Friction and Wear of Materials: Principles and Case Studies
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Lecture - 40
Abrasive Wear of WC - Co Coating

Hello welcome back. So in this lecture key results from the Abrasive Wear studies of tungsten carbide cobalt coatings will be discussed. So tungsten carbide cobalt material is usually called as a hard material and it is a candidate material for varieties of engineering applications for example cutting tools, rock, drill tips and also the tools and dyes in metal forming.

So the tungsten carbide cobalt material is generally found failed because of the metal binder removal followed by the fracture of this tungsten carbide grains, but all this information is available for the tungsten carbide cobalt bulk material whereas the wear behavior of the tungsten carbide cobalt coating is not well understood. So in this lecture we will see the salient results obtained in the abrasion wear behavior of tungsten carbide cobalt coatings.

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WC-Co coating

•WC- 12 wt% Co was coated by detonation coating up to a thickness of 350μm (±20μm) at three levels of oxygen to fuel (OF) ratio on a mild steel substrate.

A tungsten carbide with 12% of cobalt was coated by a detonation coating process the coating thickness of around 350 micron meter was obtained and in this detonation coating 3 levels of oxygen to fuel ratios were maintained and the coating was done at the mild steel substrate.

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WC-Co coating characteristics

Material Designation/ OF(oxygen/fuel) ratio	Coating thickness (μm)	Coating roughness, R_a (μm)	Density (g/cc)	Porosity (%)	Representative Hardness (GPa)	E (GPa)
OF-1.16	347±30	5.0 ±0.4	13.75	0.65 ±0.13	9.20	300
OF-1.50	345±25	4.1 ±0.4	14.64	0.30 ±0.10	11.15	300
OF-2.0	352±32	3.5 ±0.3	14.95	0.35 ±0.12	11.00	290
WC-12Co	Bulk	1.2 ±0.05	14.30	≅ 0	12.85*	565
Mild Steel substrate	Bulk	0.5 ±0.03	7.84	≅ 0	2.00*	210

So generally the tungsten carbide cobalt this coating is generally reported to fail because of the decarburization. The decarburization is a function of the oxygen to fuel ratio in the detonation gun process. So in this study 3 different oxygen to fuel ratios which we call OF ratios were used so 1.16, 1.50 and 2.0 and you can see the coating is around 350 micron meter was obtained.

And the roughness is between 3.5 to 5 micron meter and the density also varies from around 13.7 to 15 gram per cc with a variation of the porosity from 0.3% to 0.6% and the hardness also vary from 9 to 11 gigapascal. Similarly, the elastic modulus also vary from 290 to 300 gigapascal. So if you can see these roughness variation probably is because of the smoothening of the tungsten carbide cuboids with the change in the oxygen to fuel ratios.

And correspondingly there is a change in the hardness in elastic modulus. For the comparison the abrasion wear was also done under tungsten carbide 12% cobalt bulk material. Bulk material has a representative hardness of around 12.85 gigapascal and a modulus of around 565 gigapascal. So you can see the hardness is more than the hardness of the coated surface and as the coating is done on the mild steel the mild steel was also studied for their hardness and the modulus and the roughness.

