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# Phase Transformation and Its Effect on Dry Sliding Wear of Electro-Pressure Sintered Cobalt and Cobalt-Base Composites

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**Abstract.** Room-temperature dry sliding wear behavior of hot-pressure sintered monolithic Co, Co-20 wt.% CuSn and Co-20 wt.% WC composites were investigated. Wear tests of the materials were carried out using a pin-on-disk wear tester at various loads of 10N-100N under a constant sliding speed condition of 0.38m/s against glass (83% $SiO_2$) beads. Sliding distances were varied with a range of 100m-600m. A scanning electron microscopy was used to examine worn surfaces, cross sections, and wear debris. X-ray diffraction (XRD) was utilized to identify phases of the specimen and wear debris. All specimens exhibited low friction coefficients ranging from 0.12 to 0.4. The sintered Co exhibited distinctive wear that was characterized by shallow dug canals on worn surface, a very thin detaching surface layer, and fine debris. Thermal transformation of the Co specimen from ε (hcp) phase to α (fcc) phase occurred during the wear of the Co, which was inferred from XRD analysis of the wear debris. The transformation was suggested to cause the thin detaching surface layer and the fine wear debris of the sintered Co. The wear of the Co-CuSn composite proceeded by shear deformation of the CuSn particles, while WC particles of the Co-WC composite sustained most of the applied load, which resulted in the low wear rate with fine wear debris of the Co-WC composite.

## Introduction

Cobalt and cobalt-base alloys have been widely used as wear-resistant materials because of their superior galling-wear resistance. Because of the excellent property, they are utilized broadly for parts that require minimal wear and erosion. Cobalt is also employed as the best metal matrix (metal bond) of a diamond-impregnated sawblade segment, which is normally used for a stone sawing. Cobalt has a superb diamond-holding capability and exhibits proper wear rate for an optimum stone sawing [1]. Since cobalt is neither too soft nor too hard, wear resistance of the cobalt matrix easily corresponds to the abrasiveness of the workpiece material, which results in an ideal cutting for most workpieces. In spite of the interesting wear behavior of the cobalt and its alloys, wear mechanisms of them under various wear conditions are not fully understood, yet.

Friction and wear of various hcp (hexagonal close packed) metals were studied by Buckley et al. to find out a correlation between friction force and lattice-axis ratio (c/a) of the lattice [2]. They reported that the hcp metals with high c/a ratio exhibit low friction force and wear rate. They attributed the low friction and wear of the metals to their limited crystallographic slip system, which is caused by the high lattice-axis ratio. Wilson and Ward investigated dry wear behavior of porous hot-pressure sintered cobalt to reveal that the wear behavior of the material is strongly influenced by the amount of porosity in the sintered material [3]. Phase transformation of hexagonal metals is also reported to vary the tribo characteristics of them by many researchers [4-6]. At temperatures below 417ºC, cobalt has a hcp (hexagonal close packed, ε phase) lattice, and above the temperature, the structure is known to transform to an fcc (face centered cubic) structure (α phase). However, hot-pressed cobalt powders normally possess both α (fcc) and ε (hcp) phases [1]. The phase composition is dependent on the type of compacted powder and its processing conditions, which is not yet well understood [1]. It has been reported that the amount of the ε phase in a cobalt alloy

increases during plastic deformation through stress-induced martensitic transformation [4], while Sort and his co-workers reported a decreasing ε-phase composition with increasing deformation strain [6]. The reported results are contradictory, and the effect of the transformation on the wear of cobalt is not yet reported.

The present research was performed with the purpose of characterizing sliding wear behavior and investigating wear mechanisms of the hot-pressure sintered cobalt and cobalt-based composites. Dry sliding wear tests of sintered Co, Co-20 wt.% CuSn and Co-20 wt.% WC composites were carried out at room temperature in the air, and their wear behavior was characterized with emphasis on the phase transformation of cobalt during the wear.

