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MICROSTRUCTURAL EFFECTS IN ABRASIVE WEAR

Year-end Summary Report
for the period 15 March 1977 - 15 March 1978

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Department of Metallurgical Engineering and Materials Science
Notre Dame, IN 46556

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YEAR-END SUMMARY REPORT

INTRODUCTION

This research project was initiated on 15 March 1977, and this fourth report (the Year-end Summary) on the project consists of two parts. In Part I an overview is given of the progress made during the first nine months of the research. Most of this information has been presented in detail in the three previous quarterly reports. In Part II, the progress made in the last three months of the project is described. This information has not appeared elsewhere.

CONTENTS

PART I

PROJECT OVERVIEW

15 March 1977 - 15 December 1977

1. OBJECTIVE AND SCOPE

The objective of this research program is to establish quantitative relations between microstructure and wear resistance of low-to-high Cr white irons and Co-base powder metallurgy (PM) alloys commonly used in coal mining, handling and gasification. The specific types of wear under study are low-stress abrasion encountered in cluster and transfer equipment, and gouging operations. This objective has two facets. On the very practical side, the establishment of the optimum microstructures for wear resistance will allow (and is already beginning to allow) design engineers to make more effective decisions regarding candidate alloys for coal-related processes. In addition, the establishment of a better understanding of the physical and mechanical metallurgy of wear may lead in the longer run to the development of more economical and effective wear-resistant alloys.

This two faceted objective is being approached by means of a three-way experimental program (Figure 1), consisting of mechanical testing, metallographic analysis and wear testing. The mechanical testing is conducted in an attempt to correlate wear with more thoroughly investigated physical- and mechanical-metallurgical parameters such as fracture toughness. It is hoped that in this manner wear mechanisms may be broken down and categorized in terms of mechanical failure mechanisms which are better understood. The metallographic analysis, which includes automated quantitative metallography, is directed toward establishing quantitative, although perhaps empirical, relation between wear resistance and such microstructural parameters as second-phase size, size-distribution, shape, and orientation. The wear testing is based on laboratory rubber wheel abrasion (RWAT) and gouging abrasion (GAWT) test systems which have as much correlation to field performance as exists in wear testing. One feature of the wear testing is the characterization of the microtopography of the wear scar,

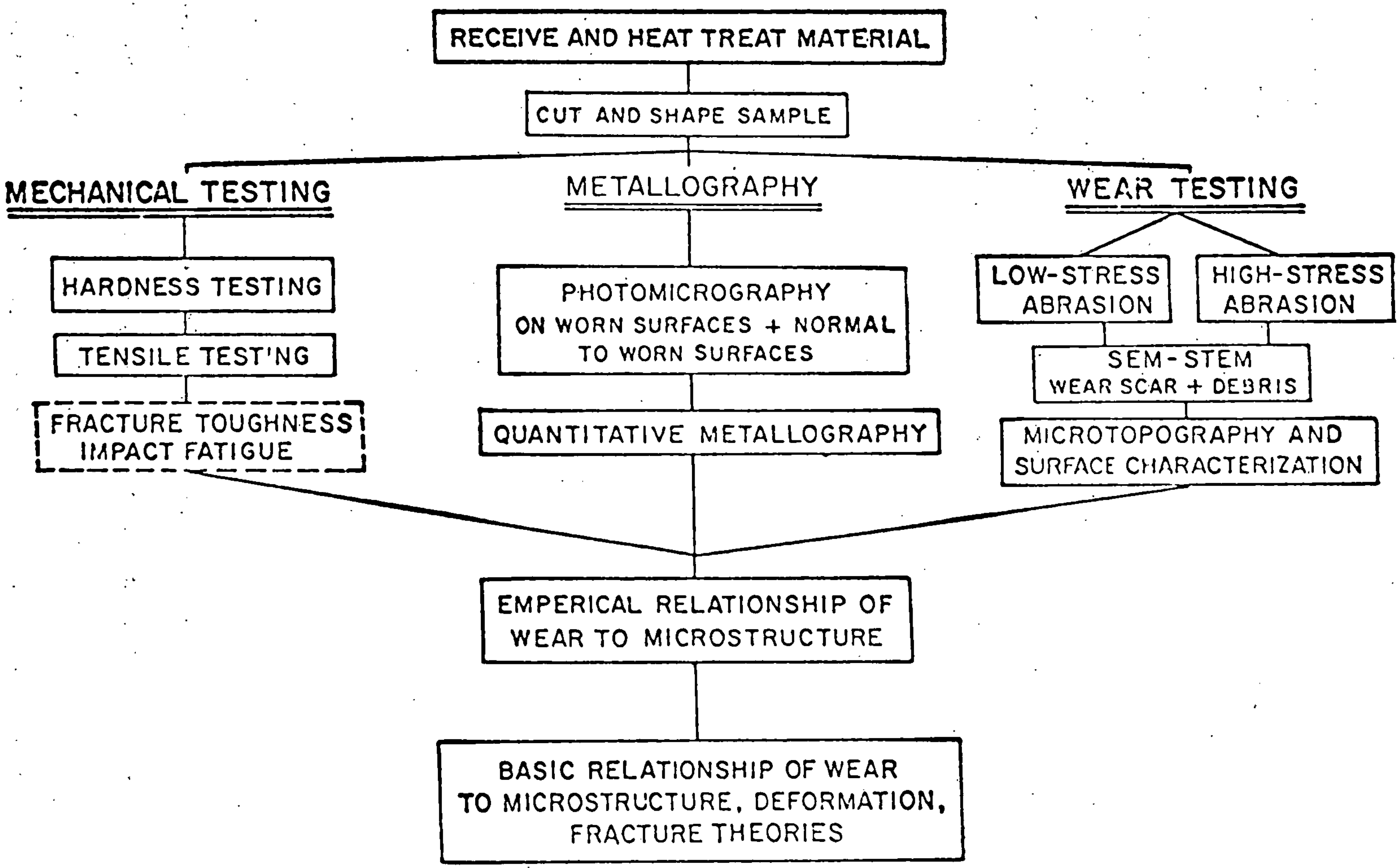

Fig. 1. Test Program Flow Chart, Contract EF 77-S-02-4246.

which may lead to additional correlations between microstructural features, material attrition mechanisms and wear-resistance.

2. TASKS AND PROGRESS

2.1 Task I - Preparation of Test Matrix

This task is complete. The matrix was forwarded to DOE - Chicago Operations Office on 6 June 1977.

2.2 Task II - Preparation of Materials

This task is now accomplished. The materials to be tested fall into two categories, alloy cast irons and Co-base superalloys (Tables I and II). All of the cast irons (see Table III for chemical analyses) have been obtained from Climax Molybdenum Research Laboratories, Ann Arbor, Michigan. Materials 2, 3 and 4 of Table I are in the form of cast plates 190 mm x 137 mm x 21 mm, the dimensions of the specimen in the Climax jaw crusher wear test. Figure 2 shows the plate geometry and indicates the manner in which rubber wheel abrasion and gouging wear specimens are cut from the plate. Note that this method of sectioning produces specimens which can be wear tested parallel, normal and across the dendrites in the as-solidified plate, thereby allowing dendrite orientation to serve as one of the microstructural variables under study in the program.

The series of Ni-Hard 4 samples (Table I, Material 1) are in the form of compact tension fracture toughness specimens 60 mm x 56 mm x 13 mm (Figure 3). These samples are easily wear tested normal to the solidification direction, but attempts will be made also to test parallel and cross this orientation in these sub-sized samples.

Each material has been subjected to wear and mechanical testing at the Climax Research Laboratories before shipment to Notre Dame. It is of special

Table I. Wear-Resistant Irons

Type	Microstructural Condition
1. ASTM532 - Type I - Ni-Hard 4	High-Cr Carbides in Austenite Decomposition Product (α + Fe_3C) with (E) 5% Retained Austenite (F) 20% " (C) 40% " (D) 85% "
2. ASTM532 - Type II - (15 Cr-3 Mo)	Cr_7C_3 Carbides in Tempered Martensite (overtempered)
3. ASTM532 - Type III - (27 Cr-2.5C)	Cr_7C_3 Carbides in Tempered Martensite
4. Pearlitic White Iron	Fe_3C Carbides in Pearlitic Matrix a) 3.5C - High Carbide Vol. Frac. b) 2.7C - Low Carbide Vol. Frac.

