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Effects of solid lubricant content and size on the tribology of NiCr-Cr_2O_3-Ag composites

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The tribological behavior of NiCr-Cr_2O_3 blended powder containing solid lubricants Ag and/or BaF_2/CaF_2 eutectic was evaluated according to the content and particle size of solid lubricant and wear temperature. A spark plasma sintering (SPS) process was used to produce bulk wear specimens. The wear tests were carried out with a pin-on-disk type instrument under dry sliding conditions. Friction coefficient, wear loss and content of transferred tribofilm were evaluated. The friction coefficient decreased with an increase of Ag content and the effect of decreasing Ag size was compatible to that of increasing Ag content.

Key words: Solid lubricant, Tribology, Silver, Spark plasma sintering.

Introduction

In a turbo-machinery component, increasing the service temperature is required in order to increase the efficiency without sacrificing the frictional resistance. Thus the thermal instability of the liquid-base lubricants is the main driving force in research to develop solid lubricant materials and processing technology. Friction and wear are very important engineering concern, and much research has been conducted to reduce the energy loss from friction and weight loss by wear. Recently, solid lubricants containing composite materials have been developed to meet these engineering requirements [1-3]. The applications of solid lubricant materials have two prominent advantages. Firstly, the limitations of liquid-base lubricant materials arising from the environmental conditions, such as high temperature and high vacuum can be effectively solved. Secondly, the dead weight of a machine system can be significantly reduced by removing the components required to feed the liquid lubricants [4, 5]. However, solid lubricant materials themselves generally show poor resistance to wear. Also, the life time is limited by the thickness of the overlay if a solid lubricant is applied as an overlay. Accordingly, a composite material, having a reasonable wear resistance and acting as a reservoir of lubricant material, needs to be developed to satisfy these tribological requirement. From these aspects, a feed stock material, NiCr-Cr_2O_3-Ag ternary system has been developed by NASA: Ag particle was added as a solid lubricant into the Cr_2O_3 particle reinforced NiCr matrix [6, 7].

In view of tribology, friction wear is largely dependent on the contents, size and distribution of solid lubricant [8-12]. So in this study, tribology behaviors were investigated in view of solid lubricants content, particle size distribution and variation of wear temperature by the pin-on-disk type sliding test at dry condition.

Experimental

The materials consisted of NiCr, Cr_2O_3 and Ag powder that were blended as one at different compositions such as NiCr-25Cr_2O_3, NiCr-24Cr_2O_3-5Ag, NiCr-23Cr_2O_3-10Ag, NiCr-22Cr_2O_3-15Ag, and NiCr-20Cr_2O_3-20Ag (wt.%) an shown in Fig. 1.

The characteristics and morphologies of the starting materials can be seen in Table 1 and Fig. 1. The blended powders with a particle size range 2-45 μm were used for the preparation of powder compacts, bulk specimens with different particle sizes [2, 15 μm] and contents [0, 5, 10, 15, and 20 wt.%] of Ag were sintered in a graphite die in vacuum using an SPS system. The SPS was heated to 830 °C for 10 minutes and held for 3 minutes with an applied DC pulse electrical discharge. The uniaxial pressure level was maintained at 50 MPa during the sintering process. The sample was cooled to room temperature in the SPS chamber.

Porosity and microhardness of as-sintered materials were measured before conducting a dry sliding pin-on-disk wear test.

The wear tests were conducted using a pin-on-disk

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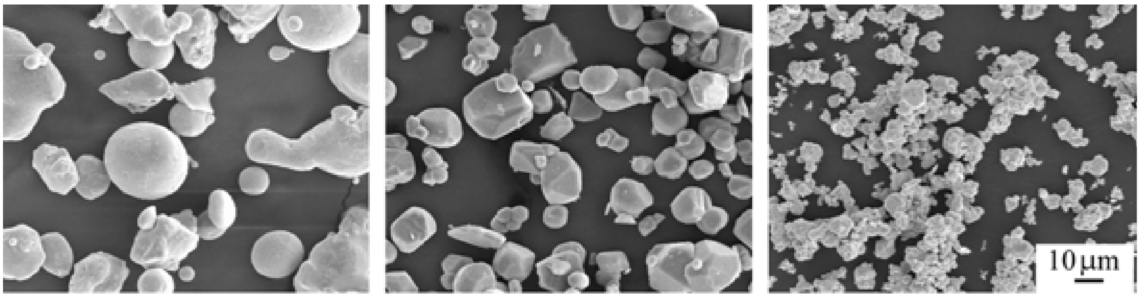


