Friction and Wear of Materials: Principles and Case Studies

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Lecture – 39
Erosive Wear of WC-Co Coating

Hello welcome back. Today in this lecture, we will go through K results obtained from importation erosion wear study of tungsten carbide cobalt coatings. Tungsten carbide cobalt is known as a hard material and this cermet because it is a ceramic of tungsten carbide and cobalt as a metal this is called a cermet.

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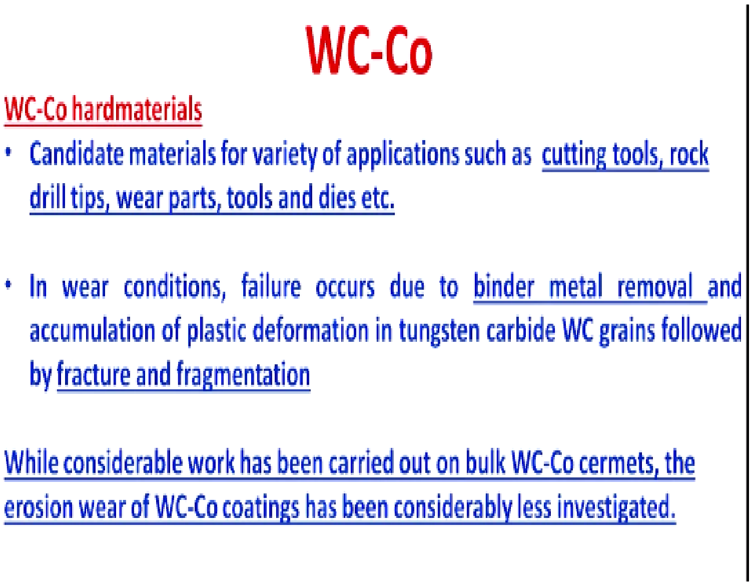

WC-Co

WC-Co hardmaterials

- Candidate materials for variety of applications such as cutting tools, rock drill tips, wear parts, tools and dies etc.
- In wear conditions, failure occurs due to binder metal removal and accumulation of plastic deformation in tungsten carbide WC grains followed by fracture and fragmentation

While considerable work has been carried out on bulk WC-Co cermets, the erosion wear of WC-Co coatings has been considerably less investigated.

So this tungsten carbide cobalt cermet is a candidate material for variety of engineering applications. For example, cutting tools, rocks, drill tips certain wear parts and tools and dies for the forming. So in all these applications there is a significance of the wear resistance. So in all applications wear resistance of this material is of primary concern, but the failures occurs in these materials because of the removal of the binder metal then followed by the removal or the fracture of this tungsten carbide grains.

But overall the tungsten carbide cobalt bulk materials are studied for their wear behavior whereