Wear of Cemented Carbide Dies for Steel Cord Wire Drawing*1

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Cemented carbide dies with five categories of composition, namely, WC–Co straight alloys, TaNbC–Co, Cr3C2–Co or VC-containing WC–Co alloys and WC–Ni alloys, were fabricated by sintering and HIP treatment. The wear behavior of these cemented carbide dies for drawing steel cord wire is examined, and material properties such as hardness, transverse-rupture strength and corrosion resistance are evaluated. It is found that the TaNbC-containing alloy shows the longest lifetime as a steel cord drawing die, followed by the Cr3C2-containing alloy, WC–Co, VC-containing alloy and WC–Ni alloy. The strength and corrosion resistance show no relation with the drawing die life. The hardness has some influence on the die life; for example, within the same alloy category, there is a tendency that the longer die life is obtained for the material with the higher hardness. However, it is not possible to explain simply from the viewpoint of hardness even why the TaNbC-containing alloy has the longest life though the VC-containing alloy has the finest grain size and highest hardness. The wear mechanism of cemented carbide dies for steel cord wire drawing was discussed, focusing on WC/Co interface adhesion. [doi:10.2320/matertrans.M2013185]

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1. Introduction

Steel cord is brass-coated steel wire used to reinforce automotive tires. WC–Co cemented carbide is widely used as a drawing die to reduce the wire diameter of the steel cord from 1.2 mm to about 0.2 mm. The wear of the cemented carbide die is the most important factor affecting the production efficiency of steel cord. Improvement of the die life would directly increase productivity of steel cords.

Studies on cemented carbide wire drawing dies have been reported that examine die surfaces during copper wire drawing,1) and the effects of shape2) and friction and lubrication3) of the die during steel wire drawing. However, there have been no reports yet on the use of cemented carbide dies for steel cord drawing. Moreover, it is thought that wear of cemented carbide dies is greatly influenced by the composition and microstructure of the cemented carbide, but as yet there have been no studies on cemented carbide dies from a materials science point of view.

In this study, in order to improve the die life for steel cord wire drawing, the abrasion behavior of wire drawing of various cemented carbide dies was evaluated and analyzed in relation to properties such as hardness, strength and corrosion resistance of the cemented carbides. WC–10%Co alloy was used as a reference material and various cemented carbides with additions of TaNbC, Cr3C2 and VC, and also with Ni binder instead of Co, were fabricated.

2. Specimens and Experimental Procedures

Commercial WC powders (grain size, 0.5–4 µm), Ta0.8Nb0.2C (1 µm), VC (1.5 µm), Cr3C2 (1.5 µm), Co (1.2 µm) and Ni (2 µm) powders were mixed in an attritor under vacuum at (10 Pa) at temperatures between 1653–1723 K for 3.6 ks. After sintering, Hot Isostatic Pressing (HIP) treatment of 40 MPa at 1633 K for 3.6 ks, in Ar was performed to remove residual pores. Table 1 shows compositions of 15 kinds of cemented carbide specimens fabricated for this study. The specimens were five types; additive-free WC–Co alloys, TaNbC-added alloys, Cr3C2-added alloys, Cr3C2 and VC-added alloys and Ni binder alloys, labeled S, T, C, CV and N alloys, respectively. A WC powder with grain size of 1 µm was usually used in preparing S, T, C and N alloys, while coarse powders with 2 and 4 µm grains were used for T and C alloys and fine WC powder with 0.5 µm grains was used for CV alloys.

Microstructure observation by SEM and Rockwell-A hardness (HRA) testing were performed on the fabricated specimens. Transverse rupture strengths were obtained using rectangular specimens with dimensions 4 mm × 8 mm × 25 mm and a span of 20 mm. Conditions for corrosion experiments were 333 K for 7.2 × 106 s (2000 h) with a wet lubricant of emulsion type liquid. Specimen surfaces were observed and mass changes measured after each corrosion test.

Figure 1 shows the shape of the dies and schematic views of the steel cord wire drawing machine. All the dies were immersed in the lubricating liquid. The composition of the steel cord was steel with 0.82%C, the surface was coated with brass and the starting diameter was 0.17 mm. The number of wire drawing stages (number of dies) was 21, the finishing wire size was set at 0.217–0.221 mm by polishing treatment, and the drawing velocity at the last stage was 800 mm/min. The dies fabricated in this study were used as the last three dies in the drawing process (Fig. 1). The other dies were cemented carbide dies normally used in manufacturing of steel wires. When the above-mentioned three dies for this study reached the end of their lives, all other dies were changed to new ones. When the wire diameter reached 0.225 mm, the die was judged to have reached its useable lifetime. The number of wire drawing experiments was 3 to 5.
and the average value of the amount of wire drawn (kg) was obtained, and finally the relative value (ratio) of the drawn amount of wire was used to evaluate die life. The relative value of drawn wire was defined as the ratio between the average wire drawn for each alloy divided by the average wire drawn for the reference alloy, S1. We refer to this as the relative value of wire production. Dies after the drawing tests were cut into halves and the wear condition of the dies was observed by SEM.

