting new ideas from many sources, MIT/IL was the principal disseminator of program information – functions greatly aided by its status as an arm of an academic institution. Meetings were supplemented by monthly, quarterly, and occasional special subcontractor reports and by frequent contact in person and by telephone between MIT/IL and these subcontractors during crucial periods of the program.

The metallurgical agency, ManLabs Inc., had been a subcontractor on MIT/IL bearing research and development on several programs for about seven years prior to the start of this one. ManLabs initially suggested the use of unconventional hardening techniques, especially thermomechanical, for spin-axis ball bearings partly as an outgrowth of their then current work. The concepts evolved over a period of about three years before this program as a result of the many technical sessions held between MIT/IL, ManLabs, and Barden.

As the metallurgical agency, ManLabs had the responsibility for the selection of stock including the grade of modified 440C to be used, the inspection

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* Superscript numerals refer to similarly numbered references in the List of References.

of stock, and the development of the special hardening treatments. After selection of certain steel-hardening treatment combinations they then had to produce sufficient quantities for bearing-part manufacture, testing the results both before and after that manufacture. ManLabs semi-independently developed techniques for rating visually observable imperfections in race grooves and further evaluated sample race grooves by taper sections.

The bearing manufacturer, The Barden Corporation, through its RPM Division, had been a subcontractor in MIT/IL bearing research and development for 18 years prior to the start of this program and was a major supplier of ball bearings for the U.S. precision-gyroscope industry. As bearing manufacturer, Barden had program responsibility for development, improvement, and application of manufacturing techniques — in a production-engineering sense, primarily grinding and finishing and very detailed supervision of all manufacturing processes in order to ensure control. Barden also rated race grooves and explored and developed several race-groove and bearing evaluation techniques. The latter included visual examination for race-groove imperfections, laser holography, infrared microscope analysis of race-groove temperatures, surface-finish profilometry and vapor-phase chromatography for changes in lubricant. In addition, the bearing manufacturer was the program's source for precision measurements of rings — needed for dimensional-stability tests and for determining size changes due to surface treatments.

1.3 Program Tasks

The effort described in this report covers program Tasks 1 through 6 which, as amended, are given below:

Task 1	Evaluate the influence of heat treatment variables on 440C type steels with regard to structural characteristics such as grain size, carbide size and distribution, and retained austenite; and with regard to mechanical properties such as hardness, strength and stability.
Task 2	Evaluate the influence of thermo-mechanical (ausforming, tempforming) and surface (nitriding, Malcomizing) treatments of Task 1 steels on structural characteristics and mechanical properties.
Task 3	Evaluate by visual examination, metrology, surface metallurgy, and race groove test, the machinability, finishability and surface characteristics of steel treatment combinations selected from Tasks 1 and 2.
Task 4	Evaluate means of reducing bearing torques.

Task 5	Manufacture precision bearings from the two best steel treatment combinations, as determined in Tasks 1 through 4, using techniques developed in this program and information from related efforts in other programs.
Task 6	Conduct life tests on the precision bearings manufactured in Task 5.

For reference, the further tasks not covered under this report can be summarized as:

Task 7	Assemble and test five Apollo I IRIG's incorporating the Task 5 instrument bearings.
Task 8	Evaluate bearing-steel surface chemistry including establishment of fundamental phenomena and development of methods of recognition of, reclamation from and prevention of contamination.
Task 9	Evaluate corrective surface treatments as developed under Task 8 and elsewhere for reclamation of bearings produced under Task 5.
Task 10.	Modify Task 5 and 9 bearings by physical/chemical cleaning techniques, primarily ion bombardment. Test the effect of these modifications using various evaluative techniques and standard gyro criteria.

The final report for Task 7 has been published(1) and final reports on Tasks 8, 9, and 10 will be published separately.

The major effort under Task 1 was by MIT/IL with a lesser one by the metallurgical agency whereas the Task 2 major performer was the metallurgical agency. The major effort in Task 3 was by Barden with lesser participation by MIT/IL and ManLabs. Task 4 was initially conceived and carried out as relatively minor efforts on the part of all three. The major effort in Task 5 was initially that of MIT/IL, then switched progressively to ManLabs and Barden as material for the final bearings was prepared and the bearings were manufactured. The major effort in Task 6 was by MIT/IL with lesser participation by the other two agencies.

The task-number structure is inappropriate for this report, partly because of the interlocked nature of the effort and partly because the subcontractual task numbers and categorizations used in the subcontractor's final report to MIT/IL do not correspond to the above.* The rest of this report will therefore not refer to Tasks 1 through 6 by number.

The program had efforts in many areas, and details of these are beyond the scope of this report. Sections A.2 through A.9 give a functional overview of the effort. Further information on subjects listed there is available on request.

1.4 Conclusions and Summation

The outstanding geometry and finish obtained on the final bearing-race grooves was found to be primarily the result of manufacturing methods and philosophy. Conventional bearing-manufacturing machinery must be kept in high "tune". This is accomplished by first analyzing the machinery, upgrading and adjusting it, and then using an "overqualified" operator during critical production stages, such as race-groove grinding. The last is truly cost-effective because, both in a program like this and in standard gyro-bearing production, the quantity is limited. Another essential ingredient in manufacture is aggressive on-the-floor supervision by the responsible engineer. Despite the range of material-treatment combinations examined in this program, bearing-manufacturing technology was found to dominate. The philosophy of "minimal stock removal in finishing", that is, establishing final bearing geometry by grinding and avoiding modifications of it in finishing, was also justified by the results.

Immediately useful race-groove-evaluation techniques brought to fruition within this program were lubricant film electrical resistance gaging (LFERG) and low-speed endurance testing (LSE). LFERG can be used to determine lot-to-lot differences as well as lot consistency, whereas LSE is a valuable indicator of some surface chemical conditions, discriminating between passivated and/or TCP-treated surfaces versus untreated ones.

The contribution of mechanical hysteresis to the overall running-torque requirement of a spin-axis ball bearing was examined and found to be minor. The subject was also proved complex, thus not justifying substantial further investigation at this time.

Several unconventional hardening techniques — thermomechanical and surface treatment — were developed to the stage of making test-bearing parts and actual bearings. Whereas improvements in mechanical properties were achieved with these treatments, the effects of bearing manufacture dominate in achieving finish and geometry for spin-axis ball bearings. This may not be the case in other

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* This lack of match should be realized if subcontractor reports are compared with this or program monthly or quarterly reports.

applications where some of the techniques, such as ausforming which increases fatigue life, may be more clearly advantageous.

Standard stock-rating techniques, using JK ratings, do not adequately screen stringer inclusions and very small (less than 0.0001-inch) imperfections. Honed stepdown bars are most advantageous for the former, whereas quantitative metallography at 500X or more can be used for the latter. Special heats of steel, 440C and 14-4-1, demonstrated that far better than normal cleanliness can be achieved.

Of the three stainless steels with various hardening treatments, 440C conventionally hardened was found to give the best race grooves. 14-4-1, conventionally hardened to avoid the processing difficulties of ausforming, is potentially better than 440C because of greater tempering resistance and concomitant dimensional stability, but has a shortcoming in cleanliness, compounded by the proprietary-alloy aspect.

Heat treatment of 440C, using the process previously developed to give high hardness, can be carried out adequately at a bearing manufacturer provided sufficient effort is put into the checking and control of the austenitizing and quenching steps.

A metallographically observable alteration of the near-surface microstructure was found to be due to the finishing process. It was concluded that this, the RA process, should not be used for spin-axis ball-bearing race grooves and a very promising alternate to it, the RB process, was developed.

The use of short-wavelength x rays (MoK_{α}) was found advantageous in measuring the amount of retained austenite in 440C-type steels where such measurements have previously had an unacceptably large variance. Further work to reduce this method to practice is needed.

The major effect that race-groove surface chemistry can play was inadvertently demonstrated because the excellent geometry and finish achieved on the final bearings eliminated most of the normally suspect variables. This conclusion led to the initiation of Tasks 8 through 10, to be reported on separately.

Hardware in the form of final bearings with modified surfaces and retainers were provided to the FBM-B group for tests in modified Apollo I IRIG's.

SECTION 2

DEVELOPMENT, DEFINITION, AND TEST OF PROGRAM BEARINGS

2.1 Introduction

2.1.1 General

The overall objectives have been given in Section 1. In order to develop running-test-verified, improved stainless-steel race grooves encompassing unconventional hardening treatments, such hardening treatments had to be developed. Machining processes compatible with the hardening treatments, and improved over the pre-existing ones, were also required. The "mainstream" effort then was:

a. The selection of steels to be used.

b. The development of hardening treatments.

c. The selection of the most promising combinations of steel grade and hardening treatment for manufacture into races, which were called "combos".

d. Evaluation of the first ten, preliminary, combos and a reference lot covering a substantial range of hardening treatment and steel grades.

e. Manufacture of the two final combos selected from among the first group on the basis of the evaluation.

f. Test of these two, Combos K and L, as gyro bearings.

The mainstream effort will be covered in this part of the report, whereas the ancillary effort, such as improvement of the race-groove machining techniques and the development of race-groove rating techniques, will be covered in Section 3 of this report.

2.1.2 Steel Grades

As a result of earlier work,* the 440C grade of corrosion-resistant steel, heat-treated to high hardness, had become standard for new design bearings for the Inertial Gyro Group. This, plus metallurgical characteristics

*AF 04(694)-305, AF 04(694)-305 S.A. No.8, and that reported in Reference 2.

favoring thermomechanical hardening treatments, made 440C the departure point and reference material. The 440B grade was chosen as a lower carbon content homolog to allow greater deformation in the hardened-and-tempered condition than 440C, and to explore the effect of fewer primary carbides (6 versus 9 volume percent for 440C) in achieving better race-groove finishes. The third grade of steel, eventually 14-4-1, was to be a variant of 440C with alloying content modified for higher tempering resistance. This was desired for core hardness in surface hardening and for maintaining hardness and corrosion resistance in strain aging. It was chosen from among several candidate materials.

2.1.3 Combo M, the Reference Lot

The timing of the program required the development of special manufacturing techniques as well as the improvement of existing ones in advance of the delivery of any combo material to the bearing manufacturer. Additionally, since the quantity furnished for most combos was limited, automatic machinery was set up on more expendable material. 440C rod from the lot available early in the program was used to fill these needs. In part, this was fully hardened as solid cylindrical slugs rather than ring-shaped parts to simulate anticipated shapes of material resulting from thermomechanical treatments. Additionally, conventionally hardened 440C provided a single material reference for variants of race-groove machining and, especially, finishing.

2.1.4 Selection of Material-Treatment Combinations for Manufacture into Preliminary Combos

Conventional heat treatment was relatively easily optimized on the basis of mechanical properties, primarily hardness, as an adjunct to materials selection. To form a basis for selection among unconventionally hardened materials, various combinations of steel and such treatments were devised and improved experimentally. Then, at predeterminate intervals, combinations deemed best choices were prepared in larger quantities to allow the manufacture of bearing-like parts (preliminary combos). The timing intervals were to allow in-program feedback to further improve material and manufacturing parameters.

2.1.5 Selection of Final Combos

The preliminary combos were evaluated on the basis of race-groove characteristics such as microscopic appearance and from lubricant film electrical resistance gage (LFERG) data without, in general, running them as high-speed ball bearings. This was necessary because full-scale running tests would not fit the time or financial scope of the program. Nontheless, a limited amount of low- and high-speed bearing operation was used to assure that the surface-hardened combos would not be subject to early drastic failure. Physical and chemical properties realized in the preliminary combos as well as manufacturing and logistic considerations were also incorporated in the ranking, leading to selection of material-treatment combinations for the final components.

2.1.6 Manufacture of Final Combos (K and L)

A specially made lot of 440C was used for final Combo K because experience with the previous program lot showed it to be too high in nonmetallic inclusion content. Although a new lot of 14-4-1 was desired for final Combo L because the amount available from the first was scant, new steel was not available in time, necessitating very parsimonious use of the old lot. Unexpected responses to the thermomechanical hardening treatment, coupled with material scarcity, necessitated corrective action (rather than culling) during bearing manufacture. Bearings of the final combos were made using the best applicable techniques developed during the time span of the program, including a finishing process designed to obviate a metallographically evident modification caused by an earlier finishing method. Bearing pieces from the final combos were evaluated by the same technique used for the preliminary combos and correspondence verified.

2.1.7 Testing of Final Bearings

Final bearings were given high-speed fixture tests in which problems connected with their surface chemistry were discovered, leading into two new tasks exploring and rectifying this. These, Tasks 8 and 9, will be reported on separately, as is the gyro testing of the bearings in the modified Apollo I IRIG's.[1]

2.2 Selection of Stainless Bearing Steels

2.2.1 Specification Requirements

Initial specification requirements covering chemical composition, quality, and response to heat treatment were established for procuring stainless bearing steels. In addition to conventional specification requirements, special requirements covered carbide size and cracked-carbide condition.

Three grades of stainless bearing steel were evaluated: 440C, as the reference grade; 440B, because of its lower carbon content; and variants of 440C, to obtain higher tempering resistance. The variant chosen was 14-4-1.*

2.2.2 Procurement of Materials

A total of 18 lots of stainless bearing steels were procured in the form of billet and rod stock. Based on the results of inspection, three initial lots were selected for making bearing rings (Lots 440C-L2, 440B-L1, and 14-4-1-L3).

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*This is a proprietary alloy, Lesco BG42, manufactured by Latrobe Steel Company. The 14-4-1 designation comes from the nominal chemical composition (Cr-Mo-V), see Table 2-1.

Table 2-1. Composition of steel lots.

Lot Number	Steelmaker, Heat No.	Type of Melt*	Chemical Composition, Ladle Analysis (Weight Percent)									Used In Combo
			C	Mn	Si	S	P	Cr	Mo	V	Ni	
440C-L2	Crucible 25847	AM	1.05	0.44	0.38	0.013	0.019	17.21	0.48	----	----	A, C, G, M
440C-L4	Carpenter 81489	VIM-VAR	1.00	0.37	0.38	0.006	0.012	16.50	0.46	----	0.018	K
440B-L1	Carpenter 810263	AM	0.90	0.48	0.37	0.013	0.016	16.60	0.53	----	0.53	B, H, J
14-4-1-L3	Latrobe C11368	VAR	1.11	0.50	0.29	0.006	0.014	14.60	3.91	1.19	----	D, E, F, I L
14-4-1-L12	Latrobe C60243	VIM-VAR	1.18	0.57	0.44	0.006	0.008	14.28	4.00	1.23	0.14	----

* AM = air melt.

VAR = air melt followed by vacuum arc remelt (also known as CEVM -- consumable electrode vacuum melt).

VIM-VAR = vacuum induction melt followed by vacuum arc remelt.

During the course of the program, it became evident that 440C-L2 was not sufficiently clean. Therefore, steps were taken to obtain another lot (440C-L4) as a special heat (double vacuum melt). Additionally, the quantity of Lot 14-4-1-L3 was deemed insufficient and another special heat (14-4-1-L12) (also double vacuum melt) was ordered. Unfortunately, the late delivery of this lot precluded its use in the final combos. General information on these lots is included in Table 2-1.

2.2.3 Inspection for Steel Quality

Based on initial inspection, some deficiencies were found with respect to nonmetallic inclusion content and carbide condition in most of the 18 lots. A more complete inspection of steel quality was carried out on Lots 440C-L2, 440C-L4, 440B-L1, and 14-4-1-L3, in order to select the best bars from these lots for making bearing rings. Individual bars of Lot 440C-L2 were selected for cleanliness, although unexpectedly high frequencies of stringers were later detected in reexamining bars. This correlates with the occurrence of such discontinuities along the bore surfaces of some Combo A inner rings. All of Lot 440C-L4 bars used were forged and ground from the as-received 1-1/8- to 0.672- and 0.438-inch diameter sizes and were found to be satisfactory after this. Individual bars of Lot 440B-L1 were selected as best material. Quality data on these lots is given in Table 2-2. Background material on inspection methods and ratings has already been published.[3]

Because shortcomings in the standard JK inclusion ratings[4] became evident in this and other programs, improved methods of inspection for stringers were developed. A more complete discussion of this effort is given in Section 4.2.5.

2.2.4 Response to Heat Treatment

The response to heat treatment of four lots of 440C, one of 440B, and six of modified 440C steels was determined with both austenitizing temperature and tempering temperature as variables in most cases. Liquid nitrogen (-320° F) subcooling and double tempering were used on each lot. Using an austenitizing temperature of 1975° F and a tempering temperature of 300° F, the 440C steels attained a hardness of R_C61.9 to 62.6; whereas the 440B steel attained a hardness of R_C61. Using an austenitizing temperature of 2100° F and a tempering temperature of 975° F, two of the three lots of 14-4-1 steels attained a hardness of R_C63.4 to 64.3. Microstructure was in each case found normal and uniform, and no quench cracks were found. Indentation yield strengths achieved were 300 ksi for 440C, 255 ksi for 440B, and 350 ksi for 14-4-1, and these are the baselines for comparing other hardening treatments.

Table 2-2. Quality of annealed steels.

Lot Number	JK Max Severity Rating of Nonmetallics Using Modified ASTM Method A*								Hard-ness (R_B)	Macro-structure	Carbide Distri-bution at 100X (No.)	Avg Large Carbide Size		Avg No. of Cracked Carbides in 3 x 3-inch Field at 1000X
	A		B		C		D					Within Bands (μin.)	Between Bands (μin.)	
	th	he	th	he	th	he	th	he						
440C-L2 (1-inch rod)	1	<1	<1	<1	<1	<1	<1	1	98.5	OK	6	690	450	4
440C-L4 (1-1/8-inch rod)	1.5	0	0	0	0	0	0	0	93.5	OK	6	600	480	4
440B-L1 (1-inch rod)	2.5	0	1.5	0	0	0	1	0	97.3	OK	4	650	450	4
14-4-1-L3 (2-1/2-inch billet)	0.5	0	0.5	0	0	0	1	0	102	OK	6	340	310	8
14-4-1-L3 (1-inch rod)	0.5	0	0.5	0	0	0	1	0	98.5	**	7	300	290	11 11
14-4-1-L12* (1-inch rod)	2	0.5	0	0	0	0	1	0	----	----	----	----	----	3

* Examined from 0.125 to 0.50-inch radial positions at 160X. Maximum severity rating indicates that this rating was found in at least 3% of the fields examined (about 125 total). The unmodified method, which results in a more severe rating, was used for 14-4-1-L12.

** Slight ingot pattern, but acceptable.

2.3 Hardening Treatments

2.3.1 General

Small specimens of each of the selected steel lots (440C-L2, 440B-L 14-4-1-L3) were subjected to various special treatments. The most promising of these combinations were eventually made into preliminary combos, as listed in Table 2-3, and the processes are described below. Details on the experimental work leading to the particular hardening parameters are generally omitted, since some of these have already been published.[5]

2.3.2 Conventional Heat Treatment

Conventional heat treatment is, for this report, defined as hardening by heating and cooling, without mechanical deformation or changes in chemical composition. Prior to this work, conventional heat treatment of 440C had been optimized to obtain maximum hardness with high corrosion resistance and dimensional stability.

Table 2-3. Preliminary combos, treatments, and steels.

Combo*	Hardening Treatment	Steel Lot No.
A	Strain-aged	440C-L2
B	Strain-aged	440B-L1
C	Malcomized	440C-L2
D	Malcomized	14-4-1-L3
E	Conventional	14-4-1-L3
F	Strain-aged	14-4-1-L3
G	Ausformed	440C-L2
H	Ausformed	440B-L1
I	Ausformed	14-4-1-L3
J	Ausformed, then Strain-aged	440B-L1
M	Conventional	440C-L2

* Combo designations K and L were reserved for final bearing manufacture.

2.3.3 Conventionally Heat-Treated Combos E and M

Bearing outer and inner rings of Combo E material (14-4-1-L3) in the soft machined condition were conventionally heat treated. A hardness of about $R_C 64$ was attained with less than 0.005-inch surface decarburization.

Combo M material (440C steel) was used in the development of machining procedures for processing combo races from hardened solid pieces. Combo M pieces, 0.7-inch diameter by 6 inches long, were conventionally heat treated.

2.3.4 Strain-aging

Strain-aging is a process using plastic deformation followed by aging at or above room temperature. Starting with a heat-treated steel in the tempered martensitic condition, an increase in yield strength generally occurs both during the straining and the aging steps. It seemed likely, therefore, that the yield strength of the program stainless steels could also be increased by appropriate versions of this thermomechanical hardening treatment.

2.3.5 Strain-aged Combos A, B, and F

Combo A, B, and F materials (440C, 440B, and 14-4-1 steel respectively) in the form of 0.7-inch diameter by 1.5-inch long pieces, were heat treated and strain-aged. The strain-aging treatments consisted of compressing (a) the Combo A pieces to 4-percent strain and aging at 250° F, (b) the Combo B pieces to 5-percent strain and aging at 300° F, and (c) the Combo F pieces to 5.7-percent strain and aging at 900° F. The compressive strains used were the maximum ones possible without barrelling or cracking. Compared to the corresponding conventional heat treatment, strain-aging resulted in increases in indentation yield strength of about 35 ksi for Lot 440C-L2, 45 ksi for Lot 440B-L1, and 15 ksi for Lot 14-4-1-L3.

2.3.6 Ausforming

Ausforming is a process using plastic deformation of a steel in its metastable austenitic condition. This condition is obtained by austenitizing a steel approximately as in conventional heat treatment, then cooling or quenching to an intermediate temperature, typically in the neighborhood of 1000° F. At this temperature, if held for a time which depends primarily on the chemical composition of the steel, it would start to transform into other phases. The desired deformation must be effected before such transformation occurs and, following this deformation, the steel must be cooled rapidly enough to obviate formation of "high-temperature" transformation products. In contrast to 52100 steel, for instance, 440C and related steels are especially suited to ausforming because they have a relatively large "bay" in their TTT* diagram; that is, there is a substantial time at the prospective ausforming temperatures before high-temperature

* Time-temperature-transformation; for more details see Reference 6.

transformation products form. Based on work with low and medium carbon steels preceding this program, it seemed likely that substantial increases in yield strength and small increases in hardness could be attained by appropriate versions of this thermomechanical treatment.

2.3.7 Ausformed Combos G, H, and I

Combo G, H, and I materials (440C, 440B, and 14-4-1 steel respectively) were made in the form of 0.7-inch diameter by 1.5-inch long pieces. Ausforming was by direct rolling of 6-inch long pieces with four 3/8-inch wide flats machined on the originally 1-inch diameter stock. Hot quenching after austenitizing was to 1050° F. About 40- to 50-percent reduction was attained in 4 to 5 passes by rolling the coupons at 1050° F. After subcooling to -320° F and aging at +300° F, the pieces were ground to 0.7-inch diameter and stress-relieved at 300° F. Compared to corresponding conventional heat treatments, ausforming resulted in increased indentation yield strength values of about 25 ksi for Combo G, 45 ksi for Combo H, and 25 ksi for Combo I.

The following methods of ausforming were also tried, but were unsuccessful: (a) extrusion employing hot canning of one-inch diameter bars; (b) rolling with and without hot canning; and (c) extrusion without canning. Extrusion with or without hot canning resulted in low hardness, whereas direct rolling (without canning) gave improvements in indentation yield strength. Although direct rolling was selected for ausforming Combos G, H, and I, direct extrusion (without canning) was considered to be the most promising ausforming method. Further development work to attain higher strength by direct extrusion is recommended.

