ning against mild steel. At low load (between 0.46 and 0.91 kg) and sliding speed (0.5 m/sec), there is a transition from mild wear to severe wear. This transition, which has been found in other rubbing systems and is generally known as $T_2$, has not been well documented by the wear results in the present work, but its presence has been established with a reasonable degree of certainty from the appearance and character of the wear debris (Tables 2 and 3, respectively).

The severe wear regime exists over a wide range of loads and speeds, and is associated with lower wear rate and coefficient of friction than normal for this type of wear.

A second transition back from severe to mild wear (designated previously $T_3$) did not become fully established in the present work, but occurred intermittently under certain test conditions. This can be seen from Figs. 3(e) and 4(c), were at given points during the test runs the wear rate (and coefficient of friction) dropped and mild wear began to set in, but did not achieve any degree of permanency. The wear debris corresponding to these runs also contained more cobalt oxide than runs of slightly different load/speed combination (Table 3).

In view of the intermittent occurrence of mild wear, it is anticipated that within a judicious range of loads and sliding speeds, the $T_3$ transition could become properly established with cobalt running against mild steel. However, the range of conditions under which it occurs would certainly be much more limited than with, for example, steel rubbing against steel [1].

The third transition, an increase in equilibrium wear rate at high loads and speeds (Fig. 5), probably occurs when frictional heating causes significant volumes of cobalt in the vicinity of contacting asperities to transform to the $\beta$ form (f.c.c.). Previous work has shown that when this happens the coefficient of friction increases to about 0.8 and the wear rate increases by about two orders of magnitude [5, 9]. The welds formed between the rubbing surfaces become much stronger, and rougher surfaces (Table 2) and coarser wear particles are produced. The high coefficient of friction causes a large increase in surface temperature ($\theta$, values $>1130$ deg C) and it is probably that easy removal of thermally softened material contributes to the high rates of wear that are obtained.

The above explanation of the third transition is supported by the X-ray diffraction results on the wear debris, which indicate that the cobalt debris changes from $\alpha$ to $\beta$ form simultaneously with the occurrence of high coefficients of friction and high $\theta$ values. The presence of austenite rather than $\alpha$-iron in the debris once this transition has occurred is probably due to alloying between iron and cobalt at the conjunctions as a result of the very high temperatures attained.

The general pattern of wear for cobalt would therefore appear to possess similarities to the wear behavior found in other systems, with the additional complication of a transition in wear due to the transformation of cobalt from $\alpha$ to $\beta$ form. The evidence for a regime of wear characterized by clean rubbing surfaces and partially oxidized debris found in a previous investigation of the wear behavior of porous cobalt [5] conflicts with the present work, but it is possible that the oxide found in the debris in that work could have arisen from oxide films on the surface of the cobalt powder.

Conclusions

1. Over a large range of rubbing conditions, very uniform wear occurs. This wear is of the severe type but the rate of wear is only moderate and the coefficient of friction is low (about 0.45).

2. Evidence has been found for the occurrence of three transitions in wear rate; namely mild to severe at low loads and speeds, severe wear back to mild at high loads and speeds and a further change to a particularly severe form of wear believed to be related to transformation of cobalt from $\alpha$ to $\beta$ form in the vicinity of contacting asperities.

3. The wear rate of the mild steel ring is 1 to 2 orders of magnitude lower than that of the cobalt pin.

Acknowledgments

Thanks are due to Mr. J. A. Shanley for assistance with the experimental work and to the Cobalt Information Centre for permission to publish this paper.

References


DISCUSSION

M. A. Clegg

The author's study is of special interest to the reader in that much higher speeds were employed than in the Sherritt work [1] and the influence of frictional heating and oxidation was shown more markedly. However it is suggested that a more detailed study at the lower speeds may show a decrease in the coefficient of friction and the wear rate due to preferred orientation, although possible at the lower loads used. Nevertheless the explanation of the author that the second transition from severe to mild wear was associated with the presence of more cobalt oxide, is certainly acceptable.

The behavior observed at high loads and speeds is consistent with an increased tendency to frictional welding due to the presence of f.c.c. cobalt and the calculated surface temperatures support the transformation model. However the pronounced retention of f.c.c. cobalt in the debris (presumably examined at room temperature) is somewhat surprising, notwithstanding that the transformation in cobalt is sluggish, and deserves further comment. Possibly alloying has taken place at the elevated surface temperatures resulting in a Co-Fe alloy debris with an f.c.c. structure at room temperature.