(a) NiCr (b) Cr_2O_3 (c) Ag

Fig. 1. Morphology of starting feedstock.

Table 1. Characteristics of feedstock materials

Constituent	NiCr (wt.%) (Matrix binder)	Cr_2O_3 (wt.%) (Hardening phase)	Ag (wt.%) (lubricant)
Nominal composition [wt.%]	75 71 67 64 60	25 24 23 21 20	0 5 10 15 20
shape	Spherical & irregular	Blocky & angular	Rounded type
Size distribution	5-45 μm	5-22.5 μm	15 μm 2 μm
Mean particle size	2-45 μm		

type sliding wear tester. The counterbody was an Al_2O_3 pin of which the microhardness was 1650 at 1 kgf loading. As-sintered wear specimens and the counterbody were polished with 800 grit silicon carbide abrasive paper. The parameters of the pin-on-disk test were: mean sliding speed, 0.12 ms^{-1}, applied load, 47 N; sliding distance, 220m; and sliding temperature, RT -200 °C. During the wear tests, the frictional force was induced and fed into a PC. Then the friction coefficient could be calculated by dividing the friction force obtained by the applied normal load. The wear loss was calculated from the difference of the mass of the specimen before and after the wear test with an electronic balance to 10^{-4} g. Worn surfaces and matching pin surfaces were observed using SEM and EDS to investigate changes in terms of phase composition and microstructures.

Results and Discussion

Characteristics of as-sintered composites

The cross-sectional morphology of as-sintered NiCr-23Cr_2O_3-10Ag wt.% [15 μm] can be seen in Fig. 2. It appears that bright areas are solid lubricant [Ag], dark areas are Cr_2O_3 and gray areas are NiCr. The area fraction of Ag changed in the surface morphology

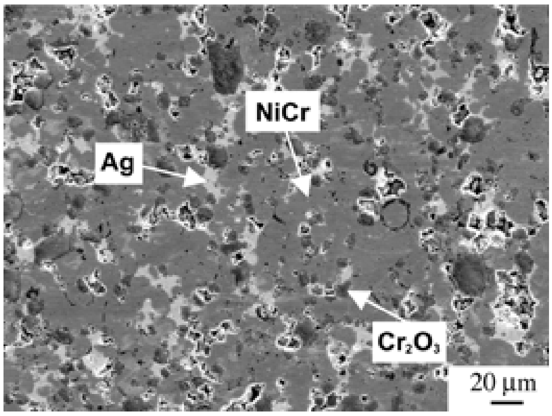


Fig. 2. Cross-sectional morphology as-sintered NiCr-Cr_2O_3-Ag.

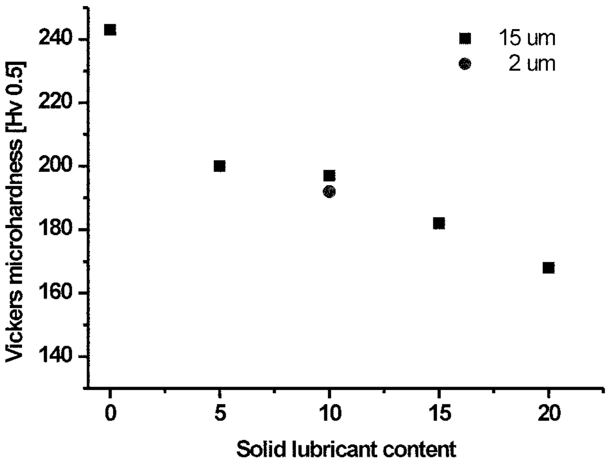


Fig. 3. The microhardness according to the solid lubricant content.

according to the Ag content. Also, as the Ag size decreased with the same content, the distribution of Ag became more uniform.