2.3.8 Ausformed Plus Strain-aged Combo J

Combo J material (440B steel), in the form of 0.7-inch diameter by 1.5-inch long pieces, was ausformed by direct rolling, and subsequently strained 2 percent and aged at 300° F. This treatment resulted in 30 ksi greater indentation yield strength than conventionally heat-treated 440B steel, but 15 ksi lower than only strain-aged 440B steel (Combo B).

2.3.9 Malcomizing

Malcomizing is a proprietary case-hardening process involving a catalytic surface treatment followed by nitriding. The objective of using Malcomizing to case-harden races was to attain as high a shear strength as possible at a depth corresponding to the maximum Hertzian shear stress under service conditions. As with other case-hardening treatments, Malcomizing results in a depth-varying chemical composition and concomitantly varying hardness. Outer smut and white layers must be removed from bearing race grooves and the soft core must not extend to high stress regions. In order to achieve this, process parameters must be optimized, extent of the various layers predetermined, bearing ring dimensions adjusted, and manufacturing tolerances controlled to fit.

2.3.10 Malcomized Combos C and D

Combo C (440C-L2) and Combo D (14-4-1-L3) were soft machined and given their initial heat treatment. The conventionally hardened rings were then ground to dimensions, based on the results of the development work, that allowed for size changes during subsequent Malcomizing. Malcomizing of these rings was carried out for 60 hours at 1060° F. This treatment resulted in total case depths of 0.013 inch and 0.0115 inch for Combos C and D respectively. The measured changes in race-groove diameter were within 0.0007 inch of expected values. Measured changes in wall thickness and in volume were found to be close to predicted values.

The Malcomized rings were sequentially given hard rough grinding, stress-relieving at 1000° F finish hard grinding and race-groove finishing operations. No evidence was found of either a smut or white layer in the vicinity of the Combo C and D race-groove surfaces. Based on the earlier tests, the depth below the finished race-groove surfaces expected to be above 295 ksi in indentation yield strength and R_C62 in hardness, was about 0.003 inch for Combo C and 0.0045 inch for Combo D. However, the hardness of the Combo C race grooves at a depth of 0.0025 inch (position of maximum Hertzian shear stress) was found to be only R_C59 versus 75 for Combo D. It is not clear whether this is due to aberrations in Malcomizing or in dimensional control during manufacture. Combo C appears to be less advantageous even than conventionally heat-treated 440C races (Combo M) in this respect.

2.4 Machining and Evaluation of the Effect of Materials and Processes

2.4.1 General

Standard gyro-bearing manufacturing technology is based on machining the race-groove-containing parts to approximate shape in automatic machinery using single-point cutting tools. In turn, this requires steels to be in the annealed or normalized state. The conventional manufacturing process follows these major stock-removal steps with soft-grinding, hardening, hard-grinding, and finishing operations. In order to emphasize the effects of material-treatment combinations (rather than treatment methods resulting in unconventionally hardened parts of near-final contour), the standard manufacturing technique was modified to accept fully hardened, solid, cylindrical slugs as input material to the bearing manufacturer. This required development of special techniques, which merged the standard bearing-manufacturing process in the steps that follow conventional hardening.

Some details on the manufacturing processes used have already been published,[7] and grind and finish techniques are described in Sections 3.2 and 3.3. Because of extensive prior experience with R4 bearings, the design of the ten preliminary combos and reference lot approximated these. On the other hand, the processing techniques developed had to have flexibility, so that these would not preclude other designs for the final bearing.

Bearing manufacturers' capability for conventionally heat-treating 440C to the optimized high-hardness levels desired was marginal at the start of this program. Because conventional hardening of 440C for reference-lot material and, as it developed later, for the program final bearings was required, the program was also used as a vehicle to improve the bearing manufacturers' heat-treatment capabilities.

No information on dimensional stability of material hardened by unconventional treatments was available at the start of the program, and it appeared likely that some of the thermomechanical treatments would result in high residual stresses and metallurgical structures less stable than normal. Dimensional-stability tests were therefore given the preliminary combos and incorporated in the final-combo manufacturing schedule at as early a stage as feasible in order to allow for potential corrective actions.

2.4.2 Processing of Hardened Bar-Stock Combos

Combos M, A, B, F, G, H, I, and J were processed from hardened bar stock. The method was first developed with Combo M — the reference lot -- to establish the capability in advance of the actual manufacture from unconventionally hardened stock, and to economize on the latter. The first step in evaluation of the thermomechanically hardened materials was determining whether they could be ground under standard conditions. In all cases, including conventionally hardened 440C bars, the grinding wheel had to be fed into the work piece at a rate sufficient to promote wheel breakdown thus obviating wheel glazing and concomitant excessive heat. No significant difference in grindability between these materials was noted. The cylindrical grind operation also served to provide right circular cylinders for the subsequent trepanning step.*

Concentric carbon electrodes in an electric-discharge machine were used to trepan to depths of approximately one-half inch. The subsequent abrasive cutoff operation produced two concentric rings, to become outer and inner bearing rings, and a small cylindrical core, samples of which were used to check material

*Occasional stock pieces were so misshapen from the hardening operations that the outside diameter of the outer ring also had to be trepanned. Drawings of the standard steps are given in Fig. C-1.

properties. Surface grinding before each cutoff operation produced a face square with the outside diameter of the rings. The first and last quarter inch of all bars were discarded because some Combo A rings had cracks tentatively ascribed to bar end effects. Difficulties encountered included voids formed in the trepanning operation by excessive feed rates and bridging of the electrode-to-work gap by conductive debris. The extent of this effect was controlled by attention to feed rate, current, and coolant flow. Another difficulty arose with some of the early manufactured parts in that one face of the rings was found to be softer than the other. The cause was traced because the only asymmetric operation was that of cutoff. The problem was obviated by using slower feed rates, greater coolant flow, and a greater stock allowance for the post-cutoff face-grinding operations.

Subsequent to the formation of hardened rings, faces were rough and finish ground, outside and inside diameters and race grooves rough ground, and four chamfers ground on each part. This was followed by the engraving of identification on each part, stress relieving, and finish lapping of faces. At this stage, the processing merged that of conventional bearing manufacture.

2.4.3 Conventionally Hardened and Malcomized Combos

Combo E (14-4-1) is the only one of the preliminary combos that was conventionally hardened and manufactured by standard technology. The Malcomized combos, C and D, required an augmented manufacturing sequence adding the surface-hardening step after the post-through-hardening grind and extra all-over grinding steps after this Malcomizing. As with other surface-hardening treatments, the resulting case characteristics vary with depth, and hardening causes unequal dimensional changes on the various surfaces so treated. Much tighter than normal dimensional control had to be exercised throughout most of the manufacturing sequence in order to have the race-groove location correct both dimensionally and metallurgically. The soft operations of Combos C, D, and E were handled as a group and, because existing tooling was easily adapted, the outer rings were made "H" type (separable) allowing subsequent assembly into, and test as, bearings.

Salt pot furnaces were used to austenitize and temper the three combos except for preliminary air tempers given Combo C. The latter, 2 plus 2 hours at 300° F, were incorporated to more closely simulate earlier samples on which initial dimensional-change data had been obtained. 1000° F tempers prior to Malcomizing were used to decrease dimensional changes from that treatment. Complex schedules of dimensional changes for outside, inside, and race-groove diameters and ring width during Malcomizing and later stress relieving were experimentally determined before machining of these preliminary combos. They were verified by running samples from these combos in advance of the main group. In general the actual changes, up to 0.005 inch, were predicted within 0.001 inch, and those affecting race grooves within 0.0007 inch, which was adequate. Special problems encountered were that automatic-lathe operations, using the same tool settings for various lots and grades of steel, resulted in different sizes because of the cutting-tool/material interaction. Salt-bath heat treatments left a tenacious scale on all surfaces, which was removed from all but the chamfers and identification stampings by subsequent machine steps. Several attempts at removing scale from those surfaces were unsuccessful and, because scale interfered in some subsequent operations, this will either have to be obviated or eliminated by extra machining steps and perhaps the omission of stamping in the future. The tighter tolerance at earlier stages and the several shifts of parts from bearing manufacturer to heat treater and back made the production of Malcomized combos substantially more difficult than that of conventionally hardened material. In addition, the failure of the sample Combo C parts to have the expected high hardness at the race-groove surface was never satisfactorily explained.

2.4.4 Conventional Heat Treatment

Work on earlier gyro-bearing programs had evolved a heat treatment, using higher than then-standard austenitizing temperatures, which resulted in higher hardness for 440C.* Still earlier work had indicated poor quality control as well as poor records of bearing-component heat treatments,[(8)] as do later investigations of gyro[(9)] and other bearings.[(10)] The higher austenitization demands a close control of heat-treatment parameters and after several attempts by several bearing manufacturers and commercial heat-treatment facilities, such heat treatments had essentially been taken over by MIT/IL. This function, compatible only on a short-term or emergency basis, first demonstrated feasibility of tightly controlled and well-documented heat treatment. Furthermore, it showed that the particular high-hardness heat treatment could be repeatably performed with moderately good equipment if the process was properly monitored. At the time the first conventional heat treatment (bar stock for the reference lot) was needed for this program, return of heat-treatment responsibility to bearing manufacturers was highly desirable.

The reference-lot parts were therefore hardened and tempered at the bearing manufacturer using their own equipment and providing detailed monitoring by program as well as heat-treatment-section personnel. The heat treatment, though successful as indicated by the later checks, alerted the bearing manufacturer to shortcomings in their processing equipment and normal procedures. By the time Combo K was to be hardened, many equipment and general procedure improvements had been instituted. Because success of the heat treatment was critical and in keeping with the general control philosophy evolved in the program, on-the-floor monitoring and test was provided by Barden's program manager

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* AF 04(694)-305.

as well as by ManLabs and MIT/IL personnel. The success demonstrated the bearing-manufacturer's competence in performing this heat treatment.

The heat treatments of the reference lot and of Combo K used a 1975° F half-hour austenitization followed by oil quench subcooling first to -110° F, then liquid nitrogen, a two-hour 300° F temper, and a repeat of the subcool and temper steps. After the major stock removal, these were followed by stress-relief treatments of one hour at 300° F for the reference lot and five hours for Combo K. Extensive details on the heat treatment as well as a specific system for monitoring and quality control are given in one of the 10H gyro specifications.(11) The reference-lot pieces were bars, 0.7-inch diameter and 6 to 7 inches long, and because they were considerably oversize, were essentially insensitive to the heat-treatment surface modification that had accompanied a substantial fraction of previous bearing production runs.(12) Hardness achieved was approximately R_C62. Combo K heat treatment in general followed the procedure of the 10H gyro specifi tion(11) with equipment qualification and quality-assurance requirements somewhat lessened since that specification is intended to provide a self-checking system for continual production. A conveyer furnace was used, but in the batch mode, with an argon protective atmosphere, and an austenitization of 1975 ±15° F. Differential hardness tests were conducted on the as-heat-treated surfaces and microhardness surveys were used to confirm the metallographic evidence of negligible (<0.0003 inch) surface modification. Hardness of the parts, R_C62.0 ±0.2, was in excellent agreement with that previously found on samples from that stock, R_C62.0 ±0.1. Microstructure was satisfactory, as was the fracture grain size (Shepherd 8) and 280 ksi indentation yield strength.

2.4.5 Dimensional-Stability Checks

All hardened steels are in a metastable state, that is, thermodynamically they tend to change their phase structure. Manufacturing techniques such as metal removal or deformation without sufficient stress relief can build in residual stresses. Phase changes as well as the relief of residual stresses cause dimensional changes and since the high-performance gyro requirement for positional control is severe, these size changes must be small. The first dimensional-stability problem encountered with 440C bearings by the gyro industry was with retained austenite, which expands in converting to martensite. This problem is obviated by subcooling as a part of heat treatment. In earlier programs* it had been found that 440C also is susceptible to a tempering reaction which results in shrinkage. Because the noted dimensional changes were deemed marginally acceptable, and because experience was limited, dimensional-stability checks on

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* Both under AF 04(694)-305.

the various program combos were needed. This requirement was further enhanced by the previously mentioned uncertainty about stability of the new phases formed as a result of the various unconventional hardening treatments coupled with the likelihood of introducing residual stresses through the thermomechanical treatments and unusual manufacturing processes.

Dimensional-stability tests had been devised on a theoretical basis, interrelating them with prospective gyro experience. Use of these tests in conjunction with another, concurrent, program* had shown that the 225° F 15-day exposure was somewhat more demanding than the 300° F 2-hour one. Accordingly, the former was used to test the various program combos. Two samples each of outer and inner rings of Combos A through J and the reference lot were subjected to a 225 ±10° F, 360-hour exposure in oil (to prevent corrosion). Outside diameters of the outer rings and bores of the inner rings were measured before and after exposure, recording both maximum and minimum diameters to a resolution of about two microinches. No significant change in roundness was found, and net size changes ranged from +2 to -14 microinches. The maximum dimensional changes were found in reference-lot rings. These were deemed not especially significant because extension of the stress relief and stabilizing treatment time from one to five hours at 300° F was already contemplated and was expected to improve stability. In general then, all of the preliminary combos were found sufficiently dimensionally stable for use in precision bearings. Hardness measurements before and after exposure were also made by the bearing manufacturer concurrent with the dimensional-stability tests, and showed a slight decrease in average hardness (approximately $R_C 0.2$) as a result of the exposure. The accuracy of these measurements was not sufficient to allow meaningful intercomparisons between the various combos but did demonstrate the systematic hardness difference between faces of some of the solid-bar-stock combo rings. This led to the above-mentioned (Section 2.4.2) improvement of the cutoff process. Two samples each of outer and inner rings from both Combos K and L, were similarly tested for stability and showed average changes of -8 microinches for Combo K and 0 for Combo L. Balls used in building Combo K and L bearings came from a lot known to be dimensionally stable from work in another program.** Further data on the dimensional stability of the various rings tested have been published[5] and details on dimensional-stability tests for rings and balls are given in two of the 10H gyro specifications.[13, 14]

Combo L material was thermomechanically hardened by somewhat different techniques than its archetype, Combo I. Tests for residual stress, using the Heyn method, were therefore incorporated in the post-hardening centerless-

* AF 04(694)-553.

** AF 33(615)-2243.

grinding operations performed at the bearing manufacturer. The data from this indicate very low residual stresses of around 10,000 psi, acceptable at that stage.

2.5 Evaluation of Combo Bearing Rings

The preliminary combos had to be evaluated on the basis of race-groove and material characteristics without full-scale running tests. The latter could not be used because of the tremendous effort and long time needed to run statistically meaningful bearing tests. On the other hand, limited tests simulating actual service conditions can be used to screen against the possibility of drastic early failure. They were used for this purpose in testing Combos C and D, the Malcomized bearings, where the very high hardness surface could result in excessively brittle race grooves. Low-speed dynamometer and low-speed endurance tests were also used as means of screening and no problems with any of the preliminary combos were found.

The preliminary combos had to be ranked, in order to choose the two material-treatment combinations most suited for the final bearings. Some standard rating techniques were used and some special ones were evolved for this purpose, generally emphasizing the visual appearance of the race groove. Those unique techniques not described before are detailed in Section 3.4 whereas some of the others are only briefly mentioned. The evaluation data on the preliminary-combo parts were organized into ten major parameters, of which eight are functional and two logistic. In turn, many of the major functional parameters have secondary and occasionally tertiary subcategories. As examples, these subdivisions come from treating inner and outer race grooves separately (when applicable), having some parameters rated independently by two or three of the program participants, and analyzing visual evaluations with separate categories such as comets, pits, and lap lines.

The major parameters and the distinct secondary subcategories are given in Table 2-4. The weighting factors were based on estimates of relative importance of the range of parameters encountered to bearing life and performance, essentially using a system often dignified with the acronym GERT (General Evaluation and Review Technique). As examples, dimensional stability of all preliminary combos was good, with even the worst still within acceptable limits. Therefore the weighting factor was small. Correlation between lubricant film electrical resistance gaging (LFERG) and bearing performance is good and the range of LFERG data is considerable, therefore that weighting factor is large. A number of iterations, varying the weighting factors, were made with the ultimate ones given in Table 2-4.

A scale of 1 to 5 (best to worst) was used with each category and, in general, several different schemes for converting the evaluation data into rankings were tried for each parameter. The ultimate ones ranged from a linear conversion (i.e., dimensional stability), truncated linear conversion (i.e., hardness, where most of the values were grouped but there was an extreme), and place within a large population (i.e., LFERG where 176 outer race grooves had been measured) to, basically, judgment (i.e., obtainability of steel which is based on pooled experience from this and other programs).

Table 2-4. Evaluation parameters.

Parameter	Major Subcategories	Weighting Factors
Functional		
Visual Evaluation	OR	15
	IR	15
Lubricant Film Electrical Resistance Gaging	OR	15
	IR	15
Hardness	Interior (Bulk)	8
	Surface of Race Groove	2
Indentation Yield Strength		6
Taper Section	OR	3
	IR	3
Corrosion Resistance		4
Dimensional Stability	OR	1
	IR	1
Raised Ridges.	IR Only	2
	Functional Subtotal	90
Logistic		
Ease of Manufacture		10
Obtainability		2
	Overall Total.	102

A perceptibly improved finishing technique for outer race grooves, RA honing (Section 3.3.4) was developed during the course of finishing the preliminary combos. Application of this technique to some samples of certain of the preliminary combos led to 17 distinct categories for the 10 preliminary combos and the reference lot. Complete evaluation data were available for only 11 of these when decision on the material-treatment combination to be used for final bearings had to be made. The missing data are principally those obtainable through taper section, and priorities for these had been so arranged that this missing information did not significantly affect the decision.

The final overall rankings, as well as functional subtotals, are given in Figure 2-1. Categories with the RA honing technique are indicated by a prime superscript, and incomplete data are accomodated by using a bar spanning the maximum-to-minimum range. It is clear that for every combo where outer-race groove samples with both the old (R) and the then new (RA) honing were rated, the latter were substantially better. This is due to better visual and LFERG ratings.

Although most of the combos ranking high overall are based on 14-4-1, an exclusion principle had to be applied because of the limited availability of this steel, which is the proprietary alloy of one steelmaker. Thus, to avoid putting all eggs into one basket, only one steel-treatment combination using this grade was allowed for the final bearings. This, Combo L, is ausformed and is analagous to Combo I. The other material-treatment combination chosen for a final combo is conventionally hardened 440C which, as shown by Combo M, the reference lot, ranks very high with the then newly developed RA honing technique. Additionally, use of this for Combo K, because it employs one of the more common bearing materials, provided an internal reference for the final bearings.

2.6 Manufacture and Examination of Final Bearings

2.6.1 General

The final bearings were to be the test vehicle of the program, incorporating those technological advances that could be focused on them, whether developed by this program or elsewhere. They, Combos K and L, were therefore made from the most promising material-treatment combinations as determined from the preliminary combos. The original program concept was that the final bearings would be validated by the Inertial Gyro Group through fixture and gyro test, using a gyroscope design current at time of test. Since the final bearing design required could only be bounded but not determined at the outset of the program, the design options on this had to be left open. Thus successively, over earlier parts of this program, options involving an integral shaft and then various R3 designs were closed, terminating the relatively small efforts (e.g., determining dimensional changes due to Malcomizing R3 bearings) that had kept these alternatives open.

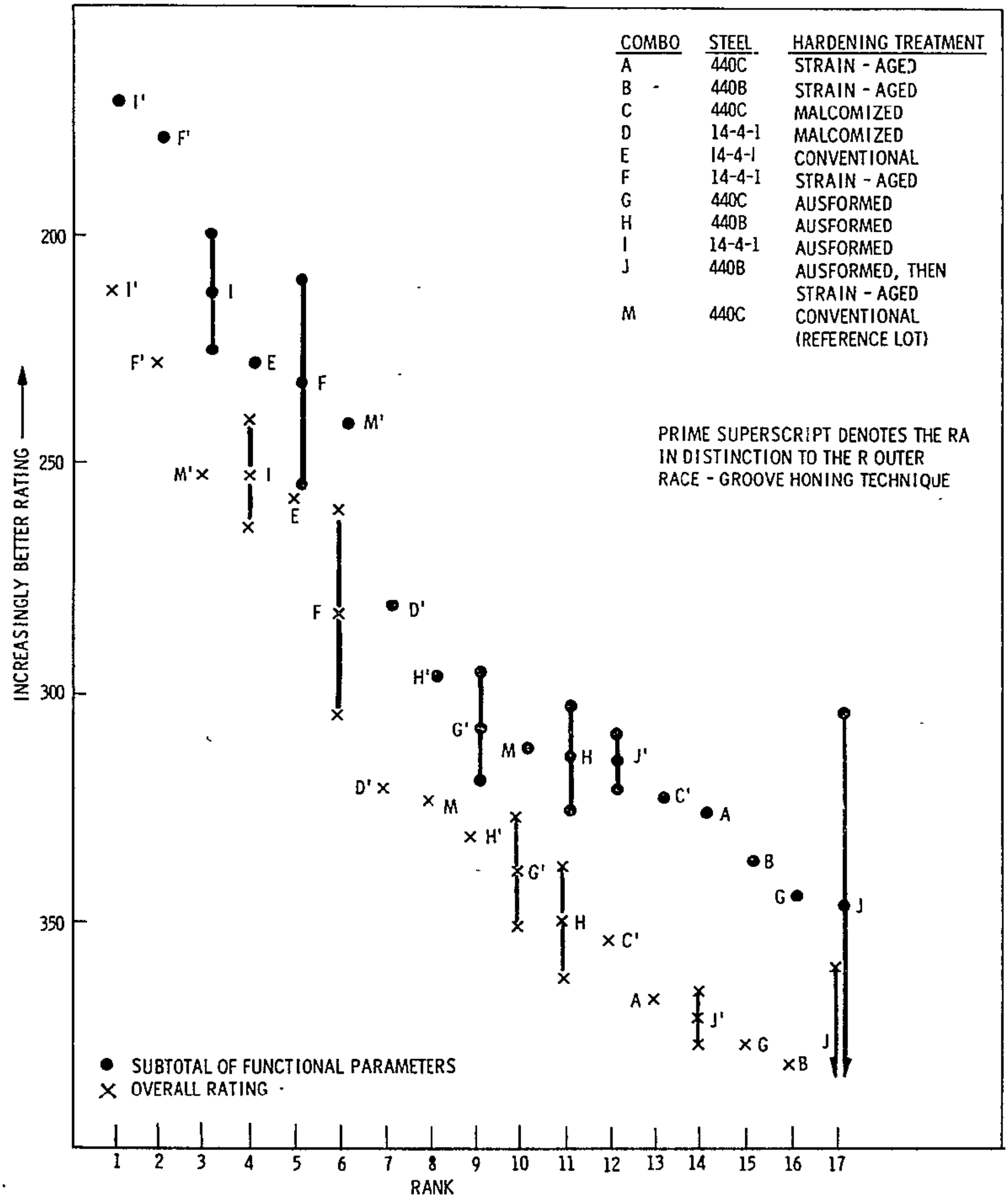

Fig. 2-1. Ratings and rank of race grooves of preliminary combos.