## Experimental procedures

Co, CuSn, and WC powders with the average size of 1.5μm, 15μm, and 6.7μm, respectively, were used to fabricate disk specimens of Co, Co-20 wt.% CuSn, and Co-20 wt.% WC compacts. Diameter and thickness of the disk specimen were 25.4mm and 4mm, respectively. The specimens were electro-pressure sintered at temperatures ranging from 800ºC to 950ºC under 35MPa pressure. Hardness and density of the sintered disk specimens were measured. Dry sliding wear tests of the sintered disks against $SiO_2$ beads were carried out in the air at room temperature using a pin-on-disk wear tester with a 0.38m/sec sliding speed. Applied wear-loads were varied from 10N to 100N and various sliding distances, from 100m to 600m, were utilized. Wear rate was calculated by dividing the volume loss of a specimen by sliding distance. Worn surfaces, their cross sections, and wear debris of the disk specimens were examined by a scanning electron microscope (SEM). Phases of the specimen and wear debris were identified by an X-ray diffraction (XRD) analysis.

## Results and discussion

**Wear test results and SEM analysis.** Hardness, density, and calculated porosity of the sintered disk specimens are listed in Table 1. The porosity of the sintered Co was the lowest, while the Co-20 wt.% WC composite had the highest porosity. Addition of the soft CuSn powder lowered the hardness of the Co-20 wt.% CuSn composite. The high porosity of the Co-20 wt.% WC composite seemed to cause the low hardness of the composite despite the hard WC particle addition.

Table 1. Hardness, density, and porosity of the sintered disk specimens.

| Sintered Material | Hardness [HRB] | Density [g/cm$^3$] | Porosity [%] |
|---|---|---|---|
| Co | 103.1 | 8.68 | 2.5 |
| Co-20 wt.% CuSn | 99.9 | 8.60 | 2.8 |
| Co-20 wt.% WC | 102.6 | 9.18 | 6.2 |

Figure 1 (a) shows wear-rate variation of the sintered disk specimens as a function of applied load, and the steady-state friction coefficients of the specimens are exhibited in Fig. 1 (b). Wear rates of all specimens increase with the applied load. The Co-20 wt.% CuSn composite showed the highest wear rate and very rapid wear-rate increase with the load, while the Co and Co-20 wt.% WC composite show similar wear rates with comparatively low increase-slope. The Co and Co-20 wt.% WC composite also display similar steady-state friction coefficient of around 0.3, while the coefficient of the Co-20 wt.% CuSn composite is much lower, 0.15.

Figure 2 shows SEM micrographs of worn surface, cross section, and wear debris of the Co specimen slid 600m at the load of 100N. The worn surface is smooth, shiny, and composed of long shallow dug canals. The surface showed neither cracks nor any significant trace of deformation. A very thin (less than 5μm) detaching surface layer with numerous cracks is shown in the cross section of the worn surface (Fig. 2 (b)). Such a thin layer detaching from the surface is not usually observed from other wear-tested metallic materials, especially at high loads. Most of the wear

debris from the Co specimen were fine particles (diameter less than 5μm). Coarse (diameter bigger than 50μm) debris particles were also observed, especially from a specimen slid short distance. The coarse ones usually contained numerous cracks, which indicates that the fine particles observed from a specimen slid longer distance partially originated from fracturing of coarse particles.