The content of pores of in the as-sintered sample were in the range of 2.2-3.5% [area fraction] and showed no relation with the variation of Ag content and size. The microhardness as shown in Fig. 3 decreased with an increase in the Ag solid lubricant content. In particular, the microhardness substantially decreased between 0 wt.% and 5 wt.% Ag.

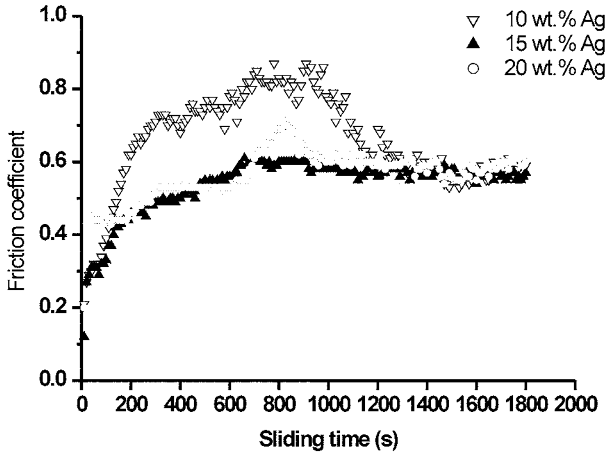


Fig. 4. Friction coefficient according to the solid lubricant [Ag] content.

Effect of Ag content on tribological behavior

To compare the friction coefficient and mass loss according to the variation of solid lubricant [Ag], a wear test was conducted. Because sample with no solid lubricant and 5 wt.% solid lubricant showed deep stick-slip phenomenon with a high friction coefficient (> 0.8), it was clear that at least 5 wt.% Ag solid lubricant was needed for a reduced frictional behavior at room temperature. The friction coefficient variation of the others [10, 15, 20 wt.%], with solid lubricant content and the wear condition, are shown in Fig. 4. The 10 wt.% content has the highest initial friction coefficient, and the 15 and 20 wt.% content specimens show a similar friction coefficient. While the 15 wt.% bulk sample shows more stability in a static state, the 20 wt.% reaches a steady state earlier but with a slight fluctuation. As the Ag content increases, the friction coefficient decreases overall.

In this system, a lower friction coefficient generally results in a lower wear loss. When the solid lubricant is 20 wt.%, the friction coefficient show a similar behavior to the 15 wt.% Ag sample. This result suggests that a lubricant content larger than the optimum content had no further effect on wear loss and friction coefficient.

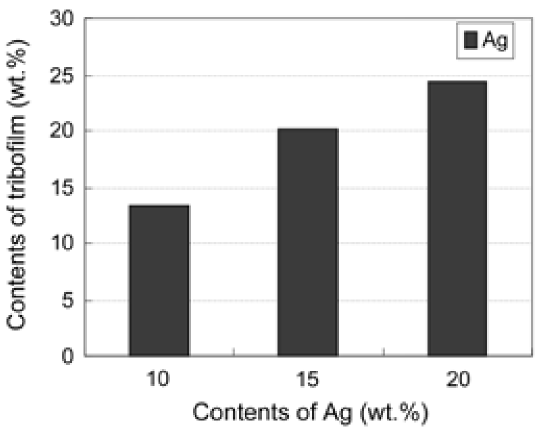


Fig. 5. Transferred Ag tribofilm content of counterpart according to the Ag content.

The Ag tribofilm contents transferred to the Al_2O_3 counterpart according to the Ag content can be seen in Figs. 5, 6. The arrows in Fig. 6 indicate the sliding direction and the dotted rectangle indicate areas of poor Ag-tribofilm. The 10 wt.% content 6(a) reveals some Ag-tribofilm rich areas with many poor Ag-tribofilm areas and the tribofilm shape is seem to be discontinuous.