3. Experimental Results

Figure 2 shows SEM microstructures of each alloy. The WC grain size of T alloys is smaller than that of S alloys, and grains of T alloys tend to become slightly smaller with an increase of the amount of TaNbC, and WC grain size of T alloys is larger when the grain size of the starting WC powder is larger. The WC grain size of C alloys is smaller than that of S alloys, and the WC particle diameters of C alloys become larger with increasing grain size of the starting WC powder. CV alloys have extremely fine microstructures by utilizing the particle effect by VC addition and ultrafine WC particle powder. The effects of TaC, Cr3C2 and VC addition on microstructures (WC grain size) of these alloys are similar to those reported in the literature.4) N alloys without other carbides have coarser WC particles than S alloys, and N alloys with Cr3C2 addition have smaller microstructures than S alloys. These results are also similar to those reported previously.4)

Hardness and transverse rupture strengths of these alloys were compared. Their average values are presented in Table 1. Hardness of T alloys was greater than those of S alloys, and the hardness rises with an increase in TaNbC content, and falls with an increase in WC grain size. Transverse rupture strengths of T alloys tend to be slightly lower than those of S alloys, and do not vary when TaNbC is added, but decrease with an increase in WC grain size.

Hardness of C alloys is higher than those of S alloys, and rise with a decrease in the amount of Co, and fall with an increase in the WC grain size. Transverse rupture strengths of C alloys are 3.3–3.4 GPa for 6%Co, which is almost equal to those of S alloys. Hardness of CV alloys is higher than those of S alloys and rise with a decrease of Co content. Transverse rupture strengths of CV alloys with 10%Co are higher than those with 6%Co and reach 3.8 GPa. N alloys without other carbides have lower hardness than S alloys, and the N alloy with Cr3C2 has a higher hardness. The transverse rupture strengths of N alloys tend to be lower than those of S alloys.

Figure 3 shows wire drawing curves for the four kinds of cemented carbide dies. The wire drawing curves exhibit a staircase pattern because the wire diameters were measured with a micrometer with a precision of 0.001 mm. The final wire diameters obtained φ0.217–0.220 mm and the lifetime of the die, was judged when the diameter reached a thickness of φ0.225 mm, although there were some cases of the wire...
diameters exceeding φ0.225 mm at the time of measurement. It is seen that wire drawing curves show some scatter in each alloys category. The cause of this scatter is complex and depends on many factors such as the type of wire rod, lubricant, material of the die and surface finishing. Studies to reduce such scatter are also required. In this study, we seek firstly to clarify underlying factors determining cemented carbide die lifetimes, and will not consider the causes of the scatter in more detail. It takes, depending on the materials and conditions, one to four weeks to conduct a wire drawing experiment. Wire drawing experiments were performed three to five times for each alloy, their average values calculated, and comparison between each kind of material performed.

Table 1 shows average values of the relative value of wire production for each kind of alloy. Relative values of wire production for S1 and S2 were in the ranges of 0.91–1.09 and 0.70–2.11, respectively, giving average values of 1.0 and 1.4, respectively. Therefore, the lifetime of S2 was slightly longer than that of S1. The relative value of T2 was in the range 0.92–2.54 with an average of 1.9, which was the highest value in this study. Moreover, the average values of T1, T3 and T4 were more than 1.5, which is significantly longer than that of S1. However, the average value of T5

![Fig. 2 SEM microstructures of the fifteen kinds of cemented carbide specimens.](image)

![Fig. 3 Final diameter of wire vs relative value of production for the drawing dies of S2, T2, C2 and CV2.](image)
was as low as 0.8. The value of C2 was in the range 0.79–1.76 and its average value was 1.4. The average values of C1 and C3 were 0.9 and 1.3, respectively. Relative values for CV2 were in the range 0.28–2.54, and its average value was 1.2. The average value of CV1 was 0.7, which was lower than that of S1. This was the lowest value for materials with Co binder. The average values of N1, N2 and N3 were below 1, indicating that their lifetimes were shorter than that of S1.

The comparison between average relative values of wire production of each alloy reveals the following trends. Comparison among the groups of alloys shows that T alloys with TaNbC exhibit the best drawing performance, followed by C alloys with Cr3C2, S alloys with no addition, and CV alloys with Cr3C2 and VC. Further, the drawing performance of N alloys with Ni instead of Co is lowest. Moreover, comparison among the same kinds of alloys shows that drawing amounts are greater for 6%Co alloys than for 10%Co alloys, and the finer the WC grain size the greater the lifetime. In the following section, the relationship between materials properties and drawing performance are examined.