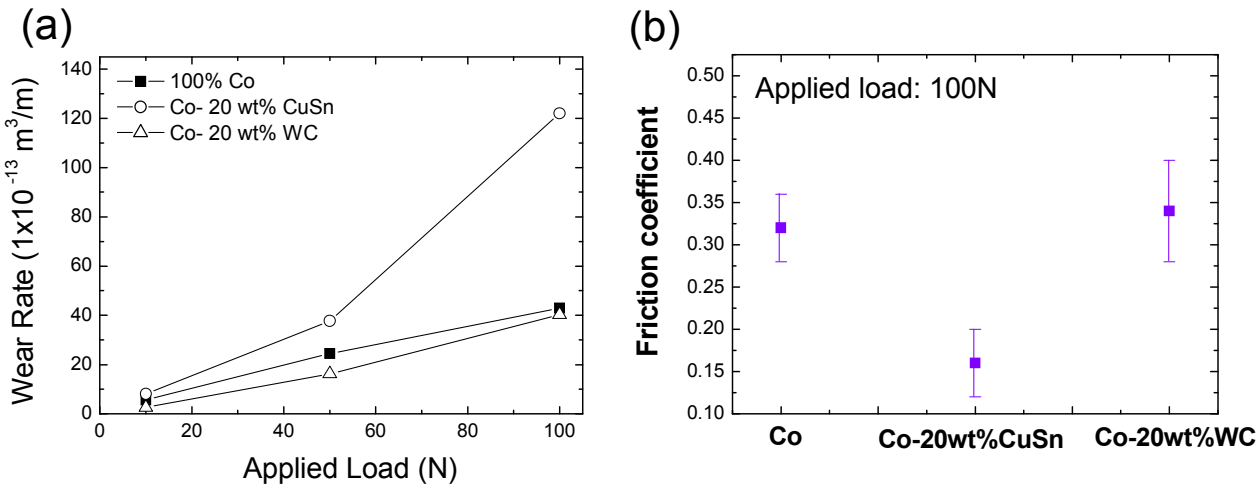


Fig. 1. Variation of wear rate of the sintered Co and Co-based composites as a function of applied load (a), and the steady-state friction coefficients of the specimens (b).

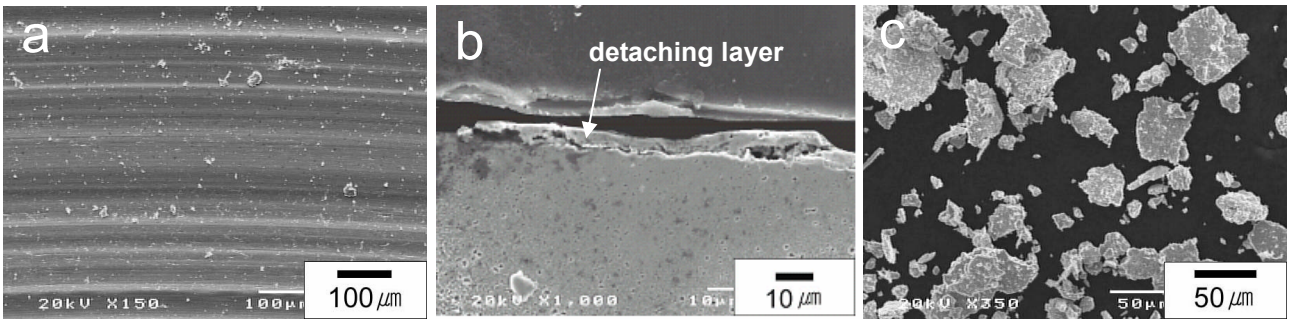


Fig. 2. SEM micrographs of worn surface (a), cross section of worn surface (b), and wear debris (c) of the sintered Co worn against $SiO_2$ for 600m at the load of 100N.

SEM micrographs of the Co-based composites slid 600m at the load of 100N are displayed in Fig. 3. The worn surface of the Co-20 wt.% CuSn specimen looks similar to that of the Co specimen except that the surface contains cracks and traces of detachment of large wear debris. The cross section of the specimen reveals elongated CuSn particles along the sliding direction at near the wearing surface. Cracks were easily found at the interface between the elongated CuSn particle and the Co matrix. Wear debris of the Co-20 wt.% CuSn composite specimen had a shape of thin plate with a width ranging from 10μm to a few hundred micrometers. These observations explain that the wear of the Co-20 wt.% CuSn composite proceeded by shear deformation of the soft CuSn particles. On the other hand, appearance of the worn surface and the cross section of the Co-20 wt.% WC composite was quite different. The worn surface shows short and narrow dug canals. The canals are composed of many grooves and ridges, which seem to be formed by frequent detachment of small wear debris. The cross section also shows uneven worn surface without the delaminating, cracked thin surface layer. Wear debris of the composite were very fine. These micrographs imply that WC particles sustain most of the applied load during the wear, and localized deformation of the Co matrix resulted in the low wear rate with fine wear debris of the composite.