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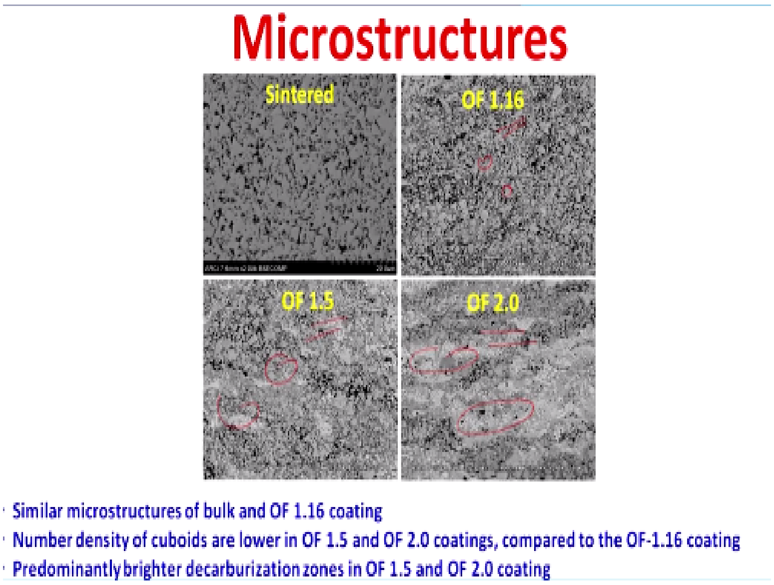

So the coating gave a microstructures which has a different characteristics with respect to the change in oxygen to fuel ratio and the number of densities of these cuboids of this tungsten carbide are lower when you have a oxygen to fuel ratio higher compared to that as you obtained for the lower oxygen to fuel ratio. So if you compare with this bulk to sinter the similar microstructure.

Only difference is this cuboids this particles of tungsten carbide are appearing on the surface clearly. Predominantly there is a brighter zones in the coated microstructures and the bright regions or the decarburization regions. You can see the decarburization regions are more when you have a coating done with the higher oxygen to fuel ratio. In another study it was found that around 45% decarburization in case of the coating done in the oxygen to fuel ratio of 2.

Whereas very small around 4% to 5% decarburization was found when the oxygen to fuel ratio is of 1.16. So with change in the oxygen to fuel ratio the decarburization was also increased.

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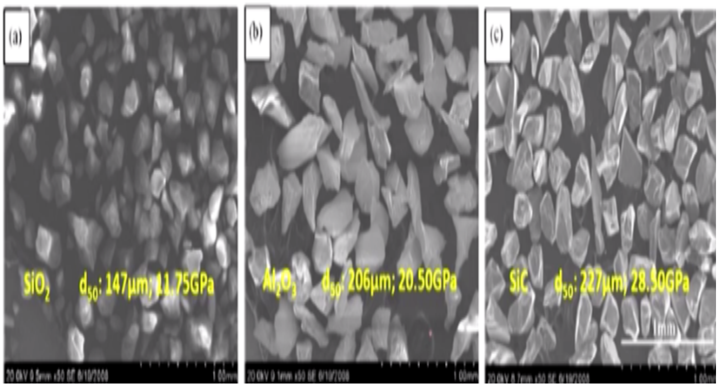
Abrasives



In this study the abrasives used were silicon oxide, aluminum oxide and silicon carbide. Silicon oxide of around 11.75 giagapascal hardness was selected which is actually similar to the hardness of these coatings right and then extremely harder abrasive of silicon carbide was also used the hardness is around 28.5 gigapascal and also aluminum oxide particle having an intermediate hardness of 20.5 gigapascal are also used.

You can see the size of the particle varied between 150 to 200 micron meter for the different abrasives.

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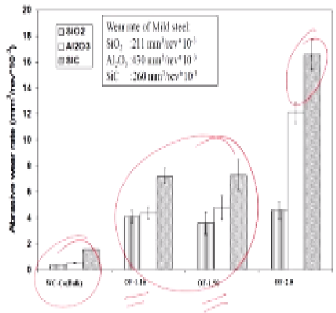
Abrasive wear results



- Comparable abrasive wear rates for OF-1.16 and OF-1.50 coatings.
- The OF-2.0 coatings exhibit a markedly higher abrasion rate.
- WC-12Co coatings with the abrasive wear rate in the range 4 to 16 X 10^{-3} mm^3 / revolution are substantially superior to uncoated mild steel with the abrasive wear rate in the range 210 to 430 X 10^{-3} mm^3/revolution.
- Abrasive wear rates of coatings are higher than that of bulk WC-12Co
- Highest wear rates are observed when SiC abrasive was used, while lowest wear rates when SiO_2 abrasive was used.