Table II. Co-base Powder Metallurgy Alloys

Type			Microstructure
1.	#6	Low carbide vol. frac.	Low solid solution strengthener content.
2.	#6KC-H	High carbide vol. frac.	Low solid solution strengthener content
3.	#19	High carbide vol. frac.	Moderate solid solution strengthener content.
4.	#98M2	High carbide vol. frac.	High solid solution strengthener content.
5.	#3	Very high carbide vol. fraction.	High solid solution strengthener content.
6.	#Star-J	Very high carbide vol. fraction.	Very high solid solution strengthener content.

Table III. Chemical Composition of White Cast Irons

Material	C	Mn	Si	Cr	Mo	Ni	S	P	N
	Element, Weight Percent								
1. ASTM 532-Type I (Ni-Hard 4)	3.22	.55	1.77	8.9	.04	5.86	.025	.032	.026
2. ASTM 532-Type II (15Cr-3Mo)	3.60	.85	.42	14.96	2.62	---	---	---	---
3. ASTM 532-Type III (27Cr-2.5C)	3.11	.8	.4	27.0	---	---	---	---	---
4. Pearlitic White Iron a)	3.52	.48	.36	1.96	---	.07	.145	.255	---
b)	2.72	.44	.37	1.78	---	.07	.150	.256	---

Table IV. White Cast Iron Heat Treatments

Iron	Heat Treatment (Matrix)
15 Cr-3Mo	Austenitized at 1800F (980C) for 1 hour, furnace cooled and stress relieved at 400F (205C) for 2 hours. (Overtempered martensite)
27 Cr-2.5C	Austenitized at 1850F (1010C) for 2 hours, air cooled and stress relieved at 450F (230C) for 1 hour. (Lightly tempered martensite)
Pearlitic (2.7C)	As-cast in sand.
Pearlitic (3.5C)	As-cast in sand.
Ni-Hard 4	C) 1380F (750C) - 8 hrs., 1020F (550C) - 4 hrs., 840F (450C) - 16 hrs. (40% γ)
	D) 450F (230C) - 4 hrs. (85% γ)
	E) 1380F (750C) - 8 hrs., cooled to - 320F (-195C) 410F (210C) - 1 hr. (5% γ)
	F) 1020F (550C) - 4 hrs., 840F (450C) - 16 hrs., cooled to -320F (-195C), 410F (210C) - 4 hrs. (20% γ)

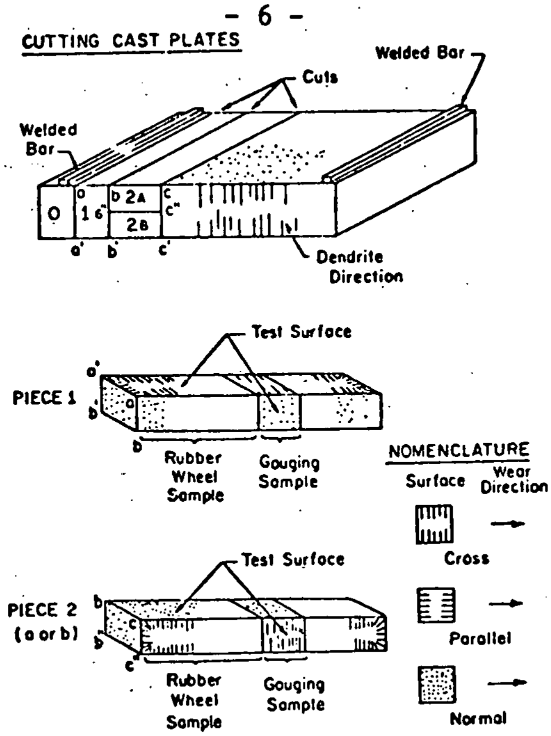

Figure 2. Sectioning scheme for obtaining rubber wheel and gouging wear test samples from cast plates.

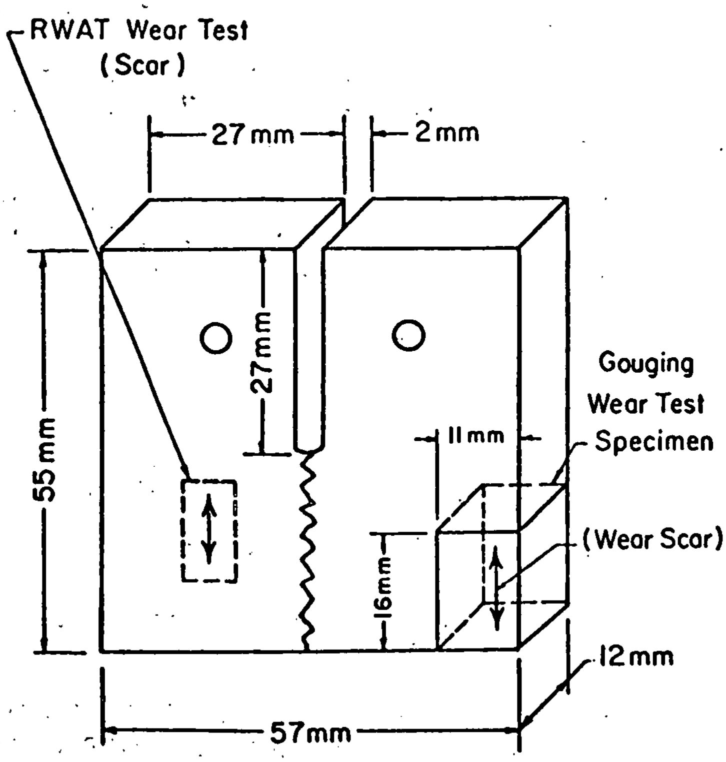

Figure 3. Sectioning scheme for obtaining rubber wheel and gouging wear test samples from Ni-Hard 4 fracture toughness specimen.

interest to note that the irons have been subjected to the Climax pin-on-disk low-stress abrasion test and the Climax jaw crusher high-stress abrasion test. Similar tests are to be employed in another DOE Fossil-Fuel project (Contract W-7405-ENG-48) under Drs. Bhat, Zackay and Parker at the Lawrence Berkeley Laboratory, so the data on these cast irons should interface well with that obtained on the other DOE project.

The alloy cast irons consist of alloy carbides of various volume fractions in tempered martensite matrices of various retained austenite contents. Their study will demonstrate the effect of carbide volume fraction and matrix toughness on low- and high-stress abrasive wear. Pearlitic white iron is a standard, inexpensive material used as baseline indicator of wear resistance. The Ni-Hard 4 samples contain 5,20,40 and 85 percent retained austenite (γ) in their microstructures and thus provide a system for the study of the effect of this variable on wear resistance. The heat treatments used to develop these microstructures are listed in Table IV.

The Co-base superalloys have been prepared by the Stellite Division, Cabot Corporation, Kokomo, Indiana, by PM techniques. They consist of fine carbides in a fine-grained FCC Co-rich matrix. They comprise a spectrum of carbide volume fractions and matrix strengthener contents and allow the study of the effect of these variables on low- and high-stress abrasive wear. Moreover, the micro-structures are simple and amenable to quantitative metallographic analysis. As with the cast irons, they are commercially relevant material, field- and laboratory-tested by their producer and used in coal mining, handling and gasification.

2.3 Task III - Wear Testing

2.3.1 Rubber Wheel Abrasion Test (RWAT)

Figure 4 is a photograph of the rubber wheel abrasion testing machine.