The 15 wt.% content sample 6(b) shows a relatively continuous and smooth tribofilm surface while the poor tribofilm area is less than for the 10 wt.% sample. The 20 wt.% sample surface is built up with a very rich and

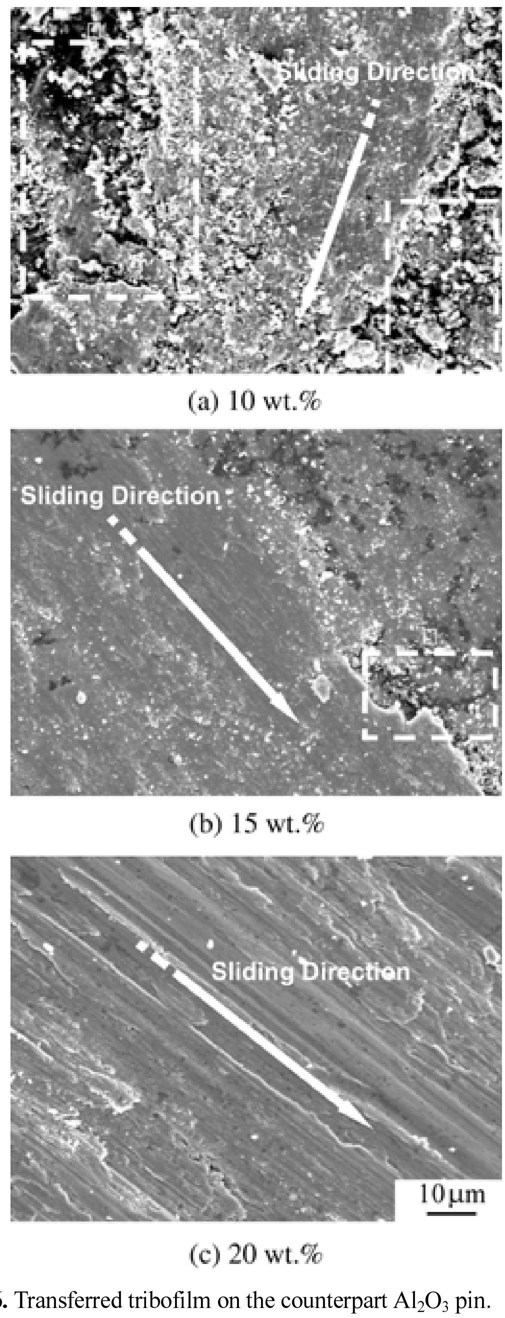


Fig. 6. Transferred tribofilm on the counterpart Al_2O_3 pin.

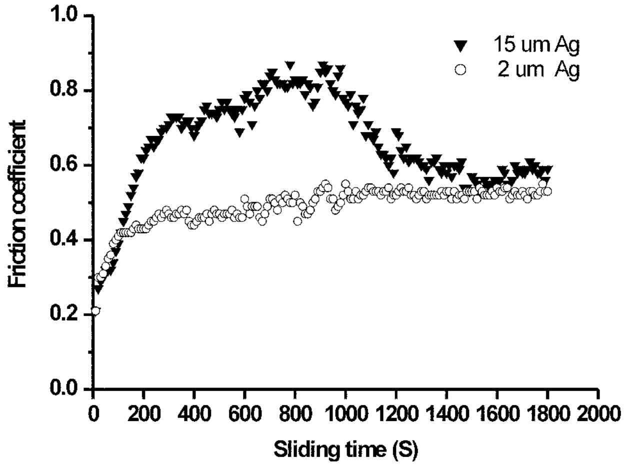


Fig. 7. Friction coefficient of different Ag particle size [2 μm, 15 μm] at the same 10 wt.% content.

continuous tribofilm. Then the solid lubricant content is higher than the optimum and produces richer and uniform tribofilm but results in an unnecessarily higher Ag transfer to the counterpart. As a result, the optimum content of Ag is about 15 wt.%, as the tribological aspects in this system and excessive solid lubricant content do not give further benefit.