Sometime after the design option fixed on the R4H configuration, NASA/MSC decided to have the final bearings tested in modified Apollo I IRIG's by the MIT/IL FBM-B group. These gyro builds and tests, the subject of a separate final report,[1] caused a requirement for bearing groups with two different contact angles: 25° contact angle for the fixture tests and 30.2° contact angle for the gyro tests. These were achieved with the same basic dimension rings by using different ball sizes. Since this was coupled with a requirement limiting aberrations in cross curvature in the region 15° on either side of the nominal contact angle, a severe constraint against rounding of the shoulder was imposed.

Production of Combos K and L started separately because of the substantially different material-treatment combinations involved. The descriptions below therefore will first deal with the separate part of the manufacture of Combo K, then Combo L, and then those manufacturing aspects they had in common. This will be followed by the examinations they had in common. Some aspects, such as the heat treatment of Combo K and the dimensional-stability tests have already been described in earlier sections.

2.6.2 Manufacture of Combo K, Separate Stages

A new lot of steel, 440C-L4, was made specially by a steelmaker for use in this program because data from earlier parts of this and other programs showed the normally present nonmetallic inclusion stringers to be a serious problem. In order to cover the various possible hardening treatments, the rod stock was obtained at 1-1/8-inch diameter. The choice of conventional heat treatment for Combo K made a smaller diameter more desirable, but schedule did not permit sufficient time for the steelmaker to effect this reduction. This was obtained through job shops, a forge and a centerless grinder, resulting in the dimensions given in Section 2.2.3. The stock was reexamined and found acceptable after reduction. Subsequently, a problem with short tool life on automatic lathe cutting the outside diameters of the outer bearing rings was encountered. This is attributed to hard spots or scale remaining from insufficiently controlled forging, annealing, or centerless grinding, but is believed to be a nonrecurring problem.

The production methods up to final grinding and finishing were substantially those of standard gyro-bearing manufacture. Exceptions to this included more detailed control to ensure that high-speed machinery was adjusted optimally before substantial amounts of the production lot were committed, and quality control during heat treatment, which was much more detailed than is that bearing manufacturer's normal practice. The latter has already been described in Section 2.4.4.

2.6.3 Manufacture of Combo L, Separate Stages

The manufacture of Combo L ran into several serious problems which had to be overcome to successfully obtain bearings. While preliminary combos were being evaluated preparatory to ranking, it was recognized that the ausforming processes used were incompatible with the quantity needed for a final combo. It was also apparent that an ausformed combo was likely, so further development exploring direct-extrusion processes was undertaken. This demonstrated the potential of the process which, with some equipment modifications, was chosen for the thermomechanical hardening of Combo L.

Additional material had been sought since the initial delivery of only half the quantity ordered for 14-4-1-L3, but problems with lack of cleanliness were encountered in the subsequent lots examined. This eventually was attributed to a change in steelmaking practice, and arrangements for a special heat, double-vacuum melted, were then made. As indicated in Section 2.2, this lot (14-4-1-L12) was found metallurgically acceptable, but delivery time substantially exceeded promise, and necessitated the sparing use of the remainder of 14-4-1-L3 for Combo L.

Direct impact extrusion was by an inertia wheel and ram mechanism that first upset the hot 1-inch diameter by 2-1/2-inch long rod to 1-1/8-inch diameter, then forced it through a contoured, lubricated die. The forward end of the workpiece was reduced to 0.70-inch diameter while the rear remained at 1-1/8-inch. The workpiece was then removed from the die by manually knocking it back out after the ram return-stroke. The ausforming was obtained by quenching the slug from the 2100° F austenitization to an 820° F extrusion temperature, extruding, and within a few seconds after extrusion, quenching further in 65°F oil. Subcooling to liquid nitrogen (-320° F) and tempering at 300° F followed these operations. The various hot operations must follow each other promptly, that is within a few seconds, in order to prevent unwanted metallurgical transformations and the nature of equipment and process preempt a substantial facility. This in turn required that all ausforming for Combo L take place within a two-day period.

Initial problems encountered in extrusion were with die shape and lubrication and with the cracking of some of the extruded pieces. The former was overcome with ad hoc changes in die shape and lubricant, whereas the latter was traced to rough notches left from saw-cutting the 1-inch diameter rod to 2-1/2-inch lengths. Cracked material and ends of the extruded rods were scrapped. Following the hardening treatment of Combo I, a 300° F temper was initially used for Combo L, but hardness was found to be substantially lower (R_C60 to 61.5 versus R_C64.5) than for Combo I. Based on other exploratory work, two additional 975° F tempers with an intermediate liquid-nitrogen subcool were given first a sample and then the bulk of the ausformed lot.

Most pieces tested at this stage were above R_C64.5, with the major increase in hardness coming from the subcooling — indicating high prior retained austenite. Cropping of the soft rear end of some of the rods was used to eliminate material below R_C64.5 and rods were submitted for bearing manufacture. Each ring blank was identified, recording the individual bar and its original location in it. Hardness tests after the trepanning operation indicated about 10 percent of rings were softer than the desired R_C64.5, with hardnesses as low as R_C61.6. Based on further exploratory work, an additional corrective treatment using three 925° F tempers interspersed with two subcools to liquid helium (-450° F) were applied, first to a sample lot and then to all rings. Measurements of the dimensional changes of the sample lot were used to ascertain that these would not be excessive, and hardness measurements of both faces of each of the 266 outer and 244 inner bearing rings were used to rank these by hardness.

Bearing manufacture then was biased so as to produce the final 40 Combo L bearings from the higher-hardness rings. Due to the loss of some of the harder parts in manufacture, the final, representative hardnesses of Combo L rings range from R_C65.7 to 64.4. The problems encountered in ausforming and recommendations for alleviating these are further discussed in Section 4.4.

Following major stock removal, Combo L bearing rings were given two 300° F 2-1/2-hour stress reliefs, interspersed with a -100° F 1-hour subcool. This treatment was first applied to a sample lot, and dimensional changes noted. Size changes were negligible and the remainder of the lot was stress relieved in the same manner.

2.6.4 Manufacture of Combos K and L, Common Stages

The productions of Combos K and L essentially merge after the stress-relief treatments. Finish grinding, especially of the race grooves, was done with the detailed controls described in Section 3.2. The techniques used, especially the fine tuning and adjustment of the grinding machines, were based on the development work preceding and concurrent with the manufacture of the preliminary combos. Additional development alleviating shortcomings found during the production of the preliminary combos also added to the technology used for the final combos. The philosophy of establishing the race-groove geometry by the grind process was used throughout as contrasted to that of improving geometry by the finish operations. The combination of constraints due to race-groove design and high contact angles obviated certain normal manufacturing techniques such as tumbling to remove sharp edges and all corners, including those of the race grooves, were hand-polished.

As detailed in Section 3.3, a number of finishing techniques was used in the production of the preliminary combos with the best technique at that stage being the RA, which had been applied to outer race grooves only. In the time between the manufacture of the preliminary and the final combos, bearings for another program had been finished and the RA technique extended to inner race grooves. Samples of this nonprogram lot were therefore used to evaluate the RA technique, as applied to a substantial number of parts. Progressively, this investigation showed that the finishing technique produced discolorations, termed carbide stains, on one side of the primary carbides in the race groove, and that underlying them was an unusual metallurgical structure. Many aspects of analysis and detection of this phenomenon have already been described.[15] The stains and peculiar structure are almost certainly due to localized deformation caused by the finishing technique and appear to correlate with poor bearing life. This necessitated a new finishing process, described in Section 3.3 as the RB technique, and required a delay of production of Combo K and L parts until it was developed and checked.

Methods used in evolving this "nonsmearing" finishing process were to first examine the results of variations of the RA and other finishing techniques, and then, at a later stage, couple the preproduction and production control in honing with on-the-manufacturing-floor examination of the race-groove finish using the techniques described.[15] The resulting finish then was without metallographically discernible modification.

The parts intended for assembly into the 40 Combo K and 40 Combo L bearings were given 100% LFERG as well as visual examination, detailing race-groove features within tolerance. Balls from a standard 440C lot were used for both Combo K and L bearings. After a sufficient background in measuring the balls of this lot had been developed, mechanical size measurements were omitted partly in order to lower the risk of damage. This was possible because none of the hundreds of balls previously measured had been found out of tolerance. On the other hand, visual examination of all balls was maintained. Visual inspection of the race grooves at the bearing manufacturer disclosed a new aspect since the finish was far less featured than normal. The higher degree of polish and greater uniformity with few imperfections accentuated the various mechanical-contact markings, e.g., those from measuring both peripheral and cross curvatures, and contact angle. The presence, implication, and allowability of such markings remains an equivocal point.

The improvement in geometry of the race groove is best illustrated in comparing the cross curvature of samples from the reference lot and from Combo K and L, as given in Fig. 2-2. The low-magnification trace in each of the Talyrond recordings is taken to indicate the overall extent of the race groove, and it can be clearly seen from the high-magnification (10,000X) trace that cross

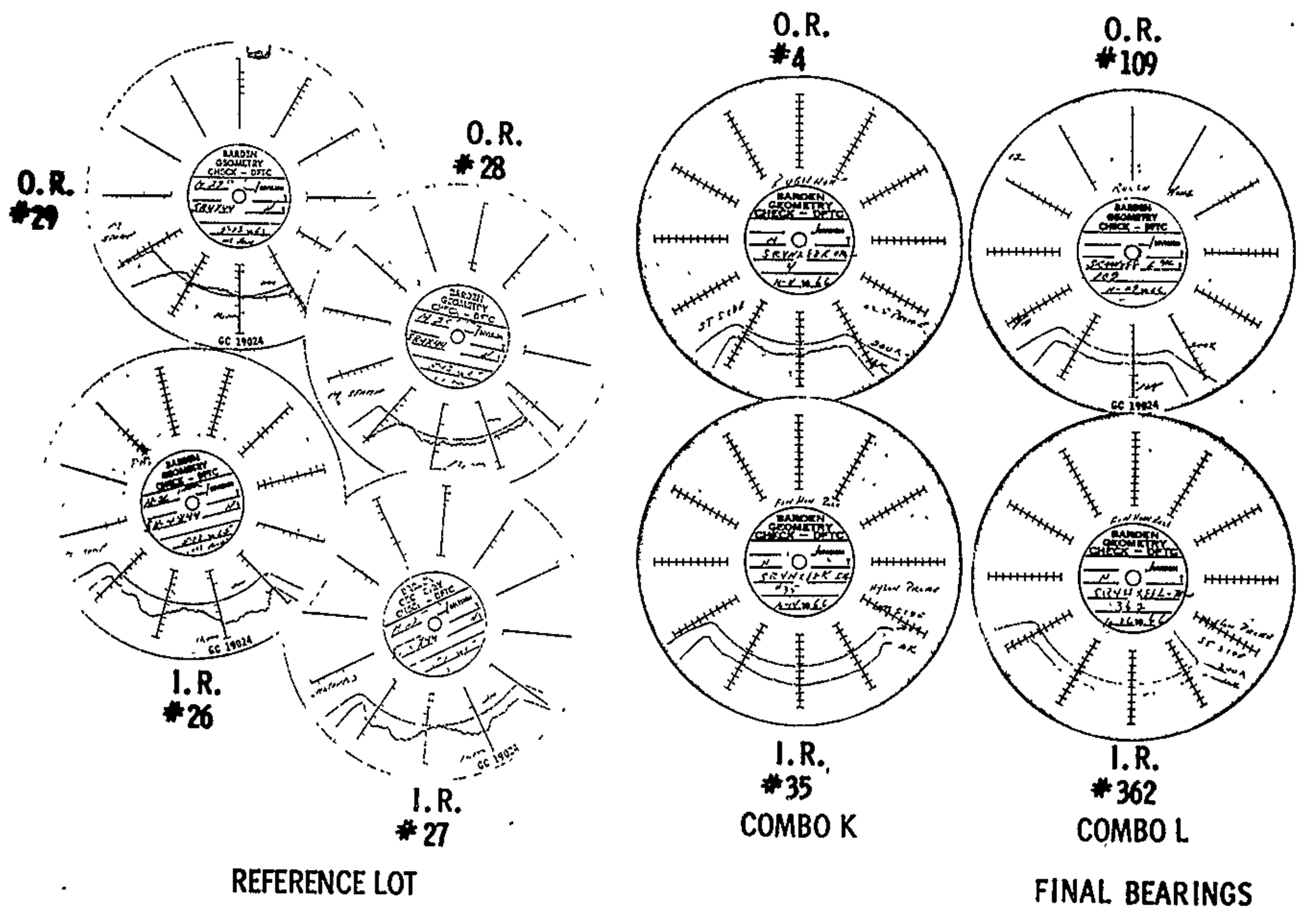

Fig. 2-2. Cross-curvature improvement.

curvature of especially the inner-race grooves was greatly improved while peripheral curvature at contact angle, as shown in Fig. 2-3, was excellent.

As indicated in Section 2.7, it was realized, partly through the test of Combo K and L bearings, that some of the cleaning and passivation procedures used were leaving a tenuous, unwanted surface chemical condition, and the passivation (Section C.3) and TCP processes on the bearings were suspended. Those few parts not thus treated were given passivation and TCP treatments at MIT/IL and form part of the statistical basis on which the correlation with surface chemical condition and running behavior were drawn.

Visual inspection of all bearing race grooves by MIT/IL and of samples by the metallurgical agency confirmed that Combos K and L had a far less featured finish than their preliminary counterparts. This is especially evident when frequency and size of fins and comet tails are compared. Combos K and L are essentially void of these imperfections above the 0.0001-inch size, and are relatively scant below this. On the other hand, there is no major difference in the frequency of small ($\leq$ 0.0001-inch) pits/inclusions. Although there is a substantial part-to-part variation in this frequency, Combo L was found especially high. Further investigation showed that this was connected with the stock lot and that detailed quantitative microscopic examinations could be used to screen against what appears to be chipped-out carbides. It is not clear whether these small imperfections are engendered by the steelmaker's processing as are the larger cracked carbides previously reported.[3]

Taper-section examination of Combo K and L samples confirmed the relatively good smoothness, especially for Combo K, and, as in previous taper sections, it was found that the near-surface hardness was greater than that of the bulk — in these instances about $R_C 3$.

Examination of Combo K and L bearing parts confirmed that these matched or exceeded the preliminary combos on which they were based in geometry, finish, and material characteristics, and thus represent a substantial improvement of technology.

2.7 Dynamic Tests of Final Bearings

Forty bearings each of Combos K and L, with spare balls, were delivered to MIT/IL for testing in fixtures and gyros. As explained in Section 2.6.1, 15 bearings from each combo were assembled for test in modified Apollo I IRIG's and are reported on separately.[1] The retainer design was inner-land riding with seven unequally spaced ball pockets, designed to give retainer stability and concomitantly expected to give a greater ball-beat-frequency output than an evenly spaced ball complement. Inspected bearings with Nylasint retainers were furnished for the modified Apollo I IRIG build and test.

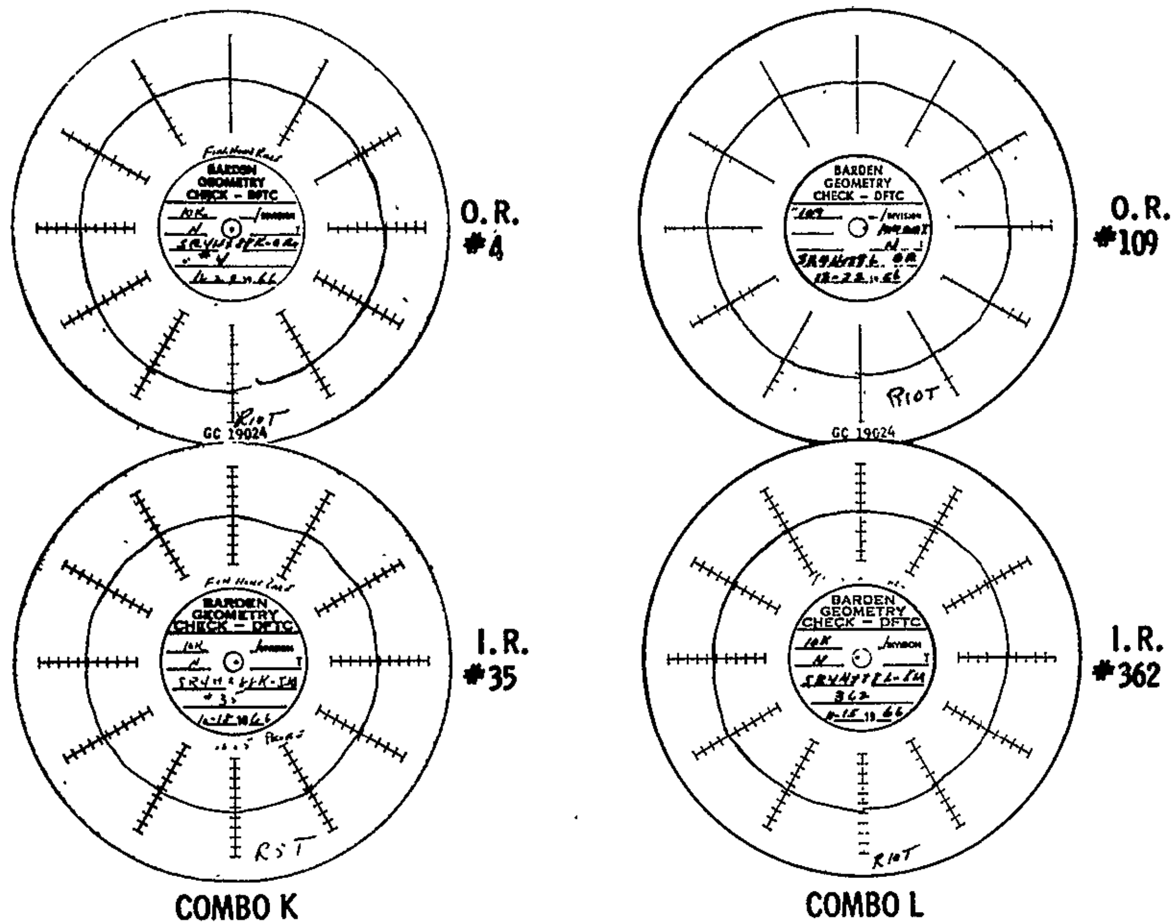

Fig. 2-3. Final bearings, peripheral curvature at contact angle.

For fixture testing, bearings were assembled into gyro wheels with all conditions comparable to those of Inertial Gyro Group R4 gyroscopes. Preload was 5 to 7 pounds at the fixture temperature of 130° F. The oil quantity was controlled by centrifuging at 12,000 g's axially for 30 minutes, which left about 15 mg of Teresso V-78 in each retainer. Running speed was 24,000 r/min with outer-race rotation in a helium atmosphere of 50 Torr.

The failure criterion in a gyroscope test can well be the performance of that instrument, declaring a bearing pair failed when it causes a predetermined performance degradation. This kind of criterion cannot be applied to fixture tests, and over the last decade a considerably more stringent one based on torque characteristics observed by a low-speed dynamometer (LSD) has been applied to this. This test[16] is based on periodically comparing preloaded-pair LSD traces with the initial one, using a moderate increase in the hash component of torque or the appearance of spikes signifying metal damage, as failure indications. On such occurrence the test is terminated and individual LSD examination given each bearing race groove and ball. This is followed by visual examination at high light microscopic magnifications (150 to 250X). The latter is deemed the most stringent criterion but, in contrast to periodic preloaded-pair LSD traces, cannot be made without unacceptably disturbing the life test. Results of the fixture tests, including the visual evaluation, are given in Table 2-5.

The group is characterized by extremely early failures, very surprising for bearings of this geometric quality, and by widespread occurrence of alterations of the race-groove surfaces with generally no lubricant deterioration. Failures of this type were concurrently observed in another bearing program* and further fixture tests as well as delivery of bearings for the modified Apollo I IRIG program were suspended and the problem examined in more detail. Based on work in the other program, many factors such as ball retainers, lubricant bearing geometry, bearing-user processing techniques, and ball lots were eliminated as not significant. The cause of failure was connected with the surface chemical condition of the race grooves, in turn believed engendered by the post-metal-removal processing steps during bearing manufacture. As a result of this diagnosis, further work under newly added Tasks 8 and 9 was undertaken to resolve the problem and test the remaining bearings. This will be the subject of separate reporting. Many of the preliminary results and details of the failure appearances, statistics, and speculations have been published.[17,18]

Bearings were provided for the modified Apollo I IRIG program only after methods of altering the surface chemical condition were available and these bearings

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Table 2-5. Results of fixture tests on final bearings.

Combo	Hours Run	Race Groove Visual Evaluation
K	5560	Run terminated for examination. Neither NA-17 nor NA-18 had failed. Normal wear tracks, no lubricant deterioration or metal damage on either.
K	170	Both NA-19 and NA-20 failed. No lubricant deterioration, but metal badly pitted and brinnelled on both.
K	350	Bearings failed. NA-21: lubricant deterioration and metal damage NA-22: no lubricant deterioration, but some metal damage
K	40	Bearings failed. NA-23: no lubricant deterioration, but extensive metal damage NA-24: no lubricant deterioration, but extensive metal damage
K	90	Bearings failed. NA-27: no lubricant deterioration, slight metal damage NA-28: lubricant deterioration and metal damage
L	1660	Bearings failed. NA-66: no lubricant deterioration, slight metal damage NA-67: no lubricant deterioration, slight metal damage

were tested to ensure that they met surface chemical criteria. In connection with the test results reported here, it should be noted that the bearings which ran 5560 hours and were stopped without failure (NA-17 and NA-18),were postrun tested for surface chemical condition and found to pass the oil-spreading criterion at that stage. In contrast, the other failed bearings of Table 2, when similarly postrun tested, were found to fail.

SECTION 3

CORRELATIVE AND SUPPORTING EFFORTS

3.1 General

A substantial amount of the program effort was in specific technical areas that in themselves are worthwhile reporting but, because of the level of detail necessary, cannot reasonably be part of the previous section on the development, definition, and test of the program bearings. Those efforts which already have been adequately reported elsewhere,* will not be covered in this section.

3.2 Improved Race Grooves — Grinding

3.2.1 General

Historically, the first method used to obtain precision gyro spin-axis bearings was that of selection of components that met specifications from a much larger group manufactured by nearly standard means, a process which has been compared to selection of red jelly beans from the usual polychromatic run.** This approach is obviously very limiting — consider that only a small fraction of any standard batch generally would meet a given specification parameter and that there are a number of critical parameters. Realizing this led to the manufacture of bearing parts that would, with relatively few exceptions in any batch, meet the specifications.

There can be major as well as minor differences in the techniques used to achieve batches of bearing rings, nearly all of which meet the stringent specifications. As a typical example of a minor difference, manufacturing processes often differ substantially in the degree to which the race groove is contoured before conventional hardening. This ranges from heat treating cylindrical rings and grinding the complete race grooves in hard parts, to leaving a protective layer of only several thousandths of an inch for removal after heat treatment. A basic difference, perhaps best termed philosophy, hinges on how the final race-groove geometry is achieved. Because there is a series of grinding and then post-grind metal removal (finishing) steps, it is possible to use the latter steps to correct some of the defects in geometry generated by grinding. The opposite

* For example, in Reference 5.

