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**NASA Technical Memorandum 79238**

**TRIBOLOGICAL PROPERTIES OF SILICON  
CARBIDE IN METAL REMOVAL PROCESS**

**(NASA-TM-79238) TRIBOLOGICAL PROPERTIES OF  
SILICON CARBIDE IN METAL REMOVAL PROCESS  
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## ABSTRACT

This paper reviews material properties as they relate to adhesion, friction and wear of single-crystal silicon carbide in contact with metals and alloys that are likely to be involved in a metal removal process such as grinding. For simplicity of discussion, the tribological properties of concern in the metal removal processes are divided into two contributions. The first, is that in which metal removal arises primarily from adhesion between sliding surfaces in contact and the second is where metal removal occurs as a result of the silicon carbide sliding against a metal, indenting into it, and plowing a series of grooves or furrows. The paper also deals with fracture and deformation characteristics of the silicon carbide surface. The adhesion, friction and metal transfer to silicon carbide is related to the relative chemical activity of the metals. The more active the metal, the higher the adhesion and friction, and the greater the metal transfer to silicon carbide. Atomic size and content of alloying elements play a dominant role in controlling adhesion and friction properties of alloys. The friction and abrasive wear (metal removal) decrease linearly as the shear strength of the bulk metal increases. The atomic size and content of alloying elements are also important parameters in controlling friction and abrasive wear of alloys. They decrease as the solute to solvent atomic radius ratio increases or decreases linearly from unity, and with an increase of solute content. The surface fracture of silicon carbide is due to cleavages of {0001}, {1010}, and/or {1120} planes.

## INTRODUCTION

Abrasion is the main mechanism involved in the finishing of many surfaces. Grinding, lapping, polishing, sanding, filing of solid surfaces all involve abrasion.

The difficulty with metal removal studies in practical situations is that the process is extremely complex, primarily because that process involves the effects of the topographical, physical, mechanical, chemical, and metallurgical nature of materials. It is, therefore, necessary to gain a better fundamental understanding of the industrial metal removal processes in order that the process efficiency may be improved by a more judicious selection of materials, lubricants and operating parameters.

Tribology encompasses a wide range of disciplines including material science, metallurgy, chemistry, physics, microbiology and heat treating as well as mechanical engineering and lubrication engineering. Tribology, herein, involves the adhesion, friction,

wear, and lubrication of solid surfaces in contact. The adhesion, friction, wear and lubrication are extremely dependent upon the basic properties of solid surfaces, that is, the physical, chemical, mechanical, and metallurgical properties. For example, a small amount of alloying element can have a marked effect on the tribological behavior of metals (1 and 2). In order to gain a fundamental understanding of the metal removal process, it is extremely important to consider basic tribological properties of materials that determine and influence metal removal (3 and 4). Such studies should be done from a point of view of the current energy situation. Because these can lead to reducing the energy consumed in the thousands of industrial grinding operations conducted today reduce the wear to grinding, cutting and drilling surfaces, and reduce the amount of charging that occurs to such surfaces which reduces their efficiency.

Silicon carbide is expected to be one of the most desirable materials from various aspects for uses in high-hardness and/or temperature applications such as turbine blades, vanes and shrouds in gas turbine engines, ceramic seals, stable high-temperature semiconductors, and first wall materials in a controlled thermonuclear reactors. Knowledge, therefore, of tribological properties of the silicon carbide surface are important not only from the point of view of metal removal, but also for high-temperature and/or high-hardness material applications.

The objective of this paper is to review the tribological properties of single-crystal silicon carbide in contact with metallic and non-metallic materials. For simplicity of discussion, the tribological properties and interrelationships between them and basic properties of materials are divided into two contributions. The first is that in which metal removal arises from adhesion between sliding surfaces in contact; and second is that in which metal removal occurs as a result of the silicon carbide sliding against a metal, indenting into it, and plowing a series of grooves or furrows. Fracture and deformation characteristics of the silicon carbide surface are also discussed.

## NATURE OF ABRASION

Abrasion can arise when a hard particle or a hard asperity plows a series of grooves or cuts, as shown in figure 1. In plowing the material first moves upward ahead of the rake face of the particle and then moves around it and into side ridges. In cutting a ribbon of material is separated from the surface. The material moves upward past the rake face. The moving of material strongly depend on the nature of the surface, tribological properties and bulk properties of both material, particle, and environment. The interaction of these

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solid surfaces during such material removal may be called "adhesive contribution". The formation of the groove and the rate of metal removal primarily depend on the topography of particle, the rake angle, bulk properties of materials, and environment. The deformation and fracture of material associated with such groove formation and material removal would be due to an "abrasive contribution". Thus, most abrasion occurs as a result of mixture of adhesive and abrasive contributions.

#### Adhesive Contribution

With regard to a discussion of the adhesion contribution to surface interactions in metal removal, single-crystal silicon carbide, pure metals, high-purity binary alloys, and a vacuum system ( $10^{-8}$  Pa) were used to ensure a high degree of purity and cleanliness, well-defined mechanical, physical and chemical behavior, environment, and to facilitate the determination of the effect of material behavior.

#### Adhesion and Friction

The removal of adsorbed films (usually water vapor, carbon monoxide, dioxide and oxide layers) from surfaces of metals and non-metals results in very strong interfacial adhesion when two such solids are brought into contact (5). For example, when a clean titanium-iron binary alloy surface is brought into contact with a clean silicon carbide surface, the adhesive bonds formed at the solid-to-solid interface are sufficiently strong that fracture of the cohesive bonds in the alloy and transfer of the alloy to the silicon carbide surface results. This is indicated in the scanning electron micrograph and x-ray map presented in figure 2. In figure 2(a) the light area of the figure, where a lot of alloy transfer is evident, was the contact area before sliding of the rider. It is the area where the surfaces of alloy and silicon carbide were sticking, one to the other and where strong interfacial adhesion occurred. All metal and alloys, which will be discussed later with reference to this friction properties, transferred to the cohesively stronger silicon carbide.

The sliding of a metal or non-metal on a silicon carbide surface results very locally in cracks and fracture pits on the silicon carbide surface (4 and 6). The cracks are primarily produced by primary and secondary cracking of cleavage planes {0001}, {1010} or {1150} during loading and unloading processes of normal load and tangential force (friction force). The micro-fracture pits are usually produced by fatigue as a result of repeated loading and unloading during multipass slidings, but fracture wear occasionally occurs as a result of a loading and unloading processes during single-pass sliding. The scanning electron micrograph in figure 3 indicates the contact region between the titanium-iron binary alloy and silicon carbide surfaces. Instead of alloy transferring to the silicon carbide, an exceptionally large fracture occurs in the silicon carbide. A large light area at the beginning of wear track is a fracture pit. The micrograph indicates most silicon carbide wear debris has already been ejected from the surface. The smooth surface at the bottom of the fracture pit is due to sub-surface cleavage along {0001} planes of silicon carbide.