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So these abrasives were used to study the abrasion wear of these tungsten carbide cobalt coating. So these abrasive wear was done using a dry sand abrasive wheel and then we get a abrasive wear rate determined in terms of volumetric material removal per revolution. So you can see for comparison the tungsten carbide cobalt bulk material was also studied for the abrasive wear.

So first of all a comparable abrasion wear rates were obtained for the coating done with the oxygen to fuel ratio of 1.16 and 1.15 almost comparable for any abrasives whereas the coating done with the oxygen to fuel ratio of 2.0 exhibited a remarkably higher wear rate. With respect to the abrasive use the silicon carbide abrasive always gave a higher abrasion wear rate whereas the silicon oxide abrasive gave a always lower abrasion rate.

In addition to that one important point is that tungsten carbide cobalt coatings the abrasive wear rate is in the range of 4 to 16 10 power-3 mm cube per revolution which is substantially superior to the uncoated mild steel with abrasive wear rate in the range of 200 to 430* 10 power -3 mm cube per revolution. So a higher the abrasion wear rate was higher for the coatings than that of the bulk material as expected.

But higher wear rates are observed always when silicon carbide was used whereas the lowest wear rate was observed when silicon oxide was used and the abrasion wear rate was intermediate when the aluminum oxide abrasion was used.

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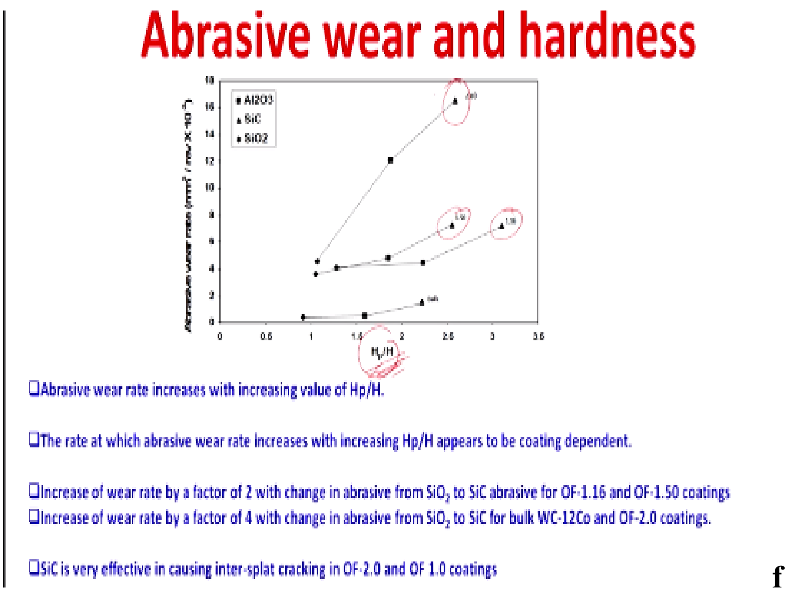

So it gave an indication that the abrasive wear is highly depended than the abrasive particles you are using. So it is very important to understand with respect to the hardness of this abrasive particles used. So in this study a ratio of the hardness of the particle to the hardness of the coating is studied with respect to the abrasive wear rate. You can see the abrasive wear rate as a function of this hardness ratio of the particle to the target.

So abrasive wear rate increases with increase in value of this ratio for any abrasive, but the rate at which the abrasive wear rate increases is different from one particle to another particles. So the rate at which the abrasive wear rate increases with increasing this ratio appears to be depended on the coating. So you can see the increase of the wear rate is almost two factors with change in abrasives from silicon oxide to silicon carbide abrasive for those coating obtained with a 1.16 and 1.50 oxygen to fuel ratio.