** W. G. Denhard, in the Introduction to April 1964 Gyro Spin Axis Ball Bearings Symposium at MIT.

philosophy evolved from prior effort and was used in this program. This aims for final geometry by tuning each of the grinding steps toward this and especially using the finishing to only reduce the as-ground surface roughness. The exemplary resulting geometry and finish amply validate this approach.

The origin of the "minimal-stock-removal" philosophy used stems from the tendency of finishing processes to correct only one aspect of geometry, such as roundness, while at best not degrading another aspect, such as cross curvature. Extensive multiple finishing operations generally do not achieve complete correction and additionally disturb piloting surfaces and severely round race-groove corners. Minimal stock removal thus emphasizes generation of near-final geometry from the earliest hard-grind stage on, and expecially by the end of the finish-grind stage — the last step at which race-groove shapes are generated by a fully piloted machine. An extra benefit of minimal stock removal is that it allows complete flexibility in choice of finishing techniques since there are no requirements for geometry corrections.

At the outset of the program it was clear that the bearing manufacturers' as-finish-ground cross curvature of inner rings tended to be poorer than that of outer rings, despite theoretically greater difficulty in generating the latter. The inherent reason(s) for the initially deficient inner-ring capability is not clear. Operationally the problem was eliminated by the combination of careful tuning and adjusting of all potentially critical components of the grinding and finishing machines and controlling the machine performance with a tight performance feedback loop. The latter was obtained by running only a very few parts before checking the output. This dual approach was used for both inner and outer rings throughout the race-groove grinding steps but will be detailed only for the main geometry determinant — the finish-grinding operations. Because these operations are critical, the machines were sequestered for the period of the program, which both allowed more careful tuning and enabled maintenance of progressive improvements. These machines, a Cincinnati Microcentric for inner-race grooves and a Bryant Model B for outer-race grooves, were completely overhauled prior to use in this program. Although these machines differ in some specifics from others that might be employed for these processes, the method and procedure used are broadly applicable.

3.2.2 Finish-Grinding Operations

The steps involved in the finish-grinding technique for minimal stock removal were:

a. Geometry — All finish-grinding operations were done in a centerless fashion, thus eliminating the effect of work head spindle errors on the part geometry. Piloting surfaces on all combo parts were lapped to ensure roundness in the range of 5 to 10 microinches DFTC prior to performing finish grinding.

b. Vibration and Stability — All machine vibrations were reduced to minimum in order to grind all grooves with finished part geometry. In addition, the stability of the wheel feed and the dresser axis were maintained at a high level. The performance of the machines was adjusted on the basis of accelerometers and deflection measurements, and monitoring with permanently attached accelerometers aided in maintaining the "tune".

c. Lot-to-Lot Uniformity — Since the various combos were not processed together, grinding machines were set aside, overhauled, and maintained in peak operating condition for use on program parts only.

d. Operators — Highly competent personnel were used to adjust and operate the finish-grinding machines. The use of such personnel enabled early recognition of any problems and engendered corrective action before large numbers of parts were damaged.

e. Gaging — Very sensitive gages for measuring such parameters as roundness, radius of curvature, deviation from cross curvature, groove wobble, eccentricity, etc., were made available to the operator of the grinding machine. Setup parts were used to qualify the machine for grinding a particular combo. During the grinding of combo parts, samples were taken at frequent intervals and checked with the appropriate gages.

f. Supervision — Supervision over all critical operations performed on the combo parts was provided directly by the project manager. In most cases it was required that the performance of a given setup be demonstrated to the project manager, using setup parts, before approving the processing of a group of combo parts.

3.2.3 Inner-Race-Groove Grinding

In addition to the initial overhaul, periodic maintenance ensured that the inner-race-groove grinder remained in optimum condition. Since grinding a piece round on this machine is primarily a result of control of vibration and excursions permitted by support mechanisms, the balance of rotating members such as the grinding wheel, wheel head motor, work head motor, clutches and brakes had to be maintained. In addition, the bearings and other supports had to be controlled and/or adjusted to maintain high stiffness. Modifications were made to improve the dresser-axis stability and thereby improve the inner-race-groove cross curvature.

3.2.4 Outer-Race-Groove Grinding

Most of the comments on grinding inner race grooves apply equally to grinding outer race grooves. Again, the major problem was the grinding-wheel dresser. In addition to stability of the dresser axis, the selection and maintenance of a good diamond dresser point was critical. The dresser was an even greater problem in outer-race-groove grinding than in inner since the wheel requires dressing for each part. Cleanliness and maintenance of the correct axial adjustment on the dresser bearings resulted in the best performance. Frequent readjustment and replacement of the diamond was necessary.

3.2.5 Dresser Recommendations

Both machines discussed above would benefit from improved grinding-wheel-dresser bearings. This could not be realized within the program. Pressurized oil bearings are recommended as the most promising solution. These would give the required stiffness and the resulting freedom from wear would both improve the dresser-axis stability and extend the time between overhauls.

3.2.6 Setup and Production

The following sequence, used for inner-race-groove grinding, will serve as an example of the measurements required during the grinding operations.

a. Dress the grinding wheel.

b. Set up a machine and adjust to grind to the proper size.

c. Grind five parts.

d. Measure as follows:

(1)	Groove diameter	100%
(2)	2-point roundness	100%
(3)	Groove location	100%
(4)	Groove roundness (Talyrond)	100%
(5)	Groove curvature	20%
(6)	Radius of curvature	20%
(7)	Groove wobble and eccentricity	40%

Every time the wheel was dressed (every 50 parts) the same procedure was repeated. Although this slowed down the normal grinder production rate, the measurements provided the required control so that nearly 100% of the parts met specifications.

3.3 Improved Race Grooves — Finishing

3.3.1 General

Gyro-bearing race-groove surface finishes are achieved by post-grind manufacturing operations. These finishing steps primarily reduce the cross-curvature roughness but also favorably affect the peripheral roughness. Use of the minimal-stock-removal approach freed the finishing operations from a need for geometry improvement, and emphasized maintenance of as-ground geometry. As a result of a prior program*, the bearing manufacturer had developed techniques for honing of outer race grooves. The best of these was the one initially applied to the preliminary combos, whereas a single series of lapping processes was used for the comparable inner race grooves. Modifications of the honing process were developed and applied to some of the preliminary combo outer race grooves as a result of difficulties encountered with some of these combos.

Conceptually, honing is a more mechanized, semi-generating process which has more overtly adjustable parameters than the soft-backed lapping processes. As such, when properly adjusted it is less likely to degrade geometry, especially when parts are recycled through finishing operations to remove race-groove blemishes. The honing experience on outer race grooves in this program motivated development of a comparable technique for inners, as explained in Section 2.6.4. Inner race grooves are more easily examined at high magnification. The availability of these with some of the same blemishes previously noted on outers in turn led to the investigation of these features (see Section 2.6.4) and the development of the RB honing technique.

Three different race-groove-finishing methods were used on preliminary combo parts during the program, and a fourth (the RB honing) was developed for the final bearings.

3.3.2 Race-Groove Lapping

The lapping procedure used on all preliminary combo inner race grooves was essentially that used by the bearing manufacturer for gyro bearings for several years. Some minor refinements were made, but the major geometry improvements achieved in the preliminary combo were due to improved grinding methods.

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Inner-Race-Groove Lapping Procedures

Operation	Time	Abrasive
Paper Lap	1 min/side	4/0 Emery Polishing Paper
Replica Lap	1-1/2 min/side	U.S. Products LA-1
Rod Lap	1 min/side	LA-1 Compound with bond paper

Description of the Operations

Paper Lap — A 175-r/min geared motor was used to drive an inner race groove against an oscillating rod holding emery paper. Rate of oscillation was 24 cycles/min with a 2-pound nominal load on part.

Replica Lap — A 100-r/min geared motor was used to drive an inner race groove against an alloy metal lap coated with LA-1 lapping compound with a 3-pound nominal load on part.

Rod Lap — This is a polishing operation with little stock removal. It was obtained by having a rod oscillating 16 cycles/min across a race groove which was rotated about 100 rpm with a 1/2-pound nominal load on part.

The three individual operations, used once serially, constituted one complete inner-race-groove finishing cycle. Combo C and D inner race grooves required a longer lapping cycle (33% and 100% respectively) to achieve the desired level of finish. The cycle times listed above were used on all other preliminary combo inner race grooves with satisfactory results.

3.3.3 Outer-Race-Groove Honing — R Type

All preliminary combo outer race grooves except C, D, I, and J were honed with a Bay State Abrasives' LAM-VG-2 stone. This is a harder stone than is normally used on ball-bearing race grooves. It contains aluminum-oxide abrasive in a vitreous binder. Penalties paid are largely those resulting from the high resistance of the stone to shape changes. All parts must have nearly identical race-groove radius and location prior to honing, and the machine must be adjusted to position each part in exactly the same place. Advantages of the hard stone include greatly lessened stone wear, excellent cross curvature, and a reasonably good finish. The finish obtained was equal to or better than the lapped finish described in the preceding section.

Combos C and D did not respond particularly well to the R-type honing and a honing cycle with a Carborundum A600-N-BY resinoid bonded aluminum-oxide stone was substituted. The resulting finish was acceptable.

3.3.4 Outer-Race-Groove Honing — Type

The A600-N-BY stone was also used to refinish some combo outer race grooves previously finished with the LAM-VG-2 stone. This double-honing process, called RA honing, was used on combo outer race grooves designated by a letter and a prime symbol. In Fig. 2-1 these combos are M', F', G', H', I', J'.

The RA-honed finish was an improvement over both the R honing and lapping methods in visual appearance and lift-off speed (LFERG). One unusual effect was noticed on some RA-honed outer race grooves. A brown mark or stain could be seen adjacent to one side of the primary carbides. After a similar finishing technique resulted in a comparable effect on inner race grooves, an intensive investigation, referred to in Section 2.6.4, was conducted to explain the cause and find a means of eliminating this and accompanying phenomena. The investigation has been described already.[15]

3.3.5 Race-Groove Honing — RB Type

As a result of the investigations mentioned above, the RB-honing process evolved. This is the R hone followed by a final diamond polishing step applied by the honing machine. RB honing eliminated the undesired effect completely. The RB method also provided an improved surface finish and appearance compared to the race-groove finishing methods discussed earlier. After many sample parts were scrutinized, the decision was made to use the RB-honing method on both inner and outer race grooves for final bearings. This method is described in further detail in Section B.3.

3.3.6 Effect of Finishing on Race-Groove Geometry

The finished part geometry requirements are given on the bearing drawings in Figs. B-1 and B-2. The cross-curvature tolerance was added after the decision to RB hone both inner and outer race grooves. The tolerance, ± 10 microinches departure from true circle (DFTC) over the contact angle $\pm 15°$, was readily met on the RB-honed race grooves but would have been difficult to meet using lapping techniques. The measured DFTC in cross curvature were consistently well below the tolerance. The peripheral roundness of honed parts is essentially determined by the finish grinding operation, so that the care taken in grinding parts appears most prominently here. The final bearings were amply within the roundness tolerance.

3.4 Race-Groove Surface-Evaluation Techniques Used in Ranking Preliminary Combos

3.4.1 General

The development and application of race-groove surface-evaluation techniques received a substantial effort. The motivations for this were the overall need for methods of evaluating bearings without expensive, very lengthy, full-scale gyro or simulation tests and the specific need for ranking the preliminary combos to allow selection of the material-treatment and finishing-method combinations for the final bearings as described in Section 2.5. Rating bearings without the running tests always leaves some questions on the validity of the techniques. In general, the premises underlying the techniques used are that smoother, more reproducible, more nearly asperity-free, harder, more corrosion-resistant race-groove surfaces will lead to improved life and performance.

Many of the techniques used are evolved from previous work. Only those used in functional evaluation (see Table 2-4) that are relatively novel and not adequately described elsewhere will be covered in this section.
Although some of these methods have had prior use, the quantifying of results, needed to allow comparison of the preliminary combos, is a unique aspect of those used for ranking. From the viewpoint of technology development, separating techniques on the basis of use in preliminary combo ranking is somewhat artificial but will serve to emphasize the degree to which the methods were "reduced to practice."

3.4.2 Visual Examination

Visual examination, especially in the 30 to 100X magnification range, is a standard screening technique for bearing race grooves and has for many years been used to ensure the compliance to specifications that forbid certain imperfections. It is deemed a quick and easy method by which an experienced operator can assess several aspects of surface finish. This method was used as an in-process check by the bearing manufacturer and all parts finished for use on this program were examined at 10 to 30X several times during their flow through grinding and finishing operations. In addition, the pressure zones of race grooves of eight parts (four inner and four outer rings randomly sampled) were given 100X visual examinations by the bearing manufacturer, who counted and tabulated imperfections and nonúniformities of several types and sizes. The Instrumentation Laboratory evaluated random samples of two inner and two outer race grooves of each preliminary combo, using normal and interference micrographs and written exposition to describe the specimens. These samples were then rated by the metallurgical agency which noted gross discontinuities and made general observations as well as categorizing, counting, and tabulating imperfections at 300X. The nomenclature used and imperfections observed by the three evaluators differ somewhat. The categories and size ranges observed are given in Table 3-1.

The quantifying of visually observed defects enabled cross comparison of race grooves, permitted the ranking of preliminary combos and checking of final bearings against their archetypes. It also clearly indicated

Table 3-1. Quantitative visual evaluation categories.

A. Defect Categories

Bearing Manufacturer	Instrumentation Laboratory	Metallurgical Agency
Pits and/or Inclusions	Raised Carbides	Grinding
Stringers	Peripheral Lines	Comets
Incomplete Lap Lines	Pits and/or Inclusions	Pits and/or Small Inclusions
Indentations (number only)	Comets	Cracked Carbides (areal density)
	Raised Ridges (IR only)	

B. Size Division or Scale Categories

Bearing Manufacturer	Instrumentation Laboratory	Metallurgical Agency
< 0.0005 inch	1 to 4	<0.0001 inch
0.0005 to 0.0010 inch		0.0001 to 0.0007 inch
> 0.0010 inch		0.0003 to 0.0007 inch
		0.0005 to 0.0007 inch
		>0.0007 inch

in what ways some finishing techniques were better or worse than others, and called attention to defects associated with steel stock lots. These side benefits were substantial and some examples have already been mentioned: the shortcomings of stock rating techniques were demonstrated by the disclosure of a previously undetected prevalence of stringer inclusions in steel lot 440C-L2 (see Section 2.2.3) and high frequency of small pits was coupled with another steel lot, 14-4-1-L3 (see Section 2.6.4). Another example is the highlighting of an undesirable effect of RA honing on Malcomized outer race grooves, which resulted in high frequencies of small pits. In general, the repeatability of quantitative ratings, as used, appears to be about 40%.

The less structured evaluation technique used by MIT/IL was more difficult to transform into rankings but, because of its open-ended character, served to point out the unexpected. The prime example of this is the observation of carbide stains that led to the more detailed investigation mentioned in Section 2.6.4. Comparison of the general characteristics of the program race-groove finishes with those of other bearings, primarily earlier ones which had not been numerically evaluated, was facilitated by the extensive descriptions. These also set the stage for individual examination of all incoming final bearings and post-run examination. The last was one of the factors that emphasized the unusual character of the early failures of the final bearings, as described in Section 2.7.

3.4.3 Lubricant Film Electrical Resistance Gage (LFERG)

The LFERG, developed under an earlier program* and applied to this program with several improvements, is a quasi-functional test of the ability of the race-groove surfaces to generate a substantial lubricant film. The LFERG consists of a mechanism in which a ball is held against a rotating bearing race groove and allowed to rotate with the ball-to-groove electrical resistance being measured by rapidly responding electric instrumentation. The numerical output used is the minimum speed at which a lubricating film is generated under load and contact-angle conditions duplicating those of the application. A detailed description of the device and its use has already been published.[19]

Since the film thickness is speed dependent, the lowest speed at which metallic contacts do not occur is a measure of surface asperities and film-forming ability. Obviously a surface with tall asperities would require a thick lubricant film which in turn requires a high speed for lift-off. Conversely, a very smooth race-groove surface (with good geometry) would be expected to have a low lift-off speed. The surface texture and surface chemical contributions to the formation of a film are also incorporated in the measurement but may not have the same effect here as the normally much higher running speed and scanter lubrication.

Measuring lift-off speed provides:

a. A guide to race-groove finishing methods
b. A measure of part-to-part uniformity
c. A screening system to check an entire race-groove pressure zone for asperities.

All measurements were with standard test conditions:

Lubrication	Flooded with Teresso V-78
Temperature	77° F

*AF 04(694)305

Ball-to-Race-Groove Force	3 lb on a single ball (equivalent to 11 lb preload with 9 balls at 25° contact angle)
Nominal Contact Angle	25° to 26°
Surface Speed Conversions	IR 100 r/min = 110 in./min OR 100 r/min = 163 in./min

LFERG data on all combo parts are given in Figs. 3-1 and 3-2 as examples of the technique. The lift-off speed given in the data is the lowest speed at which the ring will rotate while generating less than one contact (less than 25,000 ohms) per revolution. Lift-off does not occur in an abrupt transition -- as speed is increased, the number of contacts per revolution was found to slowly decrease to zero, corresponding to earlier work with sliding members.[20]

In general, comparison of the data indicates:

a. Finishing method has a greater effect on lift-off speed than the material or treatment, although bearings that have been run or stored for lengthy periods seem to have a high-resistance surface.

b. Improved visual appearance on combo race grooves generally correlates with reduced lift-off speed. Experience with nonprogram parts has provided some exceptions to this.

c. Other things being equal, combos made from 14-4-1 steel have a lower lift-off speed than combos made from 440C or 440B steels.

d. Part groups with the lowest lift-off speeds also have the least spread in readings. This indicates that the better finishes result in less part-to-part variation.

An attempt was made to identify the type of defect causing the LFERG to register a metallic contact. Using several parts, points on the race grooves giving rise to repetitive contacts were located and inspected. Two types of defects causing contacts were observed:

a. Comets, particularly ones which are large at their widest point.

b. Scratches which have obvious raised metal at their edges.

Light scratches, blended scratches, burnish marks, and pits or inclusions do not appear to cause contacts.

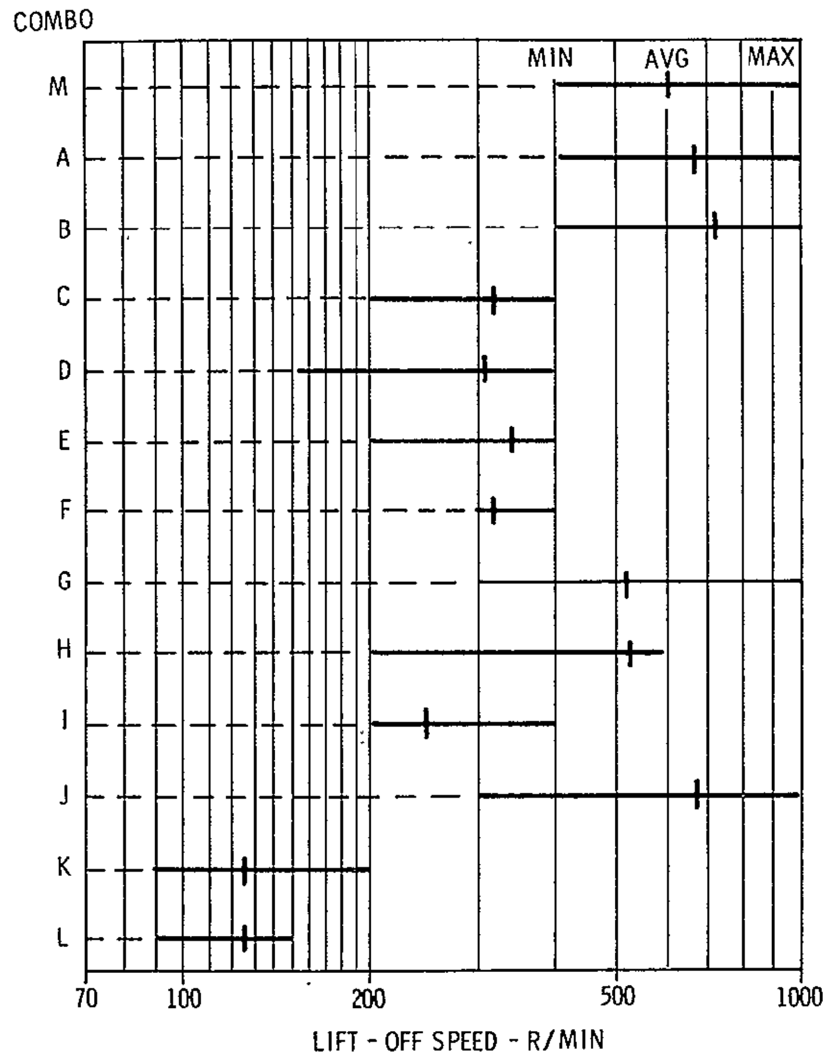

Fig. 3-1. LFERG lift-off speeds for groups of inner rings. (See Section 3.4.3 for test condition.)

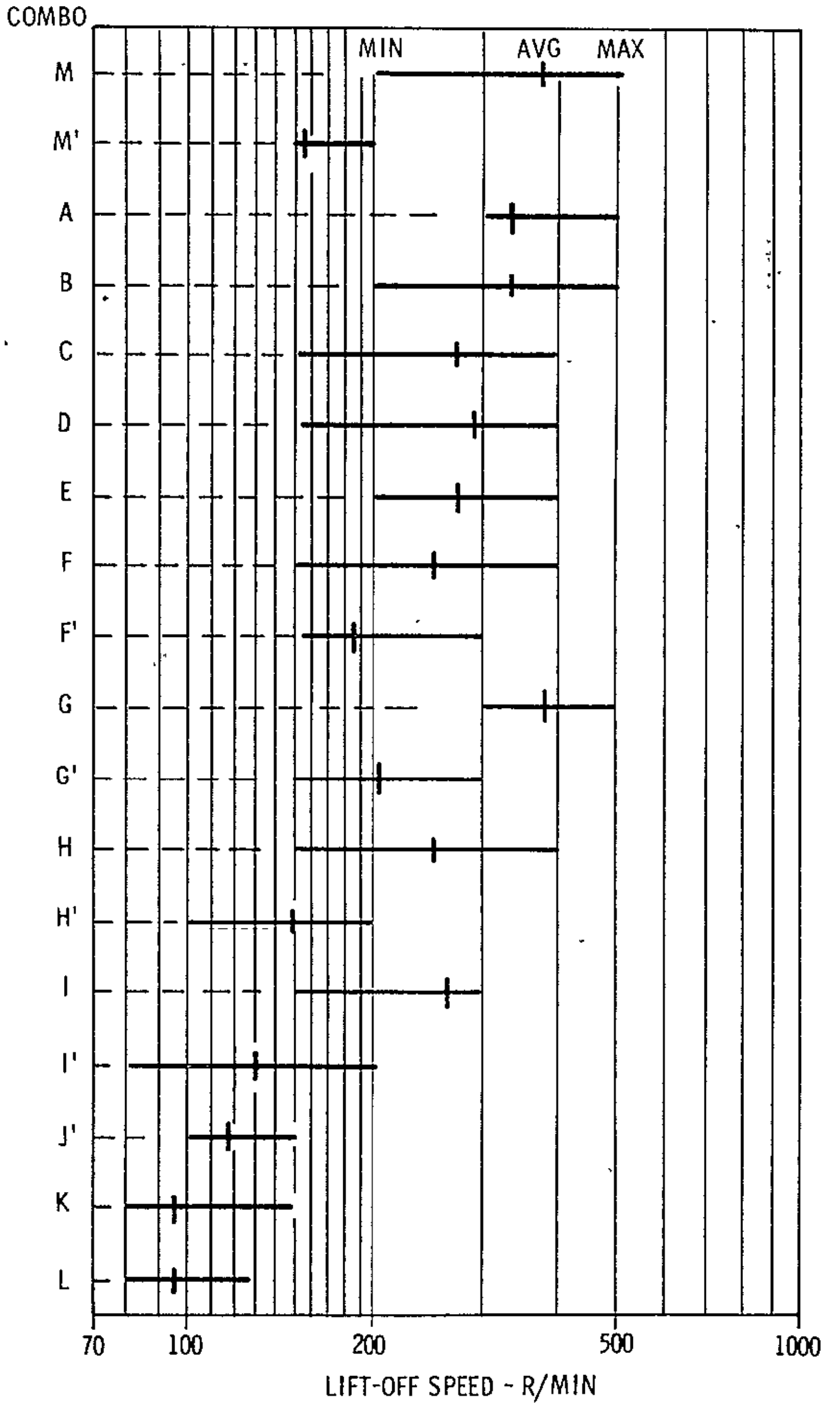

Fig. 3-2. LFERG lift-off speeds for groups of outer rings. (See Section 3.4.3 for test conditions.)

