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METALLIC TRANSFER BETWEEN METALS
IN SLIDING CONTACT EXAMINED
BY AUGER EMISSION SPECTROSCOPY

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16. Abstract

Metallic transfer between polycrystalline metals in sliding contact was examined. Hemispherical riders of iron, nickel, and cobalt were slid on tungsten, tantalum, niobium, and molybdenum disks in ultra high vacuum. Auger emission spectroscopy was used to monitor the elemental composition of the disk surfaces. Iron, nickel, and cobalt transferred to tungsten, whereas only cobalt transferred to tantalum, niobium, and molybdenum. The results of this investigation are discussed in terms of the cohesive energy and strain hardening characteristics of the specimen materials.

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SUMMARY

Metallic transfer between polycrystalline metals in sliding contact was examined. The investigation sought to establish whether metallic transfer took place from the metal with the smaller cohesive energy to the metal with the greater cohesive energy.

Hemispherical riders of iron, nickel, and cobalt were slid on tungsten, tantalum, niobium, and molybdenum disks in ultra high vacuum. The riders were loaded at 500 grams, and the sliding velocity was 33 centimeters per minute. The riders and the disks were cleaned by argon ion bombardment. Auger emission spectroscopy was used to monitor the elemental composition of the disk surfaces before and during sliding and, thus, to determine if metallic transfer from rider to disk occurred. The friction force on the rider was also measured.

It was found that iron, nickel, and cobalt transferred to tungsten, whereas only cobalt transferred to tantalum, niobium, and molybdenum. It is concluded that cohesive energy alone does not provide a sufficient basis for predicting the direction of metallic transfer for polycrystalline metals in sliding contact. The transfer pattern is discussed in terms of the different crystal structures and strain hardening characteristics of the riders.

INTRODUCTION

The transfer of metal from one surface to another is a familiar occurrence when metals are in sliding contact (refs. 1 and 2). Since metallic transfer affects the friction and adhesive properties of the metallic couple, it is important to understand the mechanism of transfer. Knowledge of the transfer mechanism can then aid in the selection of materials to reduce friction and wear in practical sliding systems.

Recent NASA studies on the transfer mechanism have been made on dissimilar mono-crystalline metals in simple touch contact (ref. 3). These studies have led to a correlation for the direction of metal transfer when the adhesive junction is broken by simple tensile fracture. In all cases investigated, the cohesively weaker material transferred to the cohesively stronger. This indicates that the interfacial adhesive junction between the dissimilar metals is stronger than the cohesive bonds in the cohesively weaker of the two metals. Therefore, the critical physical property that determines the direction of transfer is the relative cohesive energy of the two materials. Since values of the cohesive energy of the elements are well known (ref. 4), a prediction of the direction of metallic transfer is easily obtained.

The purpose of the present investigation was to examine the metal transfer process for polycrystalline metals in sliding contact. The objective was to determine whether the above correlation for the direction of metallic transfer is valid for polycrystalline metals in sliding contact. The simple correlation was expected to require modification, since the strengths of polycrystalline materials are functions of their grain structures and degree of work hardening. In addition, the interfacial adhesive junctions are frac-tured by shear stress, and not tensile stress.

Sliding friction experiments were conducted in ultra high vacuum with a hemispher-ical rider sliding on a flat disk. Auger electron spectroscopy (AES) was used to monitor the elements on the disk surface. AES thus provided verification of the atomic cleanli-ness of the disk's surface prior to sliding, as well as evidence of metallic transfer from rider to disk during sliding.

Based on the cohesive-energy concepts, the disk and rider materials were chosen to transfer metal from rider to disk, where it could be detected by AES. Accordingly, the refractory metals, tungsten, tantalum, molybdenum, and niobium, were selected as disk materials. They all have high cohesive binding energies, with tungsten having the highest (table I). The riders were iron, nickel, and cobalt. These metals have about the same cohesive energy (table I), and it is considerably lower than that of the refractory disks. Thus, transfer is expected from rider to disk in all cases.

Although the rider materials have equal cohesive energy, they exhibit different crystal structures (table I). The disks, on the other hand, have the same body-centered cubic structure. Thus, the effect of crystal structure on the transfer process could also be assessed.

APPARATUS

The experimental apparatus has been described in reference 5 and is depicted in fig-ure 1. The basic elements of the apparatus were the specimens (a 6.35-cm-diameter

flat disk and a 0.475-cm-radius rider) mounted in a stainless-steel, bakeable vacuum chamber. The chamber was evacuated from atmospheric pressure by sorption pumps and was then brought to an ultimate pressure of less than 1×10^{-10} torr by an ion pump. The pressure was measured by a cold-cathode trigger discharge gage in the low pressure range and by a hot-cathode ionization gage in the millitorr region.

The disk specimen was driven by a magnetic drive coupling. The rider specimen was supported by an arm that was mounted from a gimbal and sealed to the chamber with a bellows. A linkage at the end of the restraining arm farthest from the rider specimen was connected to a strain-gage assembly that was used to measure frictional force. Load was applied through a deadweight loading system.

An elemental analysis of the wear track on the disk's surface was made before, during, and after sliding by a cylindrical-mirror electron spectrometer with an integral electron gun. The spectrometer analyzed a 1-millimeter-diameter spot in the wear track of the disk 153° away from the contact point of the rider. Electrostatic deflection plates in the electron gun permitted the electron beam (and, thus, the analyzed spot) to be moved in and out of the wear track. The Auger spectrum was continuously displayed with a sweep time of 0.1 second on an oscilloscope screen. A typical Auger spectrum of a tungsten disk is shown in figure 2. The disk has not been cleaned, and some oxygen and carbon are present.

In order to assure metal-to-metal contact, the rider and disk were cleaned by argon ion bombardment. This was accomplished by applying a 1000-volt negative potential to the specimen at a chamber pressure of 30 to 100 millitorrs of argon. Under these conditions, a glow discharge surrounded the specimen. Although not shown in figure 1, a retractable shutter was inserted between the specimens during sputtering to prevent material sputtered from one specimen from being deposited on the other.

SPECIMEN PREPARATION

The disks were lapped to a 0.127-micrometer (5-μin.) CLA finish. They were then cleaned ultrasonically in a freon bath, washed with ethyl alcohol, and placed in the experimental chamber. The riders were first machined to a 0.475-centimeter radius and then abraded with successively finer grades of metallurgical polishing paper to remove the machining scratches. Finally, the riders were polished with levigated alumina, washed with ethyl alcohol, and placed in the experimental chamber.

The disks, after being sputter cleaned, exhibited an Auger electron spectrum characteristic of the pure metal. Whatever impurities were present in either specimen could not have contributed greatly to the transfer process since they did not appear in the Auger spectrum of the disk during sliding. In fact, the only impurities detected in the

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Auger spectra were carbon and oxygen. Sulfur, which frequently segregates on metal surfaces following heating, was absent in these experiments.

PROCEDURE

The experimental chamber was first baked at 250° C to achieve a base pressure of less than 1×10^{-10} torr. In order to assure metal-to-metal contact, the specimens were sputter cleaned in an argon glow discharge to remove carbonacious and oxide films from the surfaces. The disk was considered clean when the carbon and oxygen Auger peaks were much smaller than the Auger peaks characteristic of the pure metal of the disk. A similar check of the condition of the rider surface was not possible. The rider was therefore sputtered for about the same length of time as the disk.

Sliding was then initiated at a velocity of 33 centimeters per minute for at least 20 revolutions of the disk. The load on the rider was usually 500 grams, but some runs were made with 100-gram and 750-gram loads. Under these sliding conditions, recrystallization due to frictional heating is absent (ref. 6).