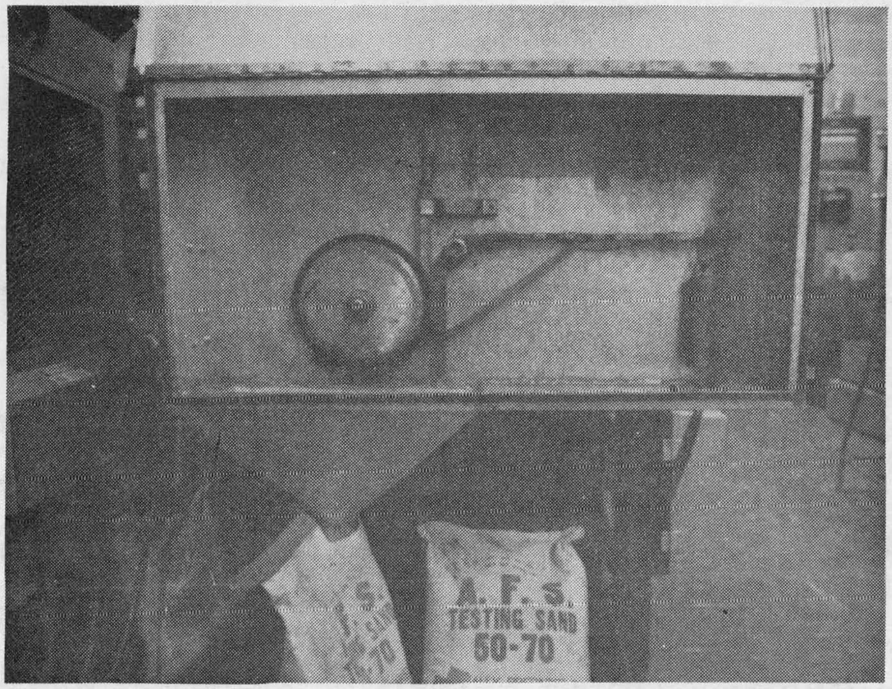

Figure 4. Rubber Wheel Abrasion Tester (RWAT)

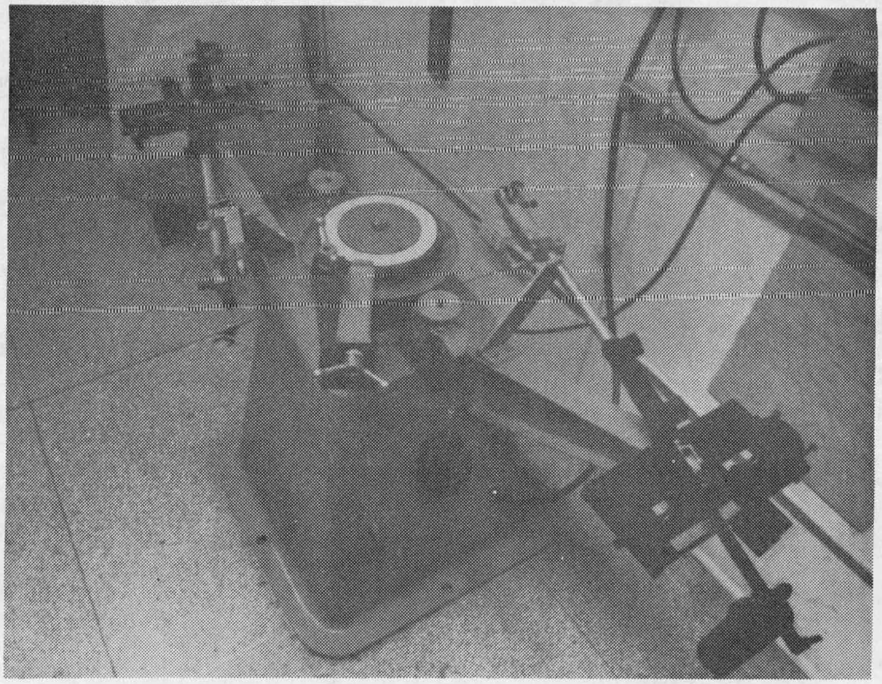

Figure 5. Gouging Abrasive Wear Tester (GAWT)

The rubber wheel consists of a 2.03 mm diameter x 12.7 mm thick steel hub rimmed with a 12.7 mm x 12.7 mm chlorobutyl rubber ring tightly bonded to the steel. The wheel rotates at a constant speed of 200 rpm or a surface rate of 2.38 m/sec (470 ft/min). The applied load is 13.6 kg (30 lb) corresponding to a stress of approximately 0.41 MPa (60 psi).

Prior to testing, each sample surface is finished to 50-75 μm by grinding parallel to the wear direction. A uniform stream of abrasive is gravity fed between the rotating rubber wheel and the test specimen through a nozzle with a 12.7 mm x 1.6 mm opening. The abrasive is a silica sand designated by the American Foundry Society as AFS (50-70). The sand is uniform in shape (slightly rounded) and has a screen size of minus 50 plus 70 mesh.

2.3.2 Gouging Abrasion Wear Test (GAWT)

The GAWT apparatus depicted in Figure 5, was developed at the ABEX Corporation Research Laboratories, Mahwah, New Jersey. Before a gouging test begins, the wear blocks are "run-in" to the point where the whole cross-section (test surface) of the wear blocks are 11.7 mm x 17.2 mm and are approximately 25.4 mm deep. A 254 mm diameter x 17.7 mm thick 70 grit Al_2O_3 grinding wheel* is used as the abrasive. The arms are set tangent to the wheel by means of an adjustable pivot point. The pivot point is set a distance of one-half the wheel diameter from the wheel center line. A load of 3.5 kg (7.7 lb) is applied to the arms by means of a cable and pullies to generate a pressure, between the block and the wheel, of 0.127 MPa (18.5 psi) in the horizontal plane (the plane of the abrasive wheel.) The number of revolutions for 365.8 m (1200 ft) of abrasive to pass the specimen surface is set on a decremental counter which shuts the system off automatically after the set number of revolutions (458-764 revolutions, depending on the wheel diameter). The speed of the wheel is set at 27 rpm.

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* Bendix Abrasives Division, Jackson, MI 49204 - Type AR-51177

Materials are ranked by an abrasion factor, A.F., which is the weight loss of the specimen divided by the weight loss of the standard.

2.3.3 Selection of Test Standards

In both the RWAT and the GAWT systems, the use of wear standards is necessary to characterize system behavior. For example, changes in SiO_2 abrasive properties from batch to batch or changes in the properties of the chlorobutyl rubber abrasion surface may introduce large systematic changes in the RWAT test results. Further, the gouging test requires that a standard material be run simultaneously with the test specimen and that the wear resistance be reported as the "Abrasion Factor".

Both annealed 1020 steel and vacuum arc-remelt (VAR) 4340 steel, quenched and tempered to hardness Rockwell C52, have been evaluated as standards. The 1020 has been evaluated because it is inexpensive, readily available, and has been used extensively as a wear standard. The 4340 has been evaluated because it is a premium, wear-resistant material, produced to strict chemical specification, and therefore may give outstanding reproducibility in wear behavior.

Figure 6 shows the RWAT weight loss of six individual samples of each material as a function of number of revolutions of the rotating rubber wheel. Note that both 1020 and 4340 give comparable spread in test results, thus indicating that they offer identical reproducibility as standards. The 1020, as expected, has greater weight loss at all stages of the test; consequently it provides the smaller ratio of variation in weight loss/total weight loss. For this reason and because it is a cheaper, more easily obtained material, 1020 has been selected as the rubber wear abrasive test (RWAT) standard.

Figure 7 shows 1020 and 4340 Abrasion Factors versus test number for five separate gouging wear tests. Each test employs two pieces of the test material.

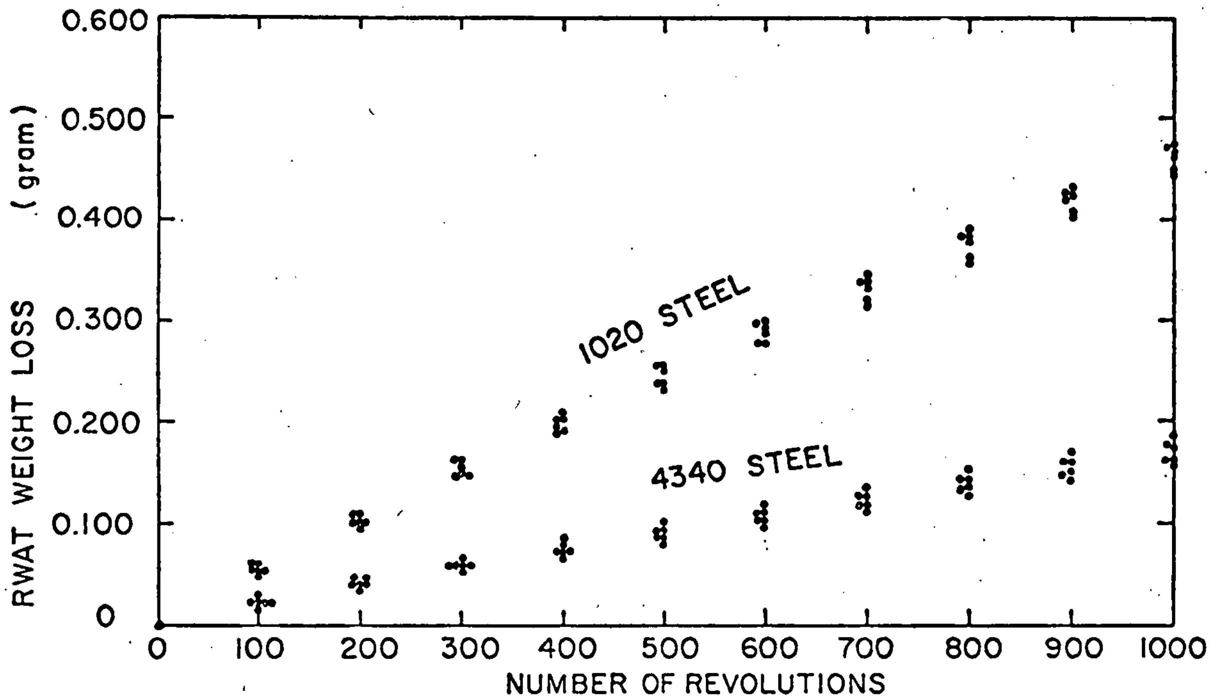

Figure 6. Variability of RWAT weight loss after 1000 revolutions for AISI 1020 and 4340 (R_c52) steels.

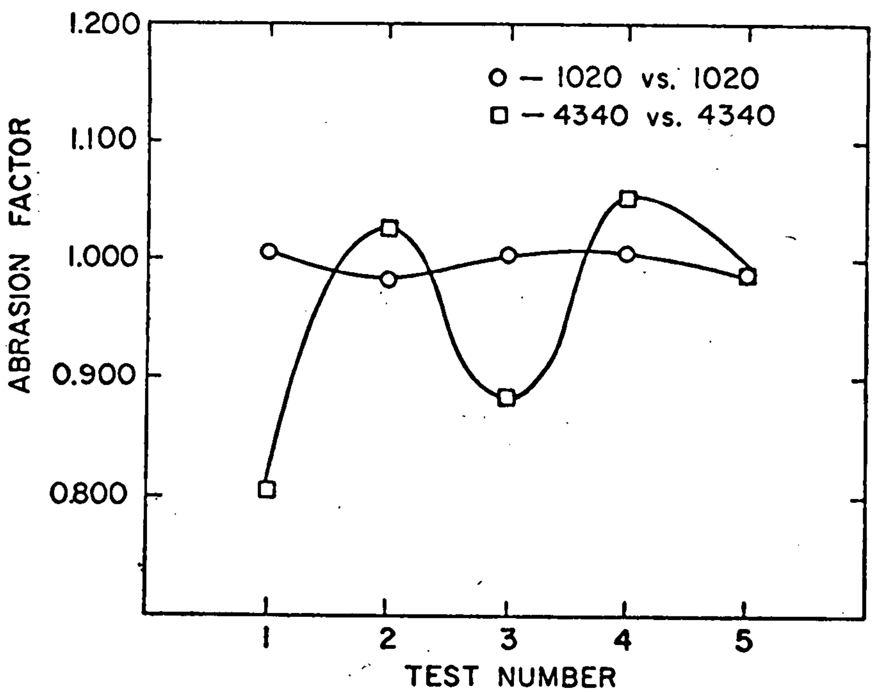

Figure 7. Variability in GAWT abrasion factor for AISI 1020 and 4340 (R_c52) steels.

At the midpoint of the test the pieces are exchanged in the test arms so that experimental variations due to misalignment or systematic error might be eliminated. At the completion of each test, the ratio of weight losses of the two pieces should be 1.000 if the pieces are identical. It is evident that 4340 displays greater variability in Abrasion Factor. The variability probably occurs because worn metal of this material tends to imbed itself or "load" into the Al_2O_3 wheel, whereas the 1020 wear particles fall away from the wheel along with the spent abrasive. For this reason the annealed 1020 steel appears to be best as a gouging test, as well as the rubber wheel test, standard.

2.3.4 Reproducibility of the RWAT and GAWT

The detailed procedures for the RWAT and the GAWT measurements have been presented in quarterly report COO-4246-2. In the RWAT, the rubber wheel travels 713 m during the course of a test. In the GAWT, the Al_2O_3 grinding wheel travels 732 m during the course of the test. Thus the total distance traveled by abrasive is essentially identical in the two tests, so specimen weight losses may be directly compared. The RWAT wear data are reported directly as specimen weight loss per test (i.e. specimen weight loss/713 m of abrasive travel). The GAWT data are reported as AF, the Abrasion Factor (specimen weight loss per 732 m/1020 steel weight loss per 732 m). Under the test conditions, the 1020 steel weight loss is normally about 1.0 g; thus the AF of the specimen is very close to its weight loss per 732 m. For these reasons both the RWAT and GAWT data may be thought of as representing specimen weight loss per about 720 m of abrasive travel under the two respective test conditions.

Both the RWAT and the GAWT have proven to be highly reproducible, having coefficients of variation v of the order of 2 to 4 percent. Each wear datum point presented represents the mean of at least 3 individual tests. Means outside of $\pm$ 3 σ control limits are disregarded, and the three tests repeated. Thusfar, in the entire test program, data have fallen outside of the control limits on only two occasions, once in the case of RWAT test series and once in the case of a GAWT test series.

2.3.5 RWAT and GAWT Results on White Irons

Figures 8 and 9 consist of RWAT and GAWT histograms for 2.7C and 3.5C pearlitic white irons, 15 Cr - 3 Mo and 27 Cr irons. The RWAT data have been obtained for wear directions both normal to and cross the solidification direction. The GAWT data have been obtained for the normal, cross and parallel directions.

A number of generalizations may be made from these data.

1. For all materials, the GAWT, with its rigidly supported Al_2O_3 abrasive of high hardness (Knoop Hardness Number KHN = 1650), produces about 10 times the weight loss of the RWAT, in which the softer SiO_2 abrasive (KHN 750) relaxes into the rubber tire. This is expected since the GAWT has been developed to simulate gouging wear, which is more a traumatic process than low-stress abrasive wear.

2. For the two low-alloy pearlitic irons, both RWAT and GAWT wear resistance increases as C content (Fe_3C volume fraction) increases. This is consistent with the usual interpretation that Fe_3C is repsonsible for imparting wear resistance to pearlitic white irons.

3. For the two low-alloy pearlitic white irons, RWAT and GAWT wear resistance is greater across dendrites than normal to dendrites. In the GAWT results, maximum wear resistance is obtained parallel to dendrite long axes. These data indicate clearly that phase shape may be exploited in optimizing wear resistance.

4. Considering its relatively high alloy content, the 15 Cr - 3 Mo alloy has mediocre RWAT and GAWT wear resistance. Its hard and highly alloyed Cr_7C_3 carbides are supported in a soft matrix of overtempered martensite. This

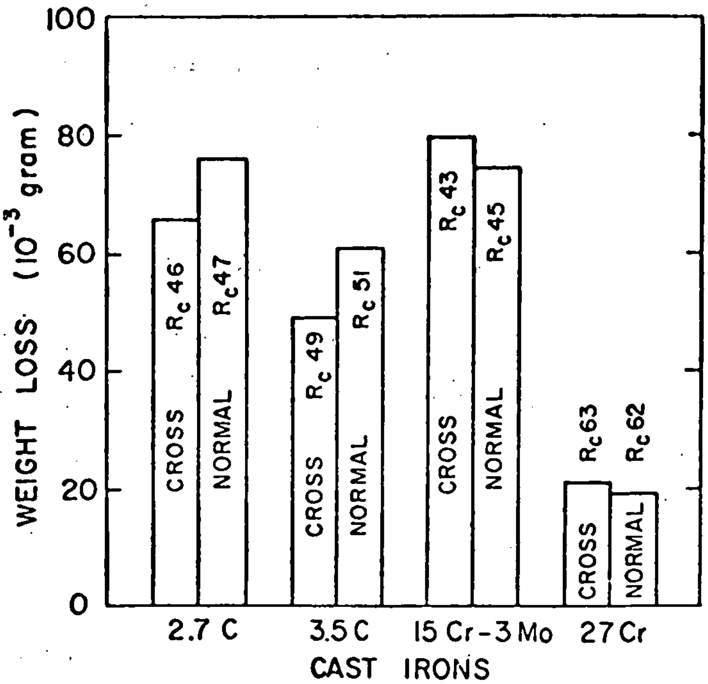

Figure 8. A comparison of RWAT weight loss for four white cast irons, each tested in two orientations relative to the solidification front.