But that coating obtained using a higher oxygen to fuel ratio of 2.0 given an increased wear rate of almost a factor of 4 with change in abrasives from the silicon oxide to silicon carbide. So we can say that silicon carbide is very much effective in causing the cracking and then more abrasive wear and then this particularly observed in the coatings obtained with 2.0 and 1.5 oxygen to fuel ratio.

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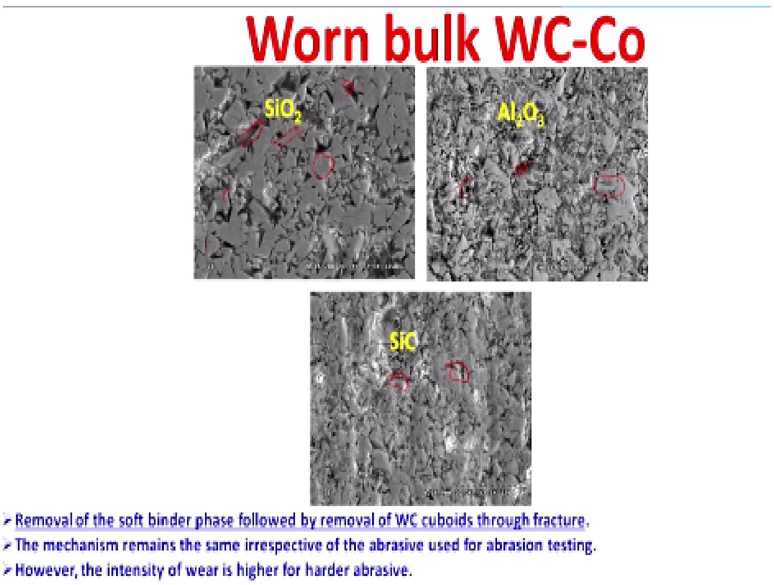

The worn surface analysis is also studied for the bulk as well as the coating. The bulk tungsten carbide cobalt material after wear shows there is a removal of this binder phase you can see the removal of this binder phase right binder phase and then there is a removal of this tungsten carbide cuboids by cracking right. So you can see lot of cracking and then their fracture.

The mechanism is like that first of all the binder phase is removed followed by the cracking of the tungsten carbide cuboids which stands on this surface. So once they fracture the total material is failed. So this mechanism is changed it does not change with abrasives used. However, the intensity of the wear is higher when we use the silicon carbide which is a harder abrasive then compared to the abrasive wear obtained when the softer abrasive silicon oxide.

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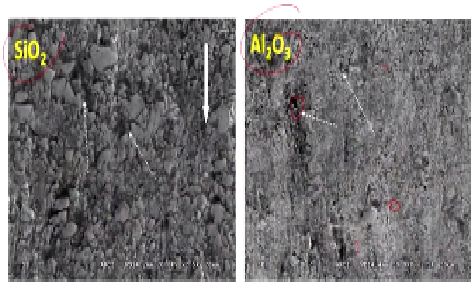
Worn WC-Co (OF 1.16)



- Weak bonding to Co binder leads to pull out of WC cuboids in case of these coatings as compared to bulk WC-12Co
- Harder the abrasive used, greater is the intensity of this pull out.

Now let us see the worn surfaces of the tungsten carbide cobalt coatings. So these are the worn surfaces of the coating obtained with a 1.16 oxygen to fuel ratio so we can see there is a change in the mechanism than that we saw in the bulk material of tungsten carbide cobalt. So the weak bonding of the tungsten carbide to the cobalt leads to easy pull outs of this tungsten carbide cuboids in case of coatings as compared to the bulk tungsten carbide cobalt and with respect to the effect of abrasive harder the abrasive greater is the intensity of this pull out.

So you can see lot of pull outs in case of the harder abrasives.