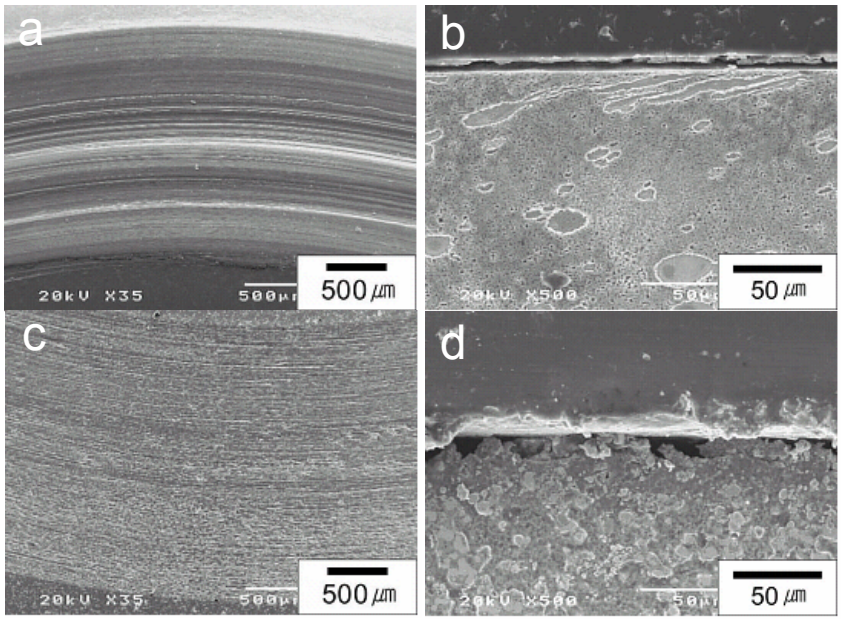


Fig. 3. SEM micrographs of worn surfaces (a, c) and cross sections (b, d) of the Co-20 wt.% CuSn composite (a, b), and of the Co-20 wt.% WC composite (c, d) specimens worn against $SiO_2$ for 600m at the load of 100N.

**Wear mechanism of the sintered Co.** The thin detaching layer and fine wear debris are the peculiar wear characteristics of the sintered Co. Such characteristics are different from those of the other hcp metals. For example, wrought magnesium that has similar axial ratio (c/a) to cobalt showed significant surface deformation during a sliding wear under similar conditions. Large bellows-like folded wear debris as well as angular particles were produced from the wear of the magnesium. Similar wear particles were reported from the wear of hcp titanium alloys, too.

To identify the unique wear mechanism of the sintered Co, phase transformation of the Co and its subsequent effect on the wear were explored. Phases of the sintered Co specimen before the wear test and wear debris after the test were analyzed using an XRD, and the results are given in Fig. 4. The sintered Co initially had both α (fcc) and ε (hcp) phases (Fig. 4 (a)). However, the wear debris possessed only the α phase, which indicates that the original ε phase had transformed to the α phase during the wear. Wear debris of the Co-based composites also showed the α phase. Transformation of the ε phase to the α phase is a thermally induced transformation, which is different from deformation-induced transformation that typically changes the fcc, α phase to the hcp, ε phase.