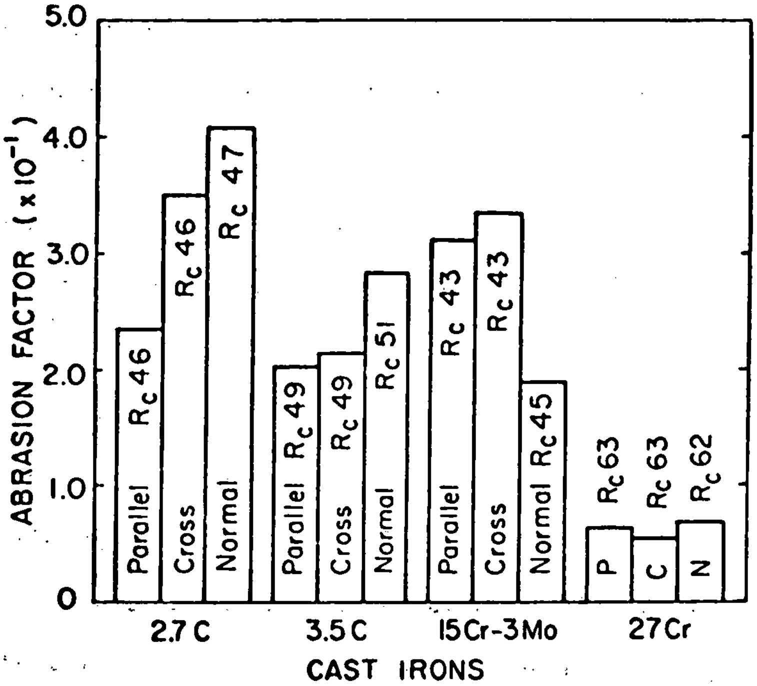

Figure 9. A comparison of GAWT abrasion factor for four white cast irons, each tested in three orientations relative to the solidification front.

indicates that carbide hardness must be coupled with appropriate matrix properties to justify the expense of alloying to increase wear resistance.

5. The RWAT and GAWT wear resistance of the 27 Cr iron are greatest. This highly alloyed iron consists of needle-like Cr_7C_3 carbides more or less randomly arranged in a hard matrix of lightly tempered martensite. Its excellent wear resistance is expected in view of its overall hardness. The lack of orientation dependence of wear resistance is not surprising since the carbides in the alloy are not aligned preferentially relative to the solidification front.

Both RWAT and GAWT wear testing have been conducted on the series of Ni-Hard 4 samples, and the initial results have been reported in the third quarterly report COO-4246-3. Additional testing has been performed during the fourth quarter, so an up-dated discussion of the wear behavior of these irons is given in Part II of this report.

2.4 Task IV - Wear Scar and Microstructure Characterization.

Standard metallography has been completed on all of the cast irons, and photomicrographs at various magnifications were included in report COO-4246-3. A summary report on quantitative metallography (QTM) has been prepared by Mr. Joseph Coyle, Project Engineer, and also included in the report. Very little experimental QTM work has been conducted to date.

During the last quarter of the project, efforts at wear scar characterization has begun. These include microtopography of wear scar profiles and are discussed in Part II of this report.

2.5 Task V - Analysis of Data.

In accordance with the project Work Statement, analysis of the data requires comparison of results from three separate sets of measurements: RWAT and GAWT weight loss tests; mechanical tests including macro and micro-hardness; metallographic studies which include standard metallography, QTM, and wear scar characterization by SEM and microtropography. The analysis process is to proceed in two steps. First, an attempt is to be made to correlate empirically RWAT and GAWT weight loss behavior to various mechanical properties and metallographic parameters. Second, in cases where empirical correlations exist, attempts are to be made to interpret them in terms of basic theories of mechanical behavior; viz. theories involving dispersion strengthening or work hardening. The purpose of the first step in the analysis is to develop empirical rules for materials' selection and/or alloy design for wear resistance. The purpose of the second step is to improve understanding of the basic phenomena of abrasive wear which in tern may lead to an improved fundamental approach in materials' selection and/or alloy design. This two stage approach in data analysis is in keeping with the two-faceted, basic-applied, nature of the project.

The most direct empirical comparison may be made between RWAT and GAWT wear resistance and micro- and macrohardness. The wear-hardness results have been presented graphically in COO-4246-3, and are summarized in Table V for the pearlitic, 15Cr - 3Mo and 27Cr white irons. In the table, n is the number of samples tested, r is the experimental linear correlation coefficient, and r_n is the minimum acceptable correlation coefficient for a valid wear-hardness correlation.

It is evident from the table that wear resistance appears to correlate better to macrohardness in the RWAT than in the GAWT. The superior correlation of the RWAT is probably not due to intrinsic differences in reproducibility in the two tests since they have comparable coefficients of variation. Further, it is not due to the fact that the GAWT include data for cross, normal and parallel specimen orientation and the RWAT only include data for cross and normal, because the parallel data lie within the spread of the cross and normal data. Rather it appears that the behavior is a true manifestation of microstructural effects, and that

Table V. Correlation of Wear to Hardness

(2.7C Pearlitic, 3.5C Pearlitic, 15Cr - 3Mo and 27Cr White Irons)

Condition	n	r	r_n	Remarks
RWAT to Macrohardness	8	.831	.707	Correlation exists
GAWT to Macrohardness	12	.711	.576	Correlation exists
RWAT to Matrix Microhardness	7	.825	.754	Correlation exists
RWAT to Carbide Microhardness	7	.521	.754	No Correlation
GWAT to Matrix Microhardness	11	.687	.602	Correlation exists
GAWT to Carbide Microhardness	11	.575	.602	No Correlation

hardness is a better indicator of wear resistance of cast irons in low-stress abrasion applications than in gouging applications. It may indicate that the hardness test, which in effect is a measure of matrix yielding in compression, simulates low-stress wear more closely than it does gouging wear which may involve impact, matrix yielding and carbide fracture. This is an important result in that it may lead to more effective predictive techniques for wear resistance.

For both the RWAT and GAWT results, wear resistance correlates to matrix microhardness (in the alloys of relatively homogeneous matrices), whereas it does not correlate to carbide microhardness. This generalization may also have metallurgical value in that it suggests that for a range of abrasive hardness and stress conditions, emphasis should be placed on alloying and processing to optimize matrix properties of white irons.

It is difficult to perform wear-hardness correlation tests for the Ni-Hard 4 series, because several phases co-exist in the complicated microstructures. Moreover, correlations involving carbide hardness are meaningless, since the same massive carbide exists in all four microstructural states. On the other hand, these materials have been subjected to extensive mechanical testing at the Climax Research Laboratories. Emphasis has been placed on tests which provide various gauges of toughness, i.e.:

1. Slow strain rate compression measurments of compression yield strength σ_y and compression ultimate fracture strength σ_u. Compressive shear strength σ_s was calculated by multipying σ_u by the sine of the angle between the compression axis and the plane along which the samples fractured.
2. Rolling fatigue tests in which cylindrical specimens were rotated and compressed at a frequency of 1700 Hz by a cluster of three work rolls. These tests generated rolling fatigue endurance limit σ_{EF}, rolling fatigue Hertzian fracture strength σ_{HE} and maximum shear strength at fatigue fracture σ_{SF}.
3. Impact bending tests under single- and repeated-impact conditions which generated impact-bend tensile strength for single impact σ_I and impact-bend tensile strength for repeated impact σ_{IR}.
4. Plain-strain fracture toughness tests, which generated fracture toughness K_{IC}.

The results of these tests are summarized graphically in COO 4246-3. Qualitative correlation of the mechanical test results indicate the following:

1. Correlations involving σ_{EF}, σ_{HF}, σ_{SF}, σ_I, σ_{IR} and K_{IC} are no better than those involving hardness, σ_y, σ_u and σ_s. Since determination of the former quantities require elaborate testing procedures, it is doubtful that their use as predictive tools is justified. Whether they have value in elucidating wear mechanisms however, may be

ascertained only after the in-depth metallographic and topographic studies are complete.

2. In general, values of properties which indicate high RWAT wear resistance indicate low GAWT wear resistance. Similarly, cases in which the RWAT-property plot passes through a maximum at a certain value of the property correspond to cases in which the GAWT-property plot passes through a minimum at the same value of the property. Thus the inversion in RWAT property and GAWT property behavior identified in the hardness correlations persists through the other property correlations. This may simply underscore the fact that the RWAT and GAWT produce two distinct mechanisms of abrasion.