The pressure in the chamber during sliding and with the electron gun operating was usually less than 1×10^{-8} torr.

RESULTS

The refractory metal disks were analyzed by Auger emission spectroscopy for transfer of rider material to the disk. The results for the 12 metal couples are presented in table II. Cobalt transferred to all four disks, while nickel and iron transferred only to tungsten.

The friction force on the rider was measured. Since all the couples exhibited a stick-slip mode of sliding to varying degrees, the average value of the friction force was used to compute the coefficient of friction (μ = average value of friction force/ load). The results are presented in table III.

The topography of the wear track on the disk was also examined by surface profilometry and micrography at the conclusion of each run, and the results are included in table III. The tracks were generally of three different classes. The tracks of those couples exhibiting frictional coefficients greater than 1 were deeply and irregularly plowed to a depth of about 12.7×10^{-4} centimeter (0.0005 in.). A photomicrograph and a surface profile of such a track (Fe/Mo) are shown in figure 3. The tracks of iron and nickel on tungsten exhibited moderate plowing to depths of about 2.54×10^{-4} centimeter (0.0001 in.). A photomicrograph and a surface profile of a nickel/tungsten track are

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shown in figure 4. Finally, all the couples with cobalt riders exhibited a very smooth track, with no observable plowing (sensitivity of 5.08×10^{-6} cm (2 μin.)). A photomicrograph of a typical cobalt track (Co/Mo) is shown in figure 5. The bright patches probably are not cobalt, but more likely are smoothed or textured patches of molybdenum. The couples with high friction coefficients exhibited plowed tracks, whereas couples with lower friction coefficients exhibited little or no plowing. The Auger spectrum of a tungsten disk after 50 passes of a cobalt rider is presented in figure 6.

DISCUSSION

The objective of this investigation was to examine the relation between the direction of metal transfer and the relative cohesive energy of dissimilar polycrystalline metals in sliding contact. Earlier studies (ref. 3) have indicated that when any two clean dissimilar metals are brought into contact, adhesion will occur. Simple tensile fracture of these couples has always been observed to occur in the cohesively weaker of the two metals in contact. Thus, the interfacial adhesive bond between the dissimilar metals is stronger than the cohesive bonds in the weaker of the two metals.

In the experiments reported herein, tangential motion was imposed on the adhesive metal junction. If the relative cohesive energy determines the direction of transfer, then iron, nickel, and cobalt should all have transferred to the tungsten, tantalum, niobium, and molybdenum disks, since the former are cohesively weaker than the latter (table I). However, table II indicates that they did not. Cobalt transferred to all the disks. Iron and nickel transferred to tungsten, but not to tantalum, niobium, or molybdenum. Therefore, relative cohesive energy alone does not provide a satisfactory guide to the direction of metallic transfer under conditions of sliding.

Before discussing the overall transfer results, it would be worthwhile to indicate that a certain aspect of the importance of relative cohesive energy is still valid. Tungsten has the highest cohesive energy and greatest resistance to shear of all of the specimen materials. Therefore, if transfer from the rider to the disk is to occur at all, it should be to tungsten; and, in fact, all of the rider materials did transfer to tungsten.

To understand the overall transfer results, the effect of crystal structure on the shear properties of materials must be considered. With sliding, the close-packed hexagonal metal, cobalt, develops a basal texture with basal planes parallel to the sliding interface (ref. 6). This is the preferred slip plane and the easy shear plane in cobalt, and the resistance to shear is minimal. Slip plane dislocations can easily move under the influence of the frictional shear force. With the limited number of slip systems operating in the hexagonal structure of cobalt, very little strain hardening occurs, and the easy shear property of the rider is maintained. The transfer of cobalt to the disks, therefore, proceeds as expected from simple adhesion concepts.

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In contrast to cobalt, iron and nickel are cubic structures and will strain harden very readily because of the large number of slip systems operable in these metals and the corresponding concentration of slip system dislocations (refs. 7 and 8). Sliding an iron or nickel rider on a disk will, therefore, result in considerable strain hardening of the rider in the vicinity of the contact.