During the course of the program, the LFERG was modified to make it more repeatable. Continued improvements in race-groove surface finish require upgrading the measuring equipment to cope with lower speeds and smaller speed increments.

As part of a separate project, a study was made which confirmed the assumption that contacts, as recorded by the LFERG, truly result from metallic contact between the ball and race groove.[19]

3.4.4 Taper Sections

Taper-section techniques were first applied to ball-bearing race grooves* during a prior program** and were further developed here. Combined, the earlier and this program's effort clearly answered a long-standing speculation, showing that the near race-groove surface metal in the as-manufactured condition is harder than the bulk. It is harder probably because of local work hardening and strain aging caused by the grinding and finishing as opposed to softer which would be the result of tempering from local heating by the same manufacturing processes. Subsequent work on another program, again using taper sections, has shown[9] that under some running conditions the near-surface metal is significantly softened.

Taper sections of race grooves are obtained by grinding a chordal plane almost tangent to the race groove at contact angle. This exposes metal near the race-groove surface and, because of the glancing angle, material originally slightly below that surface is at a much greater distance from the interface in the section. A 20X mechanical magnification is typically obtained in the direction of maximum magnification. Because the race-groove surface has a circumferential or peripheral lay, the several features of the surface contour that extend in that direction are similarly magnified. The mechanical magnification is then multiplied by microscope, typically by 1000X, to allow resolution of surface contour to about one microinch in height.

At the start of this program, the technique for sectioning at contact angle was already available but improvements had to be made in the nickel plating used to preserve edges during the cutting, grinding, metallographic polishing, and etching needed to prepare the section. A 0.0001- to 0.0002-inch layer of nickel deposited from a Watts-type bath on a cathodically cleaned surface was ultimately found best, but occasional problems with insufficient adhesion did recur.

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*A description of some other taper-section applications is given in Reference 21.

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3.4.5 Corrosion Resistance

The corrosion resistance that can be obtained is a prime reason for using stainless steel for gyro spin-axis bearings. This eases handling and cleaning and, it has been speculated, may lead corrosion-resistant steel to be a lesser catalyst to lubricant degradation. The inherent corrosion resistance can sometimes be improved by a passivation treatment. Tests were run on samples of preliminary and final combo materials to determine the effect of the various hardening treatments on corrosion resistance and to gauge the efficacy of a standard passivation treatment[22] in improving corrosion resistance. It should be noted that no test gives an absolute value of corrosion resistance and that there is no effective way to simulate the corrosion environment of bearing handling and running.

A fairly detailed discussion of the tests and implications has already been published.[5] It was found that there was a range from passing the acidified-copper-sulfate corrosion-resistance test without the passivation treatment (best) to failing before the passivation treatment and reacting violently with the passivation solution (worst). The latter was observed only and consistently with the Malcomized combos, showing extreme loss of corrosion resistance. Intermediate cases, seen with other combos, included failing before and passing after the passivation treatment. The results were categorized and assigned rating numbers for ranking of the preliminary combos.

3.4.6 Indentation Yield Strength

Hardness, the mechanical property parameter most commonly used in evaluating ball-bearing materials, is primarily a measure of resistance to substantial amounts of plastic deformation, estimated as perhaps 5%. Bulk hardness thus incorporates a substantial component from work hardening, that from zero to 5% deformation. For evaluating resistance to shallow brinnelling and other small deformations, a yield strength would be more meaningful. Because steels, as hardened and tempered for bearing use, have limited ductility, conventional tensile tests are not applicable. Furthermore, this and similar mechanical tests also have the disadvantage of requiring specially prepared specimens. A technique based on initial work reviewed by Bowden and Tabor[21] was evolved in a prior program* and applied here. Indentation Yield Strength (IYS) measurements are made by indenting a flat specimen with a small ball (1/32-inch diameter) in a microhardness tester, using a series of loads, converting the load and deformation to true stress and plastic strain, and extrapolating these to give a zero or 0.2% offset yield strength.[3, 23] The ranges of this parameter found in the combos were given in Sections 2.3 and 2.4, and some further details have been published.[5]

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* AF 33(616)-3892.

Surface-contour data obtained from taper sections included maximum peak-to-valley height (ranging from 1 to 14 microinches), coarse scratch spacings (ranging from 300 to 1000 microinches), and fine scratch spacings (ranging from 35 to 275 microinches). Material characteristics measured included a microhardness-versus-depth survey, typically from 30 microinches below the surface inward, and the depth to which the microstructure differs from that of the bulk.

The overall result of the microhardness survey was mentioned at the beginning of this section. Increases of microhardness up to R_C6 were encountered with an average of $R_C3.3$, and the depths of increased microhardness ranged from 200 to 600 microinches. It should be noted that the absolute value of the bulk microhardness often did correspond to that measured by R_{30N}, with a mean absolute discrepancy of about $R_C1.2$ and a mean difference of $R_C0.4$. This disparity is attributed to difficulties connected with the light indenting load (50 gm) used to limit the depth of penetration and limit the biasing of near-surface readings by material somewhat below it. The trend to increased hardness near the surface is unequivocal. For purposes of ranking, the difference between surface and interior hardness, as measured by the survey on the taper section, was added to bulk hardness measured by R_{30N}.

The depth to which the microstructure appears altered by the grinding and finishing processes is observed metallographically and ranges up to 135 microinches, averaging 50. The glancing angles, and thus the magnification obtained in the taper section differ in the peripheral and cross-curvature directions The observation of the correct ratio in instances of deeper modifications on outer race grooves verified that these were not sectioning artifacts. For a time it was thought that the altered microstructure observed by a light etching zone might be connected with the "smeared" structure observed primarily with the RA finish, as mentioned in Section 2.6.4 and previously reported.[15] The several samples of the RB finish ("nonsmearing") final bearings examined by taper section failed to substantiate the premise. Because the significance of the taper-section-type microstructural alteration is unknown, it was not used as a ranking parameter.

In addition to the above, apparent protrusions of primary carbides above the general contour of the race-groove surface were measured. Comparison with data from direct- and interference-microscope observations showed very poor correlation. In a number of instances, reexamination of the sections showed this due to a local defect in the plating, which had spalled from the carbide. Because of the general uncertainty, these measurements were not used in ranking, and caution must be exercised in accepting this type of data.

Although the flexibility of small specimen size is a definite advantage, the technique does require substantial effort. In contrast to the earlier work,* the IYS of the program specimens is substantially covariant with the bulk hardness, and thus the actual effect on the final ranking of the preliminary combos probably was out of proportion to the effort of measurement.

3.5 Additional Race-Groove Surface-Evaluation Techniques

3.5.1 General

Several of the race-groove surface-evaluation techniques explored were not used in rating the preliminary combos. This is due to technical limitations encountered in the development due to timing and due to combinations of these with cost-effectiveness considerations of this program. As single examples respectively: interpretation of the laser holograms was found too difficult; rotary Talysurf equipment for surface-finish measurements was not available within this country at the appropriate time; and gas chromatography, where the preliminary measurements were obtained shortly before the ranking time, did not yield clear enough data to warrant the substantial effort that would have been required to obtain samples from many bearings. Because there is a general need for evaluation techniques that do not involve close simulation of gyro operation, some of the more interesting and potentially useful techniques are described.

3.5.2 Infrared Analysis of Ball/Race-Groove Interface

Measurement of temperature in the ball-to-race-groove pressure zone by infrared emission was undertaken to provide additional means of evaluating bearing parts. These temperatures indicate aspects of the lubricant compression and asperity interaction and, to the extent to which lubricant degradation is thermally activated or enhanced, yield a parameter inherently significant to a mode of bearing failure. Knowledge of the temperature generated would assist in the selection of materials and finishes least harmful to the lubricant. The LFERG apparatus was generally used to position the ball and spin the inner ring. The first, unsuccessful, approach was by photographing the ball-to-race-groove pressure zone with infrared-sensitive film. The second approach, which produced more positive results, was with a Barnes Infrared Radiometric Microscope. The measuring instrument was positioned in the plane of the ball-to-race-groove pressure zone, looking at the entrance, and adjusted for maximum temperature reading. Infrared radiation from the pressure zone passes through the microscope's chopper and infrared optics to the detector. The field of view is a square, 0.0014 inch on a side. Visible light optics are included, permitting observation of the area being measured.

*AF 33(616)-3892.

This series of tests used V-78 and an emissivity of 1.0, as measured on bulk oil. The temperatures cited are as read from the instrument without corrections due to small area of source and lower emissivity of oil-covered metal. Both corrections make actual temperature higher than reported.

Briefly, the experiments conducted and the results are:

a. Temperature versus Speed and Load -- The temperature of the pressure zone was found to increase with increases in speed and/or load, as was expected.

b. Temperature Variation with Material — No significant difference between bearing inner rings made from 52100, 440C, or Malcomized 440C was found.

c. Temperature Variation with Direction of Rotation -- The temperature reading was 2° C higher when the surface measured was moving away from the microscope (1300 r/min, 4-lb load). This observation is probably biased because exit temperatures should exceed entrance temperatures.

d. Ball-Track Temperature -- There was no measurable temperature rise in the race groove measured 90° and 270° peripherally from the pressure zone (1300 r/min, 4-lb load).

e. Temperature due to "Churning" — There was a temperature rise between the ball and race when the ball was deliberately spaced away from the rotating ring. With a clearance of 0.0005 inch, an increase of 1° C above ambient was noted. Similarly, a temperature rise was noted when scanning the areas where the ball approaches but does not touch the race groove.

f. Correlation with the LFERG — Comparing the temperature indication with LFERG counts under standard LFERG test conditions resulted in no measurable degree of correlation.

g. Race-Groove Temperature -- The microscope was focused on various parts of a race groove running in a counter-rotating fixture. No hot spots were found. The temperature of the bearing parts rose with running time.

These tests showed that the Infrared Radiometric Microscope was a useful tool for measuring thermal radiation from bearing parts under operating conditions. However, the infrared microscope was not considered to be useful as an evaluative tool without further work to improve sensitivity, since no differences between various types were discerned. Some operational difficulties with the microscope, eventually repaired by the manufacturer, precluded some further work that should be done in investigating the exit region.

3.5.3 Laser Evaluation of Race-Groove Surfaces

The coherent and monochromatic light of a laser, reflecting from a race groove, contains effects from the race-groove curvature, self interference, and microgeometry. The experiments were directed toward two potential uses: detection of defects in race grooves and measurement or rating of surface finish. A Spectra-Physics Model 130 laser was used. This HeNe laser, with a hemi-spherical resonator, produces a 0.3-milliwatt CW beam of 6328 Å (visible red) wave length. Generally, the full 0.1-inch diameter beam was used to illuminate the specimens, but occasionally an 8X microscope objective lens was used to focus it. Figure 3-3 shows the equipment layout for the race-groove examination. The race groove reflected the beam onto a screen, where it was observed and photographed, and/or onto a photocell through which intensity as a function of sample orientation (rotation) was recorded. Photographs of defects taken with a standard microscope were compared with the laser data.*

In elucidating these effects, flat and cylindrical surfaces, inner and outer race grooves, ball-lapped, tumbled and as-ground parts were examined. Using the focused beam setup, it was found that interference fringes can be formed in the reflection from a race groove without restrictions on part size as is the case with the interference microscope. Residual lap lines on a race groove cause lines to appear in the reflection, indicating that the reflection yields a measure of the finish on the part. No one-to-one correspondence could be established and it is believed that the individual lines in the reflection are made up of information from all points in the race groove. The reflection therefore is an indicator of average race-groove finish and geometry. Thus, the photocell reading from the reflection can give an average quality measurement of the race-groove surface, so long as the variations due to the finish predominate over reflectivity variations.

Methods of correlating the information gained from the reflected laser beam with the race-groove micrograph are still needed. An aid in this may be the electrical signal which can be generated with a photocell since this could be manipulated to produce various readouts.

It is concluded that the laser method has potential value in the examination of race-groove surface finishes, but that a substantial effort in

*A number of these and other data were given in a special report.[24]

A 2

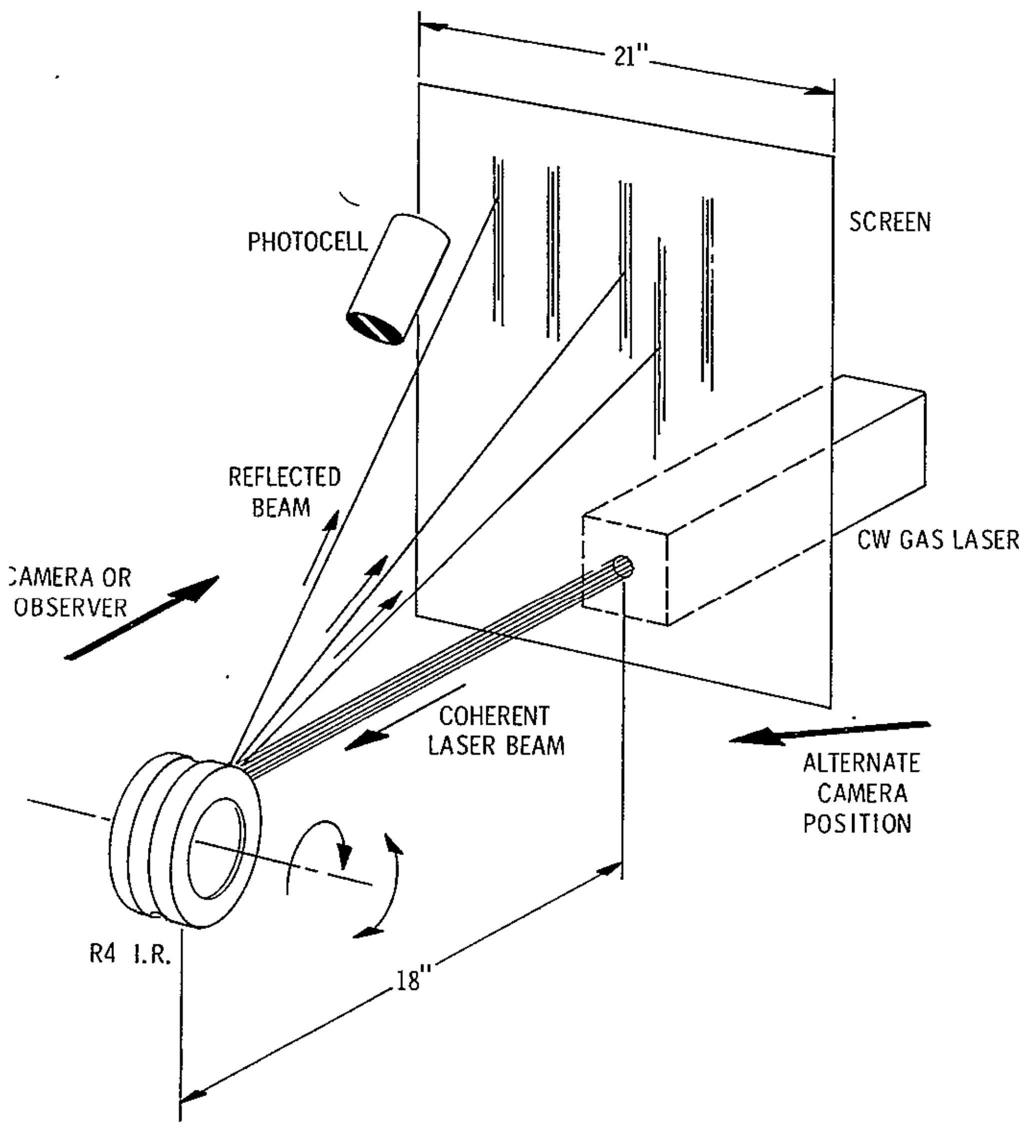

Fig. 3-3. Equipment layout for race-groove examination with laser beam.

modifications, improvements, and correlations is still needed before the technique can become an evaluation tool.

3.5.4 Lubricant Analysis by Gas Chromatography

The lubricant in a gyro bearing is usually the most sensitive indicator of impending failure. Often, prior to failure or damage, inspection of the lubricant reveals a change of color and signs of thickening, implying chemical changes. A more sensitive indicator than the human eye should be able to detect symptoms earlier in the life of the bearing. This would allow prediction of potential life, providing a briefer test for comparing bearings and a great aid to instrument reliability forecasting.

Gas chromatography can analyze small quantities of lubricant in a gyro bearing, "finger printing" the chemical compounds present. To explore the potential for delineating changes in the lubricant, two bearings were run in a low-speed endurance (LSE) test, on the assumption that LSE oil degradation is comparable to that in high-speed tests. Specimens were obtained by soxhlet extracting all oil from the bearing. Since LSE failure times are quite repeatable, specimens for 1/3 and 2/3 as well as zero and full failure times were obtained. Some procedural mistakes vitiated the desired comparison of individual constituent concentrations but, working with ratios and other information, it was concluded that:

a. A change in lubricant composition occurs within the first third of the typical running time to failure.

b. New constituents appear at the failure point determined by the LSE torque trace.

c. Instrumental sensitivity is adequate to define some running changes with a sample of only 10 micrograms of V-78.

The technique thus appears to have potential. The methods of sample preparation and instrument operation are given in Section C.4.

3.5.5 Surface-Finish Measurement

Surface finish or microtopography has always been of prime interest to bearing manufacturers and users. Unfortunately, surface-finish measurements are difficult to make on doubly curved surfaces like race grooves. Profiling instruments— that is, ones that trace the surface with a stylus — are often used to obtain numerical data.* At the beginning of this program the ability to finish race grooves had outstripped the capabilities for profiling measurements for surface roughness, although Talyrond traces were sometimes used for this. As a Rotary

* Reference 25 gives many details on profiling and defines the terms used in this section.

Talysurf was developed in England, samples of some of the preliminary combos were sent there and data compared with that obtained by the taper-section technique. The good correlation, obtained shortly after the closing date for ranking data, encouraged the bearing manufacturer to acquire the machine and increased the program confidence in the taper-section data.

The Rotary Talysurf, an instrument similar to the linear Talysurf long used on flat surfaces, was used with a 50-microinch-radius stylus at 0.1 gram pressure. Data were taken with a 0.003-inch cutoff setting, with that summarized below being an average of approximately four samples.

		Surface Finish microinches AA	
	Sample Group	Cross Race	Peripheral
Reference Lot	Inner race groove	1.20	0.50
	Outer race groove R finish	1.00	----
	Outer race groove RA finish	0.65	----
Combo K	Inner race groove	0.85	0.35 to 0.40

The finish of typical 440C balls of AAA grade, as used in all the program bearings was found to be 0.80 microinch AA. These data demonstrate some of the improvements obtained in the program and, since the measuring instrument loses accuracy below a microinch, shows finish technology again overtaking metrology.

3.5.6 Low-Speed Endurance

A low-speed dynamometer (LSD)[16] has long been used to evaluate finish and defects of race-groove surfaces and balls by operating a bearing under conditions that preclude the formation of the elastohydrodynamic film (1 r/min, near usual preloads — say 10 lb on an R 4). As mentioned in Section 2.7, the LSD also can serve as an indicator of degradation in a bearing. The boundary lubrication condition in the LSD is a severe one leading to limited life at 1 r/min. This low-speed endurance (LSE) was found to be strongly dependent on the surface chemical condition of the race grooves, with typical LSE times for untreated 52100 and 440C bearings being 2 to 6 hours, after which time the LSD torque trace indicated bearing — usually lubricant — deterioration. The LSE test was further investigated in this program and, in combination with some work in another program,* it was shown that passivation (see Section B. 6) and/or TCP treatment

*AF 04(694)-305 S.A. No.8.

(see Section B. 7) of the bearing race grooves before the test would greatly extend LSE. The LSE runs in this phase were generally stopped at about 150 hours without failure. Within the limits of the test, passivation and/or TCP treatment of the balls was found neither advantageous nor harmful. It must be realized that the operating conditions of LSE and gyros are so different that no parallel between these can be drawn, thus vitiating LSE as a rating parameter. Nonetheless, many boundry-lubrication or dry-friction operations, such as contact-angle matching and cross-curvature gaging, occur in bearing manufacture and gyro construction. Passivation and TCP treatment of both races and balls is therefore advocated, principally as a result of the LSE data. The LSE test with time extended well beyond 150 hours further proved useful in sorting out other surface chemical differences in bearing race grooves.[18]

SECTION 4

DISCUSSION OF SELECTED TOPICS

4.1 Introduction

In a technology development program there always are areas in which information or further interpretation is added to a substantial existing body, which is the result of prior or concurrent work. This section will cover some of these aspects and present some conditional recommendations for future effort.

4.2 Improved Bearing Steels

4.2.1 Background

Several directions for improvement of the stainless bearing steels used in this and other gyro spin-axis bearing programs can be readily defined on a conceptual basis. On the other hand the benefit of improved steel, realized through reduction of manufacturing rejects and part inspection costs, and through bettering life and performance, are not quantifiable. An earlier program* attempted to sort out the effects of steel cleanliness on running behavior of bearings by carefully examining a number of steel lots used in manufacture. The problem was found to be a multivariant one. It is doubtful that clear correlation would have been found even if the originally intended amount of bearing tests had been able to be carried out.

This fuzzy situation leads to a somewhat arbitrary trade-off process between bearing users and manufacturers,and steel makers with risks on both sides. The former pair bet that more stringent specifications for bearings and steel stock will result in improved life and performance and lowered manufacturing costs. The steelmaker risks his investment in trying to institute these changes in the hope of making a higher profit from his product by either a higher volume or unit price. But the overall quantity of precision gyro bearings made is very small and some of the steel desirata quite advanced. Thus the methods to provide the incentive to the volume-oriented steel industry are limited. Incentive methods, including information feedback, were incorporated in this as in previous programs.

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* AF 04(694)-305.