3. The RWAT and GAWT wear correlations involving σ_u or σ_s offer an advantage over those involving σ_y or hardness, since they are monotonic without extremal points. This has an advantage from a predictive viewpoint since wear resistance is a smooth single function of the two technical properties.

3. SUMMARY OF PART I

In the first nine months of the project, effort has been concentrated in in procuring materials, developing sample preparation techniques and perfecting test procedures. The following major test objectives have been achieved:

1. The RWAT and GAWT test procedures have been established, and both tests have been refined to the point where reproducibility is excellent. AISI 1020 steel has been selected as the standard reference materials.

2. All test materials have been obtained. An acceptable method for producing wear and metallographic samples have been perfected.

3. Metallographic techniques for the study of the microstructures of the alloys by conventional and quantitative metallography have been found.

4. All RWAT and GAWT testing has been completed on the cast irons. In addition the mechanical testing correlations have been completed on the Ni-Hard 4 series. A number of qualitative wear-microstructure correlations are evolving.

i. In alloy white irons, wear resistance is a strong function of such parameters as carbide volume fraction, carbide shape and matrix strength. Situations readily arise in which the effort and expense of alloying is wasted because the various effects of such microstructural parameters on wear are not balanced.

ii. In the Ni-Hard 4 irons, retained austenite may improve or may decrease wear resistance depending on its relative amount and the type of wear under consideration.

iii. In the Ni-Hard 4 irons, macro or microhardness is not as good a gauge of wear resistance as is compressive shear or ultimate strength.

iv. In the irons other than the Ni-Hards, macrohardness and matrix microhardness are good gauges of RWAT and GAWT wear resistance. Carbide microhardness is not, which may indicate that for white irons, more emphasis should be placed on alloying and processing to optimize matrix properties.

v. In the irons other than the Ni-Hards, macrohardness and matrix microhardness correlate to RWAT wear resistance better than GAWT wear resistance. This may indicate that low-stress abrasion mechanisms may be understood in terms of basic theories of plastic deformation.

vi. RWAT and GAWT wear resistance correlate to hardness and compression test properties at least as well as they do to properties which are much more difficult to measure.

In the last three months of the project, research has centered on more extensive wear testing of the Ni-Hard 4 series, RWAT wear scar topography of the Ni-Hard 4 series, characterization of the behavior of the abrasive during wear testing, and RWAT testing of the six Co-base PM alloys. These results are summarized in Part II of this report.

PART II

PROGRESS REPORT

15 December 1977 - 15 March 1978

1. FURTHER WEAR TESTS ON Ni-HARD 4

The microstructures of the Ni-Hard 4 alloys consist of massive primary high-Cr carbides separated by regions of retained austenite (γ) and austenite decomposition product (a mixture of α and Fe_3C termed "pearlite" in alloy iron practice). The volume fraction of γ has been varied by heat treatment, so each sample contains γ and "pearlite" of differing thermal history and properties (See COO-4246-2 for micrographs of the alloys). This introduces a complexity into the interpretation of wear data since not only volume fraction of phases but the nature of the phases themselves change from sample to sample. These points will be addressed in detail in subsequent reports.

It was reported in COO 4246-3 that abrasive wear weight loss passed through a maximum at 40% retained γ in the RWAT and the AMAX pin test (APT) . In contrast, weight loss passed through a minimum in the GAWT. It is not unusual for the relative wear resistance of various microstructural forms of a given material to change as wear test conditions are altered. As described in the last quarterly report, Grunlach and Parks have found that high Cr irons have maximum wear resistance in the austenitic form when run against SiC (KHN 2100) or Al_2O_3 (KHN 1650) abrasives in the APT. When run against a softer abrasive, garnet (KHN 750), they display maximum resistance in the martensitic condition.

One possible reason for the ranking reversal in the RWAT and GAWT may be the intrinsic difference between the tests (e.g. loosely supported abrasive <u>versus</u> rigidly supported abrasive). Another reason may be the nature of the abrasive used. In order to obtain an estimate of the validity of either one of these hypothesis, RWAT tests were run on the Ni-Hard 4 with the loose Al_2O_3 abrasive from which the GAWT wheels are fabricated. This abrasive is of approximately the same average size range (50-100 mesh) as the SiO_2 routinely used in the RWAT (50-70 mesh); however it is much harder (KHN 1700 <u>versus</u> KHN 750) and much more angular than the semi-rounded quartz sand. The RWAT weight loss on Al_2O_3 are given in Figure 10, in which the SiO_2 RWAT, the APT and the GAWT test results are also displayed.

As expected, RWAT weight losses with the Al_2O_3 abrasive are much larger (a factor of 50) than with the softer, semi-rounded quartz. Moreover, the sharp maximum in weight loss which appeared in the APT and the original RWAT tests is not present. Indeed the data show a monotonic increase in weight loss with increasing specimen macrohardness. If anything the data are more similar in magnitude and hardness dependence to the GAWT results than to the RWAT or APT results. The behavior points out once again that hardness is often an unacceptable design parameter in designing for wear resistance. It also indicates that changes within a given wear test procedure may easily cause changes in results that are greater than those brought about by substitution of an entirely different test. Finally, they underscore that the study of wear mechanisms must include a study of the abrasive as well as the target material.

2. TESTS ON THE RWAT SiO_2 and Al_2O_3 ABRASIVES

One facet included in the Work Statement of this project is the study of the wear debris, since such a study might lead to a better understanding of wear mechanisms. In the RWAT, as in many field applications, the abrasive contacts the target over a finite wear path before it exits the system. During this time, both the target and the abrasive are degrading and generating debris. The abrasive debris may alter the very nature of the wear process, so its characterization is essential in wear research. For example, a rounded abrasive which initially causes material attrition by plastic deformation may fracture into angular fragments which produce attrition by a cutting action.