Considering the cases of iron and nickel sliding on tantalum, niobium, and molybdenum, evidently the region most resistant to shear in the adhesive contact zone lies in the iron and nickel riders. This resistance to shear is a consequence of the strain hardening of the riders with sliding to the extent that they offer greater resistance to shear than do the disks. The rider strain hardens faster than does the disk because the rider is continually worked, whereas the disk is being worked along the entire circumference of the wear track. Shear, therefore, occurs in the tantalum, the niobium, and the molybdenum, and some of the molybdenum is transferred to the rider, as verified by AES analysis of the rider for the case of the nickel/molybdenum specimens.

On the other hand, for iron and nickel sliding on tungsten, the disk material with the greatest resistance to shear, an intermediate situation obtains. It was found that transfer occurred from the disk to the rider (as verified by AES analysis of the rider for the case of Fe/W). This transfer in both directions indicates that the shear strengths of the work-hardened rider and wear track of the disk were about the same.

Therefore, while the cohesive energies of iron, nickel, and cobalt are similar, the strain-hardening characteristics of the metals undergoing sliding are different. The consequence of this difference is the failure of relative cohesive energy alone to provide a satisfactory guide to metallic transfer in this geometrically asymmetrical situation.

The concepts employed here to discuss the transfer pattern are also consistent with the nature of the wear tracks on the disks and the friction of the couples. The strain-hardened iron and nickel plowed the tantalum, niobium, and molybdenum disks. These couples also exhibited high friction. The couples with cobalt riders, on the other hand, exhibited lower friction and did not plow the disks at all. This is consistent with the easy shear properties of cobalt. The iron and nickel riders on tungsten exhibited moderate plowing, which is expected for this case of two-way transfer.

CONCLUDING REMARKS

The results obtained with Auger electron spectroscopy show that nickel, iron, and cobalt transfer to the tungsten disk, whereas only cobalt transfers to the tantalum, molybdenum, and niobium disks. On the basis of cohesive energy alone, all three rider materials should transfer to all four disks. It is thus concluded that cohesive energy alone does not provide a sufficient basis for predicting the direction of metallic transfer for polycrystalline metals in sliding contact.

During sliding, tangential shear can result in an alteration in the nature of the materials in and near the contact zone. Both texturing in hexagonal metals and strain-hardening can influence observed results. These effects may be sufficient to reverse the direction of metal transfer from that seen in simple adhesion experiments.

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TABLE I. - CRYSTAL STRUCTURES AND PHYSICAL

PROPERTIES OF SPECIMENS

Metal	Crystal structure at 25° C (a)	Cohesive energy, kcal/(g)(atom) (b)	Shear modulus, kg/cm^2 (b)
Iron	Body-centered cubic	99.4	0.831×10^{-6}
Nickel	Face-centered cubic	101.7	.765
Cobalt	Close-packed hexagonal	102.3	.779
Tungsten	Body-centered cubic	199.7	1.56
Tantalum	Body-centered cubic	186.7	.7
Niobium	Body-centered cubic	174.3	.382
Molybdenum	Body-centered cubic	157.1	1.18

[a]From ref. 8.
[b]From ref. 4.

TABLE II. - METALLIC TRANSFER

FOR DISSIMILAR METALS IN

SLIDING CONTACT

Disk	Rider	Transfer of metal from rider to disk
Tungsten	Iron	Yes
	Nickel	Yes
	Cobalt	Yes
Tantalum	Iron	No
	Nickel	No
	Cobalt	Yes
Molybdenum	Iron	No
	Nickel	No
	Cobalt	Yes
Niobium	Iron	No
	Nickel	No
	Cobalt	Yes

TABLE III. - FRICTION COEFFICIENT AND CONDITION OF WEAR TRACK FOR

DISSIMILAR METALS IN SLIDING CONTACT

[Sliding velocity, 33 cm/min; load, 500 g.]

