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INFLUENCE OF DIRECTION OF ROLLING ON WEAR OF ZINC

by

Maurice Georges Allion

A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
MASTER OF SCIENCE

Major Subject: Nuclear Engineering

Signatures have been redacted for privacy

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I. INTRODUCTION

In 1958, Imig (1), in his unpublished thesis for the Master of Science, reported his study of wear measured by radioactive tracer and differential weighing method. Imig used Armco iron as the radioactive wear material. This study will also be on metallic wear, but rolled zinc will be used, and in particular the effect of stresses and deformations produced by rolling will be investigated.

II. LITERATURE REVIEW

A new method of wear investigation has become possible in the last few decades with the development of radiotracer and radioisotope techniques. Before that, the conventional method, either by the change of weight of the specimen, the microscopic examination of the surface or the chemical analysis of the lubricant, was neither practical nor realistic. These methods were time consuming, costly, and did not duplicate operating conditions in the sense that normally the machine studied had to be torn apart, some of the parts extracted, tested and then replaced, which was quite different from what actually occured.

The first interested in wear research on an industrial scale were the automotive and aircraft factories. Wear is a slow and minute process. Shidle (2) estimated that when a five-ton truck has finally worn out, it has lost only five pounds of metal.

Several metals have already been used for the radioactive methods. These metals must fulfill certain conditions concerning their half-lives, their mode of decay and their own properties. Radiochromium was used successfully by Burwell and Murray (3). Kerridge (4) conducted tests with copper (Cu^{64}) with activity up to 400 millicuries and with silver (Ag^{III}).

Tests (5) were conducted using an internal combustion engine, first with a piston ring of Fe^{59} activated and then with piston rings containing inserts of zinc (Zn^{65}). For the latter tests the rings had been activated by pressing dowels of $radiozinc^{65}$ into them or by using electroplating to fill an annular groove 0.2 mm. in depth and 0.25 mm. in width.

Some metals have a relatively short decay like copper (12.8 hours) or silver (7.5 days). Some others have isotopes with short and long half-lives, like iron with Fe^{59} (46 days) and Fe^{55} (2.94 years), where the resultant half-life has to be determined experimentally because it can vary from the mathematically predicted value.

Although wear studies have been made on a large variety of materials, it does not seem that zinc has ever been considered, except under the form of initial survey by Hirst and Lancaster (6).

III. PURPOSE OF INVESTIGATION

Zinc was the metal chosen for this study. Pure zinc irradiated in a neutron flux becomes radioactive. Of the various isotopes formed which decay, only Zn^{65} has a sufficiently long half-life (245 days) to be useful. Zn^{69m}, the isotope with the second longest half-life (13.8 hours), does not have to be taken in consideration because of its too short half-life. Further, Zn^{65} decays with emission of gamma-rays of 1.11 Mev. energy.

The author wanted to investigate the effect of cold rolling on zinc, in particular its change of behavior, if any, in a wear study.

Moore (7) in an investigation of the properties of the strength of rolled zinc found that specimens cut across the grain (perpendicular to the direction of rolling) are somewhat stronger and stiffer than specimens cut with the grain (parallel to the direction of rolling).

At the beginning of this study the author planned to conduct tests both with inactive and active samples. Unfortunately the last part could not be achieved because of a temporary shut-down of the CP-5 reactor at Argonne National Laboratory in Chicago, Illinois.

It was impossible to schedule other reactors with a high enough level flux, on the order of 10^{13} neutrons/cm^2 x sec., within a reasonable period of time. For this reason, the study was limited to inactive tests and to a method of wear determination by weighing.

IV. ANALYSIS OF THEORETICAL CONSIDERATIONS

The variables considered in this study are listed below with their units, their symbols and their dimensions.

Symbol	Variable	Units	Dimensions
W	wear rate	gm./sec.	MT^{-1}
F	load	dyne	MLT^{-2}
V	velocity	cm./sec.	LT^{-1}
T	time	sec.	T
θ	temperature	deg. C	θ
Properties of the samples			
D	diameter	cm.	L
ρ_{Sa}	density	gm./cm.^{3}	ML^{-3}
h	heat of fusion	cal./gm.	L^2T^{-2}
C	specific heat	cal./gm.deg.C	$L^2T^{-2}\theta^{-1}$
k	thermal conductivity	cal./sec. cm.deg.C	$MLT^{-3}\theta^{-1}$
H_{Sa}	hardness of material	dyne/cm.^{2}	$ML^{-1}T^{-2}$
π_{12}	initial roughness of the sample		0
π_{13}	crystal structure of the sample		0

Symbol	Variable	Units	Dimensions
	Properties of the cast-iron disk surface		
H_{Su}	hardness of disk	dyne/cm.^{2}	$ML^{-1}T^{-2}$
π_{15}	initial roughness of the surface		0
π_{16}	crystal structure of the surface		0
	Properties of the lubricant		
ρ_L	density	gm./cm.^{3}	ML^{-3}
μ	viscosity	gm./sec.cm.	$ML^{-1}T^{-1}$
π_{19}	geometry factor		0

Of these 19 variables, 14 can be expressed in terms of the four fundamental dimensions, mass (M), length (L), time (T) and temperature (θ). The five remaining variables are dimensionless. An equation with $19 - 4 = 15$ dimensionless Pi terms can be written for each sample. In this investigation the only variables considered were wear rate, load, and velocity. The only difference between the samples was the crystal structure π_{13}.

For runs with the same load and speeds, the wear rate difference between samples will only be due to the change in π_{13}, which may be expressed as $W = \phi(\pi_{13})$.

V. EXPERIMENTAL INVESTIGATION

A. Description of the Apparatus

The apparatus was essentially the same as the one used by Imig (1) for his thesis "Wear of Armco Iron Measured by Radioactive Tracer and Differential Weighing Methods". However, this apparatus was altered in an attempt to improve its performance. According to Imig (1), the two main causes of trouble were:

(1) Difficulty in measuring the frictional force

(2) Difficulty in keeping the flow rate of the lubricant constant.

Imig pointed out another source of trouble which he believed responsible for some inconsistent results in his tests. This was the change in the angle of contact between the sample and sliding surface during a test, or from test to test.

The apparatus shown on the photograph of Figure 1 and on Figure 2 consisted of a rotating cast iron disk on which the sample being tested rode. The apparatus was designed to allow variation of both load and sliding velocity.

The principle of measurement of the frictional force was kept the same, but the total weight of the indicator arm was decreased. The distance between the axis of

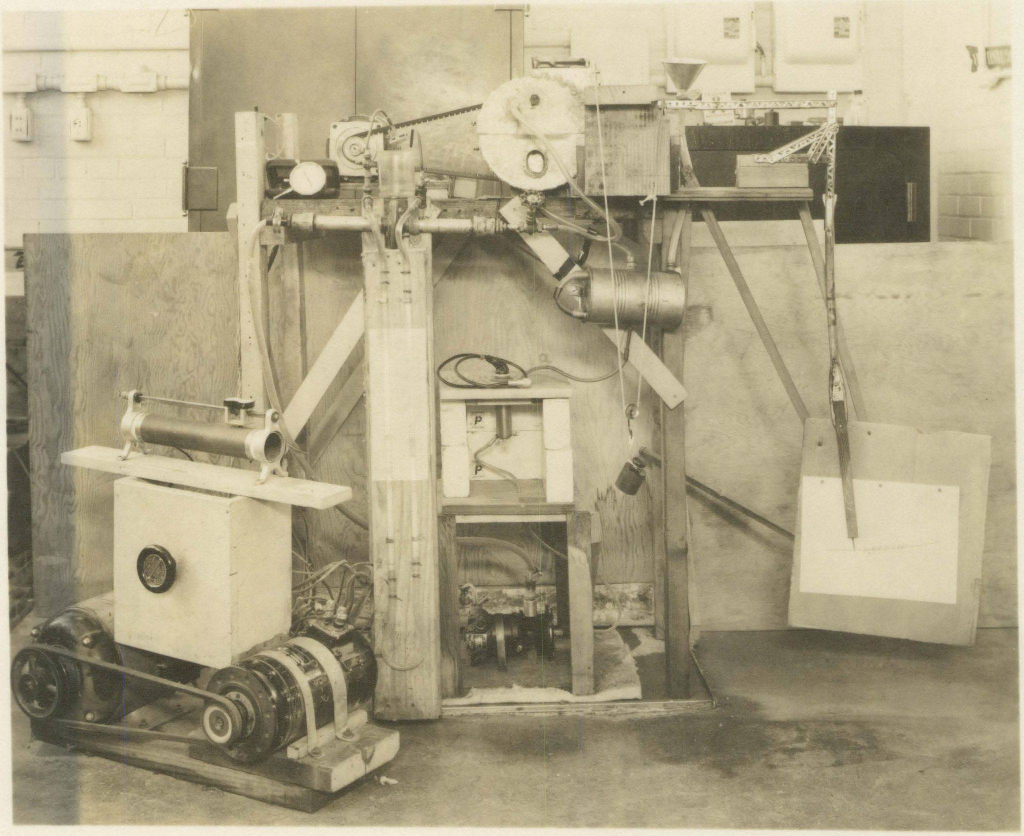

Figure 1. Photograph of the apparatus

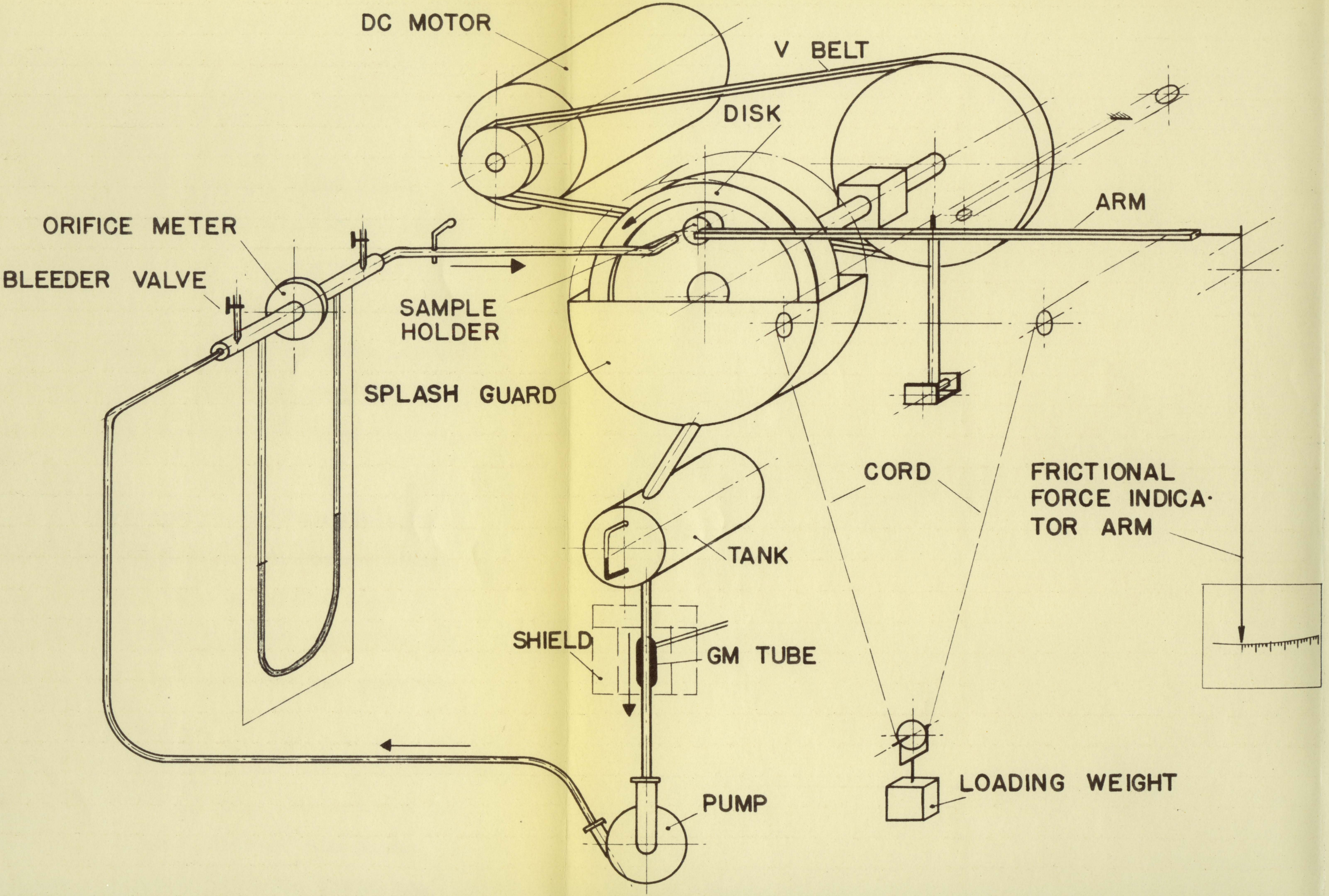

FIG. 2 APPARATUS

rotation of this indicator arm and the point where the horizontal arm was connected was also decreased. These two changes increased the angle of rotation of the indicator arm for a given friction force, increasing the sensitivity by a factor of about 2.

The lubrication circuit was redesigned. The fluid drained from the lower splash guard into a tank which acted as a reservoir. A level indicator made it possible to check the amount of fluid in the tank at any time. One of the purposes of this tank was to ensure that the GM tube located below was always full of fluid which was necessary for its geometry to remain constant. For all runs the tank was kept half-full.

From the tank the fluid passed through the double wall GM tube which was shielded by lead bricks two inches thick.

At the bottom of the apparatus the fluid was pumped up through an orifice meter, then through a valve and finally directed against the face of the disk close to the position of the sample.

The orifice meter was added to make possible the measurement of the flow rate of fluid circulating. The orifice itself was 1/8 in. in diameter. On each side of the plate having the orifice there was a bleeder valve to bleed the air which otherwise would stay trapped giving inconsistent results. The U-shaped glass tubing was half-full of water.

Kerosene was the fluid used as the lubricant for all the tests conducted in this study. The slight difference of density combined with the non-miscibility of water and kerosene gave good sensitivity.

A calibration curve of the orifice meter was taken. Results are shown in Table 1. From the experimental data an average constant a = 154.6 was obtained which was used to compute a theoretical curve. Experimental and theoretical curves are plotted in Figure 3 as flow rate versus difference of pressure. The curves are similar. A difference of pressure of 20 mm. of water giving a flow rate of 360 gm./min. was chosen for all the tests and no attempt was made to study the correlation between wear and flow rate.