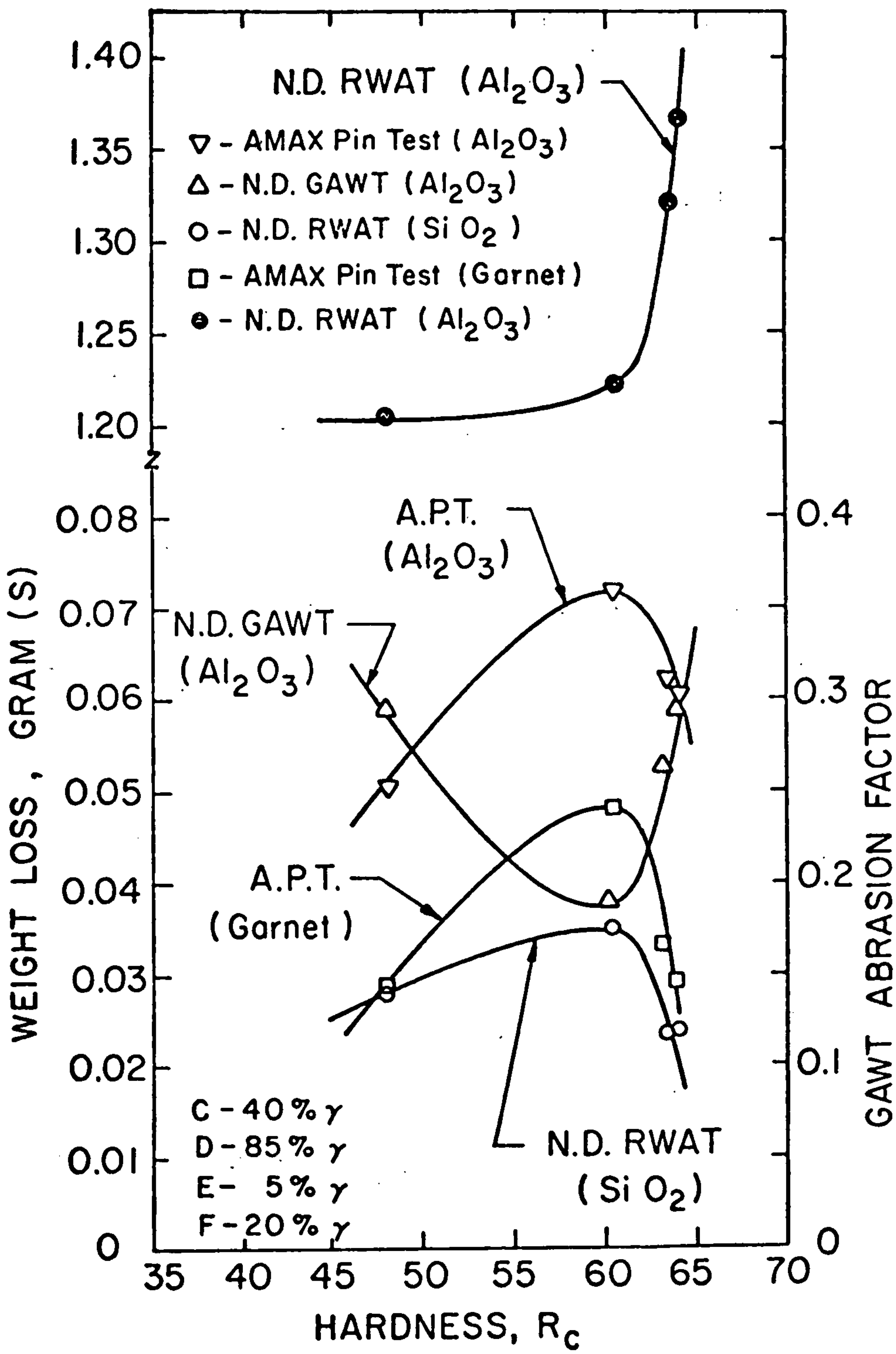

Figure 10. RWAT, APT and GAWT test results on Ni-Hard 4 samples.

As a first step in the study of target and abrasive debris, the sieve analyses of the sand used in the RWAT and the Al_2O_3 used in the GAWT (and for one series of tests on the RWAT) have been obtained for new abrasive and for abrasive degraded in the RWAT, (Figures 11 and 12).

The unused SiO_2 abrasive has a sharp unimodal particle size distribution peaking at 250μm, mesh size 60. The RWAT process causes the abrasive to change drastically, producing a broad distribution of finer SiO_2 debris. Preliminary tests indicate that this debris is more angular than the original sand.

The new Al_2O_3 abrasive has an average size of 212μm, mesh size 70, very nearly that of the SiO_2 abrasive; however the particle size distribution is bimodal. Thus comparative tests between these two abrasives should reflect the fact that particle size distribution is a distinct variable. It is apparent that the Al_2O_3 abrasive does not degrade as markedly as does the sand, but some fragmentation, especially of the larger particles, does occur.

RWAT tests have been conducted on the AISI 1020 steel standard material with new and used SiO_2 and new and used Al_2O_3 abrasive. The results are summarized in Table VI. Suprisingly the wear behavior is identical for new and used sand,

Table VI. RWAT Weight Loss of AISI 1020 Steel
New and Used Abrasive

Abrasive	Weight Loss, grams (average of three tests)
New SiO_2	0.4611
Used SiO_2	0.4616
New Al_2O_3	1.9093
Used Al_2O_3	1.5907

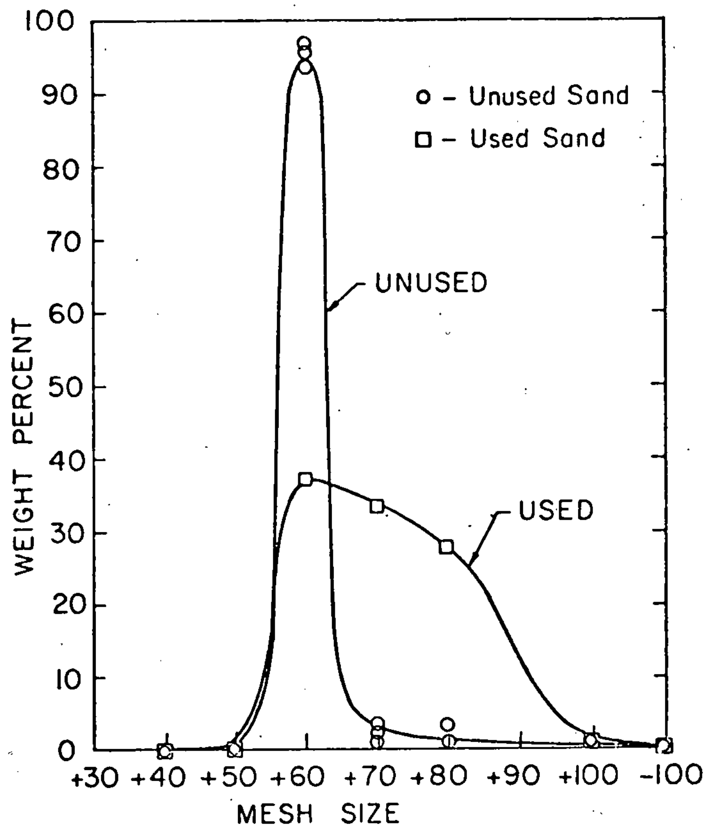

Figure 11. Sieve analysis of fresh and used semi-rounded quartz abrasive employed in the RWAT.

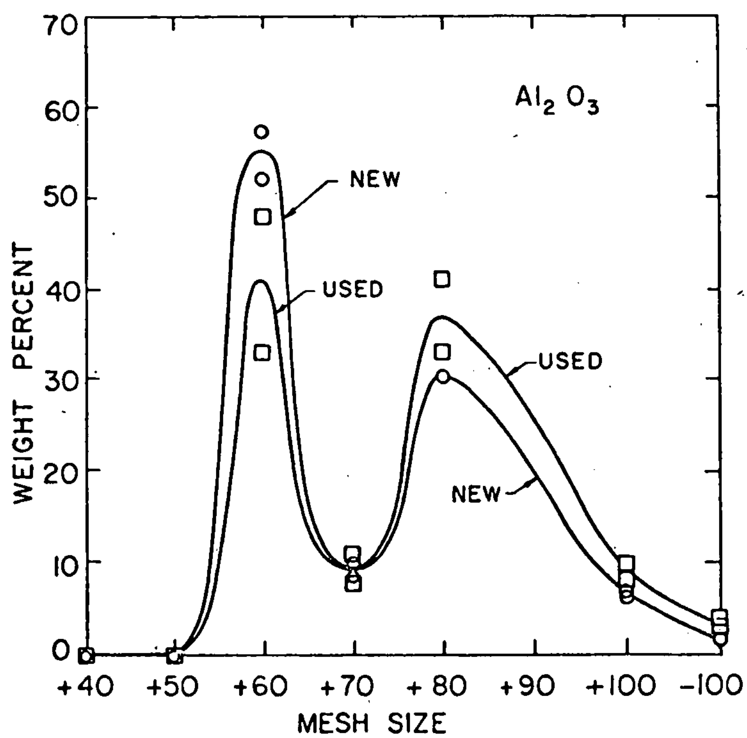

Figure 12. Sieve analysis of Al_2O_3 abrasive used in GAWT wheels. Data for fresh abrasive and abrasive degraded in the RWAT against Ni-Hard 4.

although the used sand has a markedly different particle size distribution than the unused. In contrast, weight loss with the new Al_2O_3 abrasive is substantially greater than that obtained with the used abrasive, although Al_2O_3 does not degrade markedly during use. These results reinforce the importance of the study of the abrasive and target wear debris. Such studies are in their preliminary stages.

3. MICROTOPGRAPHY OF Ni-HARD 4 RWAT WEAR SURFACES

In the original proposal it was postulated that microtopographic studies of the wear scar might lead to an understanding of wear mechanisms. For example, wear scar roughness may correlate to second-phase size or orientation. Microtopgraphic scans of Ni-Hard 4 RWAT wear scars have been obtained at the Inland Steel Research Laboratories, East Chicago, Indiana. The scars were traced with a .0127 mm diamond stylus on a Sloan Profilometer which is interfaced to a computer for direct data reduction. Scans perpendicular to the abrasion direction for the Ni-Hard 4 RWAT samples of varying retained γ are presented in Figure 13. The wear scar profiles are quite similar, although the weight loss variation for the four microstructures was about 30%. These preliminary tests indicate that profilimetry may have little use in shedding light on wear mechanisms. Computer analysis of these RWAT data and on data from the other white irons is in progress.