Disk	Rider					
	Iron		Nickel		Cobalt	
	Friction coefficient, μ	Condition of wear track	Friction coefficient, μ	Condition of wear track	Friction coefficient, μ	Condition of wear track
Tungsten	0.6	Plowed lightly	0.5	Plowed lightly	0.7	Smooth
Tantalum	>1	Plowed	>1	Plowed	.7	Smooth
Molybdenum	>1	Plowed	>1	Plowed	.7	Smooth
Niobium	>1	Plowed	>1	Plowed	.7	Smooth
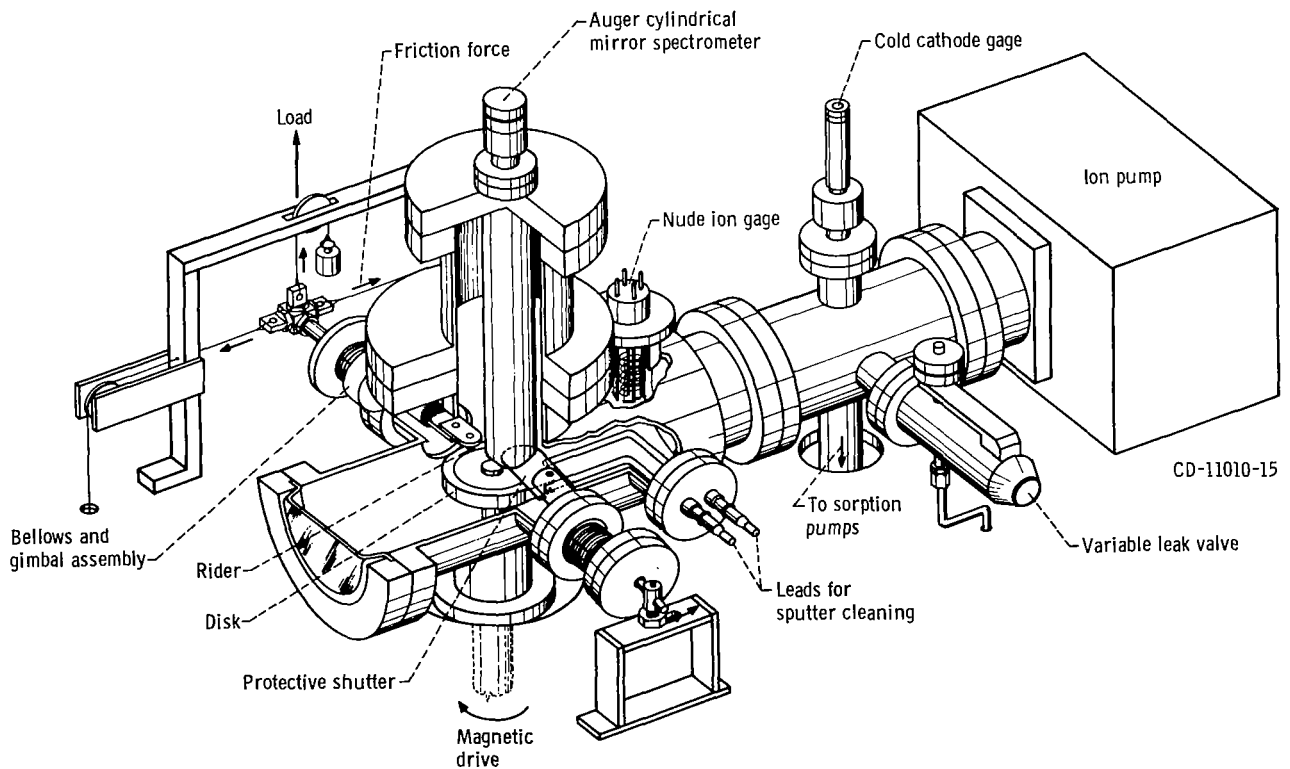
Figure 1. - Friction apparatus with Auger spectrometer.
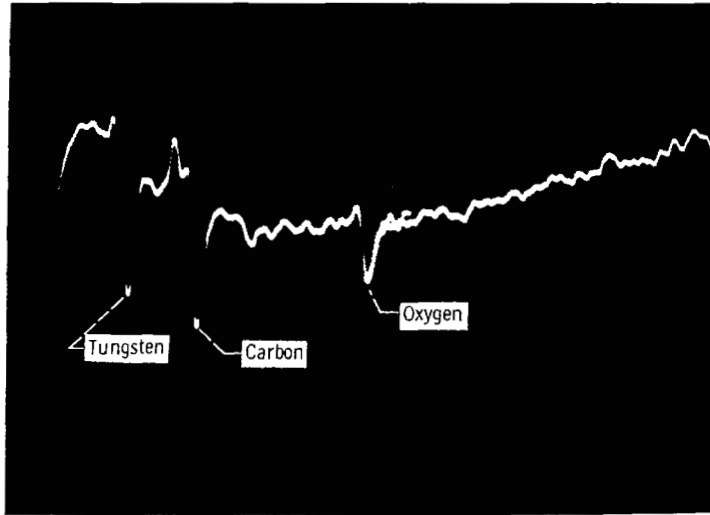
Figure 2. - Auger spectrum of tungsten disk before sputter cleaning.