Effect of Ag size on tribological behavior

The friction coefficient was controlled by varying the Ag particle size with the same Ag content. As the solid lubricant size is decreased, the friction can be decreased in the early stage of a friction test as shown in Fig. 7. The 15 μm size solid lubricant shows a higher friction coefficient than that of the 2 μm size in the initial state and reaches a steady state gradually. However, the 2 μm size Ag has a low friction coefficient, and the steady state is reached very early after a small amount of sliding.

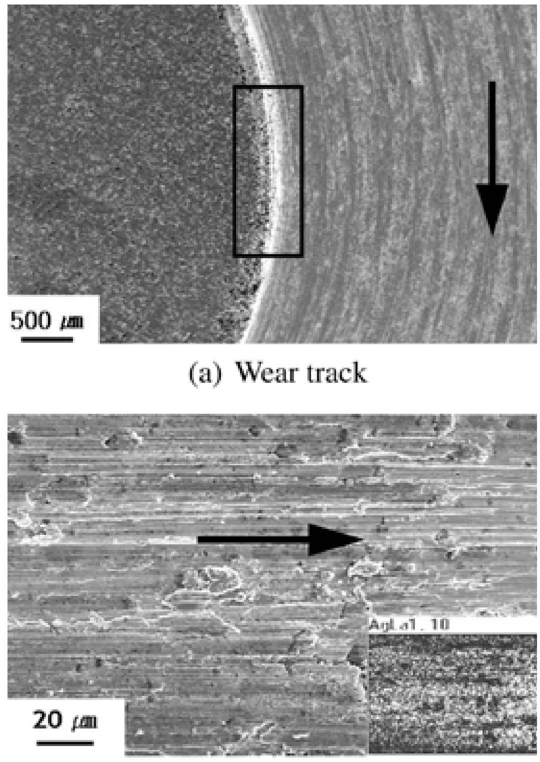
Table 2 shows the wear loss according to the solid lubricant particle size with the same content. The 15 μm size Ag gives about double the wear loss. It is felt that became the initial friction coefficient affects the wear loss in a dominant way. So the early arrival at the steady state and stable friction coefficient reduce wear loss.

The reason why a smaller size Ag particle had a lower initial friction coefficient and lower wear loss is due to the uniform Ag distribution as shown in Figs. 8 and 9.

Figure 8 shows the wear track morphology in the specimen with 2 μm size solid lubricant added. The

Table 2. The Wear loss of different Ag particle sizes [2 μm, 15 μm] at the same 10 wt.% content after a wear test

	2 μm	15 μm
Wear loss (mg/m)	2.7	5.9



(b) Wear track and mapping of Ag

Fig. 8. The sliding surface of 2 μm size Ag particle after a wear test.

arrows give the sliding direction and the rectangle at (a) is the boundary along the wear track. The sliding surface shows a smooth and uniform wear track distribution along the sliding surface. Also the track boundary line appears clear with little fluctuation. Ag is uniformly distributed on the wear track as shown in the mapping of Ag in Fig. 8(b).

Figure 9 shows the sliding surface morphology of the sample with 15 μm size solid lubricant added. The wear track has a selectively rough shape along the sliding surface and the track boundary is a tidy shape. Ag shows an irregular distribution on the wear track as seen in the mapping of Ag in Fig. 9(b). Figure 9(c) is a cross-sectional image of A rectangular area in Fig. 9(b). The 15 μm size Ag containing sample reveales deep wear damage by fracture in the Ag poor area as shown in Fig. 9(b). The poor Ag tribofilm area shows evidence of fatigue of the sliding surface. The size of the solid lubricant particle affects the distribution and then, the irregular distribution effects the formation of the tribofilm. The smaller size lubricant Ag particle seem to supply lubrication better and form a more uniform tribofilm.