B. Description of the Samples

The samples used in the tests came from a plate of rolled zinc 7/16 in. thick. Two samples, each 1/8 in. in diameter and 5/8 in. long, were used. One was machined with the longitudinal axis parallel and the other perpendicular to the direction of rolling, both in the same plane which was located at the half-thickness of the plate.

Hereafter the samples will be referred to as:

Specimen A: The sample parallel to the
direction of rolling

Table 1. Data for the orifice meter

Run	Period of time min.	ΔH mm.	W gm.	Flow rate Q gm./min.	Q^2 kg.^{2}/min.^{2}	Constant $a=\Delta H/Q^2$	Theoretical flow rate kg./min.
1	2	2	132	66	0.0174	(115)[a]	0.114
2	1.5	9	408	272	0.167	(54)	0.232
3	1	16	330	330	0.109	147.0	0.322
4	1	39	496	496	0.246	158.5	0.503
5	1	46	528	528	0.280	164.0	0.546
6	1	118	845	845	0.713	165.8	0.875
7	1	59	605	605	0.366	158.5	0.618
8	1	18	340	340	0.116	155.0	0.342
9	1	72	660	660	0.446	161.5	0.683
10	1	26	441	441	0.195	133.0	0.411
11	1	27	430	430	0.185	146.0	0.418
12	1	47	548	548	0.300	157.0	0.551
						1546.3	

[a]average = 154.6

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[a] Run 1 and 2 are discarded for the computation of the constant a.

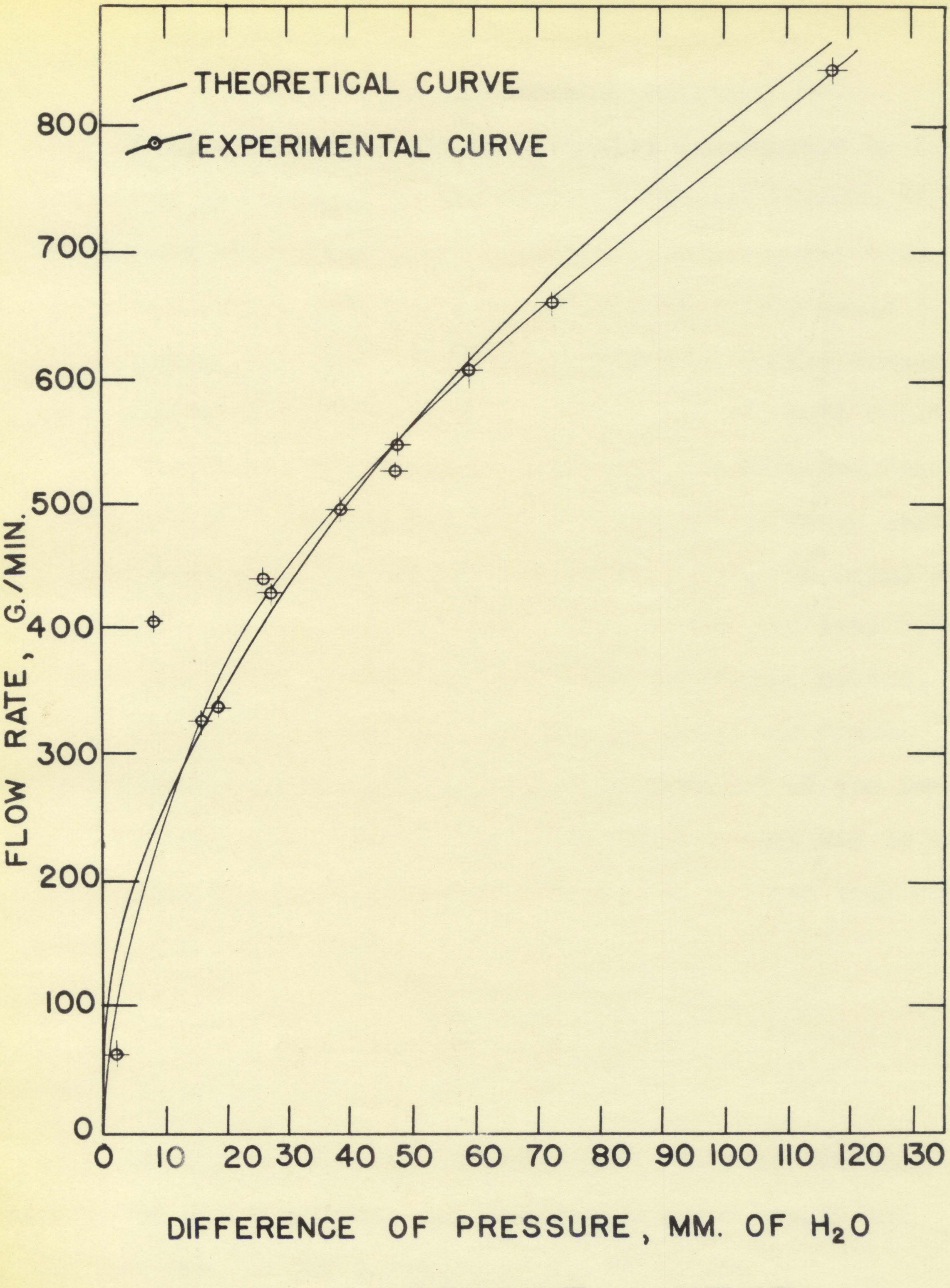


Fig. 3 ORIFICE METER

Specimen B: The sample perpendicular to
the direction of rolling.

In an effort to avoid the troubles encountered by Imig caused by the changes in the angle of contact between the sample and sliding surface, a rectangular notch was made in the extremety of each specimen. These specimens could fit in a hole of the sample holder. The sample holder consisted of a cylindrical piece of steel with a 1/8 in. hole drilled along its longitudinal axis. This hole was threaded for the first 3/4 in. from one end, for a screw with a tenon which fitted into the notch of the specimens. A dot of paint was placed on the specimen to ensure that it had the same orientation each time it was inserted into the sample holder. Thus, the specimen was held and its position was fixed.

Moreover, the screw allowed an adjustment of the length of specimen coming out of the hole. This length had to be kept small because experience proved that one too long would bend under large loads.

C. Variables Considered

Speeds from 300 rpm. to 1500 rpm. could be obtained by means of two rheostats, one for the DC power supply and another one for the armature of the DC motor.

The cast-iron disk was driven by the DC motor by means of a V-belt drive which gave a reduction factor of 3.6. The distance between the specimen and axis of rotation was 1 7/8 in. The linear velocity of any point of the disk coming in contact with the specimen was 11.78 in./min./rpm. of the disk. The ratio between motor speed and linear frictional velocity was 3.27 in./min./rpm. of the motor. Hence, the linear velocity varied from 982 in./min. to 4910 in./min.

Three loads were used, 500 gm., 1000 gm., and 1500 gm. A load of 500 gm. was the smallest one which would give an easily detectable amount of wear for a run of 30 min. A load of 1500 gm. was the largest one which could be used without producing plastic deformation of the specimen, specially at high speeds.

The loads were suspended by a block and a pulley running on the cord so that the weight of the load was equally distributed between the two cords.

VI. TESTS CONDUCTED AND RESULTS

A. Break In for Lubricated Tests

A series of runs was taken to see how the break in occured between the zinc specimen and the cast-iron disk when no lubrication is provided. Loads of 500 gm. and 1000 gm. were used while the speed was varied from 300 rpm. to 1500 rpm. by increments of 300 rpm.

The same runs were taken for both specimens. Regardless of the length of the run, readings of the speed of the motor, the frictional force and the difference of pressure were taken every five minutes. After each reading, the motor speed and the difference of pressure were corrected, if necessary, and their values averaged to get final data. The specimens were cleaned with carbon tetrachloride and dried before each weighing.

Results of these tests for the two loads are shown in Tables 2 and 3 and plotted as wear versus time in Figures 4 and 5.

For the 500 gm. load, the amount of wear was of the order of 0.05 mg./run which was about the smallest difference of weight measurable on the four-place chainomatic balance used in all the tests. For the 500 gm. load, the wear for specimen A became constant after 5 minutes at the

Table 2. Results of dry tests showing break in

Run	Period of time min.	Load gm.	Speed rpm.	Frictional force gm.	Initial weight mg.	Final weight mg.	Loss mg.	Cumulative loss mg.
				Specimen A				
1	20	500	302	68	839.18	839.15	0.04	0.04
2	20	500	298	70	839.15	839.10	0.05	0.09
3	20	500	300	75	839.10	839.05	0.05	0.15
4	20	500	299	80	839.05	839.00	0.05	0.19
5	20	500	301	77	839.00	839.95	0.05	0.23
6	20	1000	305	140	838.95	838.60	0.35	0.35
7	20	1000	304	255	838.60	837.90	0.70	1.05
8	20	1000	310	235	837.90	836.85	1.05	2.10
9	20	1000	302	260	836.85	835.70	1.15	3.25
10	20	1000	307	240	835.70	834.40	1.30	4.55
11	20	1000	301	240	834.40	833.15	1.25	5.80

Table 3. Results of dry tests showing break in

Run	Period of time min.	Load gm.	Speed rpm.	Frictional force gm.	Initial weight mg.	Final weight mg.	Loss mg.	Cumulative loss mg.
				Specimen B				
1	20	1000	300	165	834.15	833.35	0.80	0.80
2	20	1000	304	195	833.35	832.60	0.75	1.55
3	20	1000	298	260	832.60	831.95	0.65	2.20
4	20	1000	315	295	831.95	831.20	0.75	2.95
5	20	1000	310	290	831.20	830.50	0.70	3.65
6[a]	20	500	300	80	830.75	830.70	0.05	0.05
7	20	500	296	95	830.70	830.67	0.03	0.08
8	20	500	290	100	830.67	830.48	0.19	0.27
9	20	500	310	115	830.48	830.20	0.28	0.55
10	20	500	295	90	830.20	830.05	0.15	0.70

[a] Between run 5 and 6 somebody used the balance which explains the difference of weight.