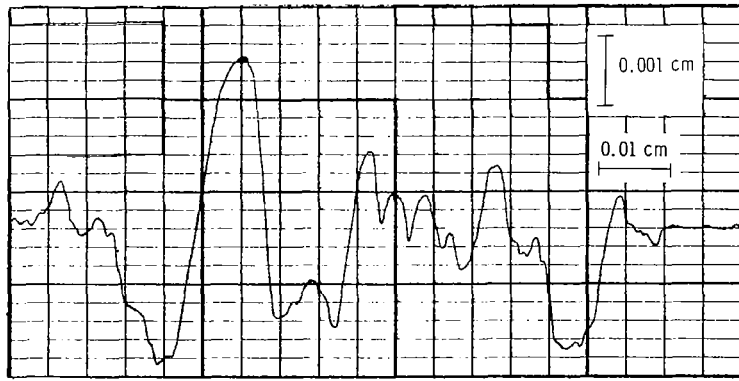
Figure 3. - Photomicrograph and surface profile of wear track of iron rider on molyb-denum disk. (The micrograph and the profile are not necessarily of the same point on the disk.)
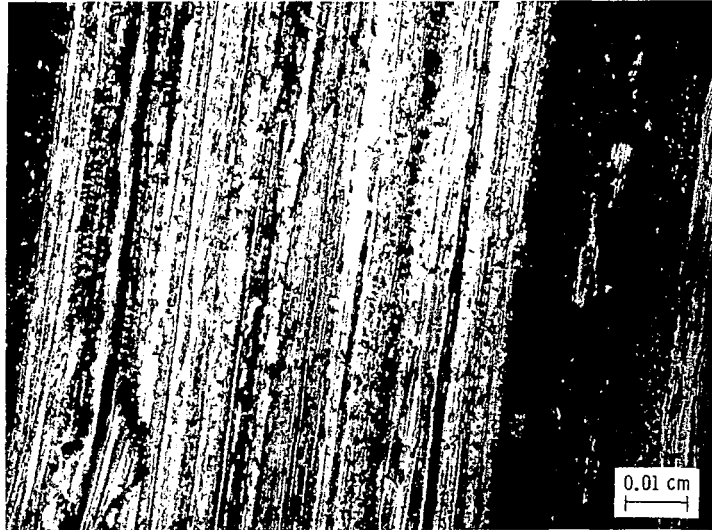
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Figure 4. – Photomicrograph and surface profile of wear track of nickel rider on tungsten disk. (The micrograph and the profile are not necessarily of the same point on the disk. Also, note that the vertical scale has been expanded relative to that of fig. 3.)