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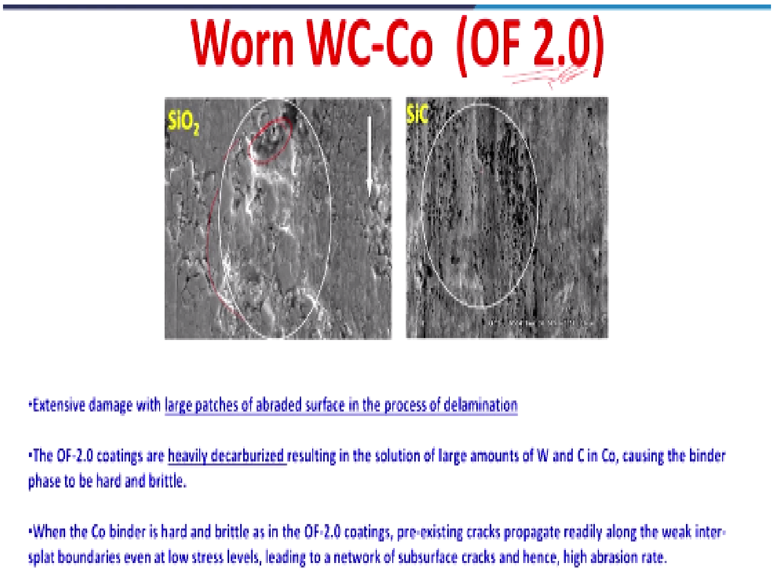

These are the worn surfaces of the tungsten carbide cobalt the tungsten carbide cobalt coating with an oxygen fuel ratio of 2.0. You can see the extensive material removal with larger patches of this material abraded and then this is delaminated. So the oxygen to fuel ratio of 2.0 coatings are heavy decarburized as I told previously the decarburization is of the order of around 45%.

So because of the heavy decarburization that results in the solution of the large amounts of tungsten and carbon in the binder phase. So once this is dissolved that is to binder phase becoming harder and brittle. So once the binder phase becomes harder and brittle. So you have these cracks propagating easily along this weak intersplat boundaries. So such a propagation is possible even at a lower stress levels.

So there is a easy propagation of this preexisting cracks and then that results into network of these cracks and hence you get a large amount of material removal. So when you have decarburization maximum that we found in oxygen to fuel ratio of 2.0 you see large patches of these material and then their delamination.

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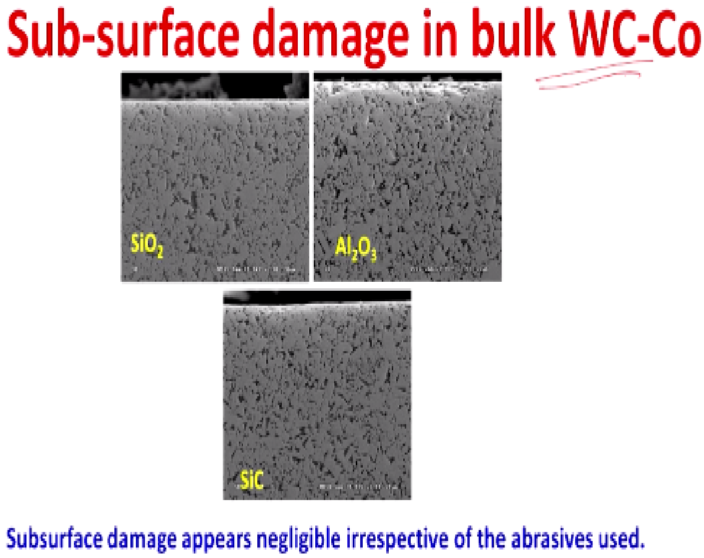

So the subsurface cracking can also be understood. So you can see the bulk tungsten carbide cobalt subsurface damage this damage appears to be negligible irrespective of the abrasive used.