In general, the silicon carbide wear debris, generated by fracturing, strongly adheres and transfers (embed) to the metal or alloy surface. Further, some wear debris, which adhered and transferred to the metal or alloy, transfers back to silicon carbide (4).

#### Chemical Effects

In the 1940s Pauling recognized differences in the amount of d bond character associated with transition metals (7). Since the d-valence bonds are not completely filled in the transition metals, the filling of d-electron bond in the transition metals is responsible for physical and chemical properties such as cohesive energy, shear modulus, chemical stability and magnetic properties. The amount or percentage of d-bond character can be related to the chemical affinity of surfaces. The greater the amount or percentage of d-bond character that the metal possesses, the less active its surface should be. The adhesion and friction of metals in contact with themselves can be related to the chemical activity of the metal surfaces (8). The more active the metal, the higher the coefficient of friction.

The d valence bond character of the metal influences the coefficient of friction for metals in contact with silicon carbide just as it does for metals in contact with themselves. The data in figure 4 indicate the coefficients of friction for some of the transition metals in contact with silicon carbide surface as function of the d-bond character of the metal. These data indicate a decrease in friction with an increase in d-bond character. Titanium and zirconium, which are chemically very active, when in contact with silicon carbide exhibit very strong interfacial adhesive bonding to silicon carbide. In contrast, rhodium and rhenium, which have a very high percentage of d bond character, have relatively low coefficients of friction.

Adhesion and friction properties of the transition metals sliding on other non-metals such as diamond and manganese-zinc ferrite are the same as observed for metals in sliding contact with silicon carbide (9).

All the metals shown in figure 4 transferred to the surfaces of silicon carbide with sliding (6). These results indicate that (1) when metal and silicon carbide are brought into contact and adhesion occurs, the interfacial bond is generally stronger than the cohesive bond in the cohesively weaker metal, and (2) on separation of the metal and silicon carbide in sliding, fracture occurs generally in the metal.

The chemical affinity of metal to silicon and carbon play an important role in the metal transfer and the form of metal wear debris generated by fracture of cohesive bond (6). In general the less active the metal, the less transfer to silicon carbide. Titanium, having much stronger chemical affinity to silicon and carbon exhibited the greatest amount of transfer.

Thus, there appears to be very good agreements between friction and metal transfer, and chemical activity of the transition metals sliding on silicon carbide surfaces.

#### Metallurgical Effects

It is well known that for metal the presence of small amounts of alloying elements in metals can markedly alter their surface activity and bulk properties (10 to 12). This also alters the adhesion, friction, and wear of metals in contact with silicon carbide. The average coefficient of friction for pure iron in sliding contact with single-crystal silicon carbide was about 0.5, as shown in figure 4. The coefficient of friction for pure titanium was about 0.6, 0.5 for pure nickel and tungsten, and 0.4 for pure rhodium. But the presence of small amounts of alloying elements such as titanium in iron can markedly alter the adhesion and friction. For example, figure 5 indicates the coefficients of friction for titanium-iron and chromium-iron binary alloys sliding on a clean silicon carbide surface as a function of solute content. The coefficients of friction increases suddenly with the presence of small amount of alloying element, and then increase

gradually with an increase of solute content. The increasing rate in the coefficient of friction strongly depends on the alloying element, particularly, its the coefficients of friction for various numbers of iron-base binary alloys and the solute-to-iron atomic radius ratio. Figure 6 clearly indicates there is very good agreement between the coefficient of friction and the solute-to-iron atomic radius ratio. The correlation in figure 6 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 coefficients of friction increases linearly as the solute-to-iron atomic radius ratio increases or decreases from unity. The increasing rate of the coefficients of friction for alloying elements, which have smaller atomic radii than iron, are much greater than that for alloying elements, which have larger atomic radii than iron. More details that are seen from figure 6 indicate that rhodium-iron binary alloys in contact with silicon carbide showed relatively low friction.

In contrast, titanium-iron binary alloys showed relatively high friction. These results may be related to the chemical activity of alloying element, that is, the rhodium is less active metal and titanium is more active metal, as discussed earlier. The good correlation for manganese, nickel, and chromium in figure 6 is due to the percent d bond character for these metals being almost the same. Thus, the atomic size of solute in the alloy is an important primary factor in controlling adhesion and friction of iron-base binary alloys contacting silicon carbide. The chemical activity of the alloying element is also an important parameter but a secondary factor relative to the solute atomic size in controlling adhesion and friction.

#### Surface Film Effects of Gases

The surface activity related to the friction properties for a clean silicon carbide-metal contact, will be strongly affected by gas-interactions with the surface, for example, the adsorption of a gas, the chemical reaction of the surface with a gas, and so on. Figure 7 shows the coefficient of friction with a single pass of sliding for silicon carbide-to-silicon carbide interfaces and silicon carbide-to-titanium interfaces with reacted and ion-bombarded oxygen or nitrogen films. The reacted oxide and oxygen-ionbombarded surfaces interact with the silicon carbide surfaces to produce two effects: (1) silicon carbide oxidizes and forms a protective oxide surface layer; and (2) the layer increases the coefficients of friction for both silicon carbide-to-silicon carbide and silicon carbide-to-titanium contacts. The effects of oxygen in increasing the friction is related to the relative chemical thermodynamic properties of silicon, carbon, and titanium to oxygen. The greater the degree of oxidation or oxygen implantation by ion-bombardment, the more chemically active the surface and the higher the coefficient of friction. In such a situation oxygen will tend to chemically bond to the surface. The nitrogen ion bombardment gives essentially the same coefficients of friction as the argon sputter cleaned surface.

The surface conditions of the silicon carbide indicated in figure 7 will be surveyed herein. Auger emission spectroscopy can detect all elements above helium and provide a surface composition analysis to a depth of four to five atomic layer (within a surface volume 10 to 30 Å deep). Figure 8(a) is the Auger spectrum taken after the silicon carbide surface had been argon sputter cleaned. It clearly reveals the

silicon and carbon peaks as well as a small argon peak. If the argon-sputter cleaned silicon carbide surface is bombarded with oxygen ions, the spectrum of this surface has these characteristics peaks: silicon peaks at 68 and 82 eV, a carbon peak at 272 eV, and an oxygen peak at 516 eV. The two silicon peaks indicate the surface is covered by an SiO layer and above that, and SiO<sub>2</sub> outer, or surface layer (12 and 13). In figure 8(b), the carbon peak, which was of the carbide type, in figure 8(a) is nearly undetectable. Figure 8(c) is Auger spectrum for silicon carbide which had been exposed to air at atmospheric pressure at 700°C, and then had been sputter cleaned. The carbon peak is barely discernible in the spectrum, leaving an oxygen peak and a chemically shifted silicon-peak (at 80 eV), indicative of a layer of SiO<sub>2</sub> on the silicon carbide surface.

