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Friction and Wear With a Single-Crystal Abrasive Grit of Silicon Carbide in Contact With Iron-Base Binary Alloys in Oil - Effects of Alloying Element and Its Content

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Friction and Wear With a Single-Crystal Abrasive Grit of Silicon Carbide in Contact With Iron-Base Binary Alloys in Oil - Effects of Alloying Element and Its Content

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SUMMARY

An investigation was conducted to determine the effect of alloying elements (Ti, Cr, Mn, Ni, Rh, and W) on the abrasive-wear and -friction behavior of a number of iron-base binary alloys. The sliding friction experiments were conducted with a 0.025-millimeter-radius spherical rider of single-crystal silicon carbide on disks of the same material in mineral oil. All experiments were conducted with loads of 0.05, 0.1, and 0.2 newton at a sliding velocity of 3×10^{-3} meter per minute with a total sliding distance of 3 millimeters at room temperature.

The results of the investigation indicate that the atomic size and content of the alloying element dominate the abrasive-wear and -friction behavior of iron-base binary alloys. The coefficient of friction and groove height (wear volume) generally decrease, and the contact pressure increases with increasing solute content. The correlation of solute to iron atomic radius ratio with the decreasing rate of coefficient of friction $-d\mu/dC$, decreasing rate of groove height (wear volume) $-dH/dC$, and the increasing rate of contact pressure dP/dC with an increase of solute content appears to be very good. Those rates increase as the solute to iron atomic radius ratio increases or decreases from unity. The abrasive-wear and -friction properties of the annealed and mechanically polished alloy surfaces were not significantly different.

INTRODUCTION

The present authors have conducted simple experiments to determine the abrasive wear of metals in order to gain a better fundamental understanding of the industrial process of grinding (ref. 1). In these simple experiments sliding friction tests were conducted with spherical, single-crystal silicon carbide riders contacting various metals. The abrasive-wear and -friction of the metals were found to be strongly related to the shear strength of the metal. The coefficient of friction and the wear volume decreased linearly as the shear strength of the bulk metal increased. Further, the abrasive characteristics of the metals in these simple experiments were found to be very similar to those obtained by Avient, et al. (ref. 2), in full-scale wear studies. The The determination of abrasive wear characteristics of materials in such simple experiments was not only more rapid and highly reliable, but also more economical than full-scale tests.

The present authors found that, with simple experiments of iron-chromium binary alloys, the alloy solution hardening observed played a dominant role in controlling the abrasive-wear and -friction of the alloys (ref. 3). The coefficient of friction and the volume of the groove plowed with a silicon carbide rider correlated directly with the chromium content in iron. The measured contact pressure during sliding correlated with the hardness data obtained by Stephens and Witzke (ref. 4). However, the exact role of alloying elements in the abrasive-wear and -friction was not clearly revealed in reference 3 because of the small selection of alloying elements.

The objective of the present investigation was to examine the effect of alloying elements (such as Ti, Cr, Mn, Ni, Rh, and W) on the abrasive-wear and -friction behavior of several iron-base, binary, solid-solution alloys. The sliding friction experiments were conducted with 0.025-millimeter-radius, spherical riders of single-crystal silicon carbide (simulating an abrasive grit) sliding on the alloy disks in mineral oil. Oil was used to minimize adhesion effects on friction. All experiments were conducted with loads of 0.05, 0.1, and 0.2 newton at a sliding velocity of 3×10^{-3} meter per minute with a total sliding distance of 3 millimeters at room temperature.

SYMBOLS

A	projected area of contact, $\pi D^2/8$
C	solute content, at. %
D	width of a groove (wear track)
H	height of a groove (wear track)
H_V	Vickers hardness
$-dH/dC$	decreasing groove height with increasing C
dH_V/dC	alloy hardening rate with increasing C
K	solute to iron atomic radius ratio
k	constant for material
k'	constant for material
m	constant for material
n	constant for material (Meyer's index)
P	contact pressure during sliding, W/A
dP/dC	increasing contact pressure with increasing C
r	radius of spherical rider

W	normal load
μ	coefficient of friction
$-d\mu/dC$	decreasing coefficient of friction with increasing C

MATERIALS

The single-crystal silicon carbide used in these experiments was a 99.99-percent-pure compound of silicon and carbon and had a hexagonal-closed-packed crystal structure, as indicated in table I. The Knoop hardness was 2954 in the $\langle 10\bar{1}0 \rangle$ direction and 2917 in the $\langle 11\bar{2}0 \rangle$ direction on the basal plane of silicon carbide (ref. 5). Table II presents the analyzed compositions in atom percent of iron-base alloys prepared by Stephens and Witzke (ref. 4). The iron-base binary alloys of reference 4 were prepared by arc-melting the high-purity iron and high-purity alloying elements (Ti, Cr, Mn, Ni, Rh, and W). The solute concentrations ranged from approximately 0.5 atomic percent for those elements that have extremely limited solubility in iron up to approximately 16 atomic percent for those elements that form a continuous series of solid solutions with iron.

EXPERIMENTAL APPARATUS AND PROCEDURE

Apparatus

The apparatus used in this investigation is shown schematically in figure 1 and is described in reference 6.