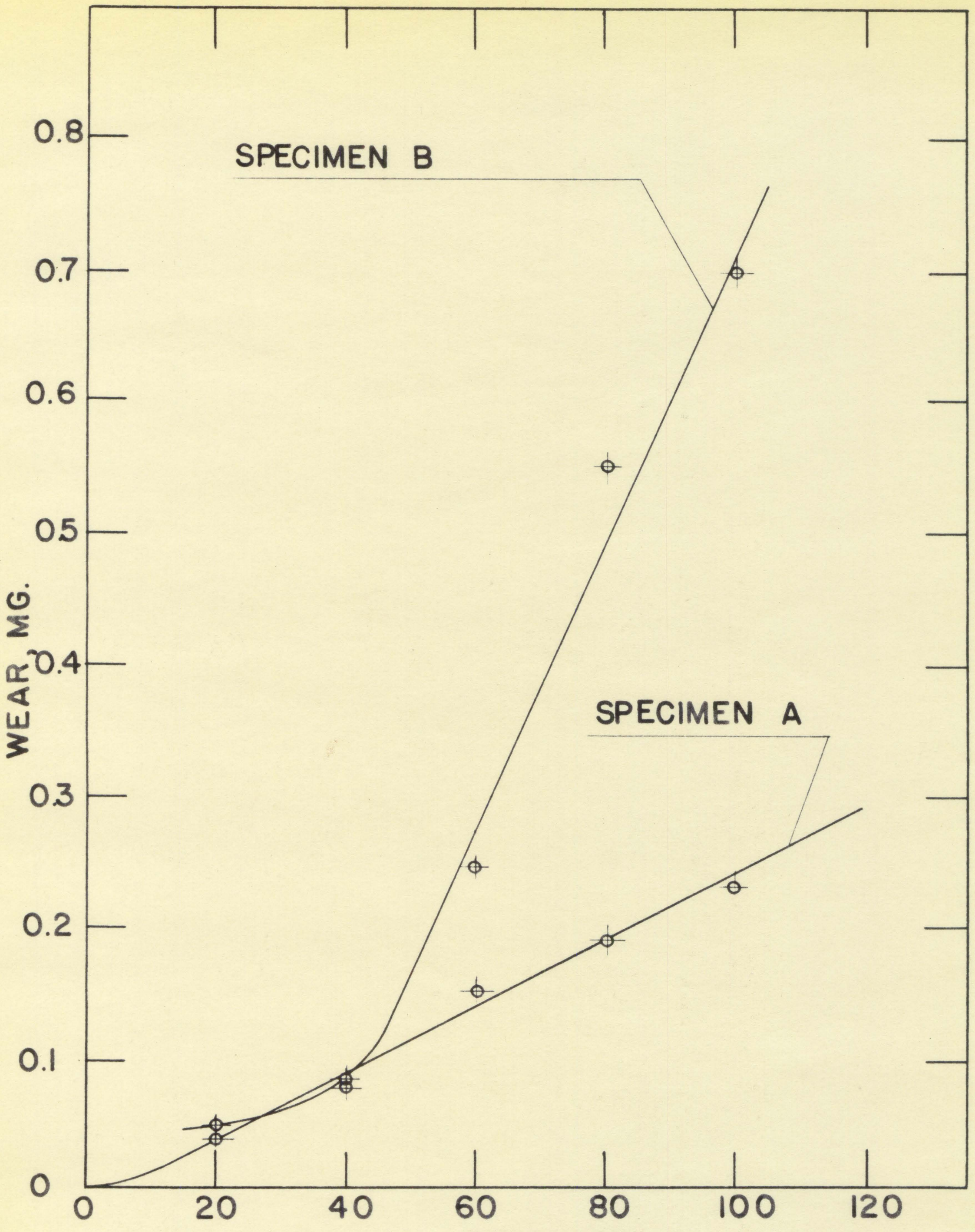


FIG. 4 BREAK IN WEAR OF UNLUBRICATED TESTS 500 G. LOAD

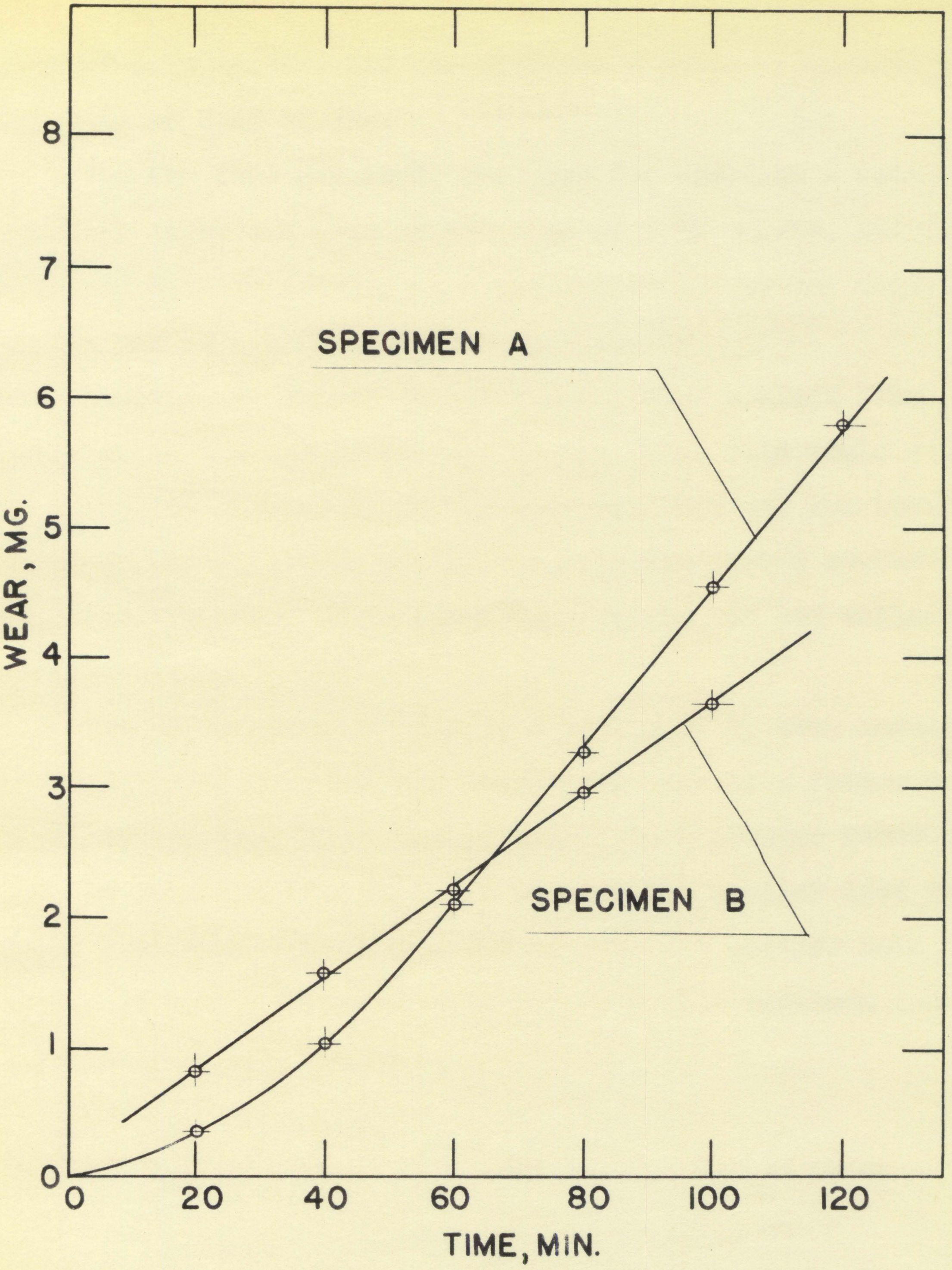


FIG. 5 BREAK IN WEAR
OF UNLUBRICATED TESTS
1000 G. LOAD

rate of 0.15 mg./hr. and for specimen B after 45 minutes at the rate of 0.65 mg./hr.

For the 1000 gm. load, the wear for specimen A became constant after one hour at the rate of 3.67 mg./hr. and for specimen B it apparently remained constant from the beginning of the run at the rate of 2.15 mg./hr.

However, it should be pointed out that a black film built up on the end of the specimens. This film could only be partially removed by carbon tetrachloride and was assumed to be graphite, either coming out from the carbon content of the cast-iron disk or in suspension in the air and collecting on the disk.

For an increase of load by a factor of 2, wear increased by a factor of 24.2 for specimen A and only by a factor of 3.31 for specimen B. However, there was a greater tendency for the graphite film to build up with the smaller load which might have been responsible for an apparent smaller rate of wear. It can be inferred from Figure 5 that specimen A wore out faster than specimen B.

B. Series A Tests with Variable Speeds and Loads

Three series of tests were conducted to check the reproducibility of the results obtained. The lubricant used was kerosene with a constant flow rate of 360 gm./min.

The first run for each specimen was made with the 1000 gm. load, then with the 500 gm. load and finally with the 1500 gm. load. Each time there was a change in load, the specimen was filed off in order to remove the eventual feather edges and two runs were taken, at the same speed of 300 rpm., to ensure complete break in and therefore constant wear rate. If the wear rate proved to be constant for these two runs the author proceeded with the experiment.

Results are shown in Tables 4, 5, and 6 and plotted in Figures 6, 7, and 8 as wear rate versus motor shaft speed.

For the 1000 gm. load, the wear appeared to be about 0.15 mg./hr. more for specimen B than for specimen A, this value being fairly constant over the speed range.

For the 500 gm. load, the wear was greater for specimen A than for specimen B, the difference being around 0.45 mg./hr.

For the 1500 gm. load, the two curves crossed each other at 900 rpm. Above 900 rpm. the wear was larger for specimen A than for specimen B by 0.50 mg./hr.

By comparing the three curves it is seen that the slope increased the most rapidly with the speed for the 1500 gm. load curves. This could come from the high load and high speed but might be accentuated by a built-up of small particles on the wear path of the disk, because it is admitted that the wear is always more severe between surfaces of same

Table 4. Series A

Results of lubricated tests for a load of 1000 gm. with different speeds

Run	Period of time min.	Load gm.	Speed rpm.	Frictional force gm.	Initial weight mg.	Final weight mg.	Loss mg.	Wear rate mg./hr.
				Specimen A				
1	30	1000	296	95	827.05	825.90	1.15	2.30
2	30	1000	300	85	825.90	824.80	1.10	2.20
3	30	1000	602	75	823.30	821.10	2.20	4.40
4	30	1000	905	75	821.10	817.25	3.85	7.70
5	15	1000	1197	80	817.25	814.85	2.40	9.60
6	20	1000	1512	75	814.85	811.05	3.80	11.40
				Specimen B				
7	30	1000	310	75	828.55	827.20	1.35	2.70
8	30	1000	298	80	827.20	balance out of adjustment		
9	30	1000	301	80	826.70	825.40	1.30	2.60
10	30	1000	599	82	825.40	823.00	2.40	4.80
11	30	1000	901	80	823.00	819.00	4.00	8.00
12	20	1000	1196	80	819.00	815.90	3.10	9.30
13	20	1000	1504	78	815.90	811.95	3.95	11.85

Table 5. Series A

Results of lubricated tests for a load of 500 gm. with different speeds

Run	Period of time min.	Load gm.	Speed rpm.	Frictional force gm.	Initial weight mg.	Final weight mg.	Loss mg.	Wear rate mg./hr.
				Specimen A				
1	30	500	301	48	803.40	802.80	0.60	1.20
2	30	500	305	45	802.80	802.05	0.75	1.50
3	30	500	607	40	802.05	801.00	1.05	2.10
4[a]	30	500	909	45	801.00	799.15	1.85	3.70
5	30	500	1209	45	799.20	797.10	2.10	4.20
6	30	500	1505	40	797.10	794.10	3.00	6.00
				Specimen B				
7	30	500	302	40	802.95	802.10	0.85	1.70
8	30	500	603	42	802.10	801.20	0.90	1.80
9[b]	30	500	904	30	776.45	775.40	1.05	break in
10	30	500	901	32	775.40	773.85	1.55	3.10
11	30	500	1199	34	773.85	771.45	2.40	4.80
12	32	500	1505	38	771.45	768.45	3.00	5.60

[a] Between run 4 and 5 there is a difference of weight coming from the change on the balance from 0.8 to 0.7 g.

[b] Edges filed off at the beginning of this run.

Table 6. Series A

Results of lubricated tests for a load of 1500 gm. with different speeds

Run	Period of time min.	Load gm.	Speed rpm.	Frictional force gm.	Initial weight mg.	Final weight mg.	Loss mg.	Wear rate mg./hr.
				Specimen A				
1	20	1500	303	135	728.70	727.50	1.20	3.60
2	20	1500	305	130	727.50	726.30	1.20	3.60
3	20	1500	604	110	726.30	723.85	2.45	7.35
4	20	1500	906	115	723.85	721.10	2.75	8.25
5	21	1500	1203	120	721.10	716.10	5.00	14.30
6	15	1500	1504	155	716.10	699.15	6.95	27.80
				Specimen B				
7	20	1500	302	118	722.45	720.85	1.60	4.80
8	20	1500	300	95	720.85	719.35	1.50	4.50
9	20	1500	601	98	719.35	716.70	2.65	7.95
10	20	1500	903	100	716.70	713.95	2.75	8.25
11	20	1500	1207	115	713.95	709.75	4.20	12.60
12	15	1500	1500	165	709.75	703.55	6.20	24.80

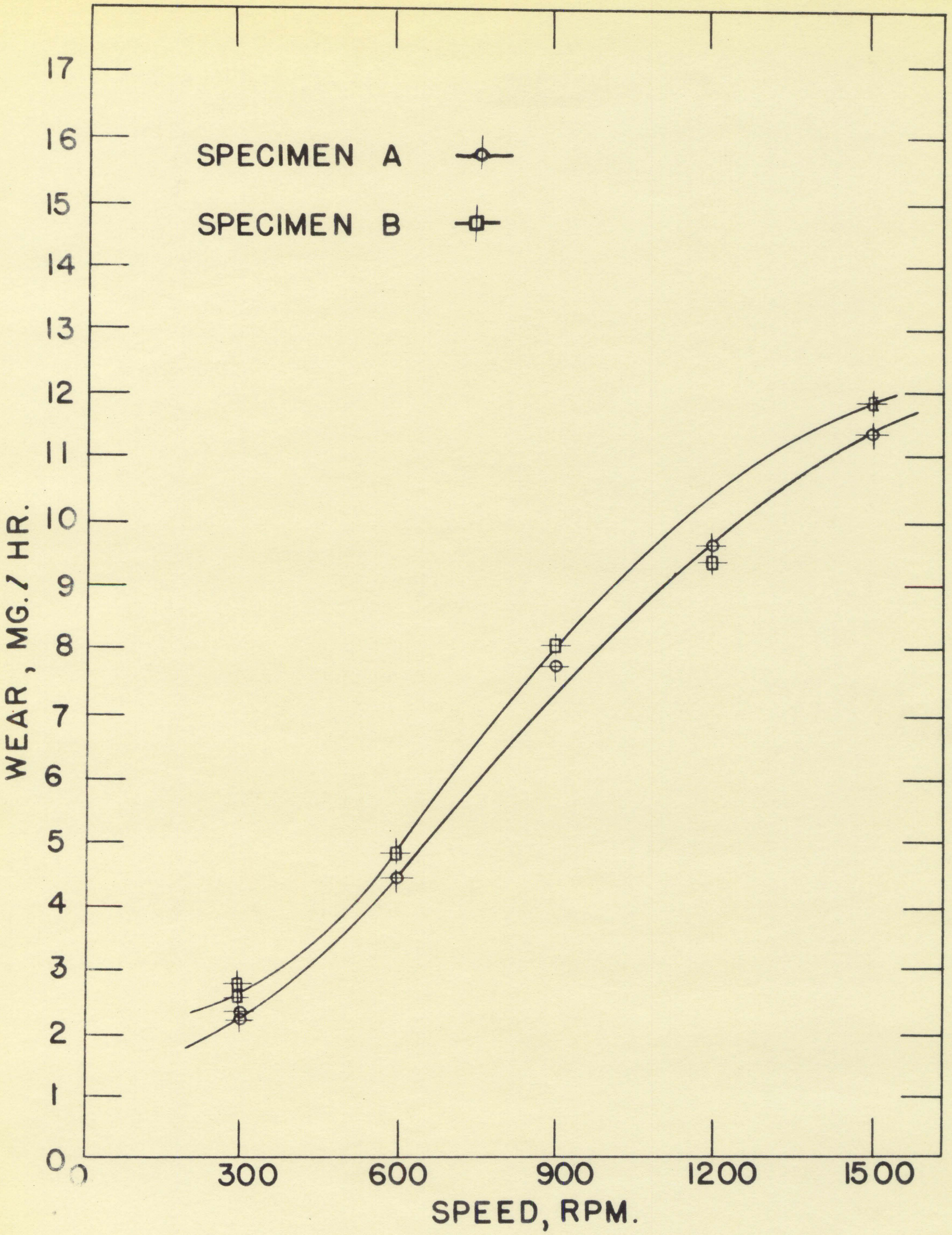


Fig. 6 WEAR VS. SPEED
SERIES A - 1000 G. LOAD

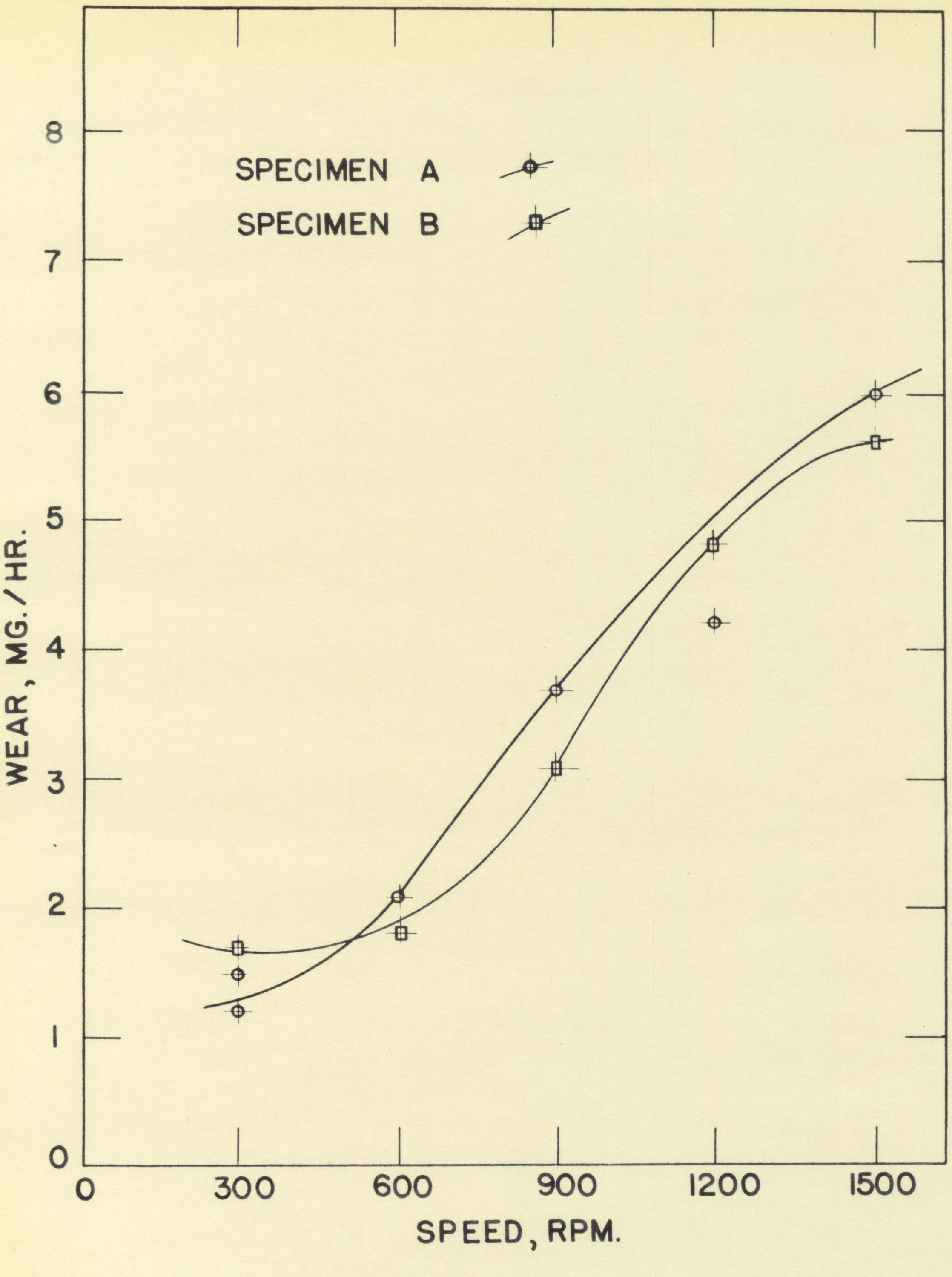


FIG. 7 WEAR VS. SPEED
SERIES A - 500 G. LOAD

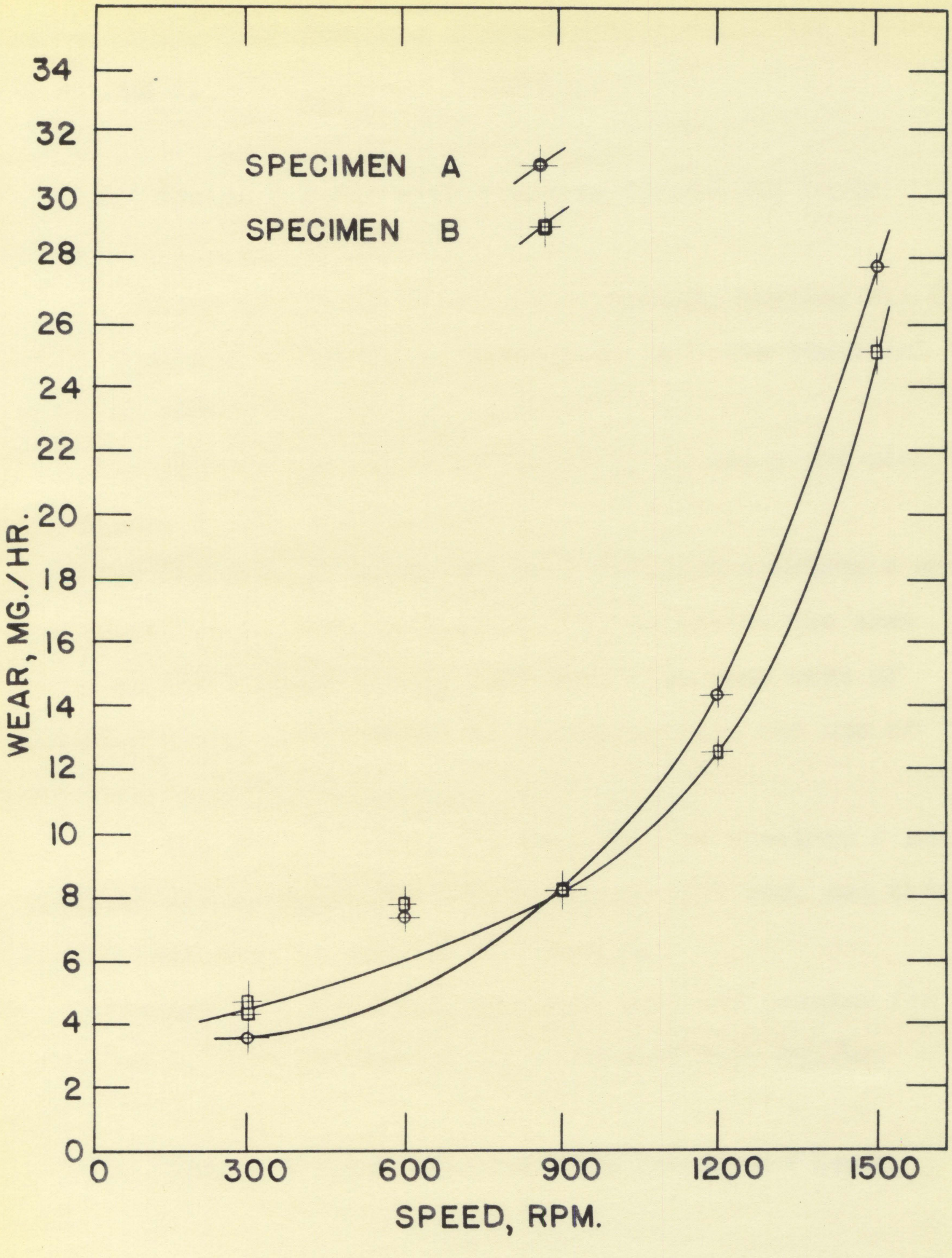


Fig. 8 WEAR VS. SPEED
SERIES A - 1500 G. LOAD

composition. The disk was cleaned only between the series A, B, and C.

C. Series B Tests with Variable Speeds and Loads

A second series of tests was conducted, keeping all the conditions and variables as closely as possible identical to those of series A.

The results are shown in Tables 7, 8, and 9 and plotted in Figures 9, 10, and 11.

For the 100 gm. load, the wear rates of specimen A and B differed by as much as 3.60 mg./hr. to become the same value at the highest speed, 1500 rpm. The wear rate of specimen A was always equal to or larger than the one of specimen B.

For the 500 gm. load, the wear rate of specimen A was slightly larger until the speed reached 1100 rpm. and then became less than it was for specimen B.

For the 1500 gm. load, the wear rate was greater for specimen B, with an average difference of 0.30 mg./hr.

D. Series C Tests with Variable Speeds and Loads

The same procedure as was followed on series A and B was used for a third series. The results are shown in

Table 7. Series B

Results of lubricated tests for a load of 1000 gm. with different speeds

Run	Period of time min.	Load gm.	Speed rpm.	Frictional force gm.	Initial weight mg.	Final weight mg.	Loss mg.	Wear rate mg./hr.
				Specimen A				
1	32	1000	302	75	786.60	785.00	1.60	3.00
2	30	1000	604	75	785.00	781.00	4.00	8.00
3	30	1000	898	70	781.00	777.10	3.90	7.80
4[a]	30	1000	600	75	777.10	774.90	2.20	4.40
5	30	1000	1204	60	774.90	770.75	4.15	8.30
6	30	1000	1500	65	770.75	765.80	4.95	9.90
				Specimen B				
7	30	1000	305	50	759.80	758.65	1.15	2.30
8	30	1000	302	55	758.65	757.55	1.10	2.20
9	33	1000	603	60	757.55	756.10	1.45	2.64
10	30	1000	900	55	756.10	754.40	1.70	3.40
11	30	1000	901	52	754.40	752.80	1.60	3.20
12	30	1000	1201	62	752.80	750.45	2.35	4.70
13	30	1000	1504	65	750.45	745.55	4.90	9.80

[a] Run 4 was to check again the high value of run 2. It is assumed that a feather edge broke off during run 2.

Table 8. Series B

Results of lubricated tests for a load of 500 gm. with different speeds

Run	Period of time min.	Load gm.	Speed rpm.	Frictional force gm.	Initial weight mg.	Final weight mg.	Loss mg.	Wear rate mg./hr.
Specimen A								
1	30	500	301	50	746.10	745.40	0.70	1.40
2	30	500	303	48	745.40	744.75	0.65	1.30
3	30	500	605	40	744.75	743.85	0.90	1.80
4	30	500	904	35	743.85	742.40	1.45	2.90
5	30	500	1198	34	742.40	739.70	2.70	5.40
6	30	500	1502	28	739.70	737.40	2.30	4.60
Specimen B								
7	30	500	304	28	735.80	735.25	0.55	1.10
8	30	500	305	26	735.25	734.75	0.50	1.00
9	30	500	602	25	734.75	733.90	0.85	1.70
10	30	500	904	27	733.90	732.60	1.30	2.60
11	30	500	1201	26	732.60	730.45	2.15	4.30
12	30	500	1503		730.45	728.10	2.35	4.70

Table 9. Series B

Results of lubricated tests for a load of 1500 gm. with different speeds

Run	Period of time min.	Load gm.	Speed rpm.	Frictional force gm.	Initial weight mg.	Final weight mg.	Loss mg.	Wear rate mg./hr.
				Specimen A				
1	20	1500	302	155	684.20	682.40	1.80	5.40
2	25	1500	304	160	682.40	679.90	2.50	6.00
3	30	1500	604	125	679.90	675.80	4.10	8.20
4	20	1500	903	130	675.80	672.90	2.90	8.70
5	20	1500	1202	135	672.90	667.50	5.40	16.20
6	15	1500	1499	145	667.50	660.30	7.20	28.80
				Specimen B				
7	20	1500	303	130	676.85	675.25	4.80	4.80
8	20	1500	304	130	675.25	673.90	4.05	4.05
9	20	1500	600	125	673.90	671.10	8.40	8.40
10	20	1500	900	130	671.10	668.25	8.55	8.55
11	20	1500	1203	105	668.25	662.70	16.65	16.65
12	15	1500	1503	130	662.70	652.85	30.40	30.40

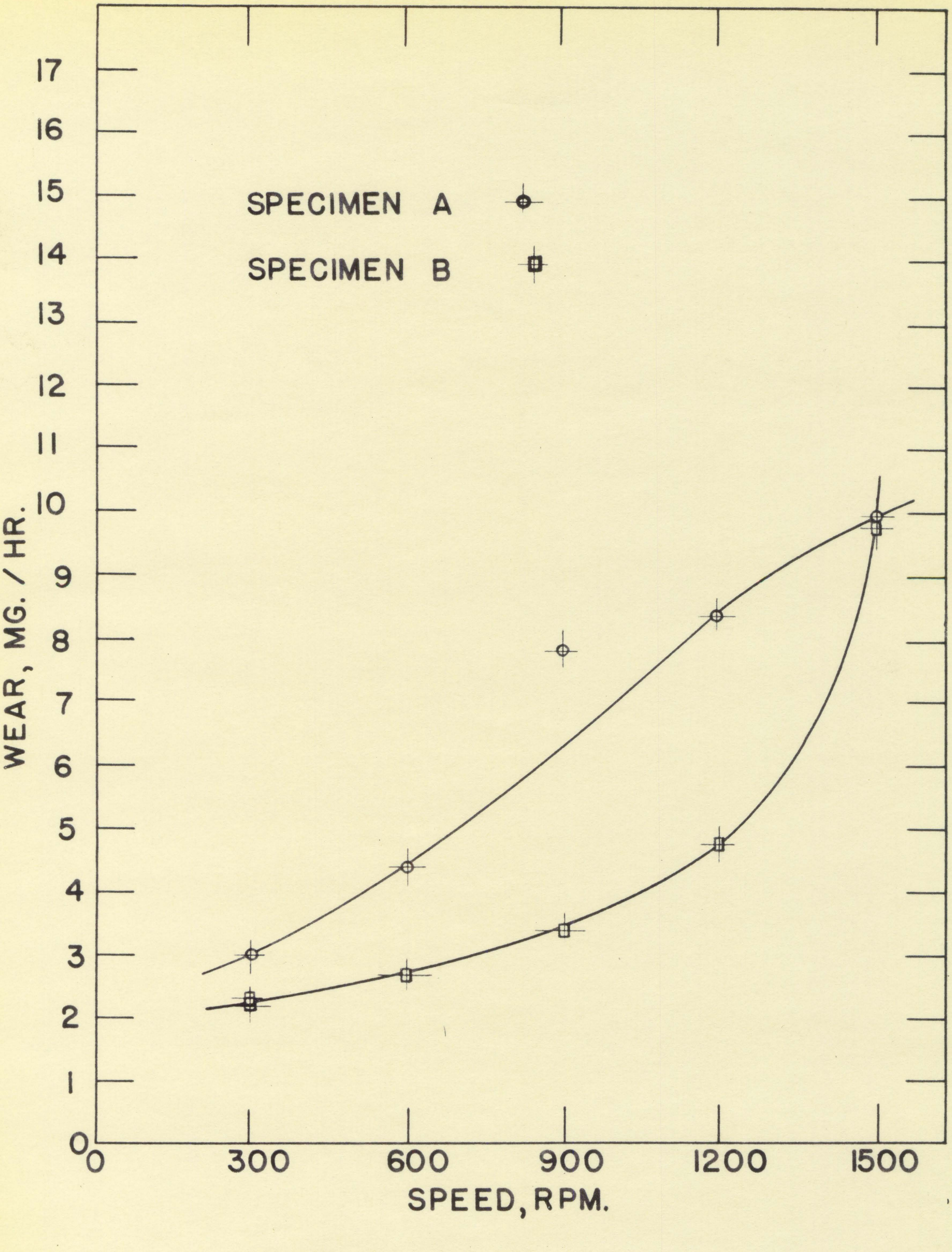


FIG. 9 WEAR VS. SPEED
SERIES B - 1000 G. LOAD

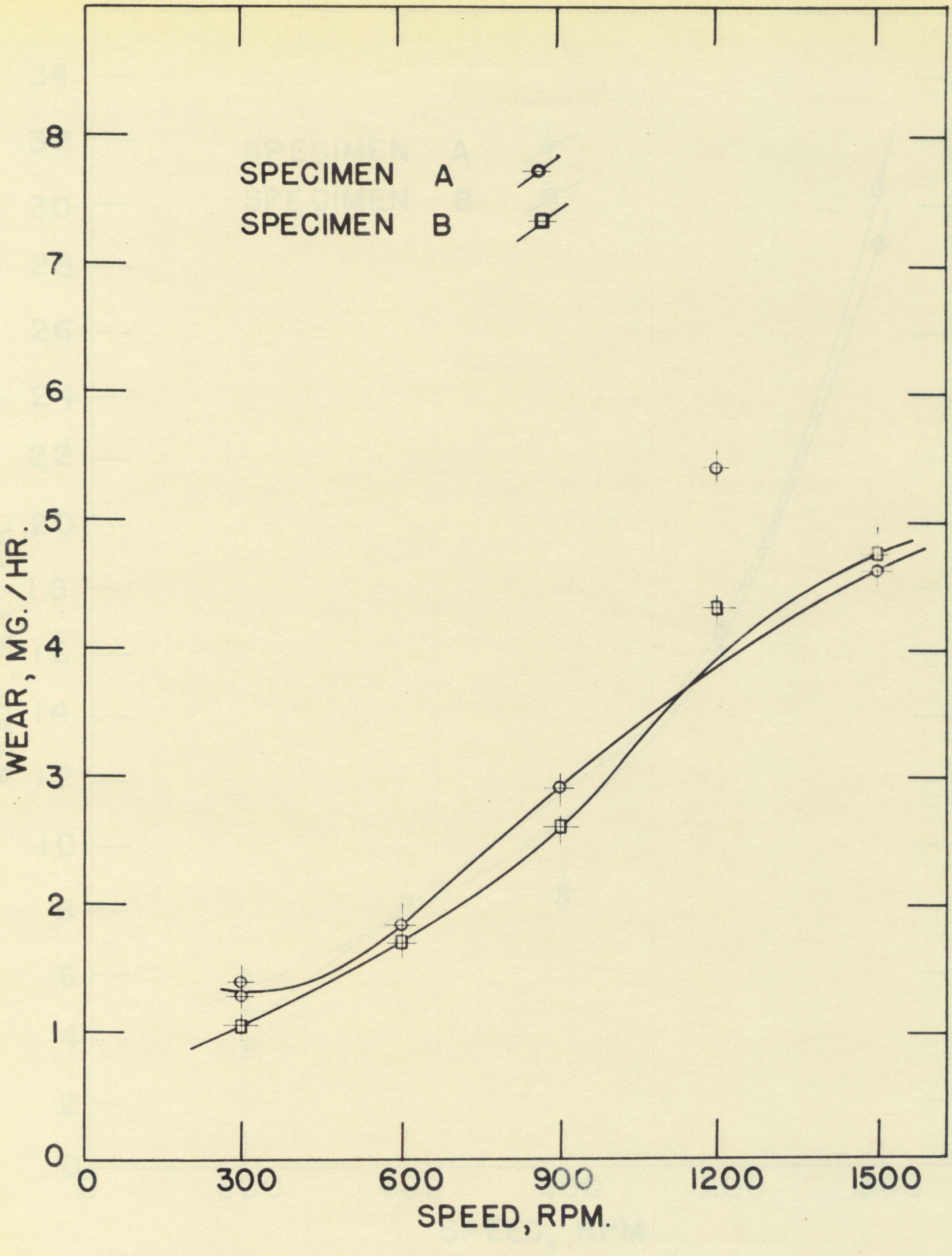


FIG. 10 WEAR VS. SPEED
SERIES B - 500 G. LOAD

Tables 10, 11, and 12 and plotted in Figures 12, 13, and 14.

For the 1000 gm. load, the wear rate of specimen A was larger, except at the highest speed. The difference was approximately 1.10 mg./hr.

For the 500 gm. load, due to the fact that the wear rate was relatively small, the results were not so reliable. Around 350 rpm., 1200 rpm., and 1400 rpm. the wear was apparently the same for the two specimens. But between 350 rpm. and 1200 rpm. the wear rate was larger for specimen A.

For the 1500 gm. load, the wear rate for both specimens increased very much above 900 rpm. Specimen B had a larger wear rate which was 11.4 mg./hr. more at 1200 rpm.

Table 10. Series C

Results of lubricated tests for a load of 1000 gm. with different speeds

Run	Period of time min.	Load gm.	Speed rpm.	Frictional force gm.	Initial weight mg.	Final weight mg.	Loss mg.	Wear rate mg./hr.
Specimen A								
1	30	1000	301	85	643.80	642.35	1.45	2.90
2	30	1000	303	90	642.35	640.70	1.65	3.30
3	30	1000	602	80	640.70	638.45	2.25	4.50
4	30	1000	904	75	638.45	635.80	2.65	5.30
5	30	1000	1201	78	635.80	631.50	4.30	8.60
6	30	1000	1503	70	631.50	625.95	5.55	11.10
Specimen B								
7	30	1000	303	85	638.35	636.95	1.40	2.80
8	30	1000	304	85	636.95	635.40	1.55	3.10
9	30	1000	601	80	635.40	633.10	2.30	4.60
10	30	1000	902	78	633.10	630.25	2.85	5.70
11	30	1000	1203	70	630.25	626.50	3.75	7.50
12	30	1000	1504		626.50	620.35	6.15	12.30

Table 11. Series C

Results of lubricated tests for a load of 500 gm. with different speeds

Run	Period of time min.	Load gm.	Speed rpm.	Frictional force gm.	Initial weight mg.	Final weight mg.	Loss mg.	Wear rate mg./hr.
				Specimen A				
1	30	500	303	35	611.80	610.80	1.00	2.00
2	30	500	306	35	610.80	609.80	1.00	2.00
3	35	500	607	38	609.80	608.10	1.70	2.90
4	30	500	904	30	608.10	606.40	1.70	3.40
5	30	500	1205	30	606.40	604.50	1.90	3.80
6	30	500	1505	32	604.50	602.30	2.20	4.40
				Specimen B				
7	30	500	307	28	608.40	607.20	1.20	2.40
8	30	500	305	37	607.20	606.15	1.05	2.10
9	30	500	601	30	606.15	604.90	1.25	2.50
10	30	500	907	30	604.90	603.40	1.50	3.00
11	30	500	1203	25	603.40	601.50	1.90	3.80
12	30	500	1505	28	601.50	599.40	2.10	4.20

Table 12. Series C

Results of lubricated tests for a load of 1500 gm. with different speeds

Run	Period of time min.	Load gm.	Speed rpm.	Frictional force gm.	Initial weight mg.	Final weight mg.	Loss mg.	Wear rate mg./hr.
				Specimen A				
1	25	1500	301	125	596.40	594.85	1.55	3.72
2	25	1500	304	115	594.85	593.05	1.80	4.30
3	20	1500	603	110	593.05	590.95	2.10	6.30
4	25	1500	903	125	590.95	586.30	4.65	11.20
5	20	1500	1202	115	586.30	581.80	4.50	13.50
6	15	1500	1501	160	581.80	573.30	8.50	34.00
				Specimen B				
7	25	1500	303	155	591.80	590.20	1.60	3.84
8	25	1500	305	140	590.20	588.55	1.65	3.96
9	20	1500	605	130	588.55	586.80	1.75	5.25
10	20	1500	904	175	586.80	582.80	4.00	12.00
11	20	1500	1202	120	582.80	574.50	8.30	24.90
12[a]	15	1500	1504	195	574.50	536.00	38.50	144.00

[a] The large amount of wear is certainly due to an edge breaking off

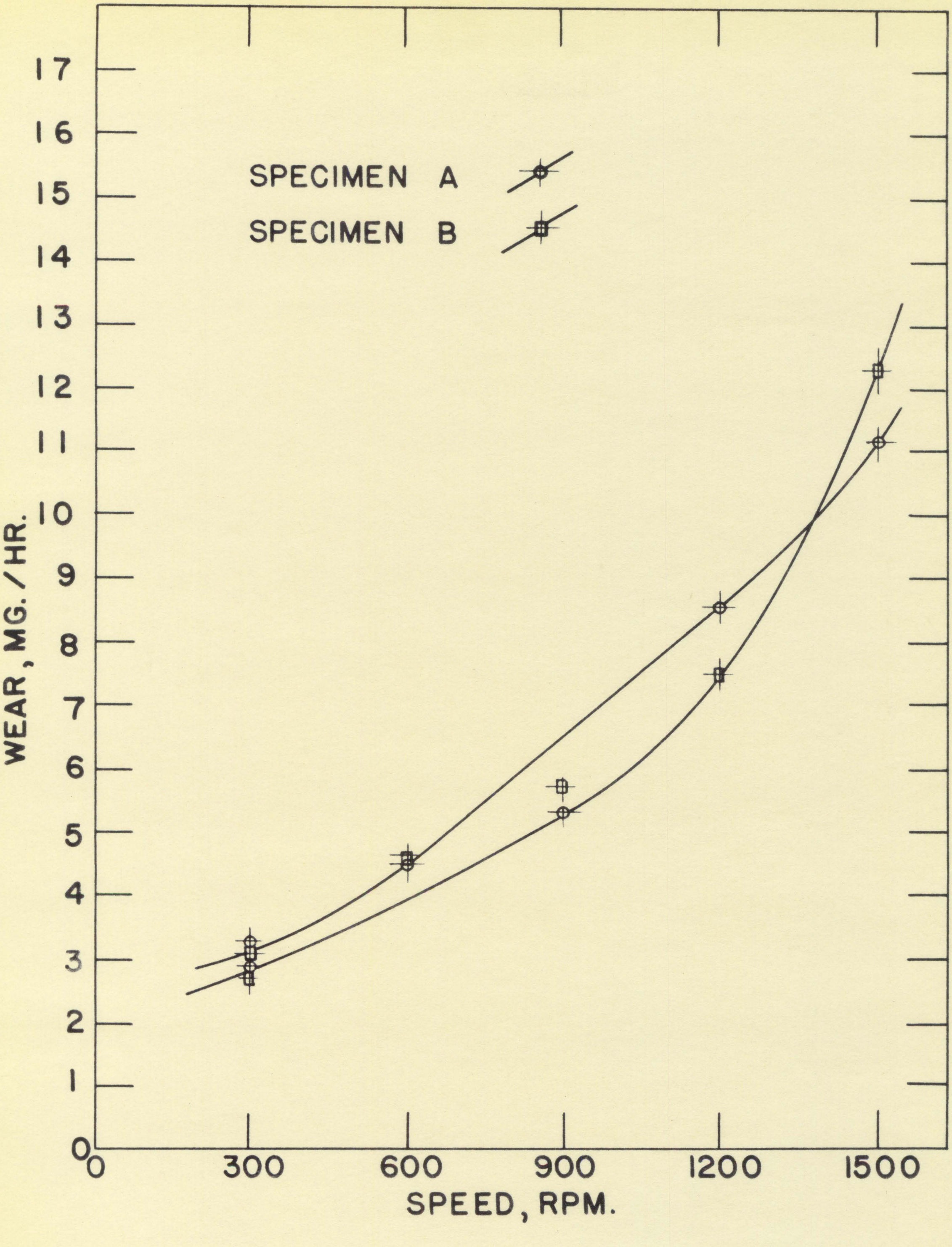


FIG. 12 WEAR VS. SPEED
SERIES C - 1000 G. LOAD

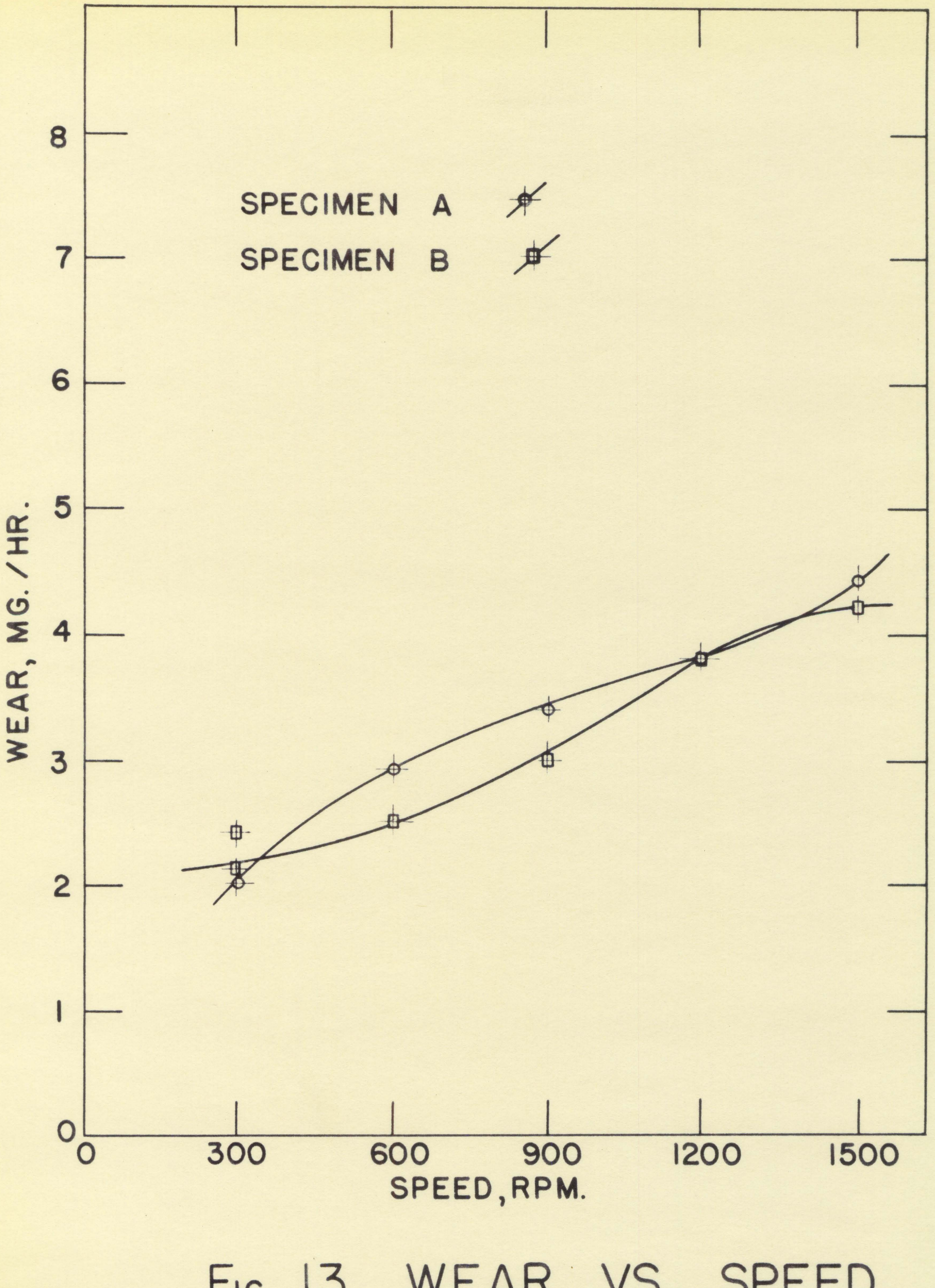


FIG. 13 WEAR VS. SPEED
SERIES C - 500 G. LOAD

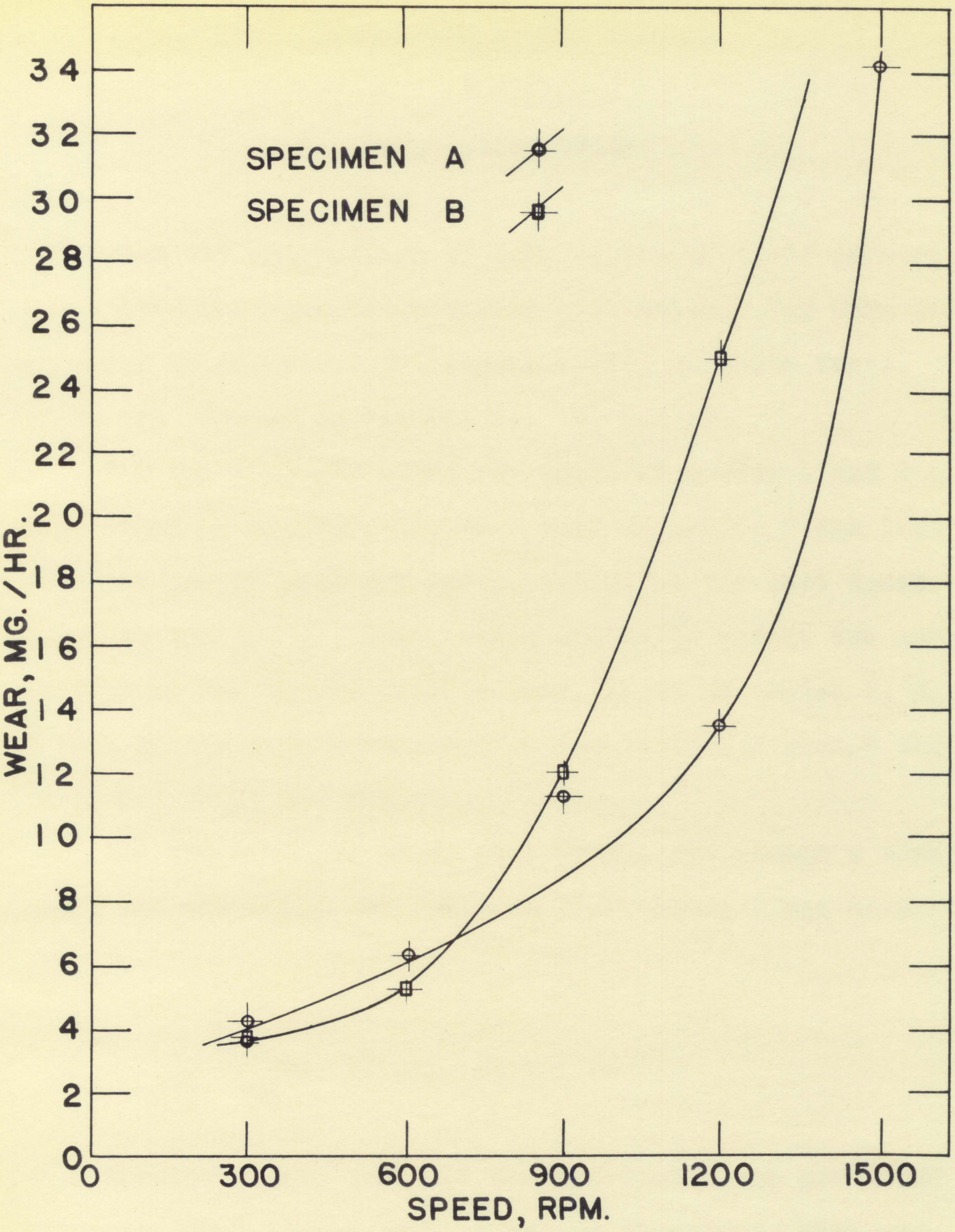


FIG. 14 WEAR VS. SPEED
SERIES C - 1500 G. LOAD

VII. DISCUSSION OF THE RESULTS

A. Comparative Study

With the examination of each series of tests completed, a comparison of the three series will be made for each load in order to establish the repeatability of these tests. Results are plotted in Figures 15, 16, and 17.

For the 1000 gm. load, the tests of series A and B were very similar, however, the wear rate of series C was lower than the one of series A and B, except at the last speed.

For the 500 gm. load, where one would expect the largest deviations due to the smaller wear, tests of series A, B, and C fell in the same range, except for test of series B which increased above 900 rpm.

For the 1500 gm. load, five curves are within a narrow range but the curve for specimen B of series C was slightly higher.

B. Metallographic Tests

Metallographic tests of the specimens were conducted to determine what effect rolling had on structure, size and orientation of the grains of zinc.