#### ABRASIVE CONTRIBUTION

##### Abrasion and Friction

Abrasion occurs when a silicon carbide grit slides on the metals and alloys. The sliding involves plastic flow and the generation of metal wear debris. For example, with a spherical silicon carbide rider on a metal, the sliding action resulted in a permanent groove, with considerable amount of deformed metal piled up along the sides of the groove in the metal surface, and with the formation of metal wear debris. The evidence is indicated in the scanning electron micrographs presented in figure 9. The wear particles exist primarily on the sides of the wear track and/or transferred to silicon carbide rider at its tip. The amount of metal or alloy removed, however, was very much less than the volume of the groove plowed out by the silicon carbide rider. Avient, et al. (14) indicate that abrasion on dry emery leads to an amount of metal removal corresponding to only about 10 percent of the volume of the grooves plowed out by the abrasives.

The width D and height H of a groove are defined in figure 10. Contact pressure P during sliding may, then, be defined by  $P = W/A$ , where W is the applied normal load and A is the projected area of contact and is given by  $A = \pi P^2/8$  (only the front half of the rider is in contact with the flat specimen). The relation between the groove width P generated by the rider and the load W would be expressed by  $W = kb^m$ , which is known as Meyer's law (15). The value of m as determined for cubic and hexagonal metals lies between 2.0 and 2.2, except for titanium and zirconium. With titanium and zirconium, m is near 2.8. The m-value of titanium and zirconium might differ from these of other hexagonal metals because titanium and zirconium do not slip predominantly on the basal planes (slip plane, {0001}; slip direction, {1120} such as do the metals magnesium, cobalt, and rhodium). Titanium and zirconium slip predominantly on the prismatic planes (slip plane, {1010}; slip direction, {1120} during plastic deformation).

##### Mechanical Effects

Khruchchov and Babichov (16) found that the resistance of metals to abrasive wear was related to their static hardness under two-body conditions; that is, the inverse of the abrasive wear rate is proportional to the hardness for a large number of annealed pure metals. Avient, Goddard, and Wilman (14) theoretically and experimentally indicate that the resistance of metals to abrasive wear was inversely proportional to the Vickers hardness of the fully work-hardened surface region on abraded metal. Similar results have been obtained by Rabinowicz, Dunn, and Russel (17) under three-body conditions. No attempt, however, has been



made to explain in detail abrasion and friction in terms of the more basic mechanical properties of metals such as shear strength. Further, there is a great lack of fundamental information relative to the friction energy dissipated in the abrasion wear process. Such information can lead to reducing the energy consumed in such operations as grinding.

Sliding friction experiments were conducted with a spherical silicon carbide rider sliding on a number of metals in oil. Oil was used to minimize adhesion effects on friction. Figure 11 indicates the coefficients of friction, the groove heights corresponding to the groove wear volume, and contact pressures as a function of shear strength of metal. The coefficients of friction and the groove heights correlate with the shear strength of the metal, and the relationship are approximately linearly decreasing. They are governed by the shear strength of the bulk metal. In figure 11 the contact pressure is nearly proportional to the shear strength of the metal.

Such relationship between the groove height or contact pressure, and shear strength of metal was also observed with a spherical silicon carbide rider in sliding contact with metals in dry argon (18).

#### Metallurgical Effects

In foregoing section, the effects of alloy elements on adhesion and friction were discussed. Those effects on abrasion and friction will be discussed herein. Figure 12 indicate typical data of the coefficients of friction and the groove height for a number of binary alloys as a function of solute content in atomic percent.

In general the coefficient of friction and groove height decrease with an increase in solute content, as shown in figure 12. The average rates of decrease in the coefficient of friction and the groove height also strongly depend on the alloying element. In contrast, figure 12 (a) indicates the contact pressure increases as the solute content increases, and the increasing rate in contact pressure depends on the alloying element.

Figure 13 presents the decreasing rates of coefficient of friction -  $dh/dc$ , and groove height -  $dH/dc$ , and the increasing rate of contact pressure  $dp/dc$  with an increase of solute contents as a function of solute to iron atomic radius ratio. 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 -  $dh/dc$ , -  $dH/dc$ , and  $dp/dc$  increase as the solute to iron atomic radius ratio increases or decreases from unity. The rates of change are minimum at a solute to iron radius ratio of 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 (19).

Leslie concluded in his review that the atomic size misfit parameter is a reasonably good indicator of the strengthening of  $\delta$ -iron by the addition of low concentration of substitutional solutes (20). The present authors have already shown that the abrasion and friction are strongly related to the shear strength of the pure metals. These two conclusions suggest that abrasion and friction can be correlated with atomic size misfit and shear strength in alloys and metals.

#### CONCLUDING REMARKS

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There are many properties such as chemical, metallurgical, physical and mechanical of metals and silicon carbide which influence the nature of the interface, and tribological properties of the solids. When clean silicon carbide and metal surfaces are brought into contact, strong bonding forces can develop across the interface. The adhesive bonding at interface is stronger than the cohesive bonding in the cohesively weaker metal. On separation of the two solids metal transfer to the silicon carbide is observed. The effects of the nature of bond character of the metal and alloying elements (atomic size misfit and solute content) can alter interfacial behavior, that is, adhesion, friction, and metal transfer. Surface films on metals and silicon carbide which interact with the contacting solid surfaces can strongly influence their tribological properties.

When a silicon carbide grit slides on the metal surface, the silicon carbide indents into it and plowing and/or cutting of a series of grooves occurs. The effects of shear strength of metal and alloying elements are important factors in controlling abrasion and friction.

