COO-4246-6

# MICROSTRUCTURAL EFFECTS IN ABRASIVE WEAR

Quarterly Progress Report
for the period 15 June 1978 - 15 September 1978

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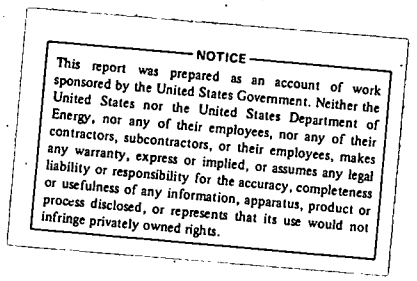


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## ABSTRACT

This project is directed toward correlating low-stress and gouging abrasive wear to microstructure in a series of alloy white irons and Co-base powder metallurgy (PM) alloys. In this quarter, additional tests have shown that low-stress abrasion resistance increases in a general way with hardness, whereas gouging wear resistance correlates to a significantly lesser extent. For gouging wear in particular, increasing hardness, carbon and alloy content are inefficient means to increase wear resistance.

Low-stress rubber wheel abrasive tests (RWAT) have been conducted with unused and used $SiO_2$ and $Al_2O_3$, and sample weight loss and abrasive size degradation have been monitored. Relatively small changes in abrasive size distribution are found to be associated with marked differences in sample weight loss. Microtopographic analysis of the wear scars generated with all four types of abrasive indicate that wear-resistant alloys exhibit smoother wear scars.

In gouging wear or in low-stress wear against $SiO_2$, maximum wear resistance is found at intermediate carbide volume fractions ($v_f$) and matrix alloy contents. For low-stress testing against $Al_2O_3$, wear resistance increases linearly with $v_f$.

CONTENTS

## 1. OBJECTIVE AND SCOPE

This work is directed at establishing quantitative relations between microstructure and wear resistance of low-to-high Cr white irons (ASTM Series 532) and Co-base powder metallurgy (PM) alloys commonly used in coal conversion processes. The research involves study of gouging wear resitance, such as is necessary in mining operations, and low-stress abrasion resistance, such as required in coal and coal-product handling and transfer operations. The project has both applied and basic aspects. On the applied 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. From the basic viewpoint, 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.

The project has been in existence for about 18 months, during which time most of the testing and analysis has been conducted on the white irons. The majority of this, the sixth project quarterly report, is devoted to test results on the Co-base PM alloys.

## 2. TASKS AND PROGRESS

### 2.1 Task I - Preparation of Test Matrix

Task completed 6 June 1977.

### 2.2 Task II - Preparation of Materials

Task completed 15 March 1978.

The white iron and Co-base alloy materials have been obtained. The compositions, heat treatments and microstructures of the white irons have been discussed in the quarterly report, COO-4246-4, and a similar discussion for the

Co-base alloys has been given in the last quarterly report, COO-4246-5.

## 2.3 Task III - Wear Testing

### 2.3.1 Co-base PM Alloy Test Matrix

The six Co-base alloys chosen, whose chemical compositions are listed in Table I, are among the most erosion and erosion-corrosion resistant materials commercially available. In addition to being commercially relevant, the series of alloys comprise an interesting system for study since they span a range of increasing carbide volume fraction in matrices of increasing solid solution strengthener content (Table II).

### 2.3.2 Rubber-Wheel Abrasion Testing

#### 2.3.2.1 The Abrasive and the RWAT

The RWAT has been developed as a test for low-stress abrasion, a process during which, by definition, the abrasive remains unchanged. Preliminary tests, as reported in quarterly COO-4246-3, indicated that in fact both $SiO_2$ and $Al_2O_3$ abrasive degraded in size during testing. The $SiO_2$ abrasive, of average mesh size 50-70, broke down in such a manner that substantial amounts (~20% of the total abrasive mass) of 70-100 mesh fine particles were created. The $Al_2O_3$, having a bi-modal size distribution peaking at 60 and 80 mesh broke down to a much lesser extent. Surprisingly, the $SiO_2$, which degraded markedly in size, lost only about 10 percent of its abrasiveness against 1020 steel, whereas the $Al_2O_3$ lost almost 50% of its abrasiveness. These preliminary tests indicated that RWAT test results must be interpreted in light of target and abrasive behavior.

Consequently a RWAT program was instituted in which triplicate samples of each Co-base PM alloy was run against unused $SiO_2$, "used" $SiO_2$ (i.e. $SiO_2$ broken down by a previous run) unused $Al_2O_3$ and used $Al_2O_3$. The same analyses for the unused, used-once and used-twice forms of each abrasive are shown in Figures 1 and 2. The break-down of the $SiO_2$ after one test is evident. A comparable additional

Table I.

Chemical Analysis of Co-base PM Alloys

| | #6 | #6HC | #19 | #98M2 | #3 | #Star J |
|---|---|---|---|---|---|---|
| B | .49 | .49 | .22 | .66 | .49 | .27 |
| C | 1.49 | 1.94 | 1.88 | 2.12 | 2.52 | 2.67 |
| Co | Bal | Bal | Bal | Bal | Bal | Bal |
| Cr | 28.99 | 28.99 | 30.17 | 30.57 | 30.91 | 31.57 |
| Fe | 1.46 | 1.46 | 1.92 | 3.09 | 2.29 | .32 |
| Mo | .32 | .32 | -- | .24 | .35 | .02 |
| Mn | .13 | .13 | 0.65 | .23 | <.1 | .58 |
| Ni | 2.13 | 2.13 | 1.42 | 4.04 | 2.20 | 1.34 |
| Si | .92 | .92 | -- | .51 | .51 | .34 |
| V | -- | -- | -- | 3.82 | -- | <.01 |
| W | 4.96 | 4.96 | 10.37 | 17.15 | 11.78 | 16.94 |