4.2.2 Carbides

The martensitic stainless steels used for ball bearings, among which are those of this program, contain two distinct categories of carbides, primary and secondary. Primary carbides are formed during the solidification process of the steel, precipitating and growing from the melt. Because these carbides are formed from carbon in excess of that soluble in the solidifying steel, they are sometimes called excess carbides, which should not imply that they are unintentional components of the steel. Primary carbides are modified by the hot working and heat-treatment processes used in reducing the ingot to bar stock, and to some extent in the subsequent hardening treatment of parts machined from the bar stock. Secondary carbides are formed as a result of the various stages of tempering which the steel undergoes after hardening.

Cracked primary carbides have been noted on this as well as previous programs, and on one* a prevalence rating technique had been developed. These apparent fractures of primary carbides probably occur in the hot working processes and it is conjectured that excessive reduction at too low a temperature may increase the frequency. It has, at various times, been noted that material from these cracked carbides detaches easily, scoring the race-groove surface being ground or finished. Undoubtedly the degree to which matrix material enters the spaces between the primary carbide pieces is important, but the techniques developed cannot discern this. Several steelmakers seem to have carbide cracking under control whereas others seem unaware of it altogether. A point in case is that most of the lots of 14-4-1 examined had very high frequencies of cracked carbides. It is felt that wider use of a cracked carbide frequency limit in bearing-material specifications would have a salutary effect on steelmaking practice.

4.2.3 Firth-Vickers' F.H.M. Steel

It was noted with interest that Firth-Vickers' F.H.M., the proprietary British stainless steel used for bearings in the U.K., appears more attractive than 440B, which is its closest equivalent in composition. 440B, because of its lesser carbon content, has a smaller volume fraction of primary carbides and concomitantly a lesser maximum hardness than 440C (see Section 2.1.2). F.H.M. with nominally a still lower carbon content than 440B was as hard as the program lot 440B-L1. This was achieved with a heat treatment which apparently did not use the high austenitization temperature and subsequent subcooling employed in this program to obtain maximum hardness for conventional heat treatment (see Section 2.4.4). Furthermore, F.H.M. has finer, better distributed primary

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* AF 04(694)-305.

carbides than 440B and 440C and appeared to contain less nonmetallic inclusions. It therefore might be an attractive alternate to 440C and 440B, but the proprietary aspect may prove to be too restrictive.

4.2.4 Nonmetallic Inclusions

Nonmetallic inclusions are unwanted impurities in these bearing steels. They are commonly measured by a JK rating on the basis of Method A,[4] which examines a limited area for the worst microscopic field at 100X. This scanning method, though fast, was found to have only limited efficacy, often missing major amounts of inclusions. It was found better to adopt Method D,[4] in which statistics of some hundred or so fields are compiled. This severity/frequency profile of the steel volume, from which race grooves would be machined, was much more satisfactory in comparing the random inclusion contents of steels than the generally used maximum-severity method. In order to avoid an overly detailed listing, Table 2-2 was condensed from such severity/frequency ratings, and some implications of these data are discussed in Section 4.2.6.

4.2.5 Inspection Techniques for Stringer Inclusions

The program used the standard as well as some special stock rating techniques. Nonetheless, it became very clear after the beginning of this program that the frequency of long stringer inclusions, contained in many steel lots, was not being correctly disclosed. As mentioned in Section 2.2.3, several new techniques were investigated. The first and basically the most successful one of these employed a honed stepdown bar. In this method a bar sample, about six inches long, is taken from the stock and machined to give four 1-1/4-inch long cylindrical steps of diameters related to the prospective race groove. After hardening, the steps are given a highly polished finish using a cylindrical honing machine.

Initially, qualitative information was obtained by microscopic examination of the stepdown bars but later data were quantified. The method used was to examine each step with ten equally spaced, circumferential scans at 100X, 0.1 inch apart, recording each intercept with a stringer inclusion. It was noted that the stringers were roughly parallel to the bar axis but often a single stringer would intercept several adjacent scans then be absent and reappear several scans later. A common hiatus for this would be 0.3 inch

Because it was found crucial to have the stepdown bars hardened for successful honing and because honing equipment sometimes is not readily available, alternative finishing processes were explored. A refinishing operation, handlapping with an impregnated silk cloth, was found substantially equal to honing and data obtained from this also reinforced those from honing. Electropolishing rough lapped surfaces was found to be less effective because several types of inclusions were dissolved, and more tedious, higher magnification (400X) examinations were needed to differentiate between stringers and carbide boundaries. Although the latter technique especially would allow the use of unhardened specimens, the above shortcomings plus the need for sensitive control of the electropolishing conditions makes it unattractive.

In an attempt to obviate the microscopic examination and in the hope of disclosing subsurface inclusion stringers, two magnetic-particle testing techniques were tried. The continuous wet method was found better than the residual wet method, but disclosed no previously unobserved stringers and responded only to the larger of those seen microscopically. This is deemed a serious disadvantage.

After it had been established that honed stepdown bars showed stringers and correlated with manufacturing experience, the reasons normal inclusion-rating techniques did not were investigated. There seem to be at least four possible explanations:

a. Standard longitudinal sections are not sufficiently parallel to the bar axis and tend to intersect stringers without revealing their extent.

b. Volume of the stock relevant to the race grooves is de-emphasized by the diametral (longitudinal) sections since these give equal weighting to other regions of the bar.

c. Polishing the unhardened metallographic specimens tends to pull out the inclusion material and fill the voids by flowing in material from the surround.

d. Since, in contrast to the machinist who works to dimension, the metallographer usually examines the surface finish obtained, he biases data by continuing the polishing operation until the "scratches" offensive to his eyes are removed.

Metallographic specimens were used in the investigation. These were diametral sections, carefully prepared to minimize axial misalignment. It was estimated that these would be parallel to the rod axis within about 1/2° whereas the stepdown bars probably had less than 1/10 of that misalignment without special care. Since the metallographic polish of the unhardened specimen was found to disclose stringer inclusion frequencies comparable to the stepdown bars, Item c was not the factor with metallographic samples. The other possibilities remain unresolved although it is suspected that, since stringers wander in and out of the honed surface on the stepdown bars, Item a is not a dominant factor.

4.2.6 Melting Methods for Special Lots of Steel

In the course of the program, it became necessary to obtain new lots of steel to substitute or supplement the initial program lots. As a result of manufacturing Combo A and C bearing rings it became clear that 440C-L2 contained large amounts of stringer inclusions. The prevalence was high enough to cause over 50% rejection of parts at the final visual inspection. Information from a prior and a concurrent program* supported the probability of a high rejection rate at this expensive stage. Initial contacts, exploring how improved 440C could be made available, had already been made. These discussions, among many other items, covered melting methods. Very briefly, it was postulated that the combination of vacuum induction melting (VIM) which obviates the need for a slag blanket, with subsequent vacuum arc remelting (VAR) to reduce the scale of the residual impurities and general structure, probably was the best of the available paths. As a result of these contacts, the steelmaker had made some special VIM-VAR heats and it was possible to order stock from one of these, which became lot 440C-L4.

Difficulties were encountered in obtaining another lot to supplement 14-4-1-L3. A number of heats, made over a period of a year, were rejected because samples showed unsatisfactory primary carbide conditions and excessive frequency of large inclusions. The next lot passed both groups of criteria but proved to have very many stringers when examined by honed stepdown bars and other methods. It was then found that the steelmaker had changed the melting process from the VAR of 14-4-1-L3 to VIM. This fits the premise that the latter process (which has a much larger molten volume) results, as a first approximation, in larger inclusions for the same nonmetallic inclusion content. In contrast to 440C, no groundwork for improved 14-4-1 had been laid, but arrangements for 14-4-1 produced by VIM-VAR eventually were made.

Comparison of Table 2-2 data on 440C-L2 and 440B-L1 with 440C-L4 shows the last to be much better in nonmetallic inclusion content, undoubtedly due to the use of higher purity materials in the initial melt and to the double vacuum melting. Improvements can also be seen in comparing 14-4-1-L3 with 14-4-1-L12. On the other hand both of the VIM-VAR vacuum melted steels still had appreciable Type A (sulfide) inclusions. It is conjectured that the use of a low sulfur iron charge in the first melt would obviate this.

Conventially heat treated as described in Section 2.4.4, 440C-L4 was found to be somewhat lower in hardness (about $R_C 62$) than previous lots

*AF 04(694)-305 and AF 04(694)-553 respectively.

examined on this and other programs (about R_C63). This is considered marginal[26] and is tentatively attributed to composition. Both carbon and chromium content are at the lower limit of the desired composition.[26] If this is the cause, it probably is a nonrecurring deficiency.

The two special heats of this program, by inclusion ratings, by honed stepdown bar, and by manufacturing results support the premise that VIM-VAR melting practice, perhaps coupled with low sulfur melt stock, is a most promising route for improving these bearing steels.

4.3 Conventionally Heat Treated 14-4-1

Latrobe Steel Company's proprietary Lesco BG42 -- a 14% Cr, 4% Mo, and 1% V steel (now also known as Lescalloy BG42) -- was used for four preliminary and one final combo. The attractive aspects, as well as shortcomings, are summarized in Section 1.4. The optimized conventional heat treatment, given in Section 2.2.4, was 2100° F austenitization followed by oil quench and two 975° F tempers. Subcools in liquid nitrogen were used before each temper to convert retained austenite.

Although there is an unresolved question about the hardness of 14-4-1-L12, the other two lots were about R_C64 after conventional heat treatment, and the IYS of 14-4-1-L3 was 350 ksi. 14-4-1 thus has higher hardness and indentation yield strength than 440C on which a lower temperature temper, 300° F, is used. Moreover, if 440C is tempered to the secondary hardening peak -- around 800° F -- some softening and a substantial decrease in corrosion resistance result. The corrosion resistance of 14-4-1, as conventionally heat treated in this program, was less than that of low-temperature-tempered 440C. 440C thus treated passes the corrosion-resistance test[22] without passivation, whereas 14-4-1 required passivation to raise the corrosion resistance to that level. On the other hand, 440C tempered to secondary hardness will not pass the corrosion-resistance test in either condition. The dimensional stability of the 14-4-1 samples (probably because of the type of temper) was found to be better than that of the 440C.

The overall results of 14-4-1 in the preliminary combos also was very encouraging. Examining Fig. 2-1, it will be noted that the three top-ranking candidates are 14-4-1. Conventionally heat treated 14-4-1, Combo E, was seriously regarded as an alternate or mate to ausformed 14-4-1, Combo I. It was concluded that the higher rank given Combo I was not particularly sensitive to the weighting factors, as given in Table 2-4. In other words, reasonable variations in these weighting factors would still result in a higher ranking for Combo I than for Combo E. Considering the short supply of 14-4-1-L3 and the continued difficulty in obtaining more material, it was decided that a second final-bearing combo made of 14-4-1 would be an over-commitment.

Some of the disadvantages encountered have already been mentioned. In spite of the apparently ample billet size of the first lot of 14-4-1, less than half the ordered amount was delivered to the program because of extensive cracking during the hot reduction processes. The steelmaker's subsequent change from VAR to VIM may have been intended to ease this manufacturing problem but, as mentioned in Section 4.2.6, also seemed to result in excessive stringer inclusions. The composition is proprietary, so only a single company makes the alloy. Because of the limited quantity made, new heats were not readily available. The experience with the special heat, 14-4-1-L12, which became available as bar stock several days too late to be used for final bearings, was probably also not unusual. Although no technical difficulties were encountered in the manufacture, deliveries slipped from the originally promised ten weeks to nearly six months. Based on prior experience with other steelmakers, this situation might be expected with any special heat of steel, at least with a small volume requirement.

If the technical advantages in other uses, such as the ability to use the secondary hardening without the decrement in hardness and corrosion resistance (which is probably more important in larger size bearings, say one-inch bore up), outweigh the detriments, the volume of 14-4-1 produced may increase sufficiently to overcome many of the logistic drawbacks. This would make the alloy -- especially in the lower cost, conventionally hardened state -- much more attractive.

4.4 Ausforming Techniques

The heat-treatment/deformation techniques used in ausforming constituted one of the most sustained trouble areas in the program. The basic process is described in Section 2.3.6 and is especially difficult to perform with high-carbon steels. The original intent was to obtain the required 50% or more reduction in area by using grooved rolls on a rolling mill. Substantial reductions should be feasible by using successively smaller grooves and limiting the temperature drop between passes. Appropriately grooved rolls for the available rolling mill could not be procured nor could access to a thus equipped mill be arranged. Metallurgical samples exploring the deformation and temperature parameters were relatively easily prepared by rolling 0.7-inch square sections with normal rolls.

After interest in this thermomechanical hardening technique was established by preliminary results, problems of obtaining the required deformation mounted. The techniques available were very limited and those tried are listed in Section 2.3.7 along with their shortcomings. Direct rolling of flat-sided round cross sections eventually had to be used in order to produce material for the preliminary combos. This technique was found very time-consuming and awkward and is not suited for scale-up to the somewhat larger quantity needed for the program final bearings and to prepare the way for still larger-quantity bearing production.

It should be emphasized that the overall problem is basically that of scale-up. It was therefore of great interest to learn, in the period between preliminary combo stock production and ranking for final-bearing combos, that Super Alloy Forge, Inc., of Hamburg, Michigan, had done work on direct-impact extrusion ausforming. Their facilities were available on a job-shop basis and they had previously aided several investigators by ausforming material. Arrangements were therefore made to experimentally ausform two or three samples each of the three program steels. This demonstrated that the equipment could perform the operation and the resultant properties were comparable to those attained by rolling.

The ausforming for Combo L bearings was done with program personnel on hand to aid and monitor the operation, which is described in Section 2.6.3. A new die had been made to produce the required size and, after starting extrusion, it became clear that the contour of the die throat had to be changed — a cut-and-try process at that installation. Since this die is preloaded by perhaps a thousand pounds of constraining rings, it speaks highly for the vendor's motivation that he was able to effect a change overnight. The die shape change coupled with changed lubricant overcame the previous mechanical difficulties but clearly latitude to adjust shape and perhaps lubricant must be allowed in future ausforming runs.

The problem with soft regions in the extruded hard bars appears to have come from two sources, retained austenite and the formation of bainite. The corrective treatment described in Section 2.6.3 was largely able to convert the high retained austenite content but should have had no effect on the bainite. Working from the "estimated" TTT* diagram for 14-4-1, there should have been a sufficiently large bay to prevent the formation of bainite, an unwanted transformation product of austenite. If, on further ausforming work with this alloy, more problems with bainite formation are encountered, slightly higher extrusion temperature or shorter hot quench times are indicated. This problem may not occur with other alloys. Since retained austenite was not a problem with conventionally heat treated 14-4-1 subcooled to liquid nitrogen temperature, it appears that the ausforming process depressed the M_F (martensite finish) temperature. This again may not be a problem with other alloys, but if 14-4-1 is similarly ausformed, changes in austenitization may ameliorate this and liquid helium subcooling immediately after ausforming should correct it.

The overall conclusion is that direct extrusion is the most promising of the ausforming techniques for manufacture of small bearing parts in quantities of hundreds to thousands. If such ausformed material is desired, further development work as described above is strongly recommended. For larger-scale production,

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* See Section 2.3.6.

modifications of the direct extrusion technique — which would allow straight-through processing instead of manual extraction of the work piece — and semiautomated techniques might be considered. The original intention of rod-rolling should also be investigated.

4.5 Hardness Measurements

Earlier work,[8] investigating hardness and heat treatments of gyro bearing rings, disclosed a substantial disparity in hardness readings by several different agencies. This was partly due to different hardness tests (scales)* being used and partly to poor measurement techniques. It was surprising to find differences of about $R_C 2$[8] since hardness is universally used as the principal physical parameter in comparing bearing materials and in checking heat treatment and steel lots. The investigation compared the use of different hardness tests and determined the optimum for gyro bearing parts (other than balls) to be R_{30N}. Among the advantages of this test, compared to R_C (the scale most frequently used in the U.S.) is the low load which lessens flexure of the part being tested and results in a substantially smaller indentation and smaller volume influenced by the test. Resolution is essentially comparable to R_C, with differences of R_{30N} 0.9 equal to R_C 1.0 in the ball-bearing-steel hardness range. It was found that repeatability of the test could be very good, the spread of extremes for four or five readings usually being less than $R_{30N} 0.3$. All R_C hardness values given in this report were measured as R_{30N} and converted.

The depth of the impression measured at $R_{30N} 80.0$ (ref. $R_C 63.0$) is 8×10^{-4} inches, with a deviation of 40 microinches equivalent to one R_{30N} point. The $R_{30N} 0.3$ spread is about a half wavelength of visible light with a purely mechanical measurement. From this aspect, it is less surprising that somewhat different results are obtained with a standard type of measurement.

Over the time span of this program, and partly in connection with it, it was found that the repeatability of measurement could be maintained within $R_{30N} 0.3$ over extended periods, that there are operator variables in the test, that operators could be trained to obtain repeatable results, and that essentially identical data could be obtained at various installations.

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* Hardness is not a fundamental parameter. It usually is taken as a measured resistance to indentation under a standardized test. The most frequently used tests are standardized by having a machine perform the loading, unloading, and often measurement of the depth of indentation. Tests, as used here, imply the use of a tester reading directly in a hardness scale, e.g., R_C, R_{30N}, R_A. Conversion between scales can be achieved by calibration, and standard tables are available[27]; but it must be recognized that conversion depends on the rheological properties of the material tested — in other words, the conversion tables are only approximate relations, with specific materials deviating from them.

Standard hardness blocks are used to test the machines both before and after a series of readings. It was found that, with well-tuned operation, all such blocks that were in good condition would give readings within about $R_{30N}0.1$ of their nominal value, not just within the $\pm R_{30N}0.7$ tolerance given on the blocks. Repeatability of averages of hardness readings of specific samples, repeated over periods of up to two years, similarly was about $R_{30N}0.2$.

The normal machine maintenance instructions, often not followed, call for special lubrication, dash pot time adjustment, etc., and must be followed to obtain good results. Periodic "preventive maintenance and adjustment" by the manufacturer's service engineer seems to not be a good idea. Several instances of well behaved machines going out-of-tune as a result of this are known. The machines were still within "factory tolerance" but not performing as well as before the overhaul. Careful relubrication, tightening of clamping screws, cleaning of pivots, etc., by the operator generally restored the machine. The best advice is to keep checking on the machine and only overhaul when thus indicated. Staying aware of the possibility of the measuring mechanism sticking at certain readings, excessive scatter and/or deviations from standard-block readings are indications of the need for tuning.

A steady, gentle manipulation of the controls is needed for good readings; but it was found that some people, despite positive motivation, are unable to acquire the knack. Operators who get very little scatter in their readings get identical hardness averages, reinforcing the validity of the measurements. After some disparities in hardness measurements between the metallurgical agency and MIT/IL in the first portion of the program, training the operators and tuning the machine by the former brought satisfactory agreement.

In order to obtain meaningful readings, the target for machine adjustment and operation must be much better than the pessimistic performance tolerances which the manufacturer suggests.

Other factors to be considered are that anvils and indenters need seating, that the mechanisms in the tester need some exercising before reliable readings can be obtained, that the mechanisms are somewhat temperature sensitive, that 440C and similar steels are usually softened by abrasive cutoff and grinding of the test surface (depths of modification of 0.06 inch with apparently very careful cutoff), and that preplanning is necessary to reserve test blocks and indenters for periodic machine performance verification. Some further information on use of R_{30N} hardness tests in checking steel lots and heat treatment are given in two of the 2FBG-10H gyro specifications.[11, 26]

4.6 Race-Groove Finish and Geometry

The race-groove finish and geometry of the program final bearings, especially as a group, were of exceptionally high quality. This has already been discussed in Section 2.6.4, and Figs. 2-2 and 2-3 give examples of cross-curvature and peripheral-roundness records. The overall quality of finish and geometry was substantially better than that of lapped or honed race grooves previously made in quantity. Incidentally, it was this exceptional mechanical quality that enabled tracing the operational difficulties (see Section 2.7) to surface chemical condition, since the many finish and geometry considerations usually present did not obscure the issue. Only two groups of ball bearings were procured by the Inertial Gyro Group since termination of the work covered in this report. These were ordered before the diagnosis of adverse surface chemical condition and a means of alleviation were confirmed, so that the ball-lapping finishing technique established earlier* was specified. In contracting for and inspecting these bearing lots for the Third Generation Gyro**, the geometry and thus the grinding and finishing technology developed and demonstrated on the program final bearings became the target or reference level. In spite of the difference in the finish technique, many aspects of the manufacturing methods, including the R-type honing, were carried to these bearings.

The smoothness of finish achieved by the RB honing has never been matched by any other standard bearing finish. The uniformity of finish of the group was also excellent, although there were some small comets, scratches, and brinnels on a few of the bearings delivered. The latter two basically arise from insufficiently careful handling and gaging. Because of their high finish, these race grooves (as mentioned in Section 2.6.4) seem to be more susceptible to such markings. This may well be an asset since similar damage, though potentially equally detrimental, would not be as noticable with another finish.

The cross-curvature geometry of the final bearings was outstanding, especially in the extent of the region that has near-perfect curvature. The primary concern is in the pressure zone — the region around the nominal contact angle — although greater extent of near-perfect cross curvature constitutes insurance in deviations from the nominal contact angle and allows, as done in this program, the assembly of a group of bearing rings to more than a single nominal contact angle. Ball lapping of race grooves, when properly done, can match the final bearings in the degree of pressure-zone cross-curvature perfection, but is unlikely to exceed it.

* AF 04(694)-305.

** NAS 12-569.

The final bearing peripheral geometry, in roundness and lack of lobing, has been matched though not exceeded by the ball-lapped bearing lots manufactured since this program. In this respect the final bearings are a pacesetter.

A group of RB-finished bearings, essentially identical to and made about the same time as the Combo K final bearings, was used in still another gyro build program.* The bearing operating conditions and requirements in this gyro differ somewhat from those in the program dynamic tests (see Section 2.7). Nonetheless, the experience of 100% bearing yield during the build phase and operation of 19 pairs from 1,000 to 22,000 hours, currently averaging about 4,000 hours, without a bearing failure indicate the high capability of the program final bearings when freed of their adverse surface chemical condition. This group substantiates the geometry- and finish-based recommendation of the program final bearings.

4.7 Mechanical Hysteresis

Motivation for reducing the power required to run a gyroscope is obvious when the mass in a vehicle needed to support an increment of power is considered.[28] Drutowski[29, 30, 31] advanced theories initially ascribing almost all of the rolling friction to mechanical hysteresis. Mechanical hysteresis can, in its simplest form, be thought of as material behaving as an imperfect spring. Loading this spring requires a certain amount of mechanical energy, but when it is unloaded not all of the energy is released, the remainder being converted into heat or stored energy within the material. A simple measure of the energy loss is specific damping capacity (SDC) which is the ratio of energy lost over the maximum energy input to the spring.

A review of published work led to a series of calculations of likely energy losses. Using simplified models and an SDC of 1×10^{-2}, mechanical hysteresis energy losses for a 12,000-r/min bearing were estimated as 0.1 of the 0.8-watt power required.[32] It was also realized that the assumption of simple energy-loss characteristics for materials was a crucial shortcoming of the various models. This vitiates many potential test rigs that could be used to rank and evaluate various ball-bearing steels in order to minimize bearing friction. Energy losses depend in complex ways not only on maximum strain and on the actual loading/unloading path, but on the temperature and speeds involved. As a single example, some of the characteristic times involved in gyro ball bearings come close to calculated jump frequencies for some atomic diffusion events in iron,[33] indicating the possibility of a strong coupling and strongly temperature- and speed-dependent energy losses.