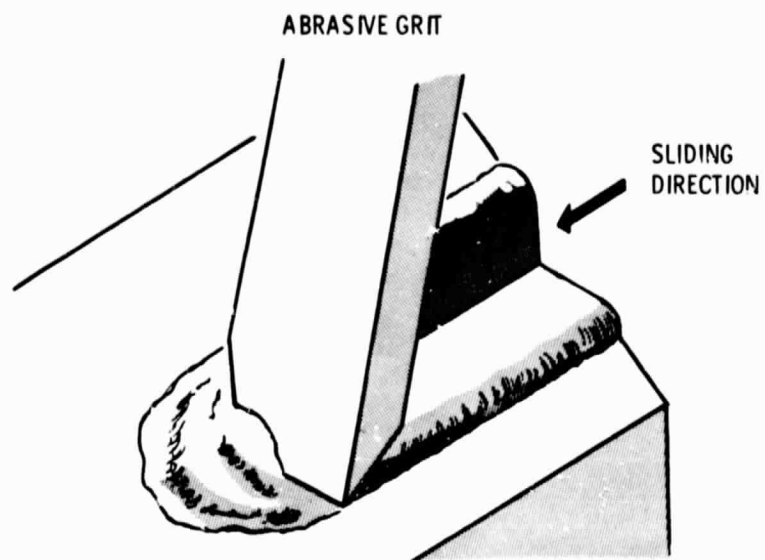
Fracture of silicon carbide can develop across the regions of real contact, which are only a small portion of the apparent contact area. Such surface fracture is due to cleavages of {100}, {1010}, and/or {1120} planes.

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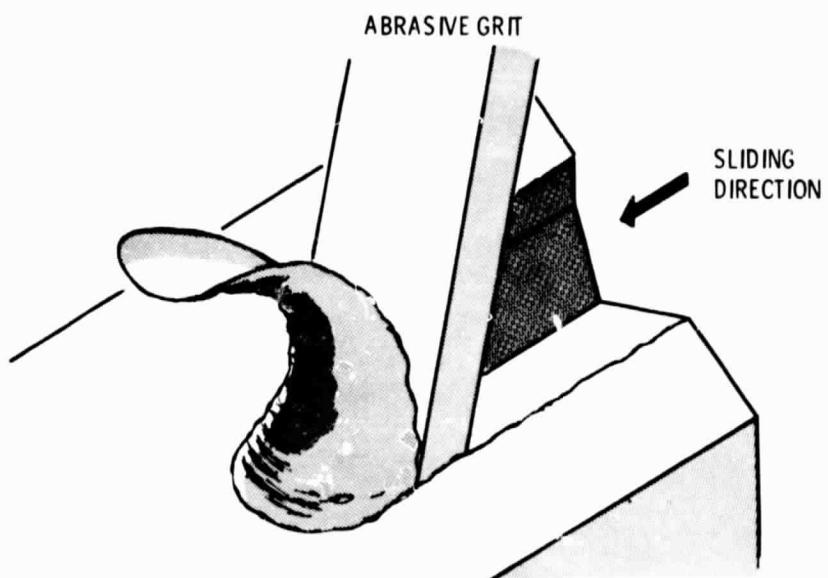
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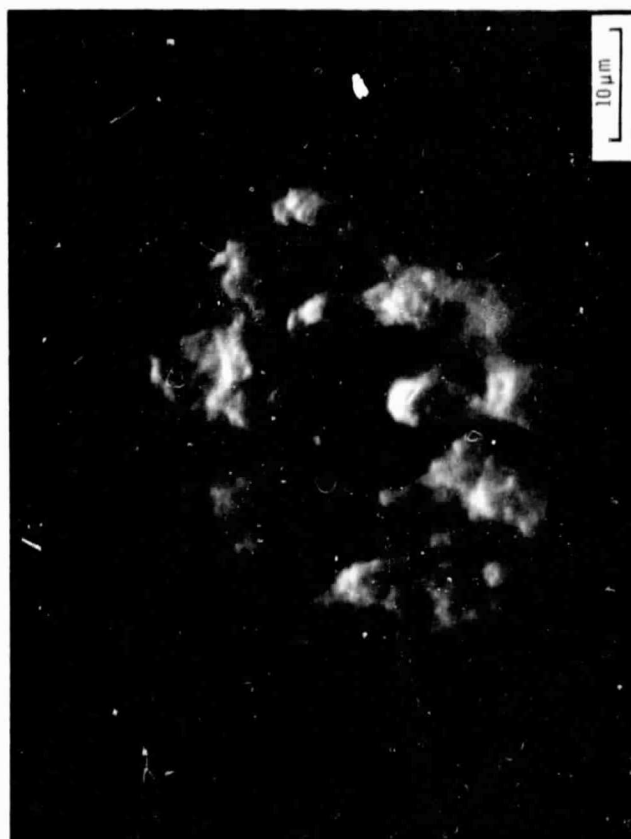
(a) PLOWING.



(b) CUTTING.

Figure 1. - Abrasion models in which abrasive grits remove material from a surface in plowing and in cutting.





(a) ALLOY-TRANSFER TO SILICON CARBIDE.

Figure 2. - 8, 12 at. % Ti-Fe binary alloy transfer to single-crystal silicon carbide surface at commencement of sliding in vacuum. Scanning electron micrograph and X-ray map of a wear track on silicon carbide (0001) surface. Sliding direction,  $\langle 10\bar{1}0 \rangle$ ; sliding velocity,  $3 \times 10^{-3}$  m/min; load, 0.2 N, room temperature; vacuum pressure,  $10^{-8}$  Pa.



(b) IRON  $K_{\alpha}$  X-RAY MAP;  $5 \times 10^3$  counts.

Figure 2. - Concluded.

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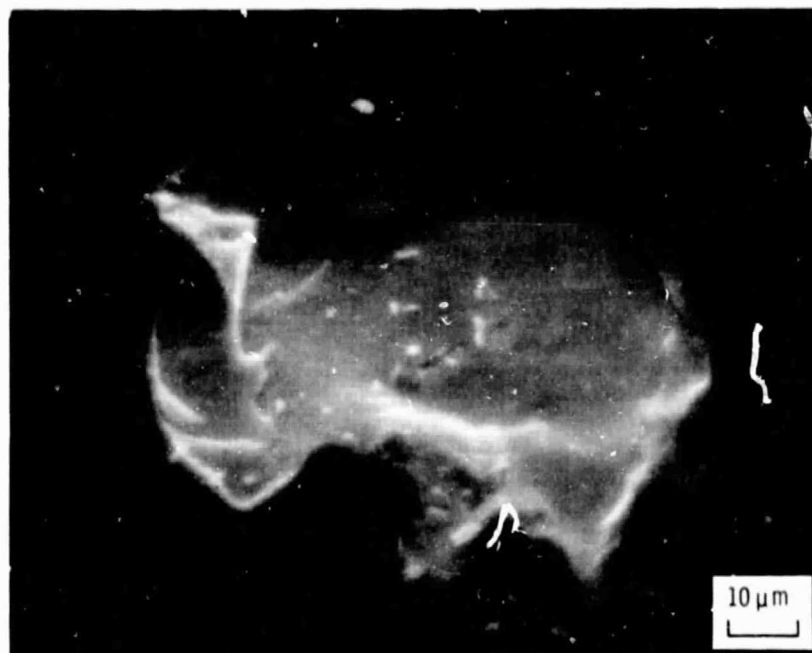


Figure 3. - Fracture pit of single-crystal silicon carbide in contact with 8.12 at.% Ti-Fe binary alloy as a result of 10 passes of alloy rider in vacuum. A scanning electron micrograph of wear track on silicon carbide {0001} surface. Sliding direction,  $\langle 10\bar{1}0 \rangle$ ; sliding velocity,  $3 \times 10^{-3}$  m/min; load, 0.2 N; room temperature; vacuum pressure,  $10^{-8}$  Pa.