Table II

Features of the Co-base Powder Metallurgy Alloys

| | | Type | Microstructure |
|---|---|---|---|
| 1. | #6 | Low carbide vol. fract. | Low solid solution strengthener content. |
| 2. | #6HC | High carbide vol. fract. | Low solid solution strengthener content. |
| 3. | #19 | High carbide vol. fract. | Moderate solid solution strengthener content. |
| 4. | #98M2 | Very high carbide vol. fract. | Very high solid solution strengthener content. |
| 5. | #3 | Very high carbide vol. fract. | High solid solution strengthener content. |
| 6. | #Star-J | Very high carbide vol. fract. | High solid solution strengthener content. |

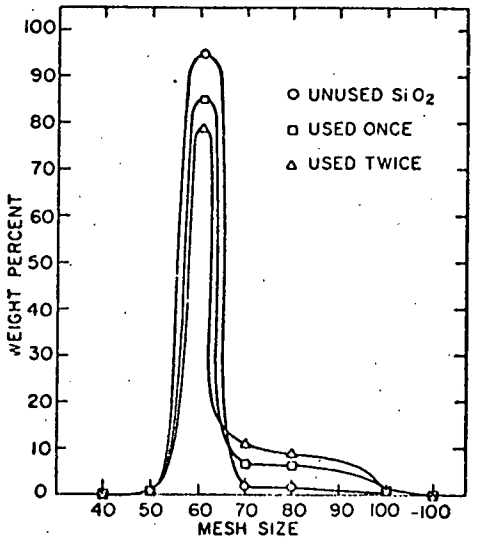


Figure 1. Sieve analysis of $SiO_2$ abrasive (unused, used once, used twice in RWAT tests on Co-base PM alloys).

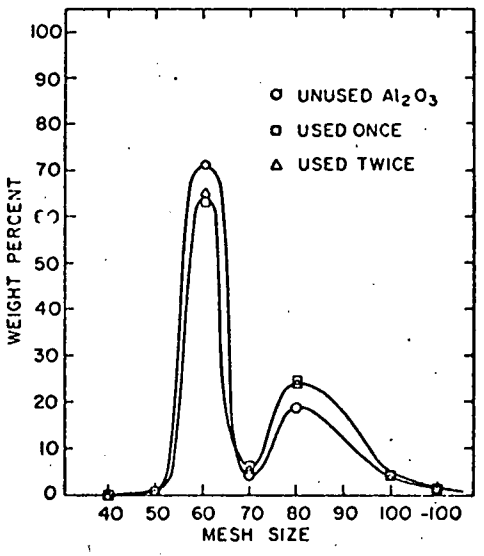


Figure 2. Sieve analysis of $Al_2O_3$ abrasive (unused, used once, used twice in RWAT tests on Co-base PM alloys).

breakdown occurs during the second test, so that after the abrasive has been used twice about 20% of it falls into -70 size classes. The $Al_2O_3$ breaks down to a lesser extent during its first usage, and does not break down further during the second usage.

2.3.2.2 RWAT Results - Unused and Used $SiO_2$

Figure 3 shows RWAT weight loss against alloy macrohardness ($R_c$) for the Co-base alloys tested against unused and used $SiO_2$. Shown in the figure are least-square straight lines fit to the unused and used $SiO_2$ data. The wear-hardness correlation coefficient r is 0.78 for unused $SiO_2$ and 0.88 for used $SiO_2$. The theory of abrasive indicates* that weight loss should vary as $(\text{hardness})^{-1}$. It has been found in this program that the data follow the direct wear-hardness correlation at least as well as the reciprocal hardness correlation, so for the purposes of simplicity the data are presented in direct form. These present data, as have previous sets, indicate that hardness provides a semi-quantitative gage of wear resistance for the RWAT.

It is evident from Figure 3 that the $SiO_2$ abrasive loses about 50 percent of its abrasiveness after one use. This effect is seen more clearly in Figure 4, in which the weight loss data are presented in histogram form.

The results with unused and used $SiO_2$ help to account for the strong differences of opinion concerning wear test results obtained at various laboratories. Small changes in abrasive behavior produce unpredictable changes in abrasiveness. As mentioned previously, the break-down of $SiO_2$ did not decrease its abrasiveness against 1020 steel; however, a marked reduction occurs against the Co-base alloys.

In a more positive vein, data with the various abrasives present the opportunity for gaining insight as to the material attrition processes governing low-stress

*See for example E. Rabinowicz, Friction and Wear of Materials (Wiley, New York, 1964) p. 168.

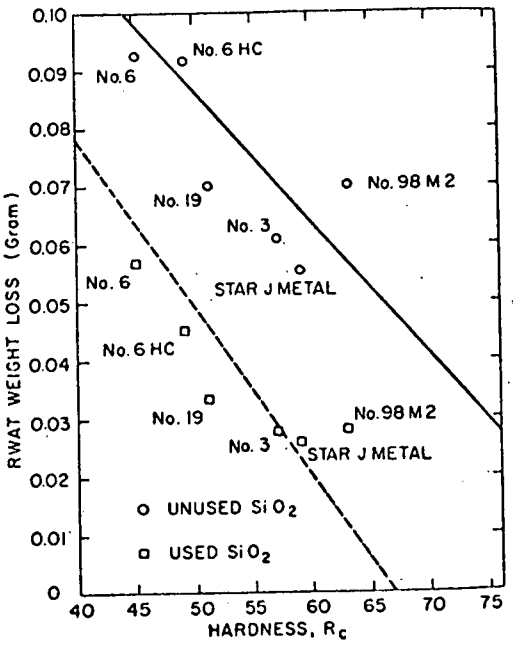


Figure 3. RWAT weight loss of Co-base PM alloys as a function of alloy hardness, Rockwell $R_c$. (Unused and used $SiO_2$ abrasive).