Specimen Preparation

The single-crystal silicon carbide rider surface was hemispherical and was polished with approximately 3-micrometer-diameter diamond powder and then 1-micrometer-diameter aluminum oxide (Al_2O_3) powder. Its radius of curvature r was 0.025 millimeter (fig. 2). And its orientation is also shown in figure 2.

The surfaces of iron-base alloy disk specimens were also polished with 3-micrometer-diameter diamond powder and then 1-micrometer-diameter aluminum oxide powder. Some of the disk specimens were annealed under a vacuum of 10^{-4} to 10^{-5} pascal for 1 hour at the temperature where maximum solubility occurs in the α region. This anneal was followed by a 16 hours or more at 300° C in order to produce single-phase, homogenized, equiaxed, strain-free specimens (ref. 4).

Experimental Procedure

Both the silicon carbide and alloy surfaces were rinsed with 200-proof ethyl alcohol before use. The friction experiments involved a single pass over a total sliding distance of 3 millimeters at 3 millimeters per minute and were conducted in mineral oil. Typical properties of the mineral oil appear in table III. All experiments were conducted at 25° C.

The heights H and widths D of the grooves (wear tracks) reported herein were obtained by averaging measurements of 8 to 10 surface-profile records. A typical surface-profile record is shown in figure 3.

RESULTS AND DISCUSSION

Deformation Effects of Mechanical Polishing

Because of concern for mechanical polishing effects on abrasive wear, this effect was examined. Sliding friction experiments were conducted with 0.025 millimeter-radius, spherical silicon carbide riders in contact with both annealed and mechanically polished alloy disk surfaces in mineral oil at loads of 0.05, 0.1, and 0.2 newton. Figure 3 shows a typical friction-force trace and surface profile of a groove resulting from such sliding. The friction-force traces obtained in this investigation are characterized by randomly fluctuating behavior, with no evidence of stick-slip (fig. 3(a)). Sliding involves plastic flow and the generation of wear debris. The surface profiles, therefore, are characterized by grooving with considerable amounts of deformed alloy piled up along the sides of the groove (fig. 3(b)). More detailed examination of the groove revealed evidence of wear debris, as already discussed in reference 1.

Figure 4 presents coefficients of friction, groove heights (peak-to-valley height of groove), and contact pressures on both surfaces of annealed and mechanically polished iron-titanium alloys as functions of titanium content in iron at various loads. A contact pressure P during sliding was estimated from the width of groove, however, it may be defined as $P = W/A$ where W is the applied normal load and A is the projected area of contact and is given by $A = \pi D^2/8$ (only the front half of the rider is in contact with the disk). Figure 4 shows that the coefficient of friction and groove height generally decrease as the titanium content increases. The contact pressure (corresponding to the microhardness) increases with increases in the titanium content. The decreasing rates of both the coefficient of friction and the groove height and the increasing rates of the contact pressure are larger for the annealed surfaces than for mechanically polished surfaces. The trends of the data, however, for both the annealed and polished surfaces are similar. Because the friction, deformation, and wear properties of the annealed and mechanically polished alloy surfaces were not significantly different, the succeeding experiments were conducted with the mechanically polished alloy surfaces. Note that the height H and width D of the groove were defined in reference 1 and are illustrated in figure 4.

Alloying Element Effects

Sliding friction experiments were conducted with 0.025-millimeter-radius, spherical, single-crystal silicon carbide riders in contact with mechanically polished surfaces of various iron-base alloys in mineral oil. The binary-alloy systems were iron alloyed with titanium, chromium, manganese, nickel, rhodium, or tungsten.

The coefficients of friction and the groove height (corresponding to the volume of the groove) for a number of binary alloys are presented in figures 5 and 6 as functions of solute content (atomic percent) at load of 0.05 and 0.1 newton. The data of these figures indicate decreases in the coefficient of friction and groove height with an increase in solute content. The examinations of figures 5 and 6 show no significant change in coefficient of friction with load, but there are obvious differences in the groove height with load. The relation between the groove height H and the load W could be expressed by $W = k' H^m$, where k' and m are constants for the material under examination (ref. 1). The average rates of decrease in the coefficient of friction and the groove height strongly depend on the alloying element. This matter will be discussed in controlling mechanisms of friction and wear.

Figure 7 presents the contact pressure during sliding for various binary alloys as a function of solute content (in atomic percent) at loads of 0.05 and 0.1 newton. The contact pressure increases as the solute content increases, and the increasing rate in the contact pressure depends on the alloying element. There is no significant change in contact pressure with load. The contact pressure was calculated from the groove width. The relation between the groove width D and load W could be expressed by $W = kD^n$, which satisfies Meyer's law (refs. 1 and 7).

Controlling Mechanisms of Friction and Wear

Alloy hardening at higher temperatures (300 and 411 K) and alloy softening at lower temperatures (77 and 188 K) have been observed in several iron-base binary alloys by Leslie and Spitzig (refs. 8 and 9), Pink (ref. 10), Leemans and Fine (ref. 11), and Stephens and Witzke (ref. 4). These investigations concluded that for many alloy systems both alloy softening and alloy hardening were controlled by atomic size misfit or the solute iron atomic radius ratio. The grooves (wear tracks) were formed in alloys primarily by the mechanism of plastic deformation (under hydrostatic contact pressure) and plowing stress, with occasional material removal.

The formation of grooves may be very similar to that of indentations in hardness test. Therefore, the manner in which the friction and wear properties correlate with the solute to iron atomic radius ratio or atomic size misfit is of interest. Figures 8 to 10 present the decreasing rates of coefficient of friction $-d\mu/dC$ and groove height $-dH/dC$, and the increasing rate of contact pressure dP/dC with an increase of solute content as a function of solute to iron atomic radius ratio at loads of 0.1 and 0.05 newton. The rates were estimated from the data in figures 5 to 7.

There appears to be very good agreement between the friction and wear properties, and the solute to iron atomic radius ratio. The correlation between each rate and the solute to iron atomic radius ratio is separated into two cases: first, the case for alloying with manganese and nickel, which have smaller atomic radii than iron, and, second, the case for chromium, rhodium, tungsten, and titanium, which have larger atomic radii than iron. The $-d\mu/dC$, $-dH/dC$, and dP/dC increase as the solute to iron atomic radius ratio increases or decreases from unity. Thus, the correlations indicate that atomic size of the solute is an important parameter in controlling abrasive-wear and -friction in iron-base, binary alloys as well as alloy hardening reported by Stephens and Witzke (see fig. 10 and ref. 4).

Leslie concluded in his review that the atomic size misfit parameter is a reasonably good indicator of the strengthening of α-iron by the addition of low concentrations of substitutional solutes (ref. 8). The present authors have already shown that the abrasive-wear and -friction are strongly related to the shear strength of the pure metals. These two conclusions suggest that abrasive-wear and -friction can be correlated with atomic size misfit and shear strength in metals and alloys.

Rider Shape Effect

Sliding friction experiments were conducted with a spherical, 0.025 millimeter-radius, single-crystal silicon carbide rider in contact with various iron-base alloys at load of 0.2 newton in mineral oil. Figure 11 presents the coefficients of friction and the groove height as functions of solute content (at. %). At loads of 0.05 and 0.1 newton, the rider shown in figure 2 are in spherical contact with alloys. But at a load of 0.2 newton, the contact of rider with alloys includes a conical portion of rider, in addition to the spherical portion. Figure 11 indicates that the atomic size (solute to iron atomic radius ratio) and content of alloying element play a dominant role in controlling the abrasive-wear and -friction properties of iron-base binary alloys, as has been already discussed.

CONCLUSIONS

As a result of sliding friction experiments conducted with spherical, single-crystal silicon carbide riders in sliding contact with various iron-base binary alloys, the following conclusions are drawn:

1. The atomic size and content of alloying element play a dominant role in controlling the abrasive-wear and -friction properties of binary, iron-base alloys.

2. The coefficient of friction and groove height (wear volume) generally decrease, and the contact pressure increases with an increase in solute content C.

3. There appears to be very good agreement between the decreasing rate of coefficient of friction $-d\mu/dC$, the decreasing rate of groove height (wear volume) $-dH/dC$, and the increasing rate of contact pressure dP/dC with an increase of solute content C and the solute to iron atomic radius ratio. Those rates increase as the solute to iron atomic radius ratio increases or decreases from unity.

4. The abrasive-wear and -friction properties of the annealed and mechanically polished alloy surfaces were not significantly different.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 6, 1978,
506-16.

REFERENCES

1. Miyoshi, Kazuhisa; and Buckley, Donald H.: Friction and Wear of Metals with a Single-Crystal Abrasive Grit of Silicon Carbide - Effect of Shear Strength of Metal. NASA TP-1293, 1978.

2. Avient, B. W. E.; Goddard, J.; and Wilman, H.: An Experimental Study of Friction and Wear During Abrasion of Metals. Proc. Roy. Soc. (London), Ser. A, vol. 258, no. 1293, Oct. 18, 1960, pp. 159-180.

3. Miyoshi, Kazuhisa; and Buckley, Donald H.: Friction and Wear Characteristics of Iron-Chromium Alloys in Contact with Themselves and Silicon Carbide. NASA TP-1387, 1978.

4. Stephens, Joseph R.; and Witzke, Walter R.: Alloy Softening in Binary Iron Solid Solutions. J. Less-Common Metals, vol. 48, Aug. 1976, pp. 285-308.

5. Shaffer, Peter T. B.: Effect of Crystal Orientation on Hardness of Silicon Carbide. J. Am. Ceram. Soc., vol. 47, no. 9, Sep. 1964, p. 466.

6. Miyoshi, Kazuhisa; and Buckley, Donald H.: Friction and Deformation Behavior of Single-Crystal Silicon Carbide. NASA TP-1053, 1977.

7. Tabor, D.: Hardness of Metals. Oxford Univ. Press (London), 1951, pp. 6-18.

8. Leslie, W. C.: Iron and Its Dilute Substitutional Solid Solutions. Metall. Trans., vol. 3, Jan. 1972, pp. 5-26.

9. Spitzig, W. A.; and Leslie, W. C.: Solid-Solution Softening and Thermally Activated Flow in Alloys of Fe with 3 Atomic Percent Co, Ni, or Si. Acta Metall., vol. 19, no. 11, 1971, pp. 1143-1152.

10. Pink, Erwin: Legierungsentfestigung in kubisch-raumzentrierten Meallen (Alloy Softening in Body Centered Cubic Metals). Z. Metallk., vol. 64, no. 12, 1973, pp. 871-881.

11. Leemans, D.; and Fine, M. E.: Solid Solution Softening and Strain-Rate Sensitivity of Fe-Re and Fe-Mo Alloys. Metall. Trans., vol. 5, no. 6, 1974, pp. 1331-1336.

12. Hume-Rothery, W.; and Raynor, G. V.: The Structure of Metals and Alloys. Fourth ed. The Institute of Metals (London), 1962, pp. 246-258.

TABLE I. - COMPOSITION DATA, CRYSTAL STRUCTURE,

AND HARDNESS OF SINGLE-CRYSTAL SILICON CARBIDE

(a) Composition[a]

Si	C	O	B	P	Others
66.6%	33.3%	<500 ppm	<100 ppm	<200 ppm	<0.1 ppm

(b) Structure

Interatomic distance		Lattice ratio, c/a
a	c	
3.0817	15.1183	4.9058
3.073	15.079	4.9069

(c) Hardness data[b]

Plane	Direction	Knoop hardness number
(0001)	$\langle 11\bar{2}0 \rangle$	2917
(0001)	$\langle 10\bar{1}0 \rangle$	2954
$(10\bar{1}0)$	$\langle 0001 \rangle$	2129
[c]$(10\bar{1}0)$	$\langle 0001 \rangle$	2755
$(11\bar{2}0)$	$\langle 0001 \rangle$	2391
[c]$(11\bar{2}0)$	$\langle 0001 \rangle$	2755

[a]Manufacturer's analyses.
[b]Ref. 5.
[c]Perpendicular.

TABLE II. - CHEMICAL ANALYSIS (REF. 4) AND

SOLUTE TO IRON ATOMIC RADIUS RATIOS FOR

IRON-BASE BINARY ALLOYS

Solute element	Analyzed solute content, at. %	Analyzed interstitial content, ppm by weight			Solute to iron atomic radius ratios (ref. 12)
		C	O	P	
Ti	1.02	56	92	7	1.1476
	2.08	--	---	--	
	3.86	87	94	9	
	8.12	--	---	--	
Cr	0.99	--	---	--	1.0063
	1.98	50	30	12	
	3.92	--	---	--	
	7.77	40	85	10	
	16.2	--	---	--	
Mn	0.49	--	---	--	0.9434
	.96	39	65	6	
	1.96	--	---	--	
	3.93	32	134	8	
	7.59	--	---	--	
Ni	0.51	--	---	--	0.9780
	1.03	28	90	6	
	2.10	--	---	--	
	4.02	48	24	5	
	8.02	--	---	--	
	15.7	38	49	7	
Rh	1.31	--	---	--	1.0557
	2.01	20	175	22	
	4.18	--	---	--	
	8.06	12	133	19	
W	0.83	30	140	12	1.1052
	1.32	--	---	--	
	3.46	23	61	21	
	6.66	--	---	--	

TABLE III. - PROPERTIES[a] OF NAPHTHENIC

MINERAL OIL

Viscosity, m^2/sec (cS), at -	
38° C	73.4×10^{-6} (73.4)
99° C	8.35×10^{-6} (8.35)
Specific gravity, at -	
16° C	0.880
25° C	0.875
Pour point, $^\circ$C	-18
Flash point, $^\circ$C	224

[a]Manufacturer's analysis.

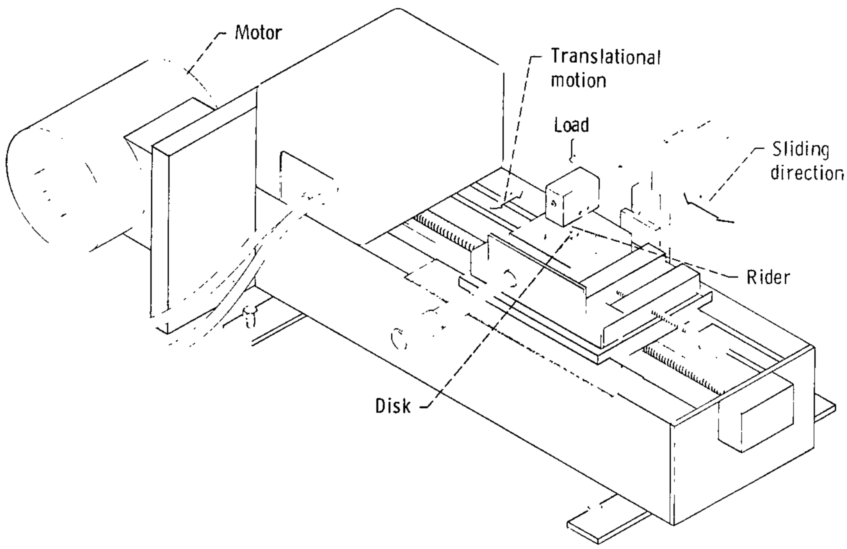


Figure 1. - Friction and wear apparatus.