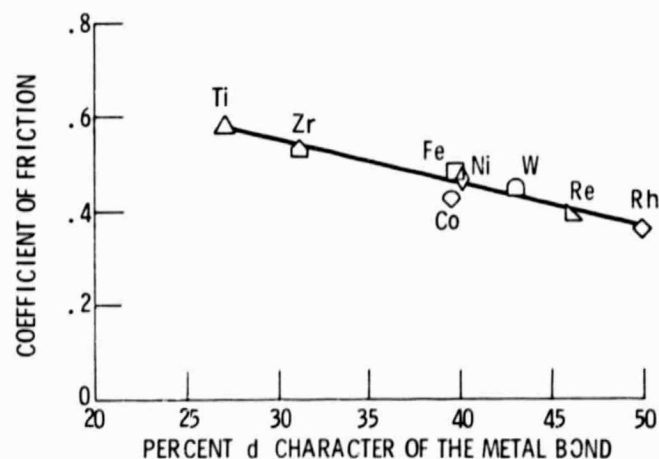


Figure 4. - Coefficient of friction as function of percent of metal bond character for single-crystal silicon carbide {0001} surface in sliding contact with various metals in vacuum. Sliding direction,  $\langle 10\bar{1}0 \rangle$ ; sliding velocity,  $3 \times 10^{-3}$  m/min; load, 0.05 to 0.5 N; room temperature; vacuum pressure,  $10^{-8}$  Pa.

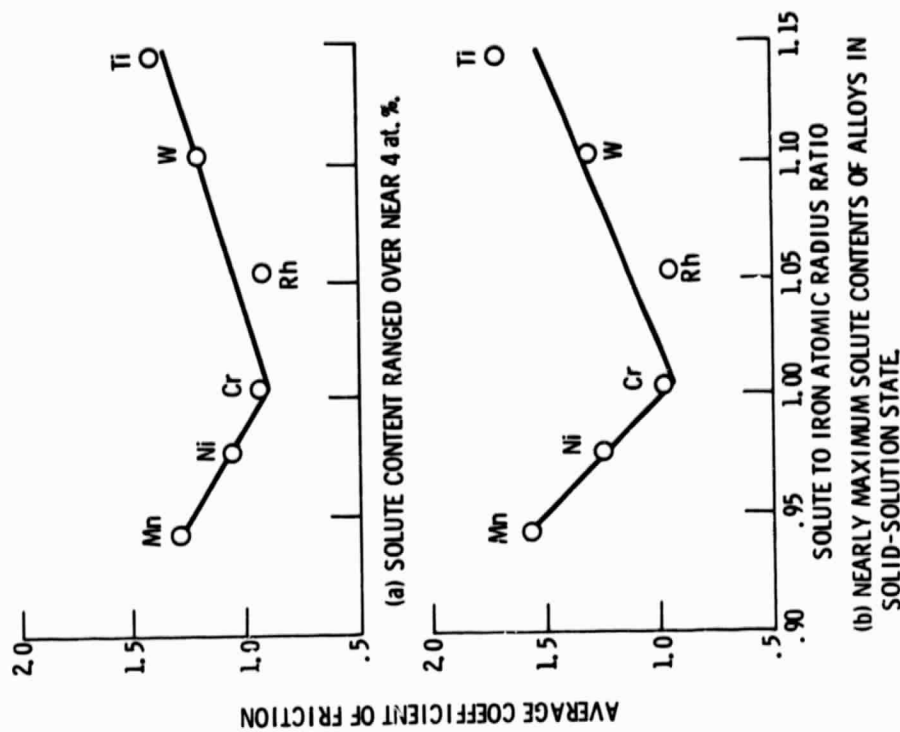


Figure 6. - Coefficients of friction for iron-based binary alloys as function of solute to iron atomic radius ratio. Single-pass sliding on silicon carbide {0001} surface; sliding direction,  $\langle 10\bar{1}0 \rangle$ ; sliding velocity,  $3 \times 10^{-3}$  m/min.; load, 0.05 to 0.3 N; room temperature; vacuum pressure,  $10^{-8}$  Pa.

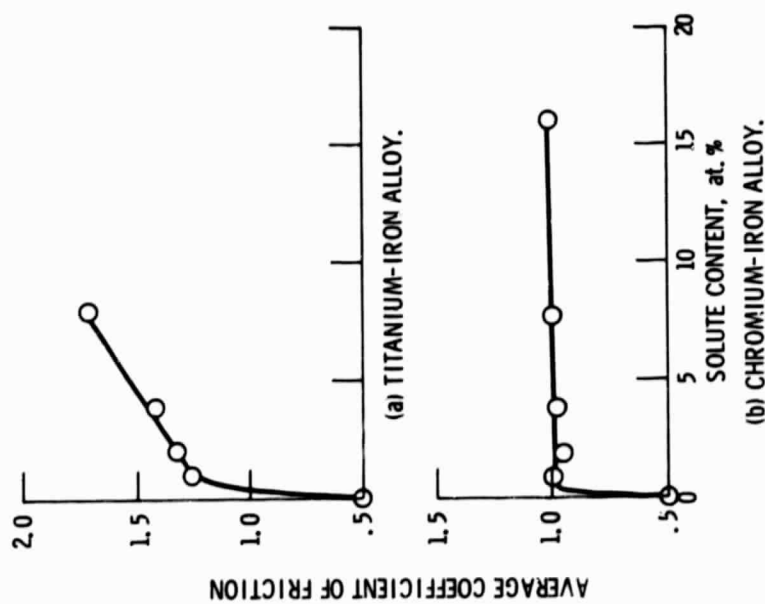
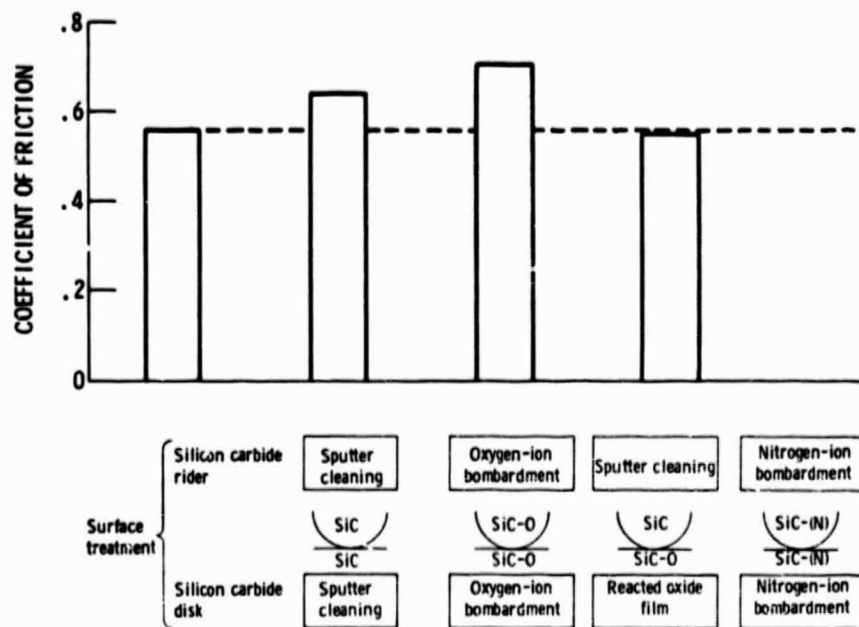
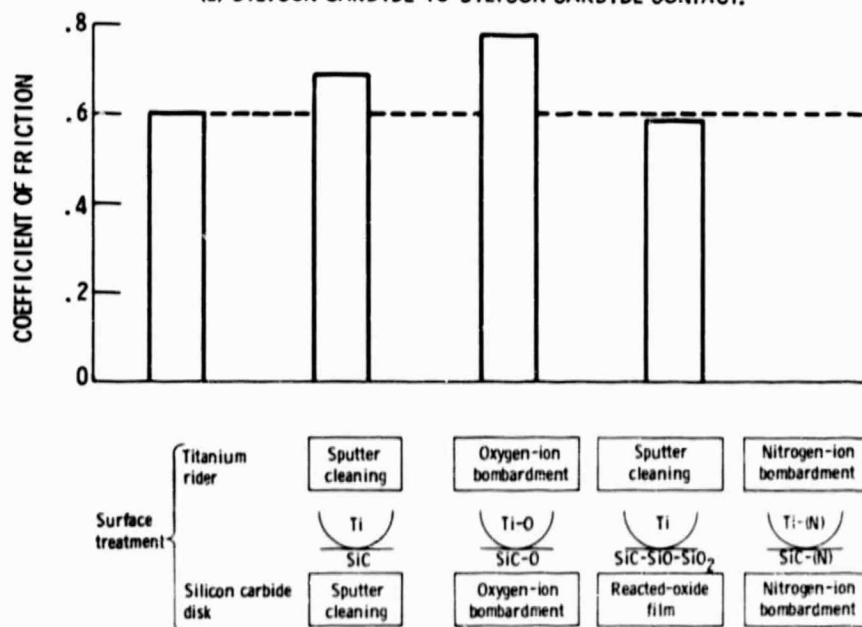


Figure 5. - Coefficients of friction for iron-base binary alloys as function of solute content. Single-pass sliding on silicon carbide {0001} surface; sliding direction,  $\langle 10\bar{1}0 \rangle$ ; sliding velocity,  $3 \times 10^{-3}$  m/min.; load, 0.05 to 0.3 N; room temperature; vacuum pressure,  $10^{-8}$  Pa.



(a) SILICON CARBIDE-TO-SILICON CARBIDE CONTACT.



(b) SILICON CARBIDE-TO-TITANIUM CONTACT.

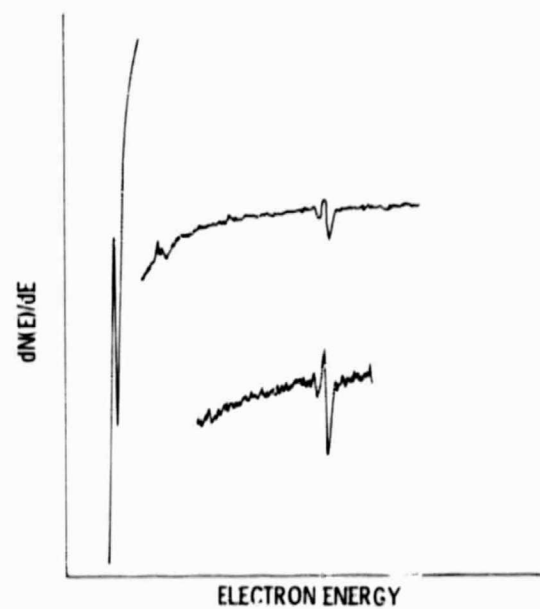
Figure 7. - Average coefficients of friction for silicon carbide-to-silicon carbide and silicon carbide-to-titanium contacts exposed to oxygen and nitrogen in various forms. Single pass sliding on silicon carbide (0001) surface; sliding direction,  $\langle 10\bar{1}0 \rangle$ ; sliding velocity,  $3 \times 10^{-3}$  m/min; load, 0.3 N; room temperature; vacuum pressure,  $10^{-8}$  Pa.



(a) ARGON-SPUTTER-CLEANED SURFACE.



(b) OXYGEN-ION-BOMBARDED SURFACE.



(c) ARGON-SPUTTER-CLEANED SURFACE WITH  
REACTED-OXIDE FILM

Figure 8. - Auger spectra of single-crystal silicon carbide (0001) surfaces.

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ORIGINAL PAGE IS POOR



(a) GROOVE AND WEAR DEBRIS (SURFACE PROFILE AND SCANNING ELECTRON MICROGRAPH).



(b) WEAR DEBRIS TRANSFERRED TO SILICON CARBIDE SPHERICAL RIDER (SCANNING ELECTRON MICROGRAPH).

Figure 9. - Wear debris and groove. Single-pass sliding of 0.04-millimeter-radius silicon carbide rider on pure iron surface; sliding velocity,  $3 \times 10^{-3}$  m/min; load, 0.25 N; room temperature; environment, argon; pressure, atmospheric.



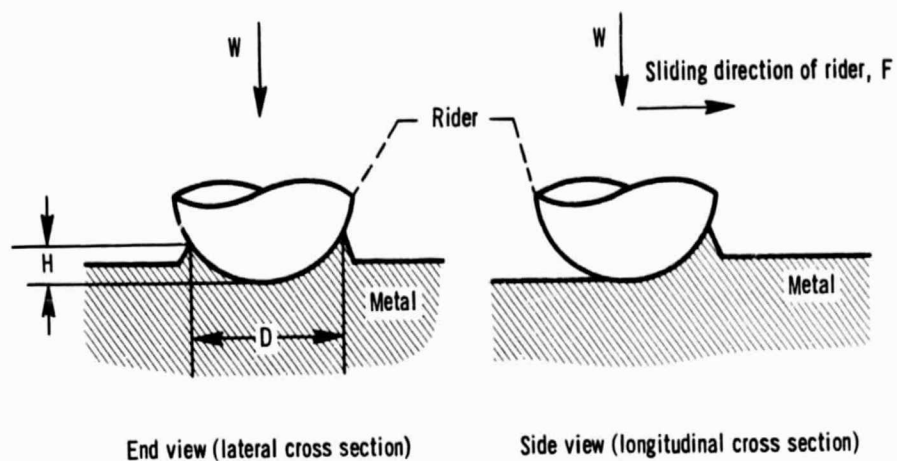


Figure 10. - Deformation of metal.

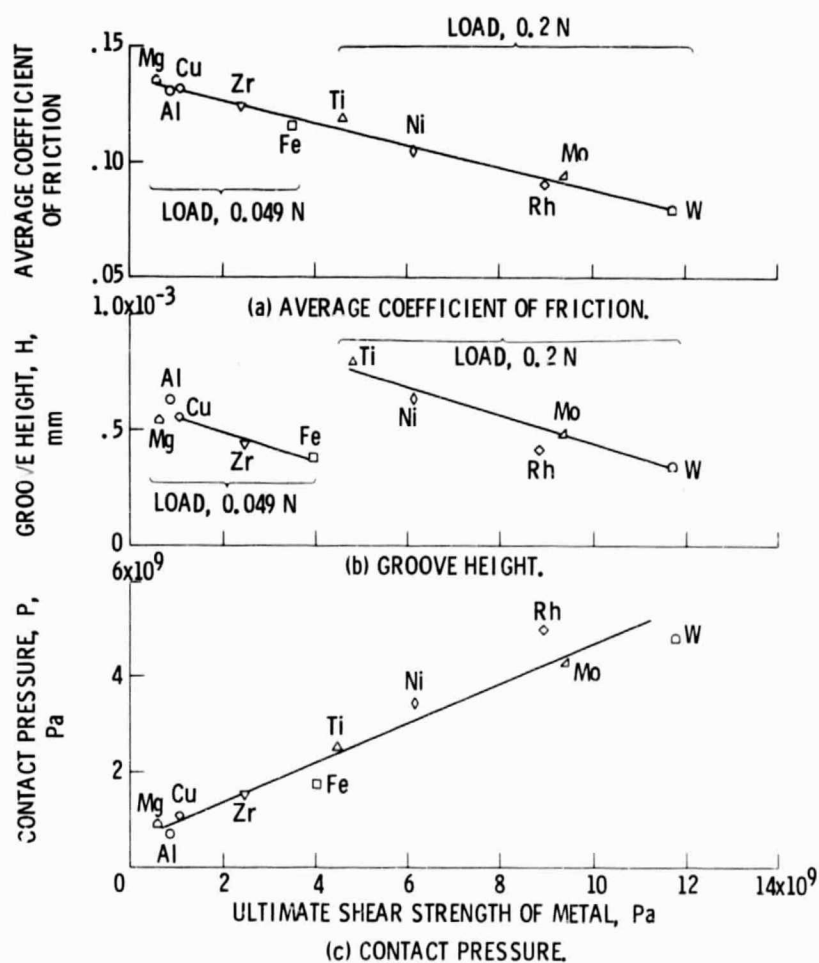


Figure 11. - Coefficient of friction, groove height, and contact pressure as a function of shear strength for various metals as a result of single-pass sliding of 0.025-millimeter-radius silicon carbide rider in mineral oil. Sliding velocity,  $3 \times 10^{-3}$  m/min; load, 0.049 or 0.2 N; room temperature.

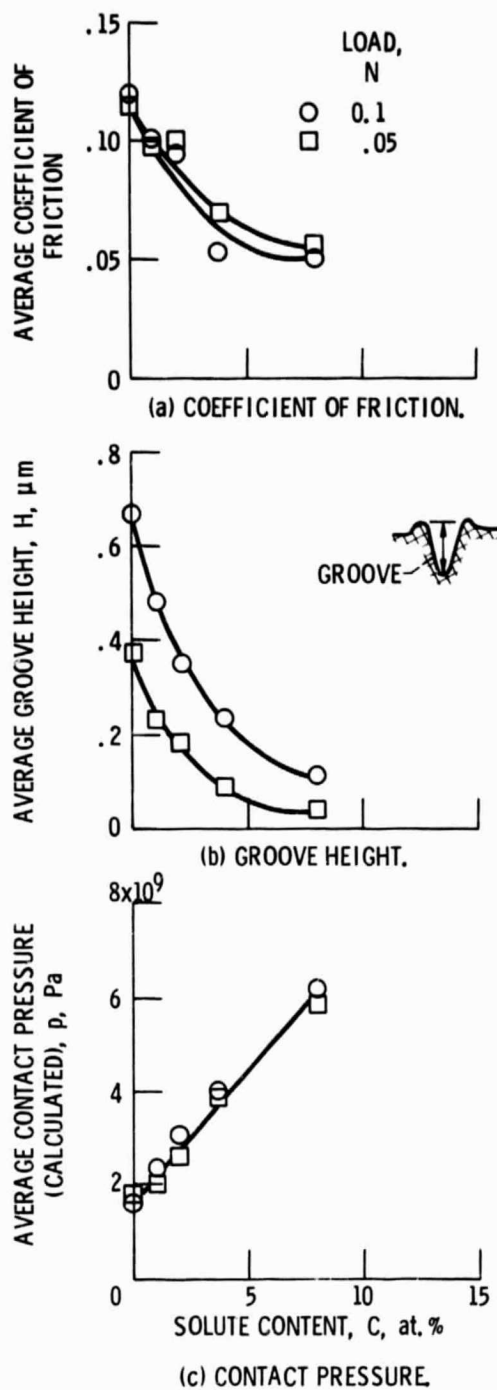


Figure 12. - Coefficients of friction, groove heights and contact pressure for titanium-iron alloy and pure iron as function of solute content. Single-pass sliding of 0.025 mm-rad. silicon carbide rider in mineral oil. Sliding velocity,  $3 \times 10^{-3}$  m/min; load, 0.1 and 0.05 N; room temperature.

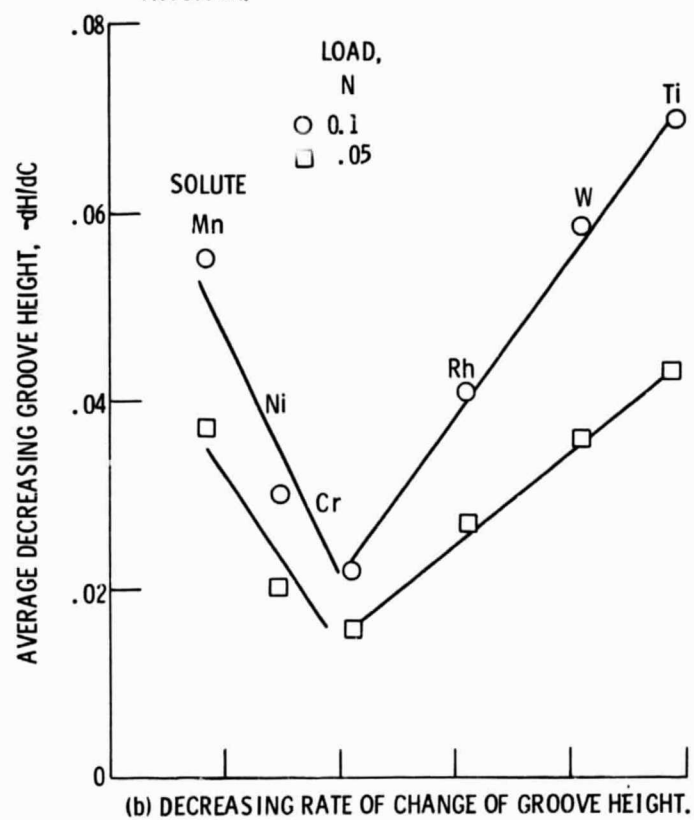
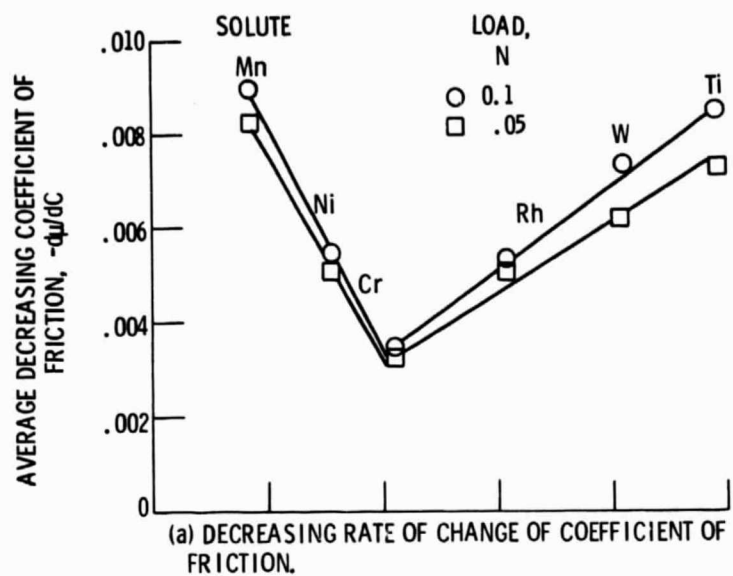


Figure 13. - Rates of change of coefficient of friction, groove height, and contact pressure as function of solute to iron atomic radius ratio.

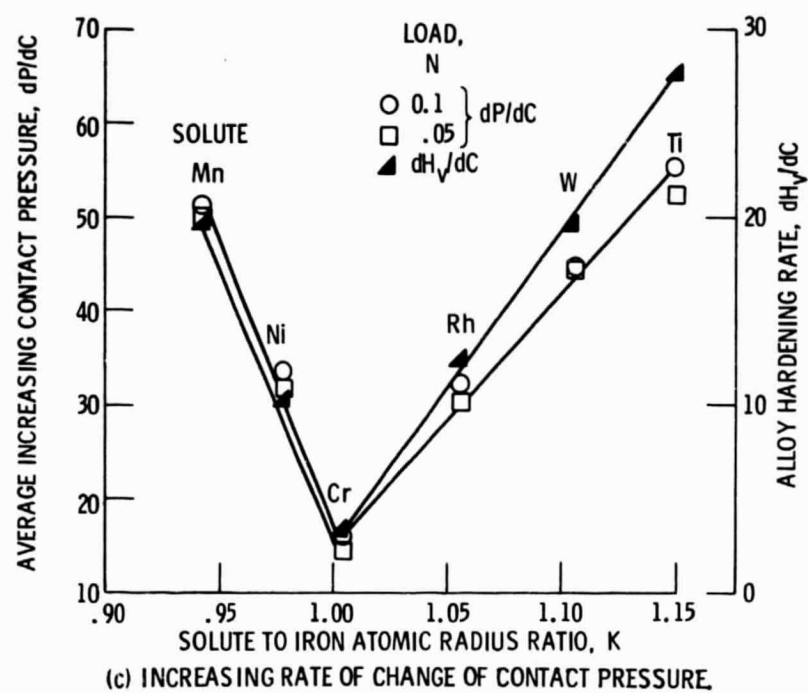


Figure 13 . - Concluded.

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16. Abstract  <p>This paper reviews material properties as they relate to adhesion, friction and wear of single-crystal silicon carbide in contact with metals and alloys that are likely to be involved in a metal removal process such as grinding. For simplicity of discussion, the tribological properties of concern in the metal removal processes are divided into two contributions. The first, is that in which metal removal arises primarily from adhesion between sliding surfaces in contact and the second is where metal removal occurs as a result of the silicon carbide sliding against a metal, indenting into it, and plowing a series of grooves or furrows. The paper also deals with fracture and deformation characteristics of the silicon carbide surface. The adhesion, friction and metal transfer to silicon carbide is related to the relative chemical activity of the metals. The more active the metal, the higher the adhesion and friction, and the greater the metal transfer to silicon carbide. Atomic size and content of alloying elements play a dominant role in controlling adhesion and friction properties of alloys. The friction and abrasive wear (metal removal) decrease linearly as the shear strength of the bulk metal increases. The atomic size and content of alloying elements are also important parameters in controlling friction and abrasive wear of alloys. They decrease as the solute to solvent atomic radius ratio increases or decreases linearly from unity, and with an increase of solute content. The surface fracture of silicon carbide is due to cleavages of {0001}, {1010}, and/or {1120} planes.</p>			
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