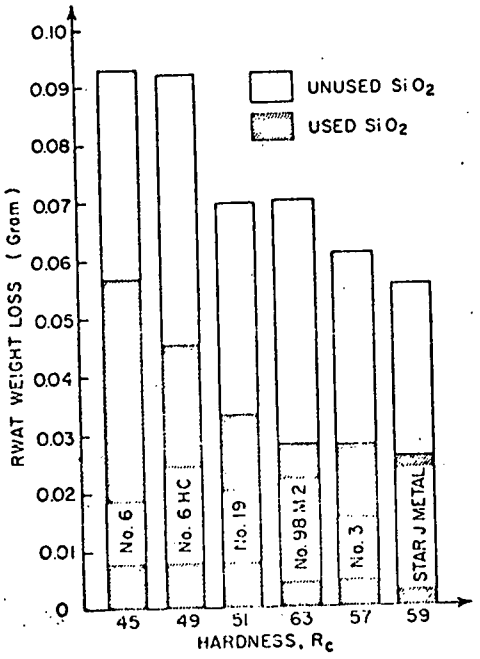


Figure 4. Histogram of RWAT weight loss for Co-base PM alloys tested against unused and used $SiO_2$.

abrasion of these materials if a correlation can be made between the relatively small changes in abrasive characteristics and the large changes in weight loss. For example, the abrasive may be degraded into small particles by the fragmenting of sharp corner particles from the parent grain (although grains of this particular abrasive are semi-rounded rather than markedly angular). The significant loss of abrasiveness in this case would suggest that micro-machining processes govern low-stress wear.

2.3.2.3 RWAT REsults - Unused and Used $Al_2O_3$

As is evident from the plots and histograms of Figures 5 and 6, RWAT testing with $Al_2O_3$ produces clear differences from testing with $SiO_2$. In the first place, the correlation between wear and harndess is extremely good for both the unused ($r = 0.94$) and the used ($r = 0.96$) abrasive. This is somewhat surprising in that a rule-of-thumb* in designing for wear resistance is that hardness is an effective design parameter until the abrasive hardness exceeds target hardness. At this point, processing to increase target hardness is considered inefficient. The $Al_2O_3$ abrasive, with hardness about 2000 KHN is substantially harder than even the hardest of the PM alloys with $M_7C_3$ hardness about 1800 KHN and yet gains in wear resistance are evident as hardness is increased. The gains are also evident for the case of $SiO_2$, about 800 KHN, but this is not surprising because the abrasive and target hardnesses are more similar in this case.

The common model* of abrasive wear is based on a situation in which an infintely hard conical abrasive particle partially penetrates the surface of a target of hardness H and removes a furrow of matter as it slides along the surface. These data show that, as many others have seen that hardness may be a useful parameter in designing for wear resistance, but that the usefulness should not be taken as an indication that the model is valid.

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*E. Rabinowicz, op. cit, p. 172.

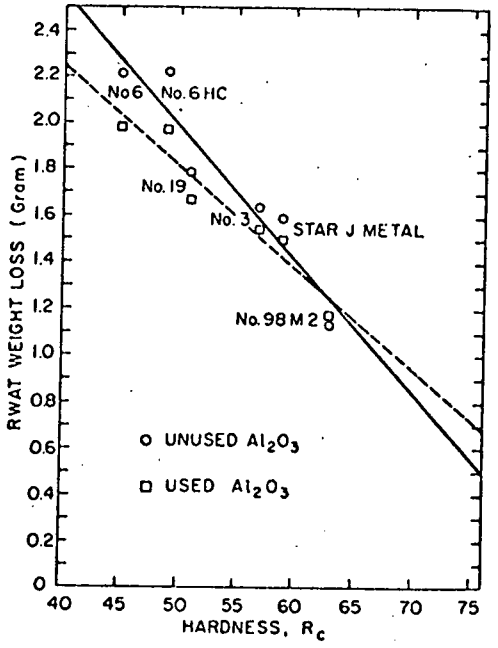


Figure 5. RWAT weight loss of Co-base PM alloys as a function of alloy hardness, Rockwell C. (Unused and used $Al_2O_3$ abrasive).

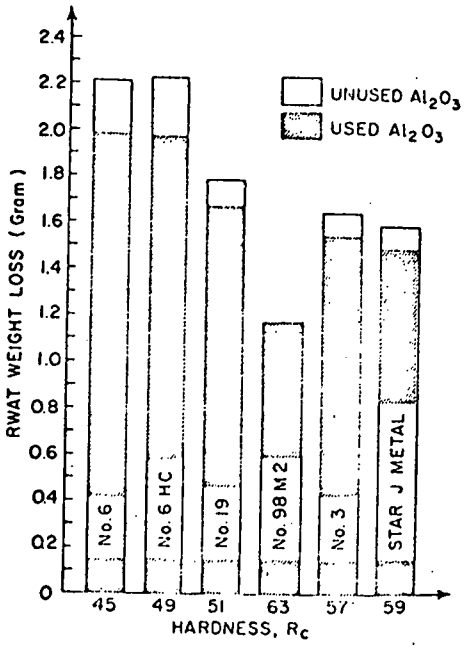


Figure 6. Histogram of RWAT weight loss for Co-base PM alloys tested against unused and used $Al_2O_3$.

The data also show that abrasive size degradation appears to have less influence on the abrasiveness of the $Al_2O_3$ than on the $SiO_2$. The differences in weight loss observed for the unused and used $Al_2O_3$ are small. This result, as well as the others mentioned for the $SiO_2$ and $Al_2O_3$ abrasives is discussed further under Task V, Analysis of Data.

### 2.3.3 Gouging Abrasion Testing

The GAWT tests results for the six Co-base PM alloys were presented in the last quarterly (COO-4246-5). They are summarized here in Figures 7 (GAWT weight loss vs $R_c$) and Figure 8 (GAWT data in histogram form). The previous RWAT data lead to the general conclusion that low-stress abrasion resistance improves as alloy cost increases. It is evident that this trend is not as clear for gouging abrasion resistance. The poorer correlation between wear resistance and alloy content in the case of gouging wear is borne out in Figure 7, with a wear-hardness correlation coefficient r of 0.65, as contrasted with the necessary value of 0.8 for significant correlation as defined in COO-4246-3.

## 2.4 Task IV - Wear Scar and Microstructure Characterization

### 2.4.1 Optical and Quantitative Metallography of Co-base Alloys

The optical and quantitative metallographic (QTM) analysis of the PM alloys have been described in COO-4246-5. The alloys consist of an array of carbides uniformly distributed in a FCC Co-base matrix. In general the carbides are of type $M_7C_3$, where M is largely Cr. The most highly alloyed material contain about 10 volume percent $M_6C$ carbides, where M corresponds to W, Co and Cr. The QTM results are re-summarized in Table III. Total carbide volume fraction, $v_f$, increases from 34 to 57% across the range of alloys, whereas carbide size is about constant with the exception of alloy #98M2 which has smaller carbides.

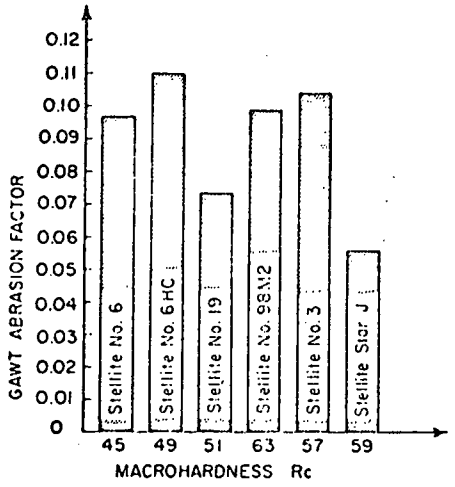


Figure 7. GAWT weight loss of Co-base PM alloys. Carbide volume fraction and/or matrix solid-solution strengthener content increase left to right.

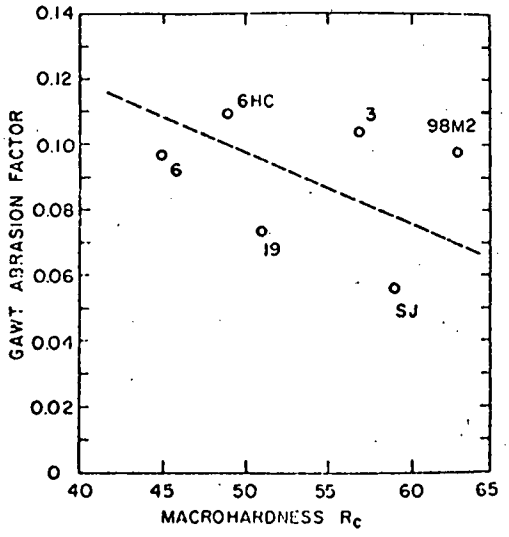


Figure 8. GAWT abrasion factor of Co-base PM alloys as a function of Rockwell C hardness.

Table III

Quantitative Metallographic Results for Co-base PM Alloys

| Alloy | Volume Fraction, Percent | | | | | Projected Carbide | |
|---|---|---|---|---|---|---|---|
| | Porosity | $Cr_7C_3$ | $M_6C$ | Total Carbides | $\sigma_v$ Std. Dev. (%) | Length per Unit Area ($cm^{-1}$) | $\sigma_L$ Std. Dev. ($cm^{-1}$) |
| No. 6 | 1.8 | 33.8 | 0 | 33.8 | 2.1 | 0.010 | .0007 |
| No. 6HC | 1.6 | 39.5 | 0 | 39.5 | 3.5 | 0.013 | .0013 |
| No. 19 | 1 | 37.4 | 0 | 37.4 | 1.4 | 0.012 | .0006 |
| No. 98M2 | 0 | 43.6 | 13 | 56.6 | 2.1 | 0.019 | .0004 |
| No. 3 | 0 | 46.3 | 8.9 | 55.2 | 5.3 | 0.011 | .0004 |
| Star J-Metal | 0 | 41.0 | 8.9 | 49.9 | 1.3 | 0.014 | .0002 |

### 2.4.2 Wear Scar Microtopography of Co-base PM Alloys

Wear scar micro-profilometry is conducted at the Inland Steel Research Laboratories. The measurements are made with a Sloan profilometer having a 0.0127 mm diameter diamond stylus. Detailed descriptions of the measuring technique and of the computer analysis have been given in COO-4246-4 and 5. In summary, the techniques and analysis produce three measures of roughness:

1. P(I) - The "actual" surface profile. A composite of both coarse and fine topographical features.
2. C(I) - The centerline profile, which consists of the coarse features only
3. R(D) = P(I) - C(I) -- The residual topography which consists of the fine features alone.

The analysis to date has been concentrated on the relation of R(I) to wear behavior. There are three quantitative measures of R(C), as defined in the last quarterly. These are:

1. AA, the average displacement from centerline.
2. RMS, the rms roughness.
3. PPI, the number of peaks per inch scanned.

The RWAT wear scars produced during the tests with unused and used $SiO_2$ and $Al_2O_3$ have been analyzed according to the above procedure. In all cases the surface trace was obtained near the top of the wear scar, where abrasive first meets target. Although the most relevant material loss mechanisms may be operating further down the scar, attention is focused at the top region for these initial measurements because of the greater ease of obtaining reproducible data. The profilometry to-date has involved considerable effort in perfecting the Inland experimental system with on-line computer analysis to our needs, so the simplest procedures are being employed at this stage.

The microprofilometry results are given in Figures 9-20. The figures are presented in sets of three (AA, RMS, PPI) for each of the four RWAT conditions: unused $SiO_2$, used $SiO_2$, unused $Al_2O_3$, used $Al_2O_3$. The topography-wear correlation coefficients are listed in each caption, and they indicate, in a general way, that the more resistant a material, the smoother will be its wear scar. The exception to this qualitative rule is found for used $Al_2O_3$, in which no statistically significant correlation exists between wear resistance and topography.

At least three problems must be addressed before these or other topographic results can be interpreted:

1. Is the Inland Steel data analysis procedure relevant to our purposes? For example, it may be more important to concentrate on the coarser detail C(I) than R(I), given the scale of the wear scar features.

At the other extreme is the question:

2. Are the three measures of microtopography, (AA, RMS, PPI), fine enough to resolve relevant features?

3. What regions of the wear scars provide useful information about the relvant material attrition mechanisms?

The general correlations found thus far indicate that it is worthwhile to consider these questions. A series of scanning electron microscopy (SEM) studies will be undertaken to define the scale of the topographic information of interest. Given the number of wear samples already in existence, the SEM studies will occupy a substantial portion of effort during the next quarter.

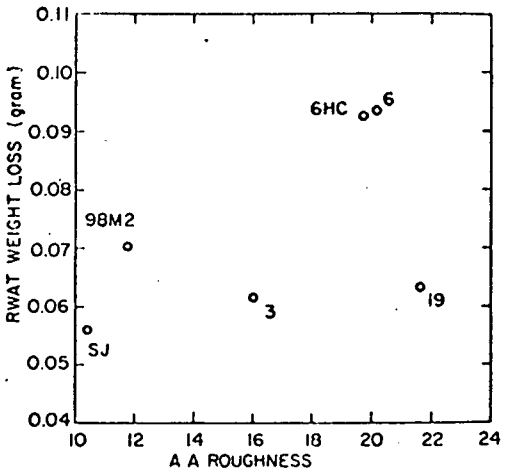


Figure 9. RWAT weight loss vs AA microtopography. (Unused $SiO_2$ - r not significant.)

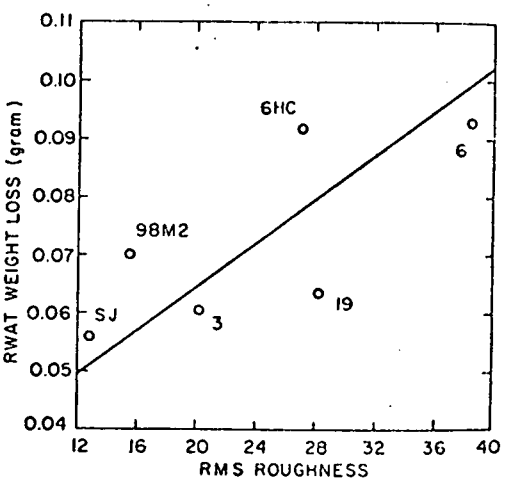


Figure 10. RWAT weight loss vs. RMS microtopography. (Unused $SiO_2$ - r = 0.62).

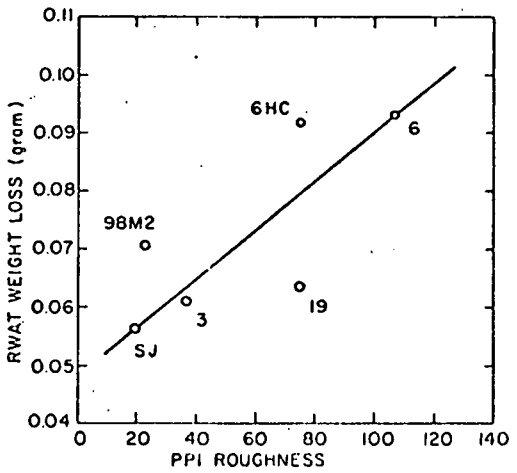


Figure 11. RWAT weight loss vs PPI microtopography. (Unused $SiO_2$ - r = 0.71).

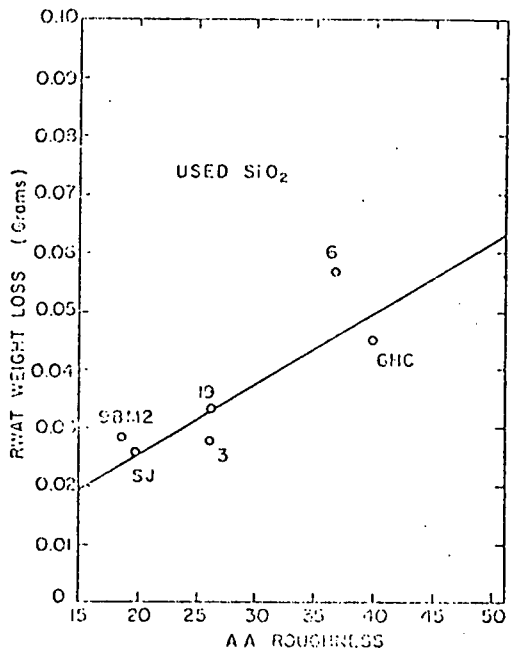


Figure 12. RWAT weight loss vs AA microtopography. (Used $SiO_2$ - r = 0.88).

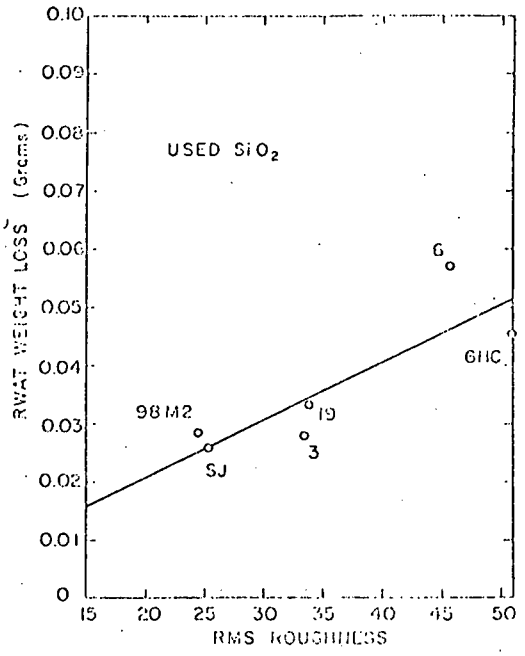


Figure 13. RWAT weight loss vs RMS microtopography. (Used $SiO_2$ - r = 0.86).

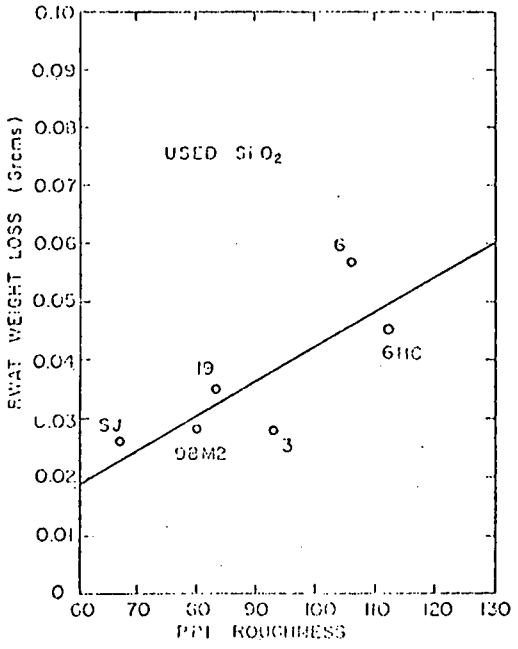


Figure 14. RWAT weight loss vs PPI microtopography (Used $SiO_2$ - r = 0.81).

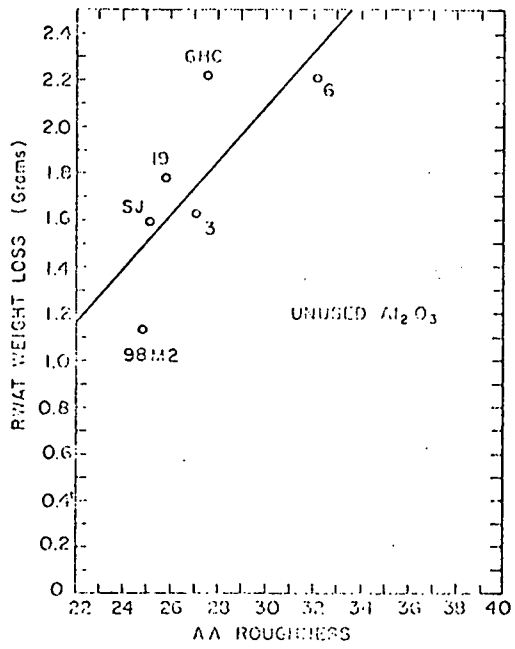


Figure 15. RWAT weight loss vs AA microtopography. (Unused $Al_2O_3$ - r = 0.75).

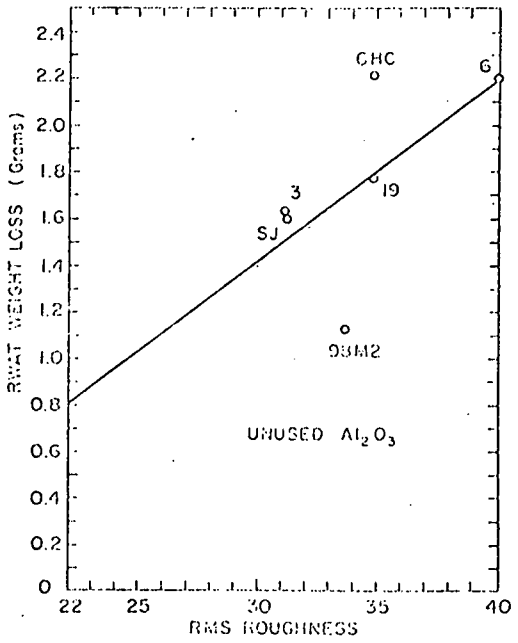


Figure 16. RWAT weight loss vs RMS microtopography (Unused $Al_2O_3$ - r = 0.61).

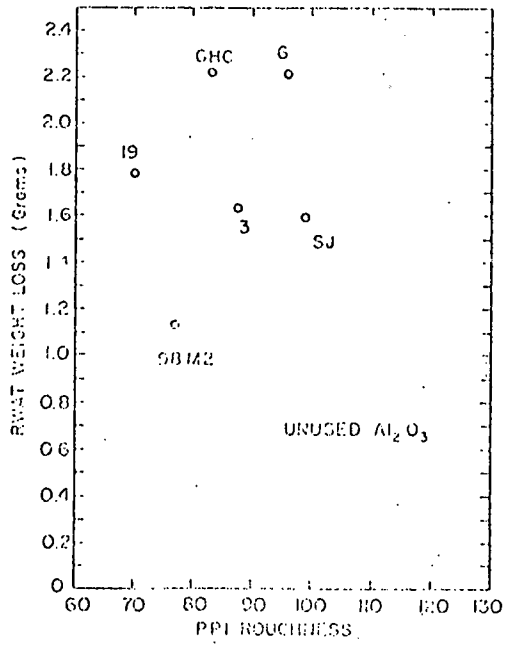


Figure 17. RWAT weight loss vs PPI microtopography. (Unused $Al_2O_3$ - r not significant)

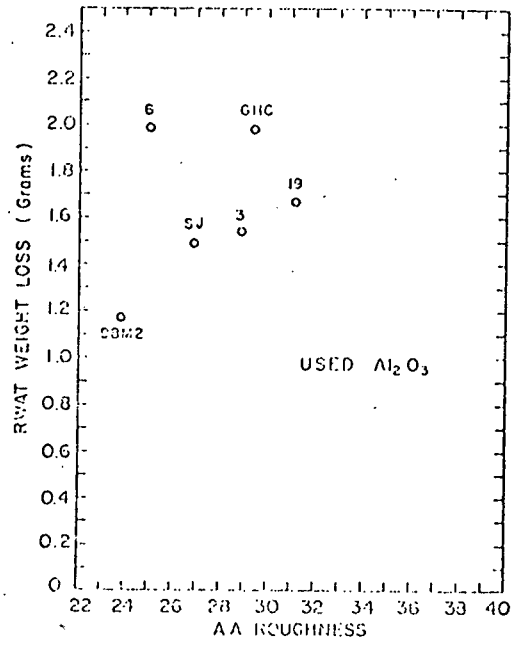


Figure 18. RWAT weight loss vs AA microtopography. (Used $Al_2O_3$ - r not significant).