One of the principal shortcomings to somewhat more realistic mathematical modeling is the lack of an analytic expression for stress or strain as a function of

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*NAS 5-11002.

coordinates in the stressed volume, even with the assumption of Hertzian contact. All that is available for a ball on a doubly curved surface is the expression for the planes of symmetry. In order to have a satisfactory stress space approach to mechanical hysteresis losses in these bearings, a three dimensional numerical stress model, substituting for the nonexistant analytic one, is desired. Because other factors such as windage, retainer friction, and retainer and ball-group dynamics seem to dominate, the development of such a model for these purposes alone is not justified. On the other hand, this problem should definitely interest the academic community.

APPENDIX A

TOPICAL SUMMARY OF WORK, PUBLICATIONS, AND PRESENTATIONS

A.1 Introduction

The program had effort in many areas, the details of which are for the most part beyond the scope of this report. Sections A.2 through A.9 provide an overview of the program by a listing of subjects covered. Further information can be obtained upon request.

Sections A.10 and A.11 list publications and presentations, other than those contractually required, which were either directly or in part based on the program work. Section A.12 provides a listing of semiformal presentations covering various aspects of the work.

A.2 Selection and Evaluation of Stainless Bearing Steels

a. Establishment of initial specification requirements

b. Review of variants of 440C including British and other corrosion-resistant steels

c. Evaluation of program lots of 440C, 440B, and 14-4-1 steels

d. Inspection for steel cleanliness by more-stringent-than-usual JK-type inclusion ratings

e. Improved methods for detection of stringers

f. Response to heat treatment, including liquid-nitrogen subcool and double tempering

g. Methods of making cleaner stainless steels

A.3 Hardening Treatments

a. Conventionally heat treating 440C, 440B, and 14-4-1

b. Strain-aging 440C, 440B, and 14-4-1

c. Ausforming 440C, 440B, and 14-4-1

d. Ausforming, then strain-aging 440C, 440B, and 14-4-1

e. Malcomizing 440C, 14-4-1, and 14-4

f. Tempforming of 440C

A.4 Machining and Evaluation of the Effects of Materials and Processes

a. Analysis of limiting shortcomings and improvement of conventional bearing manufacturing processes

b. Development of manufacturing techniques to handle hardened bar stock, e.g., trepanning by EDM

c. Improvement of heat-treatment capabilities including use of argon protective atmosphere

d. Tests for residual stress using Heyn method

e. Differential hardness including microhardness surveys

f. Modification of grinding parameters

g. Difficulties with automatic-lathe operations, probably as a result of surface scaling

h. Stringent dimensional control for Malcomized bearing rings

i. Tests for dimensional stability of bearing parts

A.5 Evaluation of Preliminary Combos

a. Limited running tests of Malcomized bearing rings

b. LSD and LSE tests

c. Techniques for converting evaluation data into rankings

d. Evaluation of combo parts by functional and logistical parameters

e. Weighting of parameters according to estimated relative importance

f. Selection of material-treatment combinations for final bearings

A.6 Manufacture, Examination, and Test of Program Final Bearings

a. Determination of final bearing design and specifications

b. Determination of separate and common stages for final bearing manufacture

c. Exploration and then use of direct-extrusion ausforming process

d. Optimization of 440C and 14-4-1 cleanliness through special double-vacuum-melt heat

e. Corrective temper and subcool treatment of 14-4-1 parts for higher hardness

f. Selection of stress-relief parameters for final bearing parts

g. Evaluation of various race-groove finishing techniques

h. Disclosure of primary-carbide oriented "smear" effect in RA finish

i. Development of RB finish technique to obviate "smear"

j. Post-manufacture metallurgical and optical inspection techniques

k. Preparation of bearings and retainers for modified Apollo I IRIG's

l. Establishment of stringent bearing-failure criteria

m. High-speed gyro simulation testing of final bearings

n. Low-speed dynamometer and high-magnification visual evaluation of effects of dynamic tests

o. Disclosure of race-groove surface-chemistry-connected failure phenomena

p. Establishment of oil-spreading test technique for race-groove surface chemical condition

A.7 <u>Development of Improved Race Grooves</u>

a. Development of minimal-stock-removal grinding and finishing techniques

b. Optimizing of bearing race-groove grinding operations, machine setup, wheel dressing, and quality control

c. Refinement of finishing techniques, especially race-groove honing

d. Optimizing of engineering supervisor to machine operator to machine interfaces

A.8 <u>Race-Groove-Surface Evaluation Techniques</u>

a. Quantitative evaluation of race-groove surface nonuniformities by optical techniques

b. Evaluation of race-groove finish, geometry, and response to manufacturing methods by taper-sectioning technique

c. Quasi-functional evaluation of surface geometry and finish by LFERG

d. Infrared measurements of ball/race-groove interface temperatures

e. Laser evaluation of race-groove surfaces

f. Lubricant analysis by gas chromatography

g. Surface finish measurements by Rotary Talysurf

h. Tests for metallographically observable alterations engendered by manufacturing processes

A.9 Miscellaneous

a. Investigation of improved x-ray techniques for measuring retained austenite

b. Investigation of mechanical hysteresis losses in rolling contact

c. Optimization of ausforming techniques

d. Improved techniques for measurement of bulk hardness

e. Techniques for measurement of indentation yield strength

f. Evaluation of prevalence and effects of cracked carbides in 440C-type steels

g. Identification of critical bearing manufacturing operations

h. Passivating and corrosion-resistance testing of stainless steels

i. Prediction of bearing-ring dimensional changes due to Malcomizing

j. Effects of TCP treating and passivation on boundary lubrication

k. Use of unequally spaced ball pockets to effect retainer control

l. Development of various active bearing cleaning procedures

A.10 Publications and Presentations Directly Based on Program Work

A.10.1 Presented at the MIT/IL Gyro Spin-Axis Hydrodynamic Bearing Symposium, MIT, Cambridge, Massachusetts, December 1966, and published in the Proceedings.

a. Lement, B. S., Cairoli, A. M., and Kreder, K., "Quality of Steels Used in Gyro Ball Bearings"

b. Palmieri, J. R., and Allen, S., "Heat Treatment of Bearing Steels" (also separately as MIT/IL Report E-2085, December 1966)

c. Allen, S., and Palmieri, J. F., "A Metallurgical Modification Caused by Finish Operations on Ball-Bearing Race Grooves" (also separately as MIT/IL Report E-2084, December 1966)

A.10.2 Presented at the Thayer School of Engineering-American Ordnance Association Bearings Conference, Dartmouth College, Hanover, New Hampshire, September 1968, and published in the Proceedings.

a. Lement, B. S., Allen, S., and Kreder, K., "Attainment of Higher Strength in Stainless Bearing Steels" (also separately as MIT/IL Report E-2330, September 1968)

b. Freeman, A. P., Allen, S., and Singer, H. B., "Ball Bearings Surface Chemistry" (also separately as MIT/IL Report E-2288, September 1968)

c. Gereg, C. V., "Precision Stainless Steel Gyro Bearing Manufacture"

A.10.3 Motion Picture

a. "Surface Phenomena Relevant to Bearing Surface Chemistry," MIT/IL, Revised April 1969

A.11 Additional Publications Containing Program Work

a. Denhard, W. G., and Freeman, A. P., "Current Ball-Bearing Technology and Its Broader Applications," AFAL-TR-68-162, September 1968 (MIT/IL Report E-2177)

b. Freeman, A. P., "Gyro Ball Bearings -- Technology Today" Presented at the Sixth AGARD Guidance and Control Meeting, Inertial Navigation — Systems and Components, Braunschweig, Germany, May 1968, and published in AGARD Conference Proceedings No. 43

c. Gereg, C. V., "The Lubricant Film Electrical Resistance Gage and Its Application to Ball Bearing Raceways," presented at MIT/IL Gyro Spin-Axis Hydrodynamic Bearing Symposium, MIT, Cambridge, Massachusetts, December 1966, and published in the Proceedings.

d. Denhard, W. G., "Cost Versus Value of Ball Bearings," MIT/IL Report E-1990, July 1966.

A.12 Semiformal Presentations of Program Work

a.	Dec. 1967	Program Review* — NASA/MSC
	Mar 1969	Program Review — NASA/MSC
b.	Jan 1968	American Society of Tool and Manufacturing Engineers Symposium on Surface Integrity, Pittsburgh, Pa.
c.	May 1968	Gyro Bearing Reviews, United Kingdom: Admiralty Compass Observatory, Slough; British Aircraft Corporation, Stevenage; Ferranti, Ltd., Edinburgh; Imperial College, London; Royal Aircraft Establishment, Farnborough; Shell Research Ltd., Chester.
d.	Nov 1968	NASA Interdisciplinary Workshop on Friction and Wear, Cleveland, Ohio
e.	July 1969	NASA Interdisciplinary Approach to the Lubrication of Concentrated Contacts, Troy, New York

* Also provided as documents GY-464b and GY-465, MIT/IL Inertial Gyro Group.

APPENDIX B

RECOMMENDED BEARING SPECIFICATIONS, PROCEDURES AND DRAWINGS

B.1 Introduction

The purpose of this appendix is to give the specifications, procedures, and drawings recommended for future production of bearings based on the program final bearings. These include post-manufacture cleaning, passivation, and TCP treatment. The information presented represents experience gained from this program as well as several others. In most steps it follows the actual manufacture of the program final bearings but differs in a few instances, e.g., passivation of the bearing rings.

The specifications and procedures are intended for producing a top-quality, state-of-the-art precision gyroscope bearing. A relaxation of some of the requirements (e.g., to better bearing delivery schedule or cost) may be possible, but this should be carefully weighed against the requirements of the specific application. Such changes would be a part of the purchase negotiations between bearing manufacturer and procuring agency.

The manufacturing and processing details covering the bearing retainer used in the program are beyond the scope of this report. Nylasint retainers were used in all program bearing wheel and gyro builds. Retainers, per Fig. B-3, must be manufactured by a qualified source.

For convenience, the bearing manufacturer's designations of Combo K and L bearings, SR4HX88K and SR4HX88L respectively, are used in the Appendices.

B.2 Heat-Treatment Procedure — SR4HX88K Bearing Rings

Use procedures for the hardening, tempering, stress-relieving, and stabilizing of 440C stainless steel bearing rings as set forth in SGA-105.[11]

B.3 Race-Groove Finishing Process — SR4HX88K/L Bearings (RB Honing)

B.3.1 Rough Hone (Outer/Inner)

Machine	Micromatic 2-HRO-5 Honer
Tool	LAM-VG-2 — 0.055- × 0.065-inch abrasive stone (Mfr. Bay State)
Coolant	50% Microcool IC-9, 50% Varsol

SPECIFICATIONS

A. RING MATERIAL AND HEAT TREATMENT

SR4HX88K: 440C, CONVENTIONAL
SR4HX88L: 14-4-1, AUSFORMED

B. RACE-GROOVE CURVATURE

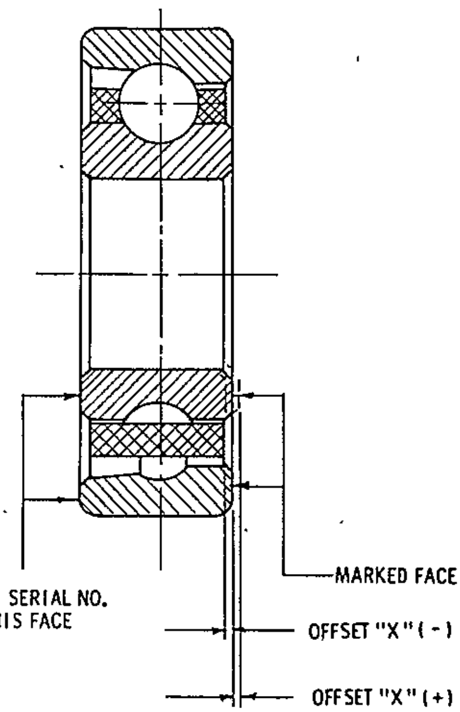
INNER: 53% OF NOMINAL BALL DIAMETER
OUTER: 57% OF NOMINAL BALL DIAMETER

C. BALLS

NUMBER: 7 PER SET, 2 SETS FURNISHED
SIZE: 3/32 NOMINAL, GRADE AAA
MATERIAL AND HEAT TREATMENT:
440C, CONVENTIONAL

D. RETAINER

NYLASINT



PERFORMANCE DATA:

A. CONTACT ANGLE 25° $\pm 1/2^{\circ}$ UNDER A 7 LB. THRUST LOAD
B. INNER RING FACE OFFSET - FLUSH WITH OUTER RING FACE WITHIN $^{+.0015}_{-.0010}$ UNDER A 7 LB. THRUST LOAD

TOLERANCES	INNER RING	OUTER RING
SQUARENESS	.000020	.000020
ECCENTRICITY	.000020	.000050
GROOVE WOBBLE	.000020	.000040
FACE PARALLELISM	.000020	.000020
GROOVE ROUNDNESS AT 25° C/A	.000040	.000040
BORE ROUNDNESS	.000020	
O. D. ROUNDNESS		.000020

RACE-GROOVE CROSS CURVATURE (TALYROND) ±.000010 MAX. DFTC AT THE C/A ± 15° - I. R. AND O. R. ANY TWO OF THE ABOVE .000020 TOLERANCES MAY EXCEED THE LIMITS BY UP TO 100% EXCEPT BORE AND O. D. ROUNDNESS. ALL ROUNDNESS TOLERANCES ARE DIAMETRAL.

BEARING SERIALIZATION: BEARING WILL BE PERMANENTLY SERIALIZED WITH NUMBERS SUFFIXED BY A LETTER SO THAT THE COMBINATION WILL NOT BE DUPLICATED. MATERIAL LOT AND HEAT-TREAT DESIGNATION WILL APPEAR ON RINGS.

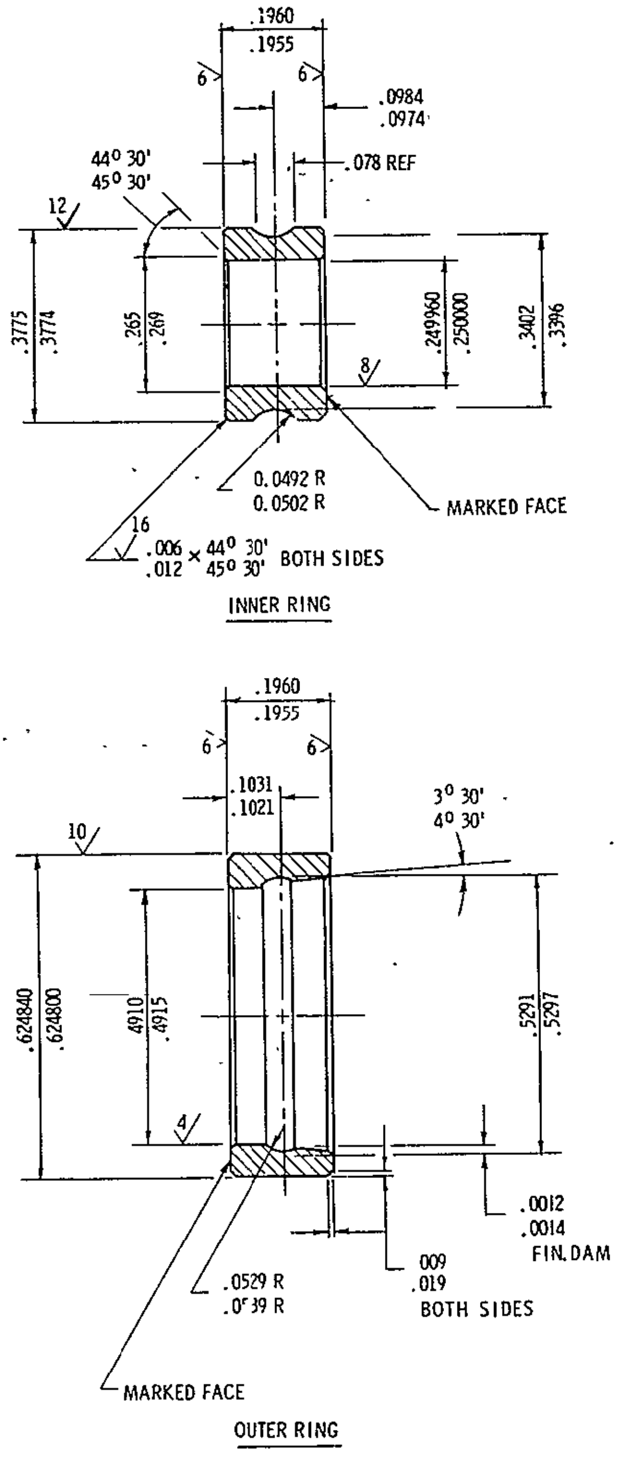
PACKAGING: INNER BAG - HEAT SEALED POLYETHYLENE BAG CONTAINING EXCESS KG - 80 OIL
OUTER WRAP - HEAT SEALED METAL FOIL ENVELOPE OF MIL - B - 131C.
MARK EACH PACKAGE WITH BEARING MANUFACTURER'S NAME AND BEARING NO., CUSTOMER'S PART NO., LUBRICANT; BEARING SERIAL NO., INNER-RING OFFSET, BALL SIZE CONTACT ANGLE, AND DATE OF PACKAGE; PLUS O. D. BORE, WIDTH, AND OFFSET DIMENSIONS TO NEAREST .000010
HOUSE FOIL ENVELOPE IN STYRENE PETRI DISH AND CLASP WITH A RUBBER BAND.

WORKMANSHIP: BEARINGS SHALL BE FREE OF CORROSION, PARTICLES AND FOREIGN MATTER, AND IMPERFECTIONS IMPAIRING PERFORMANCE AS OBSERVED AT 30 × MAGNIFICATION.

SR4HX88K AND SR4HX88L VISUAL INSPECTION AND FINISH SPECIFICATIONS WILL APPLY (SEE SECTION B. 4)

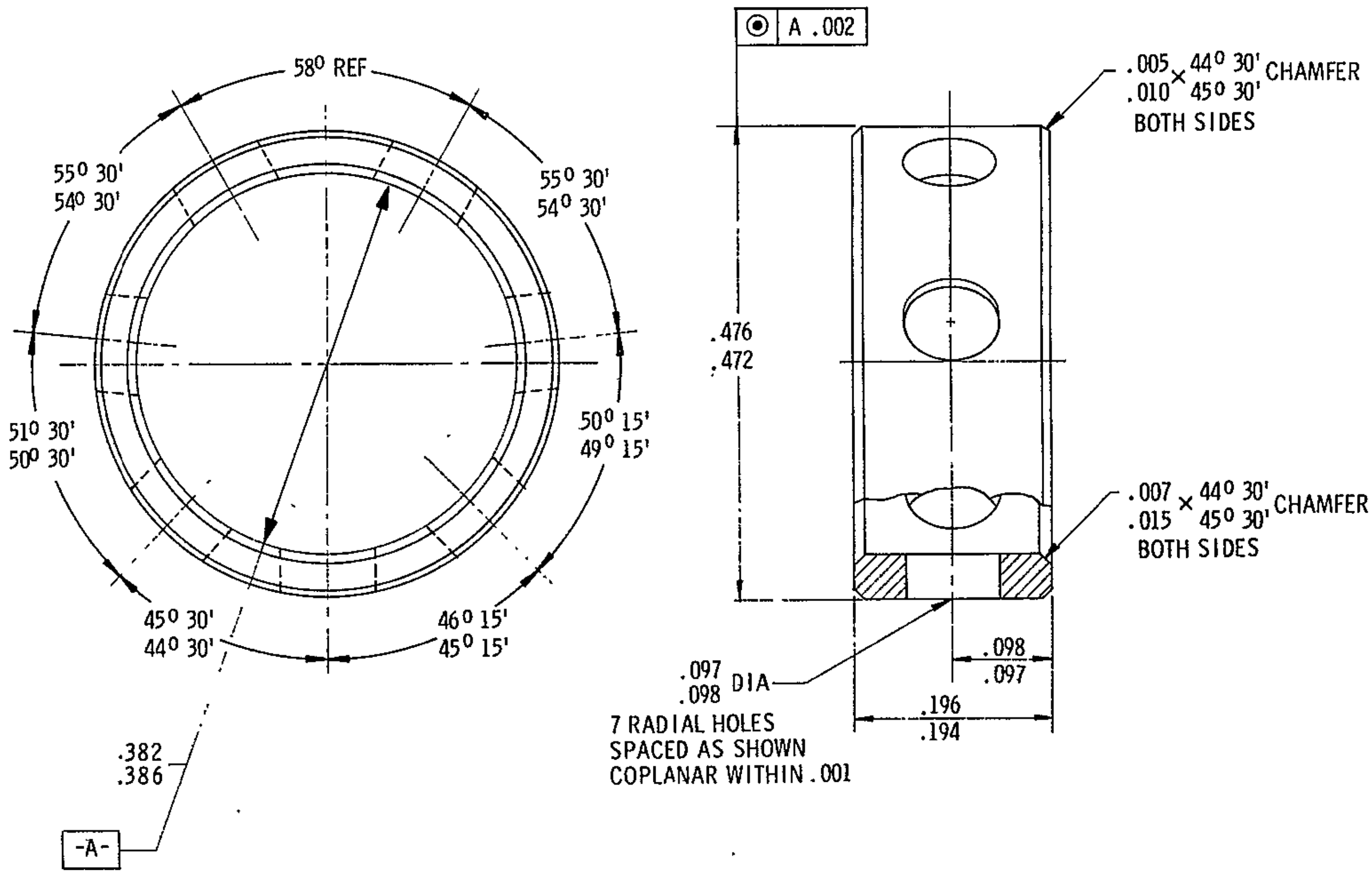
NOTE:
THIS DRAWING IS BASED ON BARDEN DRAWING SB - 571 1/2 REV. D

Fig. B-1. SR4HX88K/L bearing assembly drawing.



NOTE
THIS DRAWING IS BASED ON BARDEN DRAWING
SB-571 2/2 REV. D

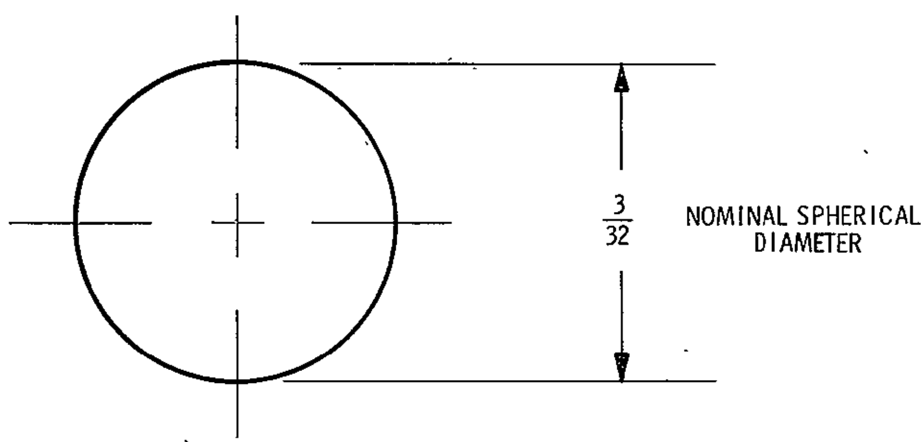
Fig. B-2. SR4HX88K/L bearing inner and outer rings.