Since the samples previously turned out were only

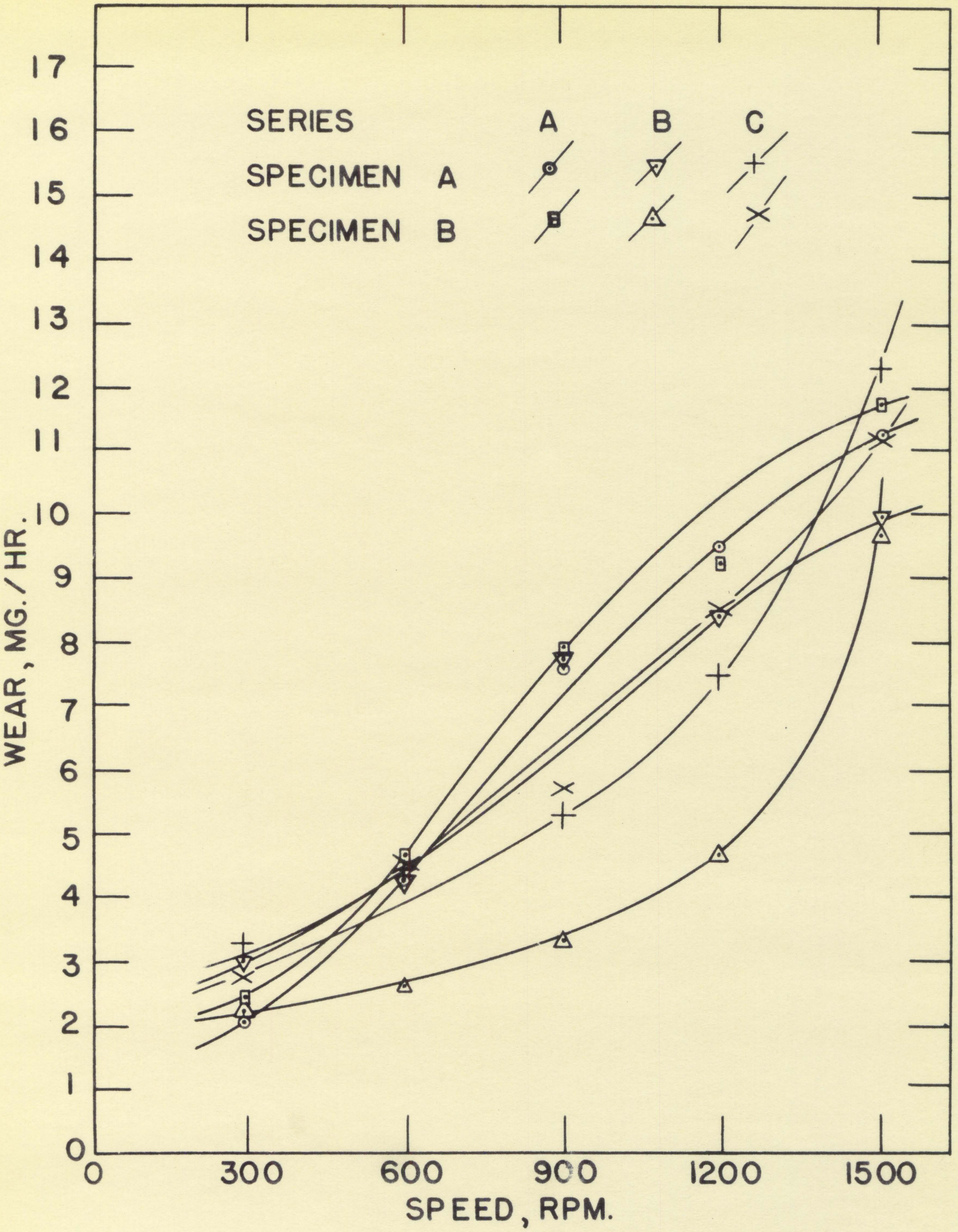


FIG. 15 WEAR VS. SPEED
SERIES A, B & C - 1000 G. LOAD

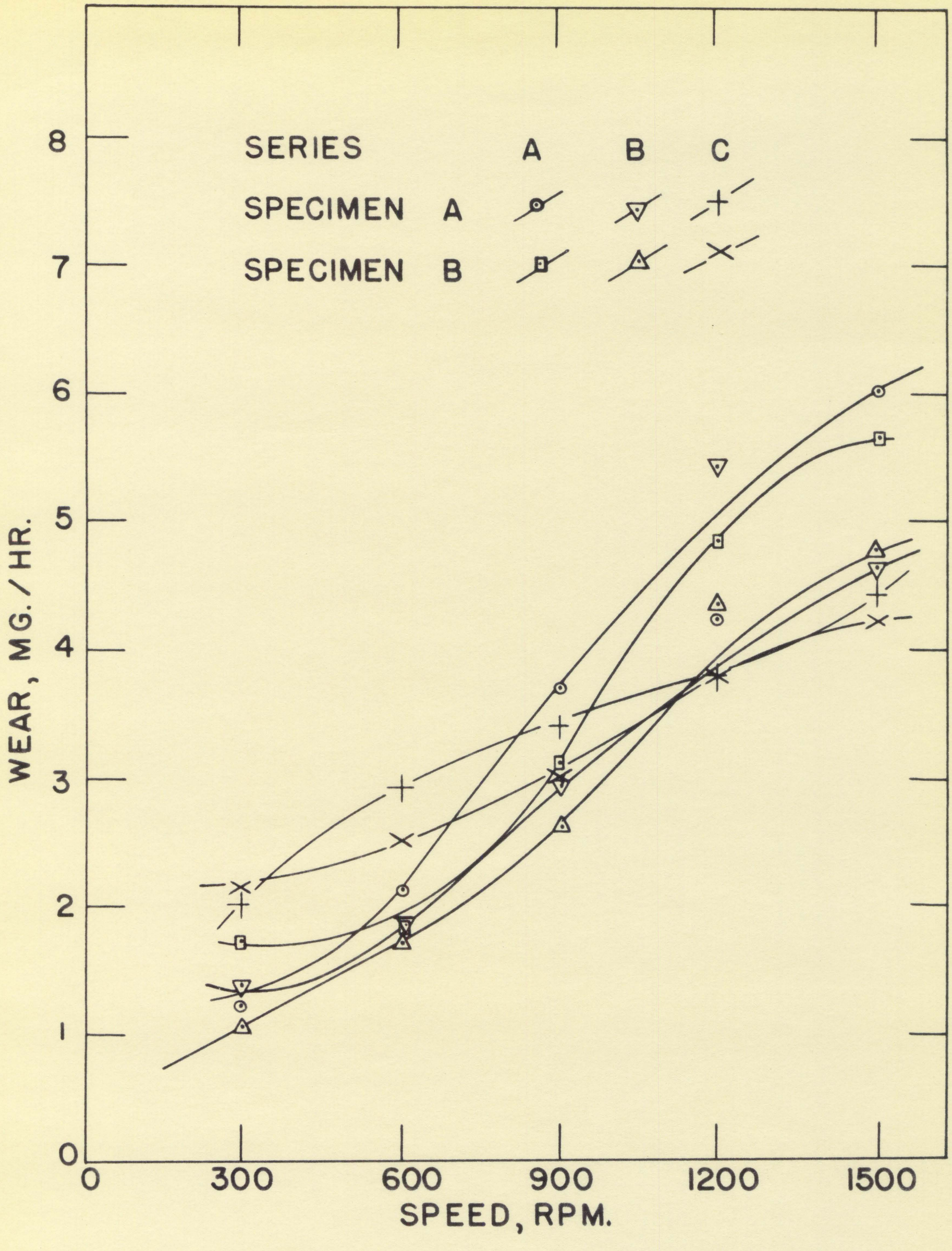


FIG. 16 WEAR VS. SPEED
SERIES A,B & C - 500 G. LOAD

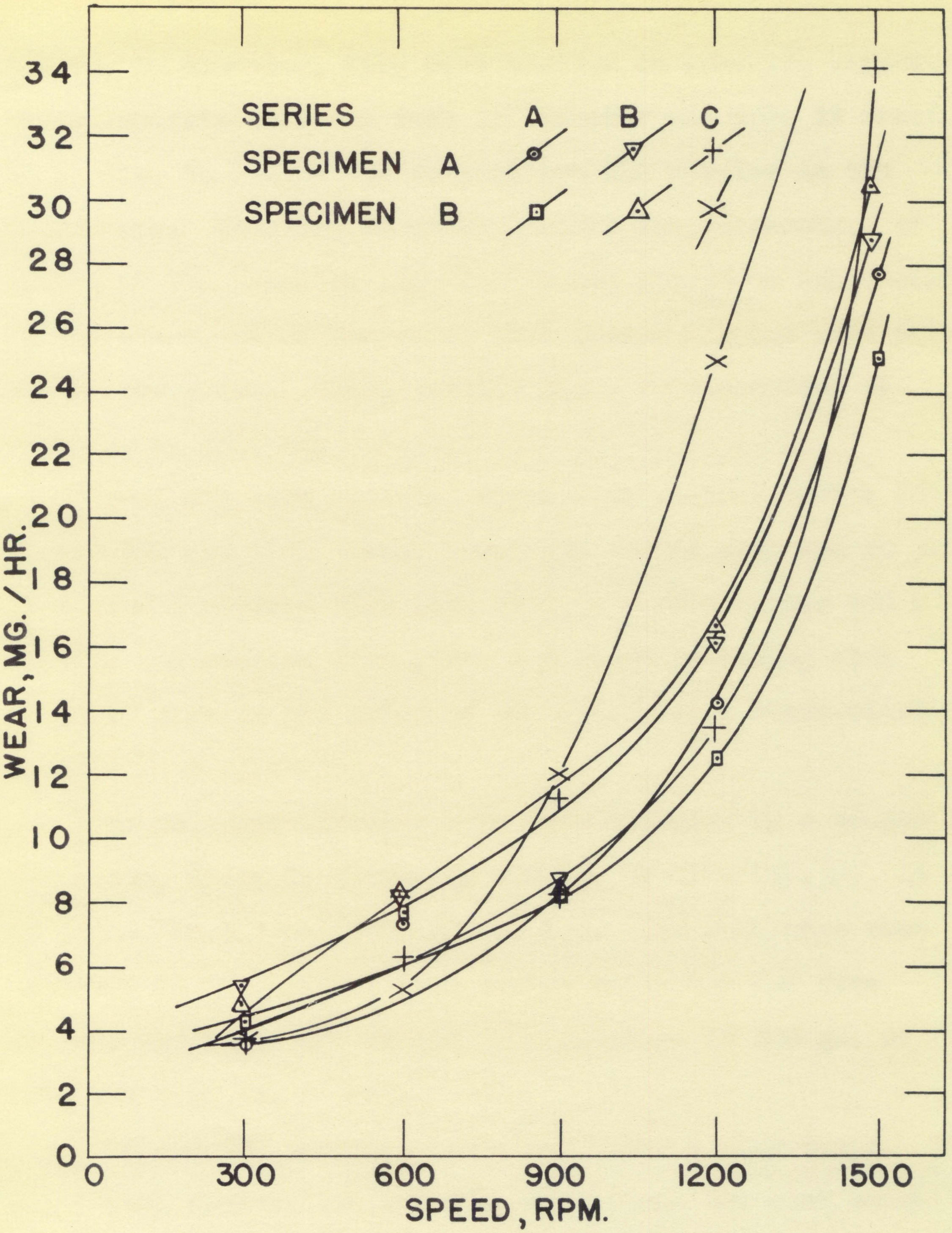


FIG. 17 WEAR VS. SPEED
SERIES A, B & C - 1500 G. LOAD

1/8 in. in diameter, they were mounted in bakelite supports. These supports were one inch in diameter and made it easier to handle, to polish and to position the samples on the microscope. However, to check whether the temperature of fusion of the bakelite (160°F) did not introduce any change in the structure of the zinc, some larger samples were cut out of the plate. These samples had a cross-section of 7/16 in. by 5/16 in.

Specimens were polished first with silicon carbon (SiC) number 320 and then number 400. The second step was to polish on a canvas covered disk with silicon carbon number 400 and finally the samples were given a diamond polishing with particle size on the order of one micron on a micro-cloth wheel.

The polished surfaces were then attacked by a reagent, Palmerton, which is formed by 200 gm. of CrO_3 (99.5%), 15 gm. of Na_2SO_4 (c.p.) and 1000 ml. of H_2O. The specimens were immersed in the reagent with gentle agitation for five seconds and then were rinsed in a solution of 200 gm. of CrO_3 and 1000 ml. of H_2O.

The samples were then examined under a microscope. Two magnifying powers, 120 and 500, were found the most adequate. Microscopic pictures are shown on Figures 18a, 18b, 18c, and 18d.

Figure 18a shows specimen A unmounted. The black lines

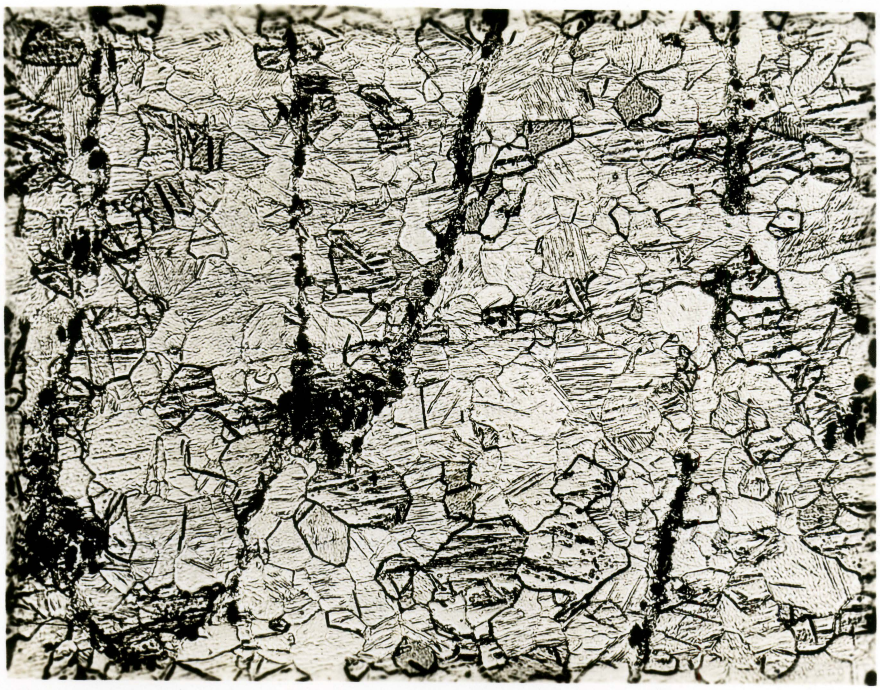


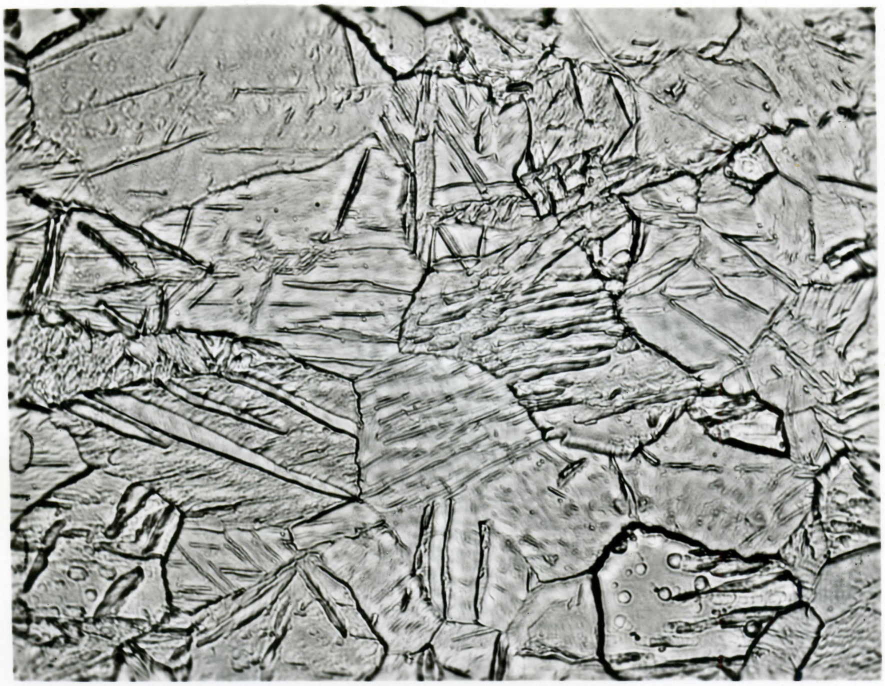
Figure 18a. Specimen A unmounted

Magnification: 120

Figure 18b. Specimen A unmounted
Magnification: 500

Figure 18b. Specimen B unmounted
Magnification: 500

50b



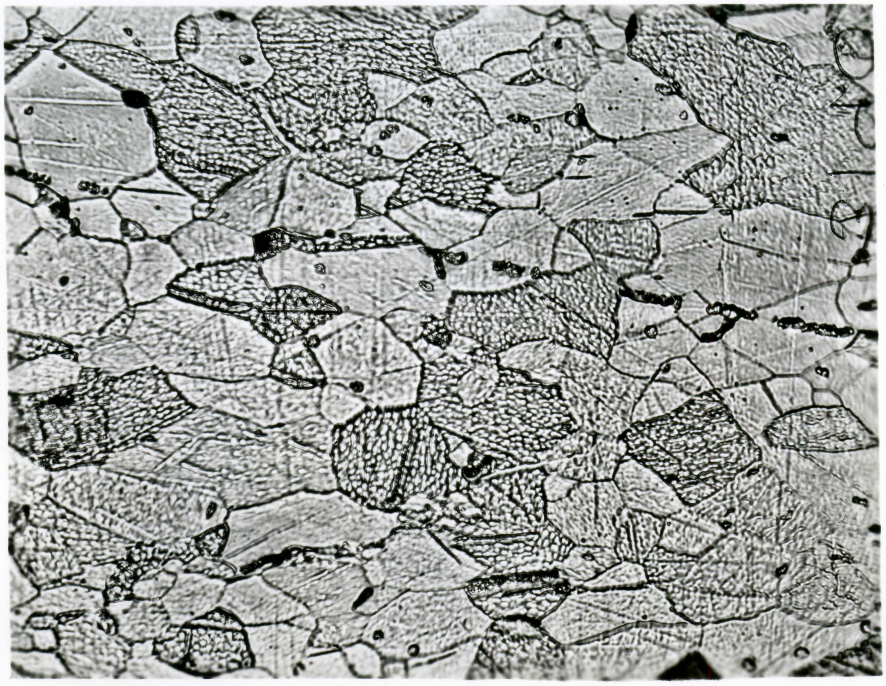


Figure 18c. Specimen A

Magnification: 120

Figure 18c. Specimen B

Magnification: 120

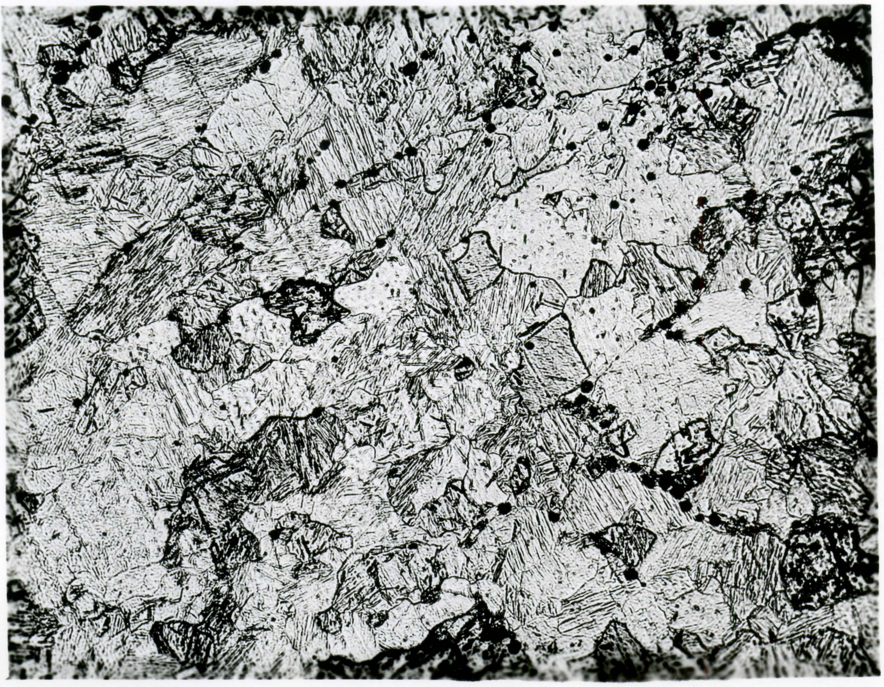
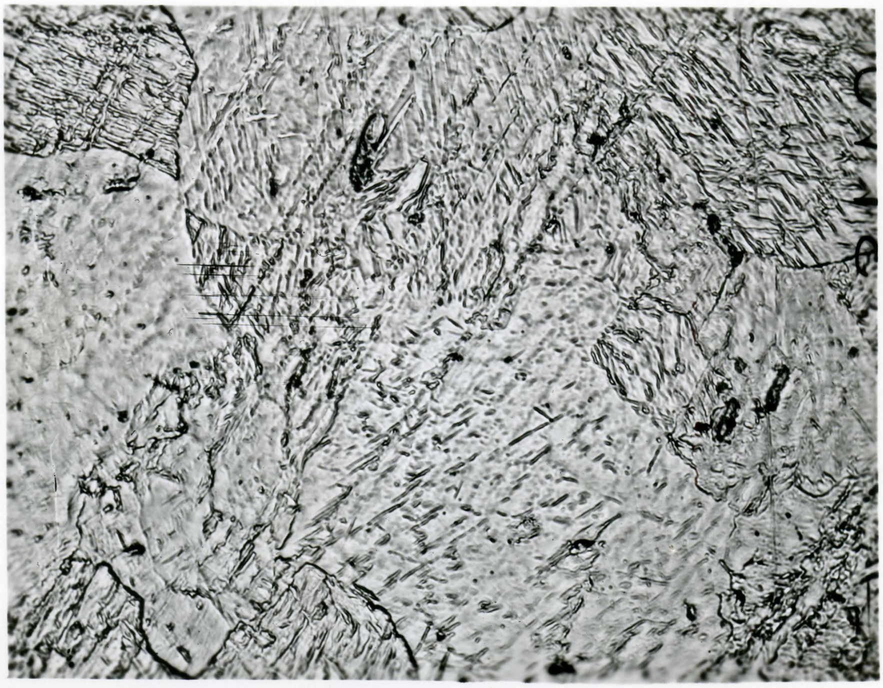


Figure 18d. Specimen A

Magnification: 500

Figure 18d. Specimen B

Magnification: 500




3/d5

show the old boundaries of the grain. The grain located in the left part of the photograph was about 0.2 by 0.85 mm. A large quantity of small crystals appears within the boundaries of an old large one. Hence, there has been a recrystallization after rolling. The recrystallization temperature which is defined as the lowest temperature at which equiaxed, stress-free grains appear in the structure of a previously plastically deformed metal, is at room temperature for zinc (7).