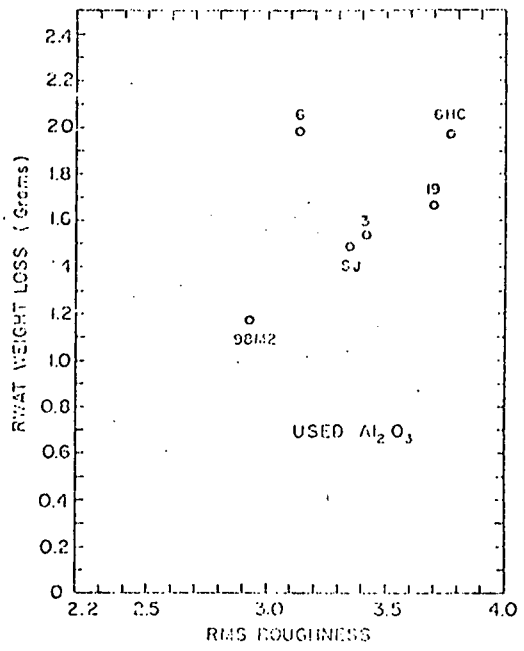


Figure 19. RWAT weight loss vs RMS microtopography. (Used $Al_2O_3$ - r not significant).

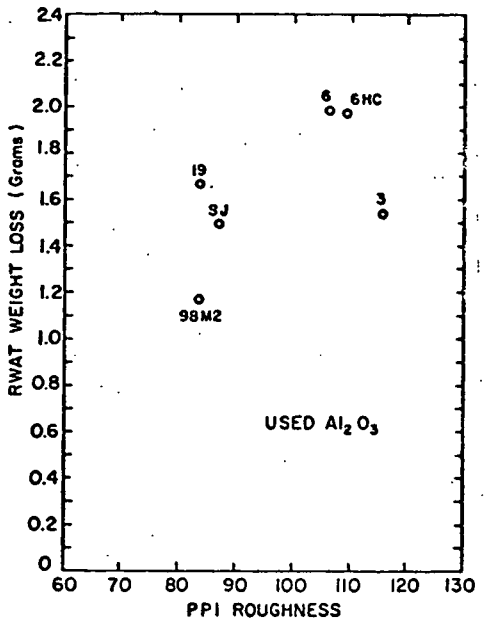


Figure 20. RWAT weight loss vs PPI microtopography. (Used $Al_2O_3$ - r not significant).

## 2.5 Task V - Analysis of Data

### 2.5.1 General Behavior of the Co-base PM Alloys

The GAWT, RWAT and microtopographic test data on the Co-base alloys may be summarized in five general statements:

1. GAWT weight loss decreases, in a very general sense, as hardness, carbon and alloy content increase.
2. Alloying appears to be an expensive and inefficient means of increasing gouging wear resistance.
3. RWAT weight loss decreases as hardness, carbon and alloy content increase. This general trend holds for unused and used $SiO_2$.
4. Hardness is an unsatisfactory parameter for characterizing the abrasive in a low-stress wear situation. The manner in which an abrasive degrades during a test may give insight to material attrition mechanism.
5. In low-stress abrasion, abrasion-resistant alloys are characterized by smoother wear scars.

These qualitative statements, especially the two regarding topography and target-abrasive interactions provide the basis for mechanistic studies of the wear process. The SEM program planned for the next quarter will involve study of both the wear scar and abrasive and should provide for the first time a coupling between the micro flow-fracture processes governing this form of wear and the macro wear data generated thus far.

### 2.5.2 Wear - Microstructure Correlations for the Co-base Alloys

A major object of the program is to use correlations between microstructure and wear to improve the understanding of wear. Although the analysis of the macroscopic wear data on the Co-base alloys is just beginning, several significant microstructural effects are evident.

The PM alloys comprise a family of increasing carbide fraction and increasing alloy (Cr + Ni + V + W) content. In Table IV are listed $R_c$ hardnesses, carbide volume fractions and total alloying element contents normalized to alloy #6, the least-alloyed, lowest-$v_f$ alloy. Since $v_f$ and alloy content cannot be varied

Table IV

Normalized Carbide $v_f$ and Alloy Content of PM Alloys

| Alloy | #6 | #19 | #6HC | #Star-J | #3 | #98MC |
|---|---|---|---|---|---|---|
| Hardness ($R_c$) | 45 | 51 | 49 | 59 | 57 | 63 |
| Normalized Carbide $v_f$ | 1.0 | 1.1 | 1.2 | 1.5 | 1.6 | 1.7 |
| Normalized Alloy Content | 1 | 1.7 | 1 | 2.6 | 2.0 | 3.5 |

independently in these commercial alloys, it is not possible to separate the respective contributions to alloy wear resistance. The difficulty is illustrated in Figures 21 through 24. When weight loss is polotted against either normalized $v_f$ or alloy content, similar functional dependencies are observed. For the unused and used $Al_2O_3$ (Figures 23 and 24), weight loss decreases linearly with increasing $v_f$ or alloy content.

Although the carbide and matrix effects may not be separated at this point, useful wear-structure generalizations are evident.

1. The similarity in the $v_f$ dependencies for gouging and low-stress abrasion against $SiO_2$ may indicate that similar material attrition mechanisms govern both situations.
2. For wear resistance against the softer $SiO_2$ abrasive, an optimum alloy content/$v_f$ exists. Alloying beyond this point is not only wasteful, it is counterproductive.

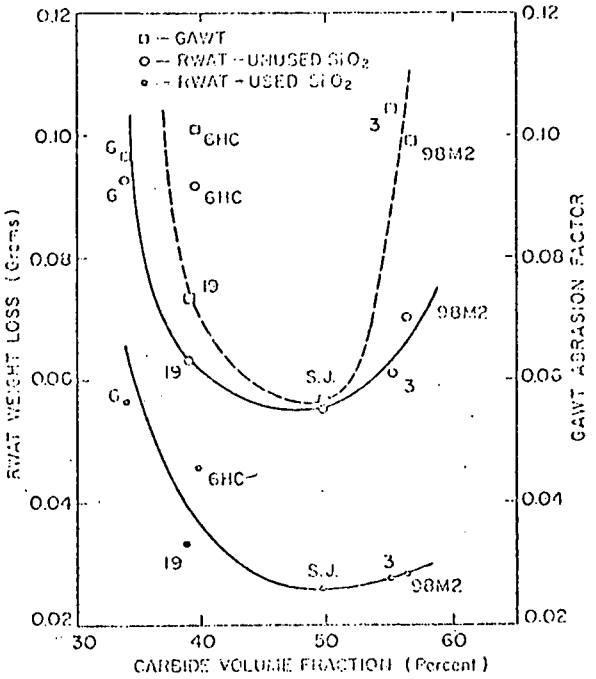


Figure 21. GAWT abrasion factor and RWAT weight loss (unused and used $SiO_2$) vs carbide $v_f$.