MATERIAL:
NYLASINT 64 HV-3 AS PRODUCED BY THE
POLYMER CORP., READING, PA.

NOTE:
THIS DRAWING IS BASED ON MIT/IL DRAWING C-127491

Fig. B-3. Retainer — SR4HX88K/L bearings.



NOTES
1. VARIATION OF DIAMETER NOT TO EXCEED ± .0000025 FOR MATCHED SET OF 7 BALLS
   MEASURE 3 DIAMETERS EACH BALL MAXIMUM OUT OF ROUNDNESS ANY ONE BALL .000003
2. SIZE TO BE SELECTED FOR PROPER CONTACT ANGLE

Fig. B-4. Balls -- SR4HX88K/L bearings.

Ring Speed	Approximately 2800 r/min about own axis
Oscillation Angle	±18° (about bottom of inner, about contact angle of outer)
Oscillation Rate	Approximately 200 c/min
Tool Force	14 to 16 lb
Cycle Time	30 to 60 sec
Stock Removal	0.00005 to 0.0002 inch per surface

B.3.2 Finish Hone (Outer/Inner)

Machine	Micromatic 2-HRO-5 Honer
Tool	Basswood stick with contoured working end, 0.055-inch circumferentia × 0.065-inch cross curvature. See Note c in Section B.3.3)
Abrasive.	1- to 3-micron diamond powder
Coolant	50% Microcool IC-9, 50% Varsol
Ring Speed	Approximately 2800 r/min about own axis
Oscillation Angle	±18° (about bottom of inner, contact angle of outer)
Oscillation Rate	Approximately 200 c/min
Tool Force	20 lb
Cycle Time	60 to 90 sec
Stock Removal	0.00001 to 0.00002 inch per surface
Finish[25]	0.8 to 1,0 microinch AA (cross curvature), 0.003 inch cutoff

B.3.3 Notes

a. Successful RB honing requires a race groove that meets most finished-part geometry specifications before honing. A slightly rough grind finish in the circumferential direction but no rougher in the cross-race direction is somewhat advantageous.

b. The following grinding wheels (aluminum-oxide abrasive) produced a ground surface compatible with RB honing:

IR — Norton A-320-M9-VG
OR — Valley Forge 54A-320-L5V-355

A very limited cross-curvature correction both in radius and DFTC, is possible. The excellent cross curvature produced by RB honing is only possible with accurate, stable machine adjustments. Accurate location of the race groove, with respect to the reference face, is also desirable.

c. The diamond powder is mixed with olive oil (14 mg diamond per fluid oz of olive oil) and the basswood stick is charged by dragging the working end across a glass surface covered with the diamond mixture. The stick is removed for recharging every 30 seconds.(cycle interrupted for this operation

B.4 Visual Inspection and Finish Specifications -- SR4HX88K/L Bearing Rings and Balls

All dimensions are in inches unless otherwise indicated.

B.4.1 Inspection Methods

a. Visual inspection of race grooves and balls is to be done 100% under 30X magnification with calibrated eyepiece, using fluorescent light and incandescent light.

b. Parts are to be clean and dry for visual inspection.

B.4.2 Definitions

a. Contact Areas -- (inner or outer race grooves) that area included by a 10° arc on either side of the specified contact angle (see Fig. B-5).

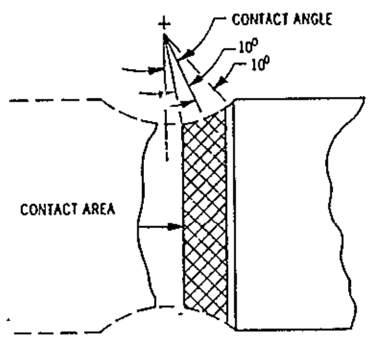


Fig. B-5. Race-groove contact area.

b. Pits and Inclusions -- metallurgical imperfections in the material, measured across major dimension.

c. Nicks and Dents -- as caused by striking with sharp object, measured across major dimension.

d. Rust or Stains -- discoloration or pitting (rust).

e. Scratches -- as caused by rubbing with abrasive or hard object(s) and excluding lap lines.

f. Tears, Cuts, or Comets -- local surface disturbances caused by lapping or grinding, measured across minor dimension.

g. Flats or Brinell marks — deformation of surface caused by excessive force of ball against other balls or against race-groove surface. Observed as irregularity in reflected light, measured across major dimension.

h. Lap Lines— circumferential lines as caused by lapping.

i. Burrs — loose or semi-loose raised material.

j. Fragmentation Denting — evidence of running during contact-angle or preload measurement.

Table B-1. Visual and finish defects, maximum size.

Defect	Contact Areas	Other Race-Groove Surfaces	Balls
Pits and Inclusions	0.001	0.0030	0.001
Nicks and Dents	none	*	0.001
Rust or Stains	none	none	none
Scratches	none	*	none
Tears, Cuts, or Comets	0.0005	---	---
Flats or Brinell Marks	none	---	0.001
Lap Lines	0.0005	---	0.0003
Burrs	none	none	none
Fragmentation Denting	(acceptable if barely visible)		

* Acceptable if dimensional tolerances not affected.

B.4.3 Visual and Finish Defects — Noncritical Surfaces

Visual defects on all ring surfaces other than race grooves will be evaluated by microscopic inspection at 10X magnification. Measurements, when required, may be made at a higher power. All surfaces shall be free of nonrandom visual defects. Random defects are permitted only as allowed below:

a. Ground Surfaces

1. Pits and Inclusions — distributed individual pits and inclusions up to 0.003 allowed.

2. Nicks, Dents, etc. — individual nicks and dents up to 0.003 are allowed if they are clean and bright and show no evidence of imbedded material or raised metal.

3. Rust and Stains — none allowed.

4. Burrs — none allowed.

5. Imbedded Material — none allowed.

6. Raised Metal -- none allowed affecting dimensional tolerance.

7. Comets, Tears, Scratches, Grind Marks, etc. — no limit in size or quantity except that they shall be random, have no raised metal, and not affect dimensional tolerance.

b. Corner Radii or Chamfers

1. Finishing Operations -- machining, grinding, lapping, stoning, polishing, and tumbling are allowed; must be bright at 10X.

2. Pits and Inclusions — 0.005 maximum.

3. Nicks, Dents, etc. — allowed if bright with no raised metal and not located at junction of corner radii or chamfer and other ground or lapped surface.

4. Rust and Stains — none allowed.

5. Blemishes — up to 0.005 allowed, providing they contain no entrapped material and are not susceptible to spalling.

6. Tool Marks — must be free of tool marks except that one single noncontinuous tool mark not exceeding 0.003 wide (or 20% or corner width — whichever is smaller — is allowed). Tool marks which are bright are allowed.

7. Scratches and Burrs -- no limit in size or quantity except that they shall be random, have no raised metal, and not affect dimensional tolerance.

8. All corners shall be blended to OD, bore and face, and mounting surfaces (applies to finished parts only).

B.5 Cleaning Procedures — SR4HX88K/L Bearing Rings and Balls

B.5.1 Cleaning Procedure During Finishing and Gaging

During the final finishing operations and gaging use: Varsol spray wash, bulk cotton and Engsol scrub, and high-pressure air drying.

B.5.2 General Cleaning Procedure* (Use after gaging and whenever general cleaning is needed)

a. Ultrasonically clean the parts for five minutes in toluene; vacuum dry.

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* Based on Reference 34.

b. Demagnetize the components.

c. Repeat Step a, using Freon PCA (Dupont) or Genesolv D, Electronic Grade (Allied Chemical).

d. Repeat Step a, using methanol.

e. Dip each component into a solution of 50% acetone and 50% methanol; vacuum dry <u>immediately</u>. (If not dried immediately, stains will develop. Re-dip and dry again.)

f. Visually inspect all parts under a microscope (at least 30X) for freedom from any film or dirt. If found, process per Step g below.

g. Rub film or dirt with a Delrin probe and any of the following solvents, and then repeat Steps a, c, d, e, and f:

Freon PCA or Genesolv D
Methanol
Toluene
Acetone

NOTES: (1) Only clean glass beakers should be used to contain the solvents.

(2) All solvents should be reagent grade or better.

B.5.3 Cleaning Procedure Following Rework

If rework is necessary, clean parts per Sections B.5.1 and B.5.2.

B.5.4 Cleaning Procedure in Preparation for Passivation

a. Clean parts per Section B.5.2.

b. Clean parts by soxhlet extracting with acetone. A minimum of 16 hours with 5 to 6 cycles per hour is recommended.

c. Store parts in acetone until ready for passivation.

B.6 Passivation Procedure — SR4HX88K/L Bearing Rings

Use procedures for passivation and subsequent test of corrosion resistance as set forth in SGA-109.[22] Passivated and rinsed rings shall be cleaned per General Cleaning Procedure described in Section B.5.2.

If rings are to go directly into TCP treatment following cleaning, submerge them in TCP per Section B.7.2c and proceed with remaining steps of Section B.7. Otherwise store rings in KG-80 pending further processing.

B.7 TCP Treatment Procedure — SR4HX88K/L Bearing Rings and Balls

B.7.1 Preparation

a. Stabilize oven at 225 $\pm 5°$ F.

b. Chemically clean coverable glass jars and fill with sufficient Tricresyl Phosphate (TCP)* to cover parts.

B.7.2 Procedure — Rings and Balls

a. Remove rings/balls from storage container. (Maintain identity of size, and batch number of balls.)

b. Carry out General Cleaning Procedure described in Section B.5.2.

c. Immediately submerge parts in TCP (record TCP batch number).

d. Place jars in oven and hold for a minimum of 72 hours at 225 $\pm 5°$ F.

e. Record duration of soak in hours. At end of soak remove jars from oven and allow to cool to room temperature.

f. Maintain all parts in TCP storage until ready to perform visual examination.

B.7.3 Inspection and Final Cleaning — Rings

a. Remove one ring at a time from room-temperature TCP and rinse in three consecutive beakers of methanol, vacuum dry, and examine visually.

b. Immediately after visual examination place ring in toluene (preparatory to final cleaning).

c. Carry out General Cleaning Procedure described in Section B.5.2.

d. Dip in KG-80 oil and package for shipment.

B.7.4 Inspection and Final Cleaning — Balls

a. Remove balls from room-temperature TCP, clean per Section B.5.2, examine visually per Section B.4, and return to room-temperature TCP if acceptable.

b. Store in TCP until a sufficient number are accumulated and ready for final cleaning.

c. Carry out General Cleaning Procedure described in Section B.5.2.

d. Immediately submerge cleaned balls in KG-80 until ready for packaging.

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* Less than 3% ortho (for safety) and complying with Federal Specification TT-T-656.

B.8 Dimensional Stability Specifications — SR4HX88K/L Bearing Rings and Balls

B.8.1 Dimensional Stability — Rings

Reference SGA-107.(13)*

After 360 ±2 hours exposure at 225 ±10° F, maximum individual ID change of the inner rings shall be no more than 5 microinches, and for the OD of the outer rings 15 microinches. Maximum average dimensional changes permissable are 3.5 and 10 microinches respectively.

B.8.2 Dimensional Stability — Balls

Reference SGA-108.(14)*

After 360 ±2 hours exposure at 225 ±10° F, maximum individual diameter change shall be no more than 3 microinches. Maximum average dimensional change permissable is 2 microinches.

Note: These references present the requirements for testing the dimensional stability of 440C stainless steel bearing races and balls. The degree to which the specifications of this section should be followed must be based on the performance/life requirements of the bearing application.

APPENDIX C

SUPPORTING INFORMATION

C.1 Introduction

The purpose of this appendix is to give some detailed information not recorded elsewhere in support of Sections 2 and 3, as well as to document a procedure which did not work satisfactorily. The former includes drawings of intermediate stages used in the preparation of bearing rings from the hardened bar combos, provides directions used in gas chromotography sample preparation, and furnishes the ball specification used in the purchase of the program ball lots from a ball manufacturer. The unsatisfactory procedure is that used by the bearing manufacturer in passivating the program final bearing rings.

C.2 Ball Purchase Specification (Used by bearing manufacturer for program balls)

C.2.1 Material (Vacuum Melted Chrome Steel AISI 440C)

a. Hardness — superficial hardness check made on ground flats R_{15N} — 90.2 to 91.8 (Ref. R_C60 to 64).

C.2.2 Geometry

a. Using a modified Cleveland Gage Block Comparator at 4-oz load, 100,000X magnification, and 0.000001 least count; ten readings on each of 45 balls selected at random from a homogeneous lot are used to form a distribution of 450 readings.

b. 98% of these readings must fall within the limits shown as diameter tolerance shown in Item d below. Example limit 0.000005 for $\pm$0.0000025.

c. No ball in the distribution may exceed the sphericity specified, and the average size of the largest and smallest ball shall not exceed the range of diameter tolerance shown in Item d below.

d. Sphericity 0.0000025
Diameter tolerance per unit container . . . . $\pm$0.0000025
Tolerance variation from size ordered . . . . $\pm$0.0000250

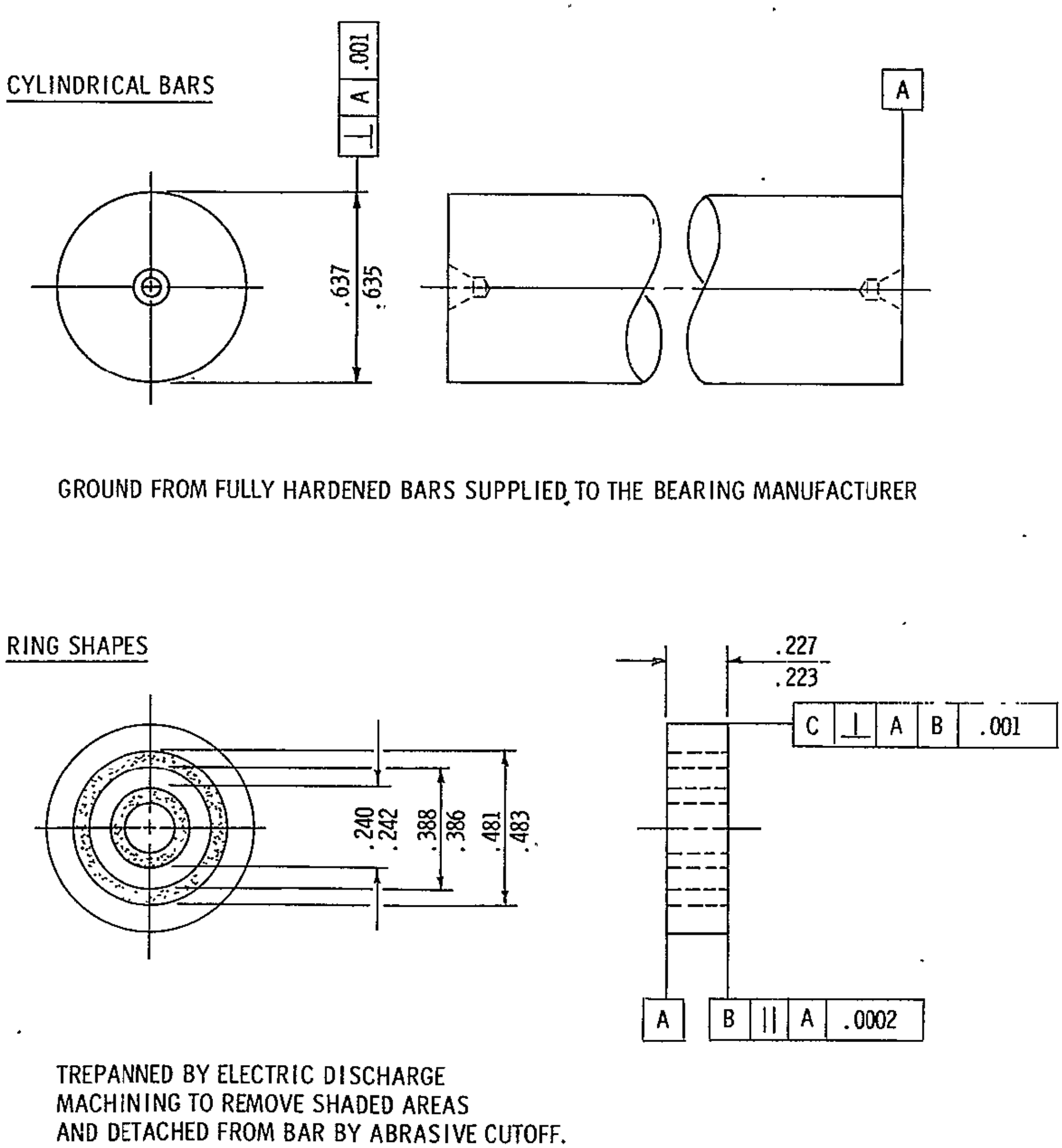

Fig. C-1. Intermediate stages — hardened bar combos.

C.2.3 Visual Appearance

Random samples are selected in accordance with MIL-STD-105D multiple sampling table AQL 2.5.

Balls are inspected under 10X binocular microscope against a white background when covered with a film of light instrument oil, 2% maximum with the following imperfections.

Pits and inclusions	0.0010
Flats and brinell marks	0.0010
Nicks and dents	0.0010
Lap lines	0.0003
Rust or stains	none
Scratches	none
Surface finish	1 microinch maximum

C.2.4 Heat-Treat Conditions

Austenitize at 1925° F for 6 to 7 minutes.
Quench in oil at 100° F.
Deep freeze at -120° F for 3 hours minimum.
Temper at 300° F for 2 hours.
Stress relieve at 300° F for 3 hours before final size lap.

C.2.5 Lot Control

Balls shall be processed in lots. All balls shall be from the same raw-material stock for any lot. Lot size shall be determined by the first heat treat and identity maintained through stress relief. All individual containers shall be marked with lot designation.

C.2.6 Certification

Vendor shall certify that each shipment conforms to this specification by forwarding lot-control information in the form of a substantiating data sheet which shall include an inspection report on hardness after heat treat and the heat-treat procedure used listing atmosphere, temperatures, and lengths of time.

NOTE: Balls are to be passivated following completion of all lapping.

C.3 Bearing Ring Passivation Procedure Used in Program
(Not recommended due to surface-chemistry problems -- Refer to Section 2.6.4)

C.3.1 Preparation

a. Passivation Solution -- pour 500 ml of deionized water into a 2000-ml beaker. Add 20 gm sodium dichromate and stir until dissolved.

Slowly pour a premeasured 200 ml of 16N HNO_3 into the solution. Make up the volume to 1000 ml by the addition of 280 ml of deionized water.

b. Wash solution — prewarm 1000 ml of deionized water. Place in a 2000-ml beaker. Add 1 oz Joy and 2 oz Triton X100. If stirring does not readily mix this solution, place the beaker on hot plate and further warm till it readily mixes.

c. Neutralizing solution — pour 700 ml of deionized water into a 2000-ml beaker. Add 100 ml of ammonium hydroxide. Make up this solution to 1000 ml by the addition of 200 ml of deionized water.

C.3.2 Procedure

NOTE: All bearing parts to be free of oil and dry. With solutions placed in convenient order and labeled as to operation sequence, perform the following:

a. Solution 1 — (Wash solution at 140° to 160° F) Place container and parts in solution and slowly agitate for two minutes.

b. Solution 2 — (Cold running tap water) Place container and parts under water, agitating slowly until rinsed, approximately two minutes, then blow dry (air).

c. Solution 3 — (Passivation solution at 110° to 120° F — under ventilated hood) Place container and parts in solution for 30-minute soak. Agitate.

d. Solution 4 — (Cold running tap water) Place container and parts under running water until solution is devoid of color, at least two minutes.

e. Solution 5 — (Neutralizing solution) Place container and parts in solution, agitating slowly for two minutes.

f. Solution 6 — (Wash solution at room temperature) Place container and parts in solution, agitating slowly for two minutes.

g. Solution 7 — (Cold running tap water) Place container and parts under water. Agitate slowly and rinse two minutes. Blow dry (air).

h. Solution 8 — (Free-running deionized water) Place container and parts in this solution for at least four minutes. Blow dry (air).

i. Solution 9 — (Methanol) Place container and parts in methanol bath.

j. With rubber-tipped tweezers, extract one part at a time. Blow dry with air gun and then filtered warm-air dryer.

k. Check under microscope for cleanliness, foreign particles, freedom from stains. Ensure parts are thoroughly dry.

l. Stained rings should be replaced in cold wash solution and operations repeated from Step f through Step k. Rings with any dry particles should be returned to deionized water bath, then methanol bath, blown dry, and visually rechecked.

m. Dip each accepted part into warm (140° to 160° F) V-78 oil.

C.4 Directions for Gas Chromatography Sample Preparation (Refer to Section 3.5.4)

C.4.1 Solvent and Oil

a. All oil samples will be taken from the quart bottle of double-filtered V-78 set aside for use on this program.

b. Carbon tetrachloride will all be from the jug purchased for this program. Keep solvent clean. No pipets, droppers, etc., are to be placed in the jug, nor is any solvent to be returned to the jug. Keep open solvent containers under fume hood.

C.4.2 Bottle Preparation

Shipping bottles are to be cleaned using normal practice for glassware (except potassium-dichromate solution). Final rinse prior to receiving sample will be carbon tetrachloride (inside of cap included). Caps will be fitted with teflon sheet liners.

C.4.3 Bearing Preparation

Assembled bearings will be extracted for a minimum of two hours in carbon tetrachloride. Vacuum impregnate for 1/2 hour minimum and centrifuge at 12,000 g for ten minutes.

C.4.4 Low-Speed Runs

Run bearing in a low-speed dynamometer at 1 r/min until torque trace shows start of lube failure. Two runs to failure will be made and two runs to 1/3 failure time and two to 2/3 failure time.

C.4.5 Removing Oil from Bearing

Place assembled bearing in extractor with 100 ml of carbon tetrachloride and extract for two hours minimum. Remove flask containing carbon tetrachloride and oil from extractor. Place flask in an ice bath and evaporate to

25 ml using a stream of nitrogen. Pour remaining 25 ml of solvent into shipping jar. Place jar in an ice bath and evaporate remaining solvent by directing a gentle stream of nitrogen at the surface of the solvent. Securely cap the bottles, label and seal the bottle in a polyethylene bag. Reimpregnate and rerun the assembled bearing as directed in Sections C.4.3 and C.4.4 above.

C.4.6 Samples Taken

a. Two from bearing run to start of lube failure

b. Two from bearing run 1/3 time a.

c. Two from bearing run 2/3 time a.

d. Two from bearing not run but otherwise processed in the same way.

e. One bottle containing 20 ml of oil from quart bottle.

f. 500 ml (in a larger bottle) of carbon tetrachloride (or two sample bottles).

C.4.7 Records

Record bearing number, running time, date, label information, and attach torque trace (initial and at time run is stopped).

C.4.8 Analysis of Specimens

The analysis by gas chromatography was done by F & M Scientific Corporation, Avondale, Pa., with the following instrument conditions:

Specimens	Teresso V-78
Specimen Size	3.5 microliter
Injection Method	Syringe
Column	4 ft of 1/4 in. SS, 3.8% SE-30, 80/100S
Instrument	810F1
Injector	295° C
Detector	295° C
Column	79° C
Program Rate	8° C/min
Carrier Gas	He at 65 ml/min
Air	380 ml/min
H_2	40 ml/min
Chart Speed	1/4 in./min
Range	10^2
Attenuation	X8

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