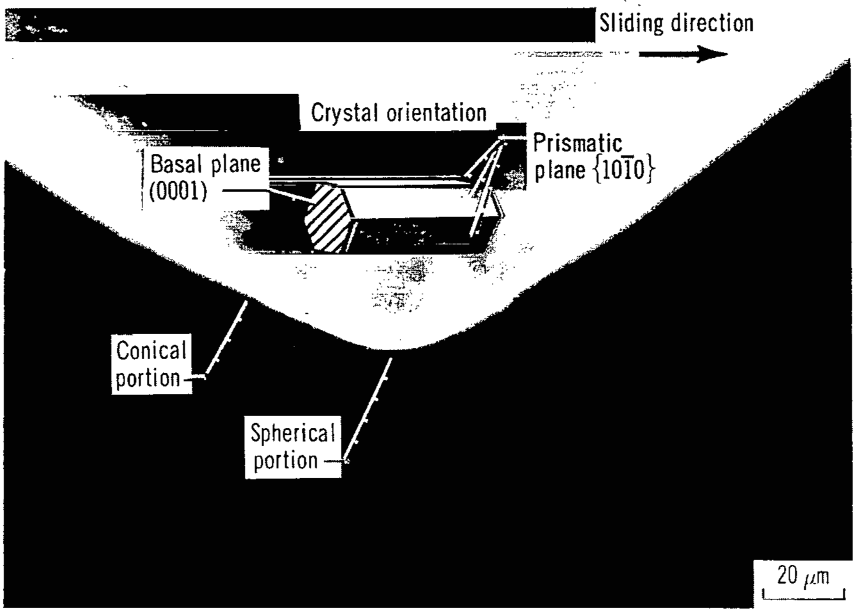
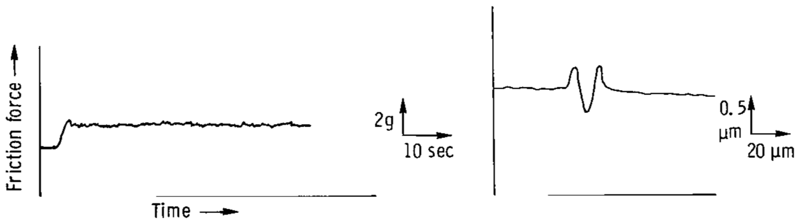
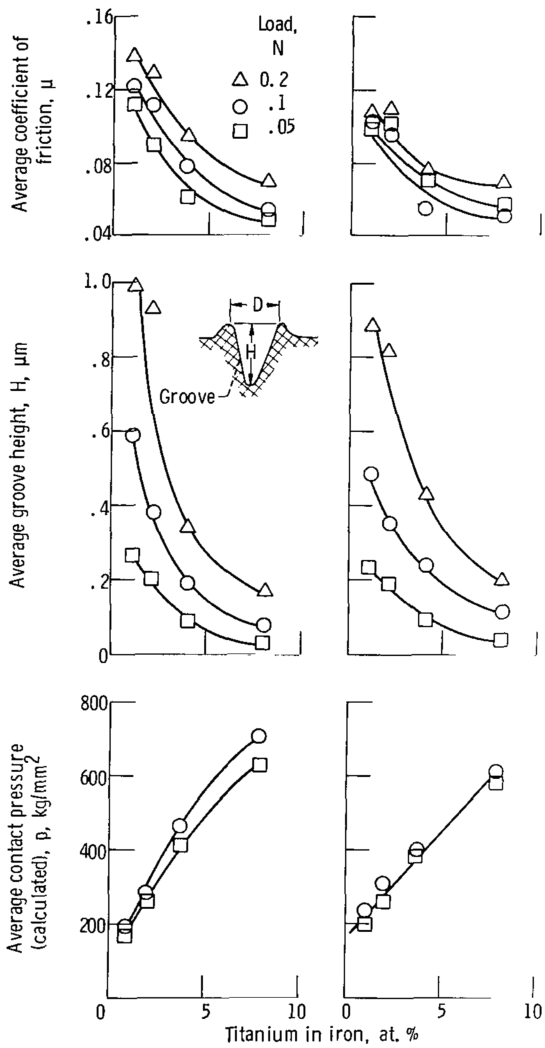


Figure 2. - Spherical silicon carbide rider. Radius, r, 0.025mm; sliding direction, <0001>.



(a) Friction force trace. (b) Surface profile.

Figure 3. - Friction force trace and surface profile of groove on iron - 1.02-Ti alloy. Single pass sliding of 0.025-mm-rad. silicon carbide rider; sliding velocity, 3 mm/min; load, 0.1 N; temperature, 25° C in mineral oil.



(a) Annealed surface. (b) Polished surface.

Figure 4. - Coefficients of friction, groove height, and contact pressure for annealed and mechanically polished Fe-Ti alloys. Single-pass sliding of 0.025-mm-rad. silicon carbide rider in mineral oil. Sliding velocity, 3 mm/min; temperature, 25° C.

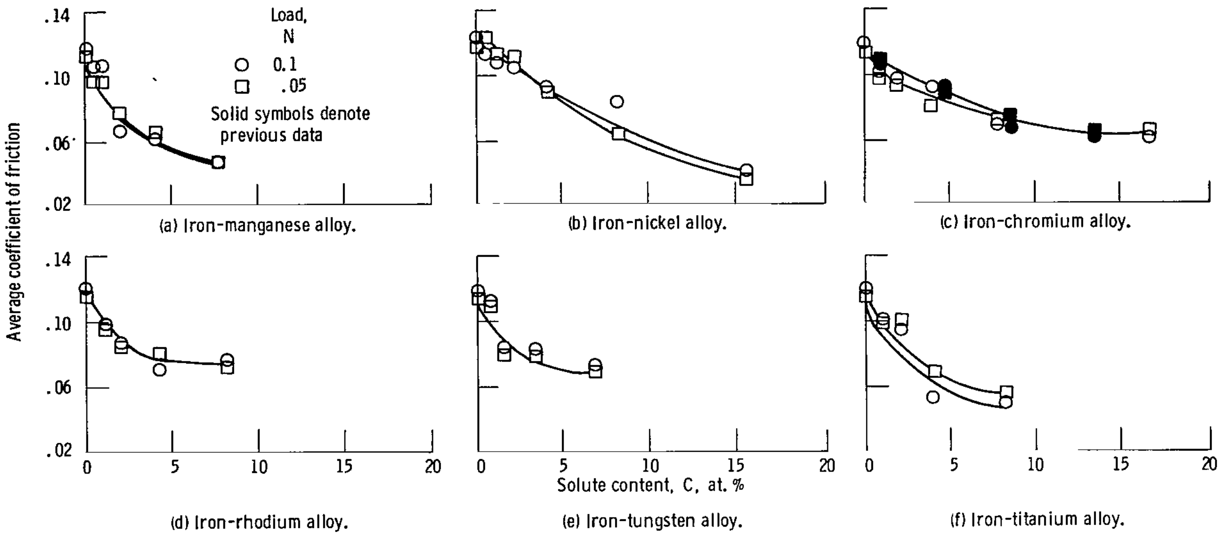


Figure 5. - Coefficients of friction for various iron-base alloys and pure iron as function of solute content. Single-pass sliding of 0.025-mm-rad. silicon carbide rider in mineral oil. Sliding velocity, 3 mm/min; temperature, 25° C.

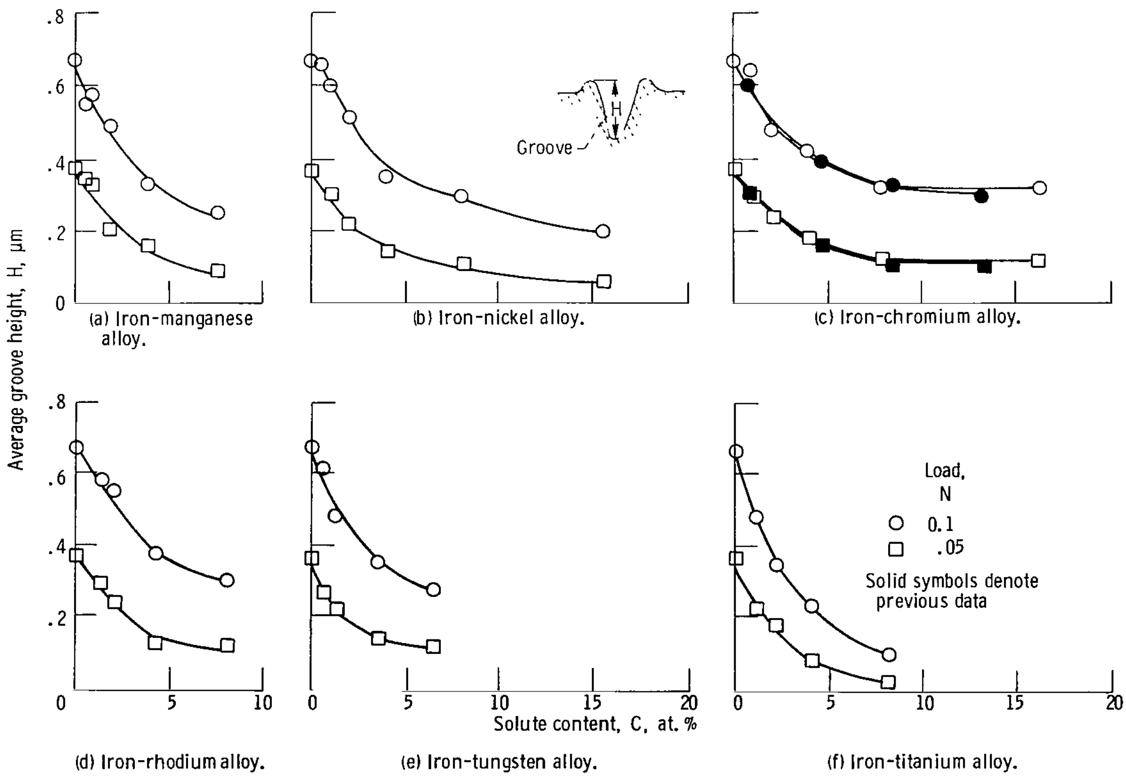


Figure 6. - Groove heights for various iron-base alloys and pure iron as function of solute content. Single-pass sliding of 0.025-mm-rad. silicon carbide rider in mineral oil. Sliding velocity, 3 mm/min; temperature, 25° C.

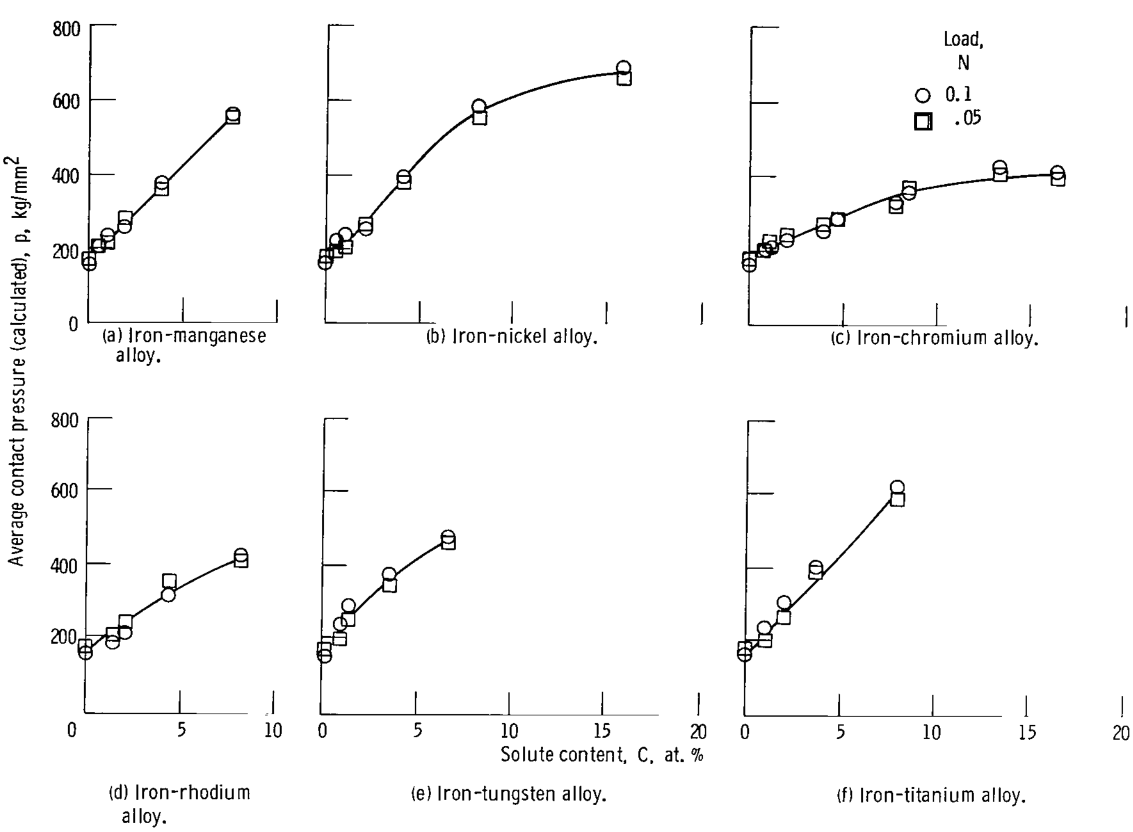


Figure 7. - Contact pressure for various iron-base alloys and pure iron as function of solute content. Single-pass sliding of 0.025-mm-rad. silicon carbide rider in mineral oil. Sliding velocity, 3 mm/min; temperature, 25° C.

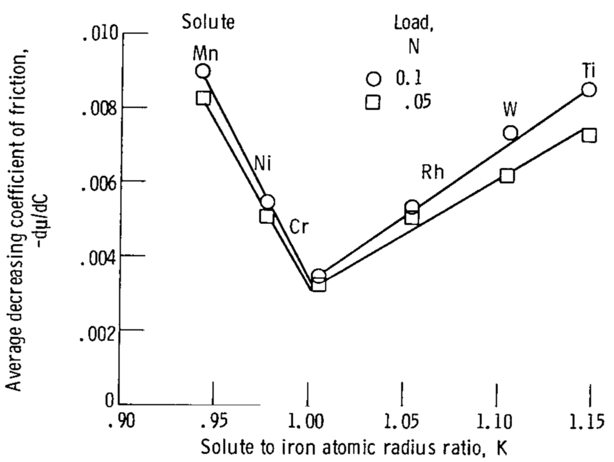


Figure 8. - Coefficient of friction as function of solute to iron atomic radius ratio.