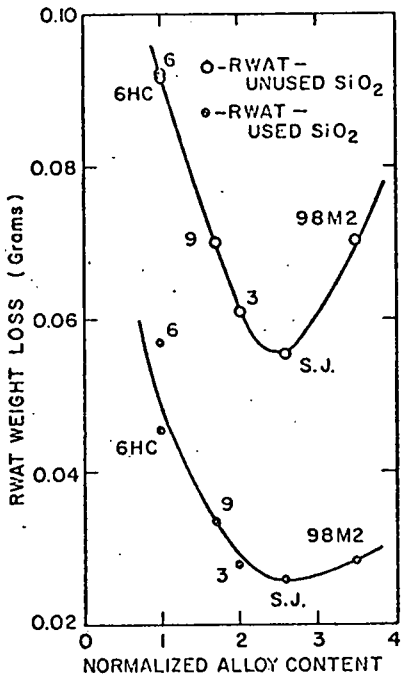


Figure 22. RWAT weight loss (unused and used $SiO_2$) vs normalized alloy content.

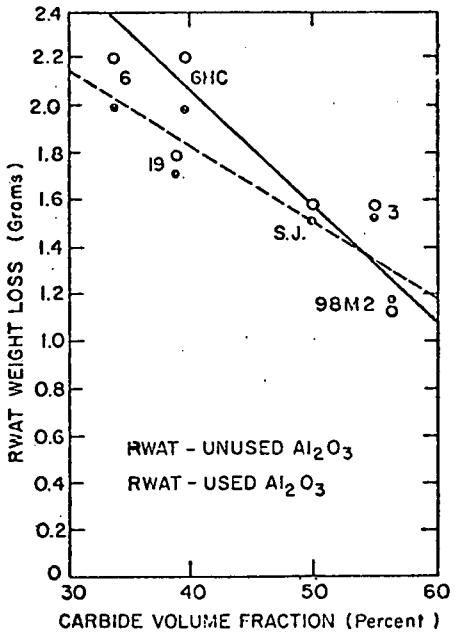


Figure 23. RWAT weight loss (unused and used $Al_2O_3$) vs carbide $v_f$.

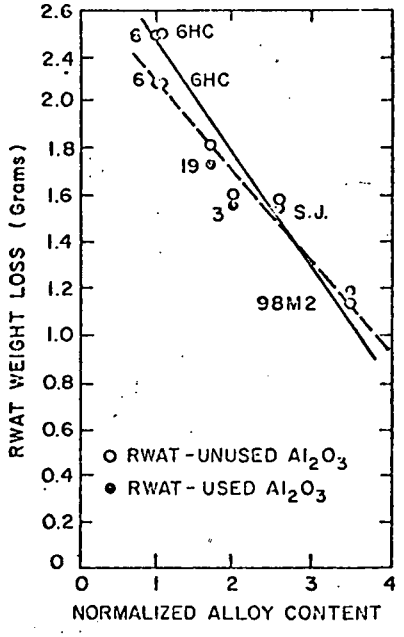


Figure 24. RWAT weight loss (unused and used $Al_2O_3$) vs normalized alloy content.

3. For wear resistance against the harder $Al_2O_3$ abrasive, increasing alloy content/$v_f$ is worthwhile.
4. In contrast to the results with 1020 steel, degradation of the $SiO_2$ causes a marked decrease in abrasiveness against the PM alloys, whereas degradation of the $Al_2O_3$ has little effect.

Tests have been proposed for a later phase of the project in which the effects of matrix alloy content and $v_f$ on wear may be separated.

## 3. SUMMARY

During this quarter, emphasis has been placed on the study of abrasive-alloy content-carbide $v_f$ interactions in low-stress abrasion of the PM alloys. The RWAT tests, followed by sieve analyses, indicate that both $SiO_2$ and $Al_2O_3$ abrasives degrade during the test. It appears that small changes in abrasive may bring about large changes in abrasiveness. Abrasive hardness is certainly not the only parameter governing wear, even in the low-stress case. SEM studies of the abrasive may provide insight as to which properties of the abrasive govern abrasiveness and which material attrition processes are operative during wear.

In a general way, target hardness is a usable indicator of wear resistance, although predictions based upon it may be in error by a factor of two or more.

The microtopography studies lead to the conclusion that more wear-resistant materials exhibit smoother wear scars. Before the topography data may be used to give insight to the wear process, the experimental procedure and computer analysis must be examined in conjunction with careful SEM studies of the wear scars.

Hardness of the PM alloys is not as satisfactory a gage of gouging wear resistance as it is of low-stress resistance. In either gouging wear or low-stress wear against $SiO_2$ optimum levels of alloying to increase matrix strength or $v_f$ exist. Exceeding the optimum values is counterproductive. For the case of low-

stress wear against $Al_2O_3$, wear resistance appears to increase in direct proportion to $v_f$.

## 4. PERSONNEL

The principal investigator, Dr. N. F. Fiore, and the co-principal investigator, Dr. T. Kosel, spent about one-third effort on the project during this summer quarter. The graduate research assistants, Mr. William Konkel and Mr. Stephen Udvardy, have devoted full-time to the work.

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Fig. 23. RWAT weight loss (unused and used $Al_2O_3$) vs carbide $v_f$.

Fig. 24. RWAT weight loss (unused and used $Al_2O_3$) vs normalized alloy content.

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