The transferred Ag tribofilm content in the counterpart surface can be seen in Fig. 10. Although the Ag content is the same, the Ag transferred tribofilm form the 2 μm size particles is much more than that of the 15 μm size particle.

The tribofilm of 2 μm sized Ag appears to contain

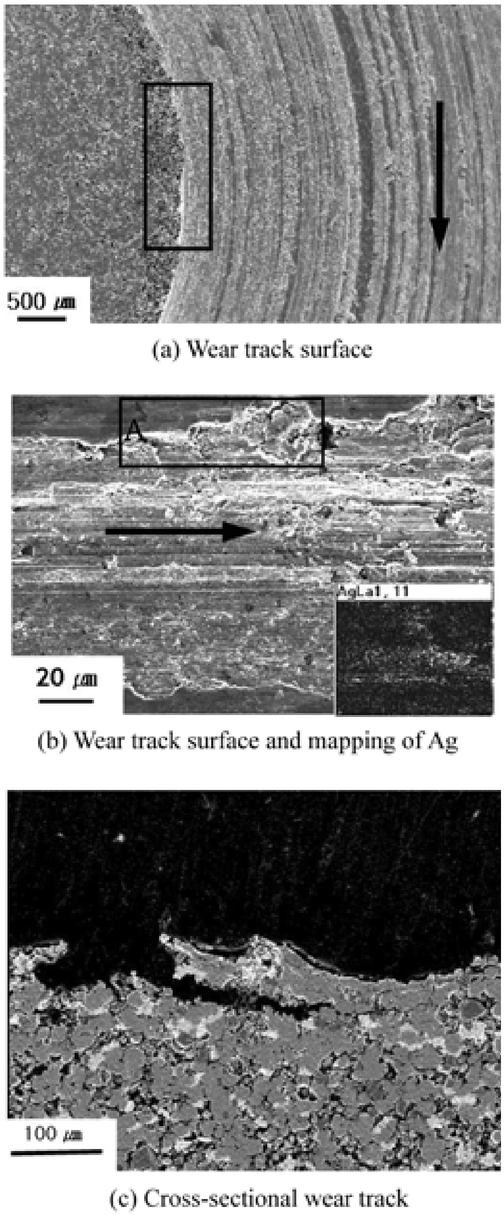


Fig. 9. The sliding surface and cross section of 15 μm size Ag particles containing sample after a wear test.

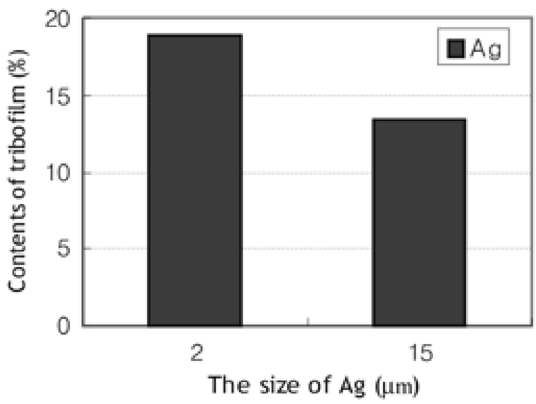


Fig. 10. Transferred Ag tribofilm content of counterpart according to the Ag content.