Figure 4 shows relationships between relative values of wire production and hardness, and those between the relative value of wire production and transverse rupture strength. Firstly, plots of the relative value of wire production and hardness show that most of the alloys with relative values of wire production above 1 have hardness around HRA92, while for alloys of higher hardness the relative value of wire production tended to be lower. In other words, relative values of wire production reached a maximum for hardness of HRA92.5 to 93. In the range of HRA92.5 to 93, the relative value of wire production of T alloys was highest, followed by that of C alloys. Moreover, the relative value of wire production of CV1 was low even with HRA93, and that of N3 was considerably inferior even with HRA92.2. On the other hand, plots of relative value of wire production versus transverse rupture strength reveal that the relative value of wire production is greater than 1 for strength of 2.8–3.4 GPa, although the relative value of wire production of some alloys with high transverse rupture strengths was low, indicating that there is no simple correlation between relative value of wire production and transverse rupture strength.

Figure 5 shows the surface structures and mass changes of dies after corrosion experiments. The results show that mass change increase in the order C2 < N2 < T1 < CV2 < S2, and SEM images show that parts of the Co phases are corroded by the lubrication liquid for all alloys. Further, excellent corrosion resistance was seen for binder phases of Co and Ni with Cr3C2, indicating that corrosion resistance does not correspond directly to the results of the wire drawing amounts.

Figure 6 shows SEM images of dies cut parallel to the wire drawing direction. The left side of each micrograph is the entrance side of the wire and the right side is the exit point. In these micrographs, multiple removal events are observed in the bearing part of S2, and comparatively clear stripe-shaped scratches (perhaps deposits) are observed in T2. Further, scratches can be seen in the passage direction of the wire in C2 while no particularly large areas of particle removal or scratches can be observed in the micrograph of CV2. However, observation of the wear surfaces of dies did not reveal any conditions that correspond to differences in wire drawing amounts of different materials.

4. Discussion

In total, fifteen different alloys categorized into five classes that can be used as cemented carbides for wear resistant tools and dies for steel cord wire drawing were fabricated and their
wire drawing (wear) behaviors examined systematically. The results reveal that the lifetime of cemented carbides containing so-called refinement additives such as TaNbC, Cr3C2 or VC tended to be longer than that of additive-free WC–Co alloys. In particular, the longest wire drawing life was observed for an alloy with TaNbC; this material should be the best for steel wire drawing dies. The relationship between mechanical properties such as hardness and transverse rupture strength of each alloy and corrosion behaviors in a lubricant and wire drawing lifetime were examined. The transverse rupture strength and corrosion resistance appear to have almost no relationship with wire drawing lifetime, but there are some correlations between hardness and wire drawing amount.

First, we discuss the effects of refinement additives by comparison with additive-free alloys. In order to consider the relation between wire drawing amount and hardness plotted in Fig. 4 in detail, we compared alloys of the same materials class (additives) and found that the wire drawing amount increases with an increase in hardness. However, such a tendency is not seen across different alloy classes. The reduction in grain size for three kinds of additives proceeded in the order TaNbC < Cr3C2 < VC, and hardness increased in the same order while wire drawing amount, in the contrast, decreased in the order TaNbC > Cr3C2 > VC. In alloys with VC, it is easy to obtain alloys with high hardness having ultrafine microstructures while the results show clearly that they are not suited for dies for wire drawing of steel cords. In contrast, alloys containing TaNbC do not always show fine microstructures, but excellent wire drawing amounts (long lifetimes). Alloys containing Cr3C2 lie somewhere between the two. Considering that ultrafine particle cemented carbides with VC are widely used in tools for ultra-precision machining such as micron drills, this result is very important when it comes to their practical use in wire drawing dies.