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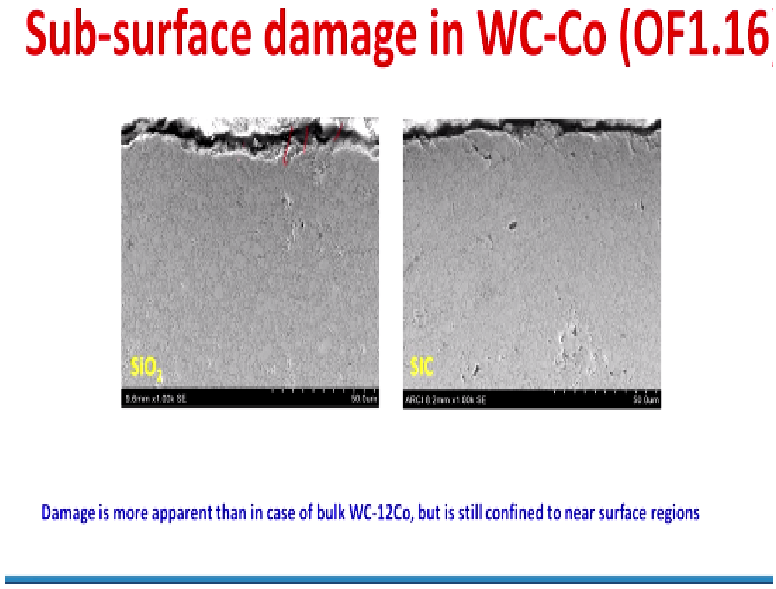

But the subsurface damage is more apparent in the tungsten carbide cobalt coating in, but it is still confined to very small regions underneath the surface okay both cases of silicon oxide abrasive or the silicon carbide abrasive.

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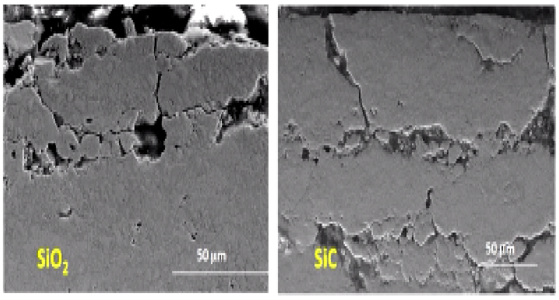
Sub-surface damage in WC-Co (OF2.0)



Subsurface cracks are quite extensive in nature and further extend to a substantial depth (around 50-125µm) beneath the abraded surface

But if you see the damage occurring for the coatings done with the higher oxygen to fuel ratio of 2.0 the subsurface damage is extensive you can see the cracking is extensive that extend to a long a substantial depth. The depth is around 50 to 125 micron meter till that depth you have a network of these subsurface cracks. So this also indicates the severe wear occurring in the coatings done with the maximum oxygen to fuel ratio of 2.0.

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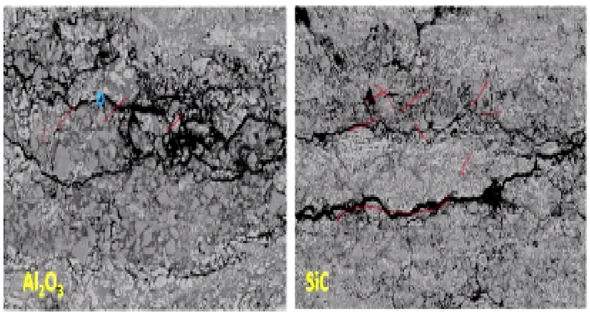
Sub-surface damage in WC-Co (OF2.0)



Crack develops and propagates along the inter-splat boundaries.

So, the crack develops and propagates along the intersplat boundaries observed in a high magnification image of this subsurface. You can see so many cracks they network and then you will have a severe wear happening because of this networking of this crack at the subsurface along this intersplat boundaries. So intersplat boundaries are the stress concentrators.

So, even the low levels of external stress there is a large amount of cracking possible along this boundary and then lead to networking of the subsurface and then removing the material from the surface in a larger extent. So this subsurface cracks and then resultant damage can also be understood with respect to the subsurface to the crack zone width and the abrasion wear rate behavior.

So, here the abrasion wear rate is plotted as a function of subsurface crack zone width. So we found the subsurface crack are dominant in case of the tungsten carbide cobalt coating done with the oxygen fuel ratios of 2.0 for the test done with the aluminum oxide silicon carbide and silicon oxide as well as that done with the coating oxygen fuel ratio of 1.0 in case of silicon carbide because silicon carbide is the harder abrasive.

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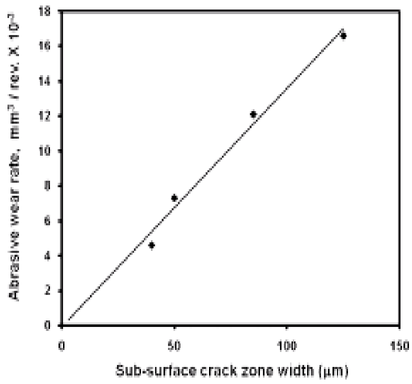
Abrasive wear as function of sub-surface damage



Subsurface cracking is responsible for the observed wear.

So, all these 4 coating gave an abrasive wear rate linear with the subsurface crack zone width. So, you can see the linear dependence of this abrasion wear rate with the subsurface crack zone width. So, we can confirm that the subsurface cracking is responsible for the higher abrasion wear rate.

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Conclusions

- The abrasive wear of detonation sprayed WC-12Co coatings exhibit a linear increase in wear rate with an increase in abrasive hardness.
- In terms of abrasives, use of SiC abrasive resulted in the highest abrasion rate, SiO_2 abrasive the lowest wear rate and Al_2O_3 intermediate wear rates, in both the detonation sprayed WC-12 Co coatings and bulk WC-12Co.

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- The abrasive wear is controlled by WC cuboid cracking and fracture in the case of bulk WC-12Co and by WC cuboid pull out in the case of coatings deposited at OF ratios of 1.16 and 1.50.
- In contrast, wear occurs by inter-splat cracking induced delamination in the in the coatings deposited at an OF ratio of 2.0.
- The extent of and the depth up to which inter-splat cracking occurs also correlates well with the abrasive wear rate in the case of coatings, primarily worn by inter-splat cracking induced delamination.

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Finally concluding the key results obtained in this study. The abrasive wear of the detonation spray tungsten carbide 12% cobalt coating exhibit a linear increase in the wear rate with an increase in the abrasive hardness. In terms of the abrasive the use of silicon carbide abrasive always resulted in a highest abrasion rate whereas the use of silicon oxide resultant in always lowest abrasion wear rate.

And always the aluminum oxide abrasion aluminum oxide abrasive gave an intermediate wear rates and this is same for the both bulk material as well as the tungsten carbide cobalt coating. Abrasive wear is controlled by the tungsten carbide cuboids cracking and then fracture. In case of bulk tungsten carbide cobalt whereas tungsten carbide cuboids pull out is observed in case of coatings.

In wear occurs by intersplat cracking induced delamination in the coatings deposited with a oxygen to fuel ratio of 2.0. So this intersplat cracking induced delamination is dominant at a higher oxygen to fuel ratios and lower oxygen to fuel ratios always gave tungsten carbide cuboids pull out in case of coatings deposited at oxygen fuel ratios of 1.16 and 1.50. In contrast wear occurs by intersplat cracking induced delamination in the coating deposited at an oxygen to fuel ratio of 2.0.

Further the extent and the depth up to the intersplat cracking occurs also agrees well with the abrasive wear rate in case of coatings primarily worn by the intersplat cracking induced delamination. So this particular study necessarily indicate the influence of the oxygen to fuel ratio in detonation spray coating of this tungsten carbide cobalt on the mild steel on the abrasion wear.

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Thank you.