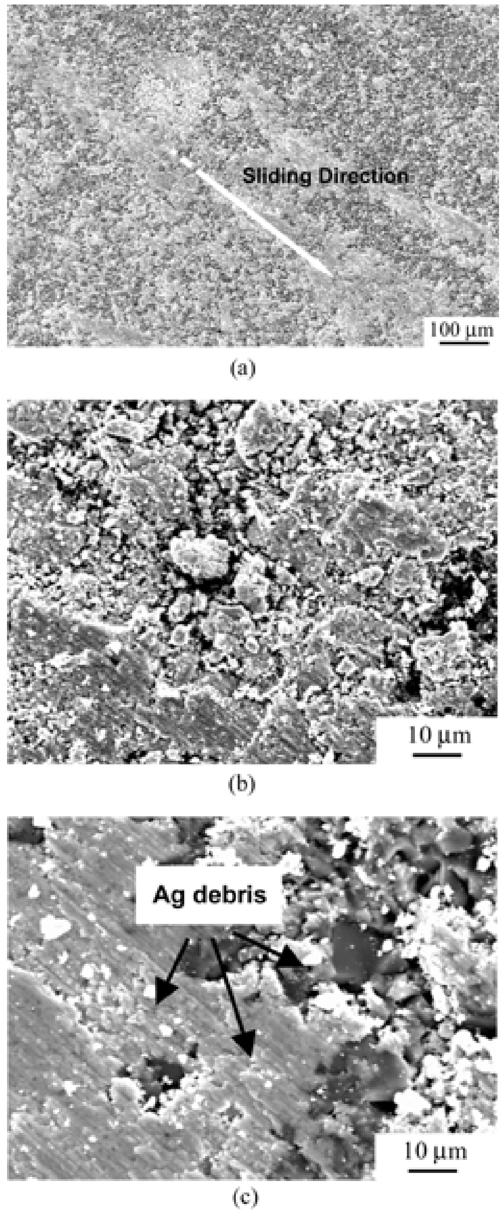


Fig. 11. Transferred Ag tribofilm on the counterpart surface.

much small Ag debris on the tribofilm as shown in Fig. 11(c). Therefore, 2 μm sized Ag can form a more uniform Ag tribofilm as shown in Fig. 11. During repeated sliding, these particles can make a new tribofilm on the counterpart and sliding surfaces reducing the friction and wear.

Effect of sliding temperature on tribological behavior

Ag is known to perform as a solid lubricant at relatively low temperatures from RT to 500 ^oC, and the friction coefficient can be controlled by the Ag content and size at room temperature. Fig. 12 shows the variation of friction coefficient of the 15 wt.% Ag (2 μm) containing sample as a function of wear test temperature. The Ag lubrication performs the best in

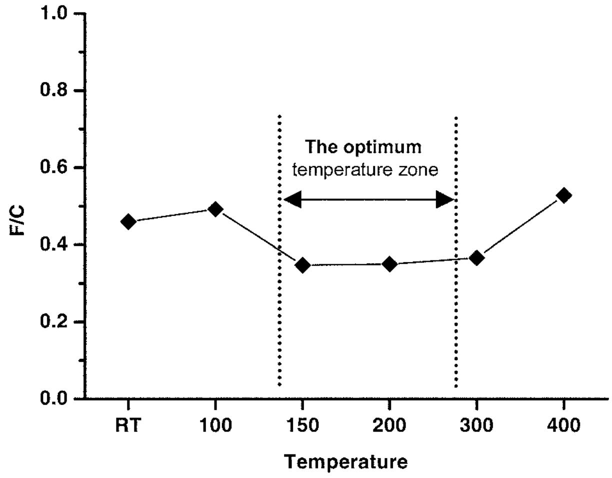


Fig. 12. Friction coefficient variation according to wear test temperature.

the 150 °C~300 °C range. Silver may carry out an important role in reducing friction at temperatures below 300 °C. At 400 °C, the friction coefficient was higher than that of sample without the silver addition [11, 13].

Conclusion

In a NiCr-Cr_2O_3-Ag SPS compact, the content and size of solid lubricant [Ag] had an influence on the tribological behavior. Also, the wear temperature is an important parameter in this system. Through this study, the following conclusions could be drawn:

(1) The friction coefficient decreased generally with an increase of Ag content. However the optimum wear loss and friction coefficient was shown at 15 wt.% Ag.

(2) The smaller sized solid lubricant [Ag] particles gave a low friction coefficient and wear loss. The effect of decreasing Ag particle size was comparable to that of increasing the Ag content.

(3) In this system, Ag showed the best tribological behavior in the 150 °C~300 °C range.

Acknowledgements

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