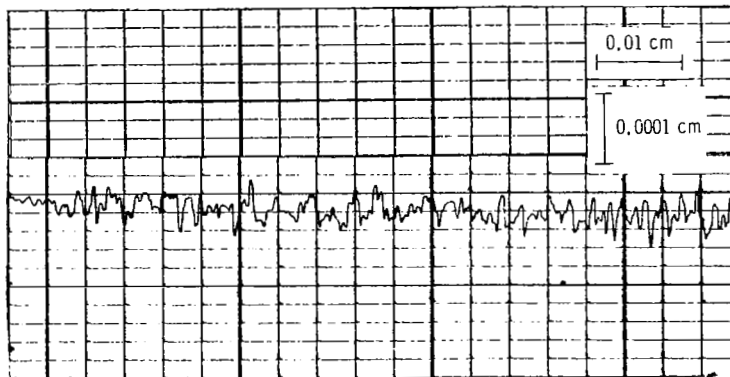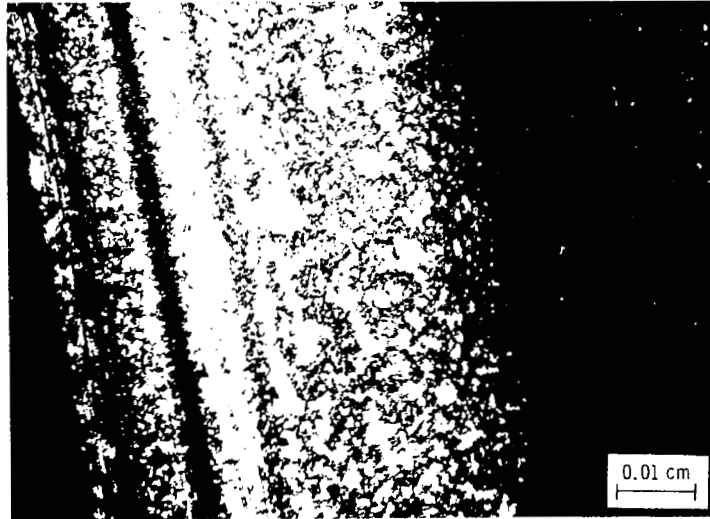
Figure 5. - Photomicrograph and surface profile of wear track of cobalt rider on molybdenum disk. (The micrograph and the profile are not necessarily of the same point on the disk. Also, note that the vertical scale has been expanded relative to those of figs. 3 and 4.)
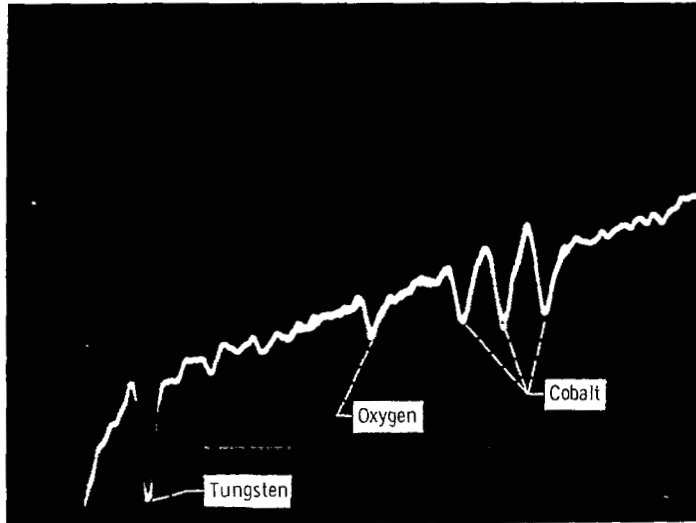
Figure 6. - Auger spectrum of a tungsten disk after 50 passes of a cobalt rider.