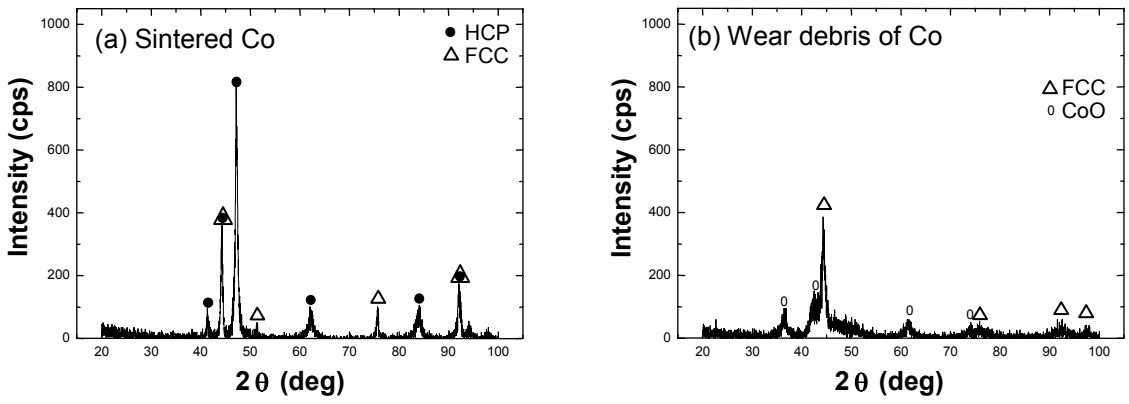


Fig. 4. X-ray diffraction pattern of sintered Co (a), and wear debris of the sintered Co (b)

The wear rate of the sintered Co increased as the sliding distance increased, which was proved by tests with various sliding distances. Such a result is contradictory to former reported results that wear rate normally remains the same or decreases with the increase of sliding distance. The rate-increase with the distance is regarded as another evidence of the thermal-transformation effect on the wear of the Co specimen. As the sliding distance increases, the temperature at the wearing surface would rise higher. The higher temperature would provide more favorable condition for the thermal transformation, which seems to induce the higher wear rate. Calculated volume occupied by an atom in an ideal fcc structure and hcp structure is 1.1128 x $10^{-29}$ $m^3$/atom and 1.1032 x $10^{-29}$ $m^3$/atom, respectively. There is a slight volume increase when the structure changes from the hcp to the fcc structure. The volume increase associated with the phase transformation could be indirectly confirmed by a dilatometer analysis of the Co specimen. It is suggested that the volume change associated with the phase transformation during the wear of the Co induced cracks beneath the wearing surface, which propagated to result in the thin detaching surface layer as well as the fine wear debris.

Since temperature-increase during the wear was postulated as the cause of the transformation, low-temperature (-50ºC) wear tests were carried out to substantiate the effect of thermal transformation on the wear of the sintered Co. The low temperature was expected to hinder the transformation of the ε hcp phase to the α fcc phase of the Co, and so to reduce the wear rate. Figure 5 compares wear rates of the sintered Co and the Co-20 wt.% CuSn specimens tested at two different temperatures, room temperature and the low temperature, -50ºC. As expected, the wear rate measured at -50ºC is much lower in both cases. More interesting thing is that the rate measured at the low temperature remains more or less the same as the sliding distance increases, while the rate at room temperature rapidly increases with the distance.

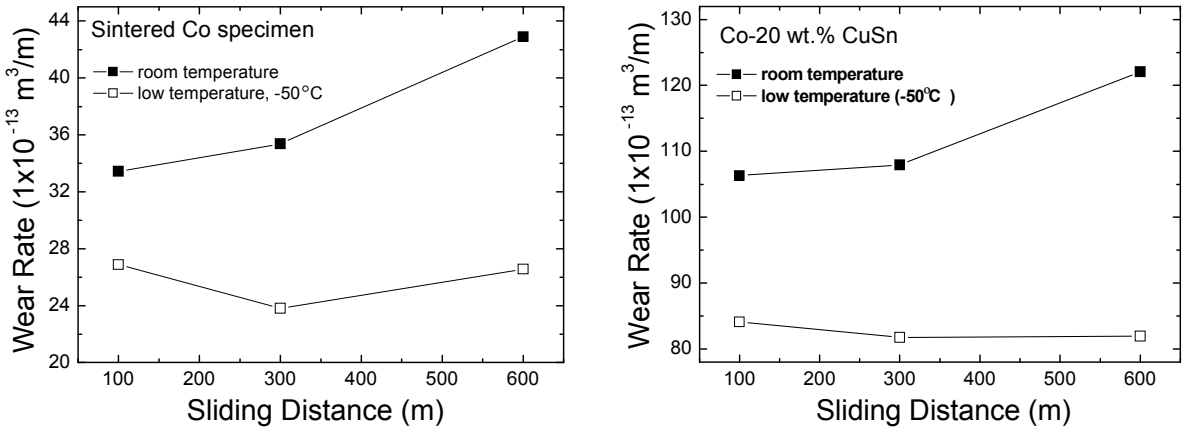


Fig. 5. Variation of wear rate of the sintered Co and the Co-20 wt.% CuSn specimens wear tested at room temperature and at -50ºC.