4. RWAT RESULTS ON THE Co-BASE ALLOYS

As is indicated in Table II the Co-base PM alloys represent a series of increasing carbide and/or increasing matrix solid-solution strengthener content. RWAT tests with SiO_2 abrasive have been completed on the series, and the test results are displayed in Figures 14 and 15. In Figure 14 the weight loss data are displayed in histogram form, with increasing carbide and/or matrix alloy content left to right. In general, the higher the carbon or alloy content, the lower the RWAT weight loss. In Figure 5, the data are displayed as a function of R_c

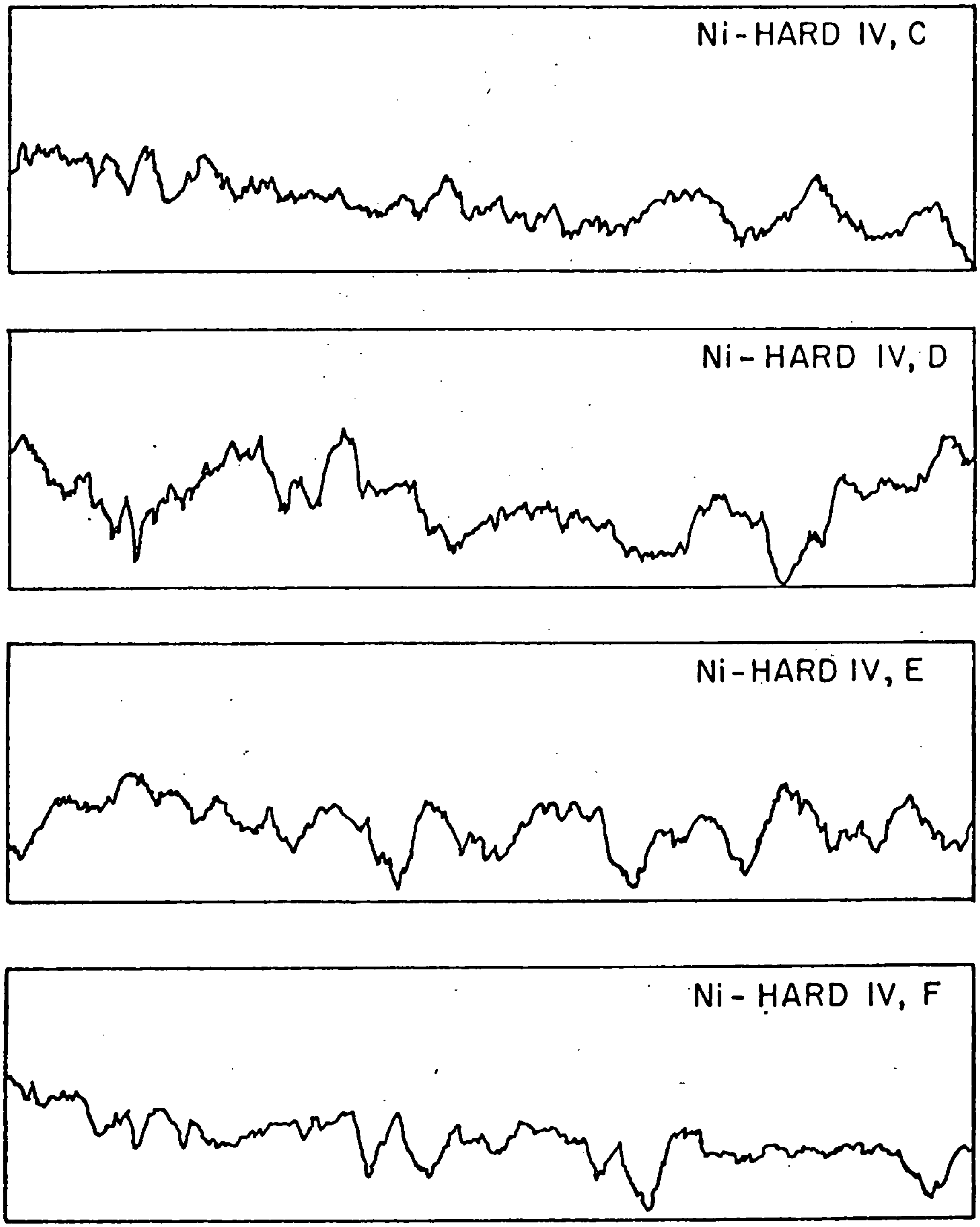

Figure 13. Microtopography of Ni-Hard 4 wear scars, perpendicular to RWAT abrasion direction. (one mm in figure = 250 μm on surface).

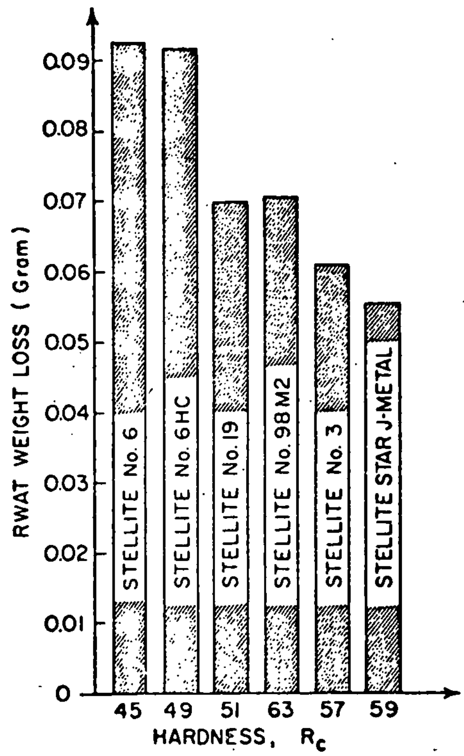

Figure 14. RWAT weight loss of Co-base PM alloys. Carbide volume fraction and/or matrix solid-solution strengthener content increases left to right.

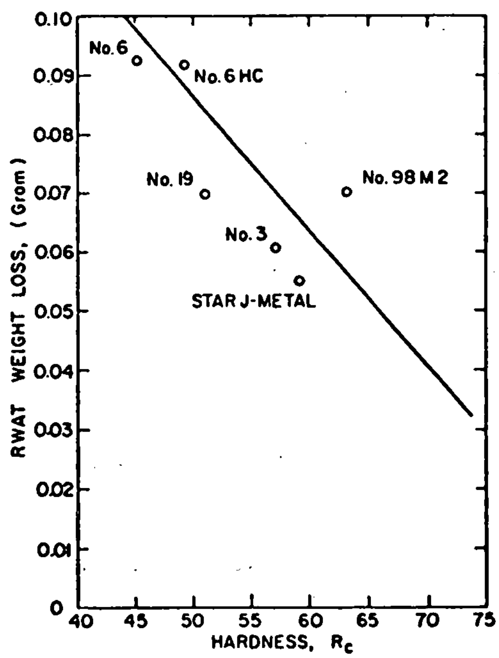

Figure 15. RWAT weight loss of Co-base PM alloys as a function of Rockwell C hardness.

macrohardness. Weight loss does not correlate well with R_c, since r for these data is about 0.7, compared with a minimum r of 0.8 required for n = 6.

Research on the Co-base alloys is just underway. Optical and quantitative metallography and GAWT testing are in progress.

5. SUMMARY

Research in the first nine months of this project has centered in developing low-stress and gouging wear test techniques. Tests in alloy white irons have indicated that microstructure plays a strong role in establishing a materials wear resistance. Various mechanical parameters, such as fracture toughness or rolling fatigue resistance, do not correlate well with abrasive wear resistance.

In the last three months of the research wear testing has been expanded to include SiO_2 and Al_2O_3 abrasives in the low-stress test. The abrasive has a strong effect in the magnitude of the weight loss and on the relative rank of wear resistance of various microstructural forms of an alloy. The abrasive degrades during wear testing, and the degraded abrasive may attack the target alloy differently than does the fresh abrasive. Microtopography appears to have limited use in elucidating wear mechanisms.

Fianlly, wear testing of the Co-base PM alloys has been initiated and in general increasing carbide volume fraction and/or matrix solid-solution strengthener content increases wear resistance.

6. PERSONNEL

The principal investigator, Dr. N. F. Fiore, has spent about one-fifth effort on the project during this quarter of the academic year. Mr. Stephen Udvardy (M.S. candidate) has devoted half-time effort to the project. In addition, a former graduate student, Mr. Joseph Coyle, has completed requirements for the M.S. and has begun full-time effort on the research as Project Engineer.

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*U.S. GOVERNMENT PRINTING OFFICE: 1978-740-306/4331. Region 4.