R. L. Prowse and L. F. Norris

The author has supplied welcome engineering data, contributing to a better understanding of the complex tribological properties of
cubic. The author indicates that the cobalt was used in the "as-received condition." Generally, this means that the cobalt was a mixture of the α and β crystalline forms. Were any attempts made to heat treat and examine the hexagonal form? The severe wear transformation would have been even more marked if the transformation was one of hexagonal cobalt to cubic cobalt rather than a mixture of hexagonal and cubic to cubic.

If one accepts the transition of mild to severe wear as being associated with the α to β transformation in cobalt, what is the explanation for the transition of severe to mild wear at low loads and speeds? Further, how is the initial mild to severe form of wear explained?

Author's Closure

The author would like to thank the discussors for their comments.

The most interesting study by Huppmann and Clegg on the friction and wear behavior of polycrystalline cobalt was not referred to in the paper because it was considered that there was no overlap between the two pieces of work. The maximum load (9.05 kg) used in the present work was much lower than the value (27.3 kg) that they found necessary to produce preferred orientation at the rubbing surfaces. Furthermore, Huppmann and Clegg used a hardened steel counterface (Rc 58-60) under rubbing conditions resulting in low frictional heating. Transfer of cobalt to the counterface occurred under these conditions, but not in the present work (see later) which employed a mild steel counterface and rubbing conditions giving rise to substantial frictional heating. Caution must therefore be exercised in comparing results from the two investigations.

Whilst alloying between cobalt and iron cannot be ruled out as a possible means of accounting for the detection of β-Cobalt in the wear debris at room temperature, the most probable explanation is the suppression of the β-α transformation which is known to occur in small particles.\(^6\)

The author would agree with Prowse and Norris that further work is necessary to elucidate whether phase transformation or brittle disintegration is the controlling mechanism of the third transition.

The steel rings were examined by optical microscopy at magnifications up to X40, but evidence for transferred cobalt particles was not found. The change in slope in Fig. 1 (α) correlated well with the build-up of oxide films on the rubbing specimens as the wear changed from severe to mild form. The transition from mild to severe wear observed with increasing load at a sliding speed of 0.5 m/s is believed due to the rubbing conditions at theasperity contacts becoming too severe for the formation of adherent oxide films.

Only a crude system was used for collecting the wear debris in this work, namely a container fixed immediately beneath the pin and ring. Fine particles of debris may have been carried away in air currents, and therefore more reliance is to be placed on the species identified rather than their relative amounts.

Attempts were not made to ensure that the cobalt was completely in the hexagonal form. In previous work (reference [3] of the paper), wear tests on specimens containing about 30 percent β phase revealed that after a short period of testing complete reversion to the hexagonal form had occurred at the rubbing surface. It is therefore believed that the presence of some β phase in the starting material would have little influence on the friction and wear behavior.

---

D. H. Buckley\(^6\)

The author has conducted an interesting study of the friction and wear behavior of cobalt in contact with steel. Care must be taken in the interpretation of wear results from pin or ring experiments where weight loss is the method used for the determination of wear to both specimens. The cobalt pin in the author's experiments is in continuous rubbing contact while any one spot on the steel ring surface experiences only intermittent contact. Thus, the surficial temperature of the pin will be higher than the ring. This can increase the amount of oxidative wear occurring to the pin.

One might anticipate that a thin film of metallic cobalt would transfer to the steel surface and ultimately cobalt would be sliding on a thin film of itself. Did the author analyze the ring to see if cobalt had transferred to the steel? This might account for the change in the slope of the wear curve in Fig. 1 (α). Further, the friction coefficients measured by the author seem to indicate that this may be occurring.

The wear data of Figs. 1 to 4 of the paper indicate a markedly higher rate of wear for the cobalt pin than for the steel ring. An examination of Table 3, however, would indicate that α-iron is one of the main constituents of the wear debris for all load and speed conditions except one. Could it be that oxidation and transfer of cobalt to the steel ring influences the ring weight loss measurements? Such affects could result in low weight loss measurements for the steel ring.

---


\(^6\) NASA–Lewis Research Center, Cleveland, Ohio.

---