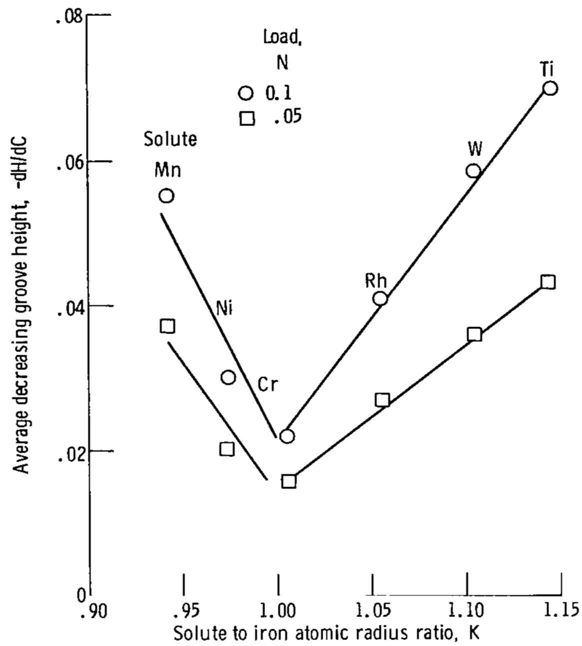


Figure 9. - Decreasing rate of groove height as function of solute to iron atomic radius ratio.

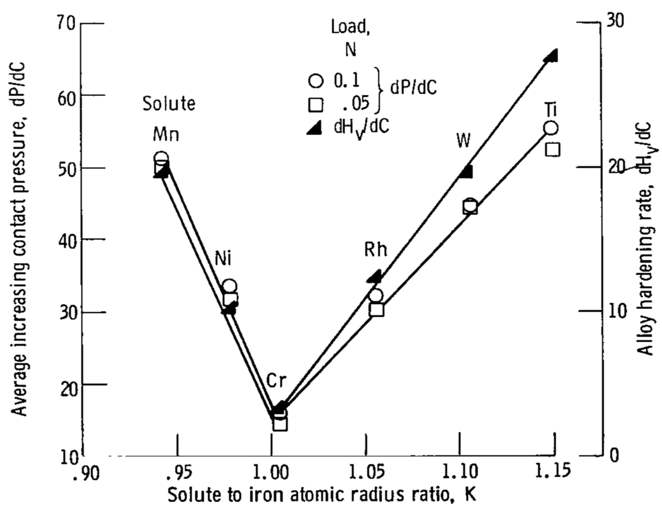


Figure 10. - Increasing contact pressure as function of solute to iron atomic radius ratio.

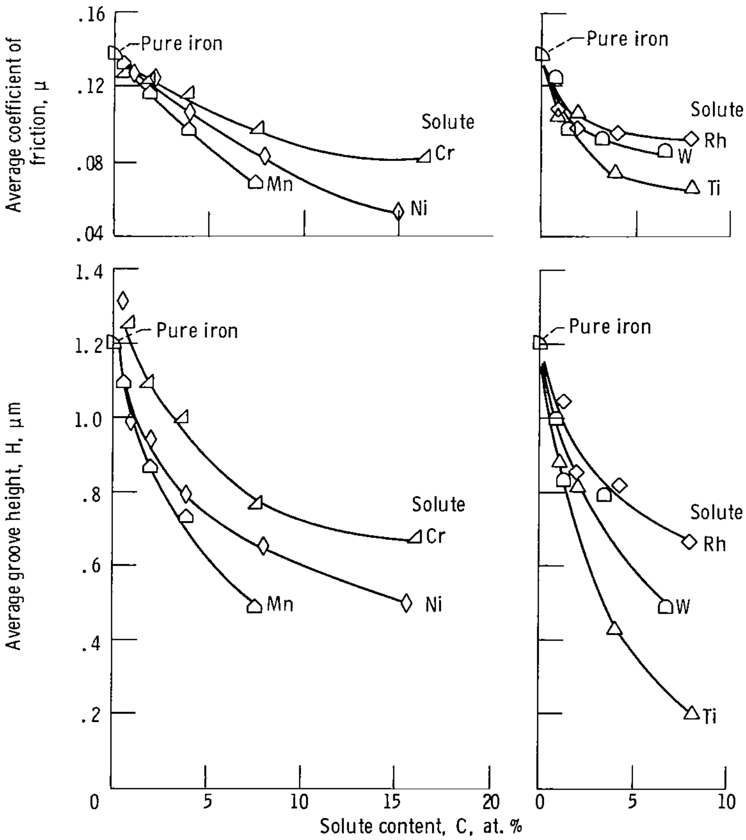


Figure 11. - Coefficients of friction and groove heights for various iron-base alloys as functions of solute content. Single pass sliding of 0.025-mm-rad. silicon carbide rider in mineral oil. Sliding velocity, 3 mm/min; load, 0.2 N; temperature, 25° C.

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16. Abstract
Sliding friction experiments were conducted with various iron-base binary alloys (alloying elements were Ti, Cr, Mn, Ni, Rh, and W) in contact with a rider of 0.025-millimeter-radius, single-crystal silicon carbide in mineral oil. Results indicate that atomic size and content of alloying element play a dominant role in controlling the abrasive-wear and -friction properties of iron-base binary alloys. The coefficient of friction and groove height (wear volume) generalloy decrease, and the contact pressure increases with an increase in solute content. There appears to be very good correlation of the solute to iron atomic radius ratio with the decreasing rate of coefficient of friction $-d\mu/dC$, the decreasing rate of groove height (wear volume) $-dH/dC$, and the increasing rate of contact pressure dP/dC with increasing solute content C. Those rates increase as the solute to iron atomic radius ratio increases or decreases from unity.

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