Figure 18b shows samples A and B unmounted with a magnification of 500 times. Specimen B has a smaller grain size than A. Figure 18c shows the sample mounted in bakelite with a magnification of 120. Probably due to the etching, grains do not appear as clearly for specimen A as for specimen B, but the latter one has a finer structure. Figure 18d shows specimens A and B with a magnification of 500.

From these series of pictures, specimen B appears to have a grain size smaller than specimen A by a factor of two. There was no noticeable difference between mounted and unmounted samples.

The longitudinal axis of specimen A was parallel to the direction of rolling, but since the wear and the microscopic study were on an extremity, it was on a face whose plane was perpendicular to the direction of rolling. Hence, the grains of zinc seemed elongated across the direction of rolling, which was rather unexpected since the rolling stresses would have a tendency to deform the crystals so that the longer axis of the grain would be parallel to the direction of rolling. However, the recrystallization phenomenon might have formed crystals larger across the grain than along it.

C. Study of the Coefficient of Friction

For all the tests conducted, the frictional force was recorded. The frictional force (9) is probably unique among the factors involved in rubbing. It used to be assumed, quite logically, that wear was directly related to the frictional force. However, the mounting number of experiments on the subject demonstrates that this cannot be generally true, that is, there can be high friction with low wear and vice-versa. It was shown (10) that not more than 1% of the total frictional force could have been absorbed by removing the worn-off material; generally, the proportion was very much less. Hence, correlation between friction and wear is not to be expected.

The coefficient of friction versus speed, for series A only, is plotted in Figure 19. Due to the lubrication, the coefficient of friction was low in all cases, the lowest value being 0.06 and the highest one 0.110.

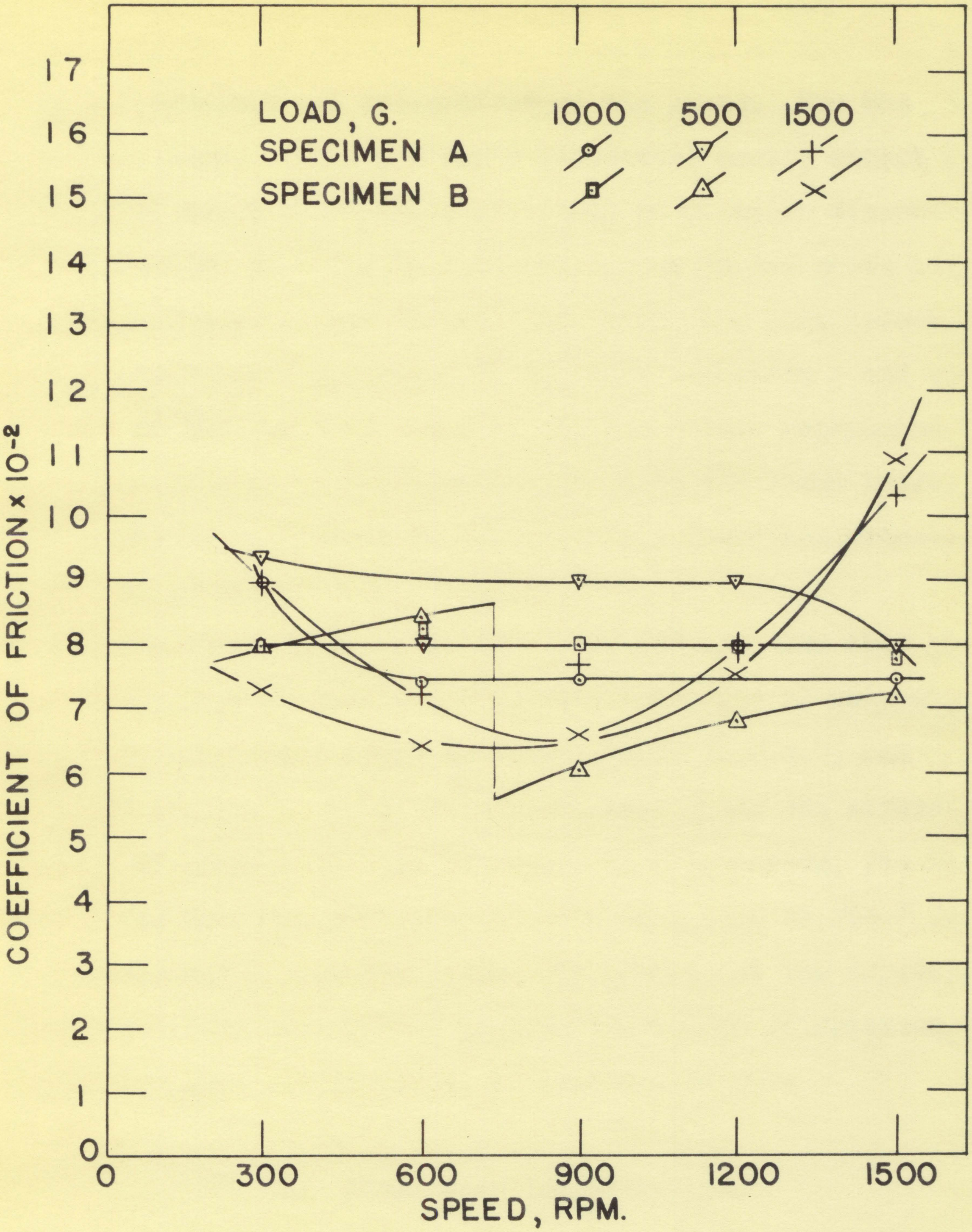


FIG. 19 COEFFICIENT OF FRICTION VS. SPEED - SERIES A

For the 1000 gm. load, the coefficient of friction was fairly constant and independent of the speed. For the 500 gm. load, specimen A had a horizontal curve, except for the last speed where the coefficient of friction dropped off. For specimen B, there is a discontinuity in the curve between 600 and 900 rpm. For the 1500 gm. load, the coefficient of friction reached a minimum of 0.065 for specimen A and specimen B at the speed of 900 rpm. It was rather unexpected that the coefficient of friction decreased as the speed increased. It might be attributed to a better film formation between sliding surfaces.

The three loads used (1000 gm., 500 gm., and 1500 gm.) produced respectively the following pressures of contacts for the specimens: 179.5 lb./in.^{2}, 89.75 lb./in.^{2}, and 269.25 lb./in.^{2}. These values are well below the stress at limit of proportionality of stress to deformation, 710 lb./in.^{2} for specimen cut with the grain and 1280 lb./in.^{2} for specimen cut across the grain. By looking at the curves, specimen A has always the higher coefficient of friction, except for the 1500 gm. load, and above 1400 rpm.

D. Final Wear Investigation

After the three series A, B, and C were examined and now that the structures of the specimens are known, it would be of interest to study how the wear compares for the three loads.

This is possible by comparing the wear rate per unit load, in mig./hr./kg. If the wear rate is directly proportional to the load, at least in the range used, the wear rate per unit load at a given speed should be the same for one specimen and for the three loads. The wear per unit load for the three series A, B, and C were averaged in Table 13 and Figure 20 shows the average wear versus speed.

The assumption that the wear rate is proportional to the load is approximately verified, except for the highest load and above 1000 rpm., where the wear becomes larger. Points for both specimen A and specimen B fall well above the border of the graph.

Table 13. Average wear per unit load for the three loads with different speeds

Series	Speed rpm.	1000 gm. load		500 gm. load		1500 gm. load	
		wear per unit load	average wear per unit load	wear unit per load	average wear per unit load	wear unit per load	average wear per unit load
				Sample A			
A	300	2.25		2.70		2.40	
B	300	3.00	2.78	2.70	3.12	3.80	2.94
C	300	3.10		4.00		2.66	
A	600	4.40		4.20		4.90	
B	600	4.40	4.45	3.60	4.55	5.50	4.86
C	600	4.50		5.80		4.20	
A	900	7.70		7.40		5.50	
B	900	7.80	6.95	5.80	6.65	5.80	6.75
C	900	5.30		6.80		9.00	
A	1200	9.60		8.40		9.50	
B	1200	8.30	8.85	10.80	8.95	11.80	10.10
C	1200	8.60		7.60		9.00	
A	1500	11.40		12.00		18.55	
B	1500	9.90	10.80	9.20	10.00	19.30	20.10
C	1500	11.10		8.80		22.60	

Table 13. (Continued)

Series	Speed rpm.	1000 gm. load		500 gm. load		1500 gm. load	
		wear per unit load	average wear per unit load	wear per unit load	average wear per unit load	wear per unit load	average wear per unit load
Sample B							
A	300	2.65	2.62	3.40	3.67	3.10	3.17
B	300	2.25		2.10		3.80	
C	300	2.95		5.50		2.60	
A	600	4.80	4.00	3.60	4.00	5.30	4.80
B	600	2.64		3.40		5.60	
C	600	4.60		5.00		3.50	
A	900	8.00	6.00	6.20	5.80	5.50	6.40
B	900	3.30		5.20		5.70	
C	900	5.70		6.00		8.00	
A	1200	9.30	7.17	9.60	8.60	8.40	12.00
B	1200	4.70		8.60		11.10	
C	1200	7.50		7.60		16.60	
A	1500	11.85	11.30	11.20	9.65	16.55	44.30
B	1500	9.80		9.40		20.25	
C	1500	12.30		8.40		96.00	

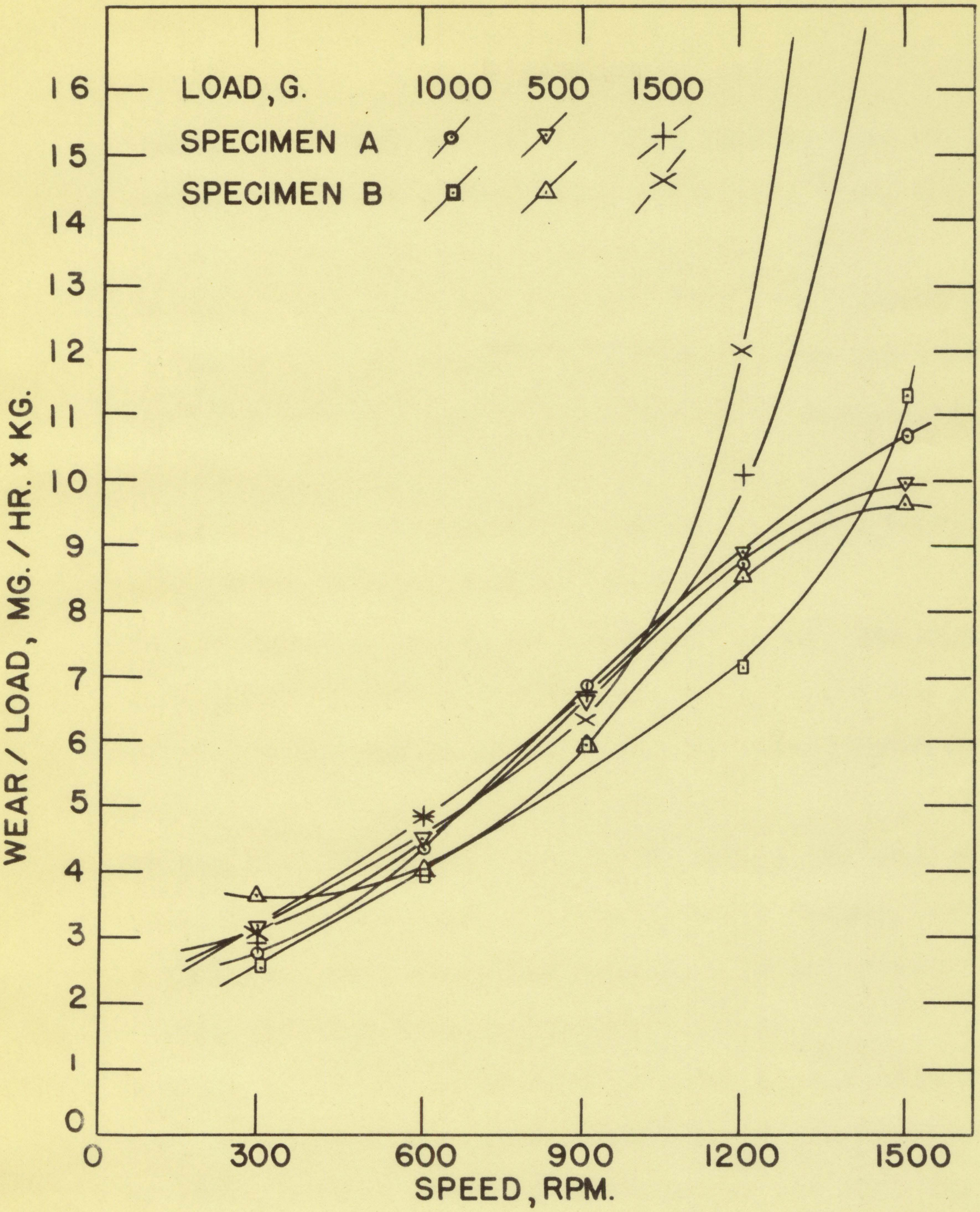


FIG. 20 AVERAGE WEAR PER UNIT LOAD VS. SPEED

VIII. CONCLUSIONS

Although a greater sensitivity with shorter runs would have been expected from a study with irradiated zinc, the conventional method gave reasonable results.

For the 1000 gm. and the 1500 gm. load, the average wear rate was the larger for specimen A. However, for the 1500 gm. mass, the wear rate was larger for specimen B, especially above 900 rpm.

It was verified also that for the two smallest loads, the wear rate was proportional to the load.

For the range of speeds used for this study, the coefficient of friction was independent of the load and not much affected by the changes in speeds. In all tests, specimen A had the higher coefficient of friction.

For the 1000 gm. and 500 gm. loads, where the wear rate is proportional to the load, specimen A wears faster, and for the 1500 gm. load, where the wear rate is not proportional to the load, specimen B wears faster.

However, it should be pointed out that factors other than load, speed, and direction of rolling seemed to affect the wear and sometimes had more influence on the wear than the variables considered.

Even though the average differences were not large, the data indicate that the orientation of the rubbing surface relative to the direction of rolling has an influence on the wear and coefficient of friction of zinc.

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