In order to study these results further, it would be necessary to consider the wearing mechanism of cemented carbides as a function of their microstructures. Figure 7 shows a model we propose for describing the wear mechanism of a cemented carbide die during steel cord wire drawing based on the findings of this study. First, wear modes can be roughly classified into two types, micro-wear and macro-wear. Here, macro-wear means a wear mode in which some portion of the die is removed by work-piece materials (steel cord). For example, the scratches seen in the bearing of the die shown in Fig. 6 are one such macro-wear. A possible cause is that hard materials other than the die piece, such as powder dust, chips from dies or impurities in work-pieces, are drawn in along with the wire. Further, such wear can be a cause of the scatter in wire drawing amount. However, for simplicity we assume that the differences in wire drawing amount obtained in this study for different classes of cemented carbides are not directly related to macroscopic wear. This assumption is supported by the observation that there is almost no correlation between transverse rupture strength and wire drawing amount of the cemented carbides. This is most likely because all of the cemented carbide materials used for this study are high strength materials for which residual pores are removed by HIP treatment, macro-wear hardly occurs. If low strength materials without HIP treatment had been used, the scatter would have been even greater and the results presented here (in terms of differences between types of material) may not have been obtained readily interpretable.
Plots of hardness versus relative wire drawing amounts, several a tendency for the wire drawing amount to fall when the hardness exceeds a certain value, in other words, the tendency that the relative values of wire production peak at a certain hardness. This is thought to indicate that the harder a material, the more likely macroscopic wear (partial chipping of a material) is to occur, owing to the brittleness of extremely hard alloys. However, frequent removal of large particles and scratches were not observed in bearing parts of dies of the hardest alloy (CV2) and therefore it is unlikely that macroscopic wear is the determining factor. In the case of dies with alloys that are harder (more brittle) than those used for this study, such macroscopic wear may be the main factor.

Based on the consideration that the wear mechanism of most importance here is micro-wear, Fig. 7 shows schematic diagrams of how wear proceeds in WC–Co with a composite microstructure; In the early stage of wear (Fig. 7(b)), the soft Co phase is worn to some depth (around 0.1–0.2 µm) for a microstructure containing the two phases WC and Co. In the following step (Fig. 7(c)), the surface of WC is worn gradually (probably micro-chipping) occurs. In the last step (Fig. 7(d)), WC grains fall off one at a time, and wear progresses more rapidly. The wear lifetime of the dies in this study is defined as the point where the wire diameter (die diameter in other words) becomes thicker by 5 µm and therefore as the point where a cemented carbide is worn by 2.5 µm compared to the original surface of the die. If the WC grain size is 1 µm, two or three WC grains will have been removed from the surface by the end of the die lifetime. Here, it is thought that process (b) is influenced by the hardness of the Co phase and its wear is suppressed more effectively for smaller WC grain sizes. Moreover, process (c) is influenced by the WC grain size, and wear of the WC phase is suppressed better for finer grain alloys. The fact that wear lifetimes are longer in finer grain alloys for alloys with the same additives indicates that processes (b) and (c) are suppressed in such alloys. Incidentally, it is possible that the differences between alloy types are influenced by process (d). It is known that in the cemented carbides containing VC and Cr3C2, these elements dissolve in Co liquid phase during sintering and are precipitated on the WC/Co interface during cooling after sintering. Such a precipitation phase (layer) may decrease the adhesion strength (holding power of the WC grains) of the WC/Co interface. In particular, the amount of precipitation is large in VC added alloys and its bad effects may be large. In this regard, since dissolution to the liquid phase is small in TaNbC added alloys, precipitation during cooling may not be a concern. Therefore, it can be understood that the ability to retain the WC grains in TaNbC added alloys is essentially the same as that in additive-free cemented carbides. The reason why these drawing amounts, which are the most important results in terms of die lifetimes, increased in terms of the additions in the order of VC < Cr3C2 < Ta NbC thus appears to be that they are related to micro-wear events of the type in Fig. 7(d) (WC grain removal) depending on the statuses of the WC/Co interface. In order to confirm this hypothesis, it is important to evaluate the strength (i.e., adhesive strength) of the WC/Co interface and which we are currently carrying out. Moreover, in order to improve further the die lifetimes (wire drawing amounts), materials design principles such as the observation that cemented carbides which do not decrease WC/Co interface strength, such as fine grained alloys with no VC, are effective will be applied in the future.

5. Conclusions

Wear behaviors during wire drawing of steel cords were evaluated for dies made of WC–6%Co, –10%Co alloys with TaNbC, Cr3C2 and VC, additives and with Ni binder phase instead of Co, their relationships with material properties were analyzed. The following results were obtained:

1) The best wire drawing performance was obtained for the alloy with TaNbC, followed by the alloy with Cr3C2, additive-free alloy and the alloy with Cr3C2+VC. The worst wire drawing properties were obtained for alloys with the Ni binder phase. Moreover, comparison between materials within the same kind of alloy group showed that wire drawing amounts were greater in 6%Co than in 10%Co and for finer WC grain sizes.

2) The relationships of mechanical properties such as hardness and transverse rupture strength of each material and corrosion behaviors using a lubricant during wire drawing were examined and it was found
that the transverse rupture strength and corrosion resistance have almost no relationship with wire drawing lifetime, although hardness does have some effect on the lifetime.

(3) The wearing mechanism of cemented carbide dies for steel cord wire drawing, it is considered that the reason why the wire drawing amounts (die lifetime) were large in the order of TaNbC > Cr3C2 > VC by the types of refinement additives is related to microscopic wear of WC grain removal depending on the status of the WC/Co interface.

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