Worn surface, cross section, and wear debris of the low-temperature tested specimen, which are given in Fig. 6, were quite different from those of the room-temperature tested specimen. They were rather similar to those of other hcp metals (Mg and Ti). The worn surface showed traces of deformation together with cracks and dug grooves (Fig. 6 (a)) and the cross section revealed long cracks underneath the surface, which propagated to form a thick detaching surface layer (Fig. 6 (b)). Large bellows-like folded wear debris were formed during the wear at the low temperature (Fig. 6 (c)). Through an XRD analysis, the debris were found to own both ε and α phases. These support the proposed transformation-induced wear mechanism of the Co at room temperature. The low temperature suppressed the thermal transformation of the ε (hcp) phase to the α (fcc) phase. The same wear mechanism could be applied to the wear of the Co-20 wt.% CuSn specimen. However, in case of the Co-20 wt.% WC composite specimen, though some phase transformation was confirmed, the coarse WC particles that sustained most of the applied load during the wear

controlled the wear of the composite specimen mostly. The porosity of the specimen also seems to influence the wear of the composite specimen.

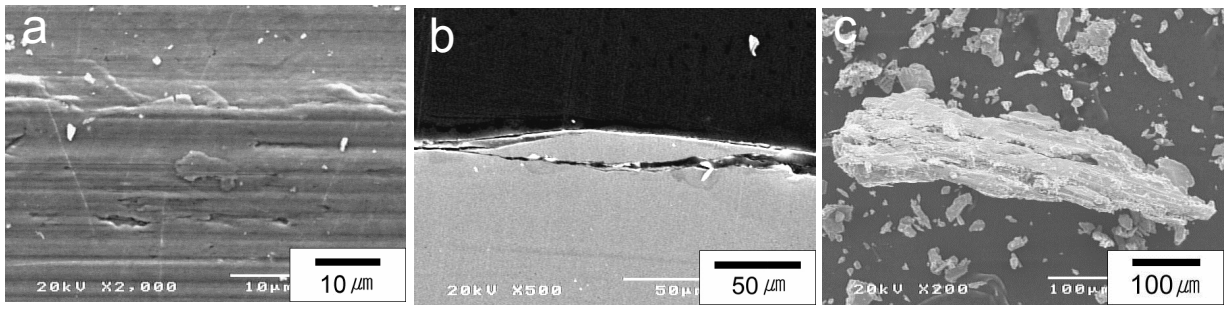


Fig. 6. SEM micrographs of worn surface (a), cross section of worn surface (b), and wear debris (c) of the sintered Co worn against $SiO_2$ for 600m at the load of 100N. The test was performed at low temperature of -50ºC.

## Conclusions

Dry sliding wear behavior of hot-pressure sintered Co, Co-20 wt.% CuSn, and Co-20 wt.% WC composites against glass ($SiO_2$) at room temperature were characterized. The Co-20 wt.% WC and the Co-20 wt.% CuSn composite showed the lowest and the highest wear rate, respectively. The sintered Co exhibited distinctive wear characteristics with shallow dug canals on worn surface, a very thin (less than 5μm) detaching surface layer, and fine debris. Thermal transformation from the ε (hcp) phase to the α (fcc) phase occurred during the wear of the sintered Co, which was inferred from an XRD analysis of the wear debris. The thermal-transformation wear mechanism was confirmed by low-temperature (at -50ºC) wear tests of the sintered Co. The transformation was suggested to cause the thin detaching surface layer as well as the fine wear debris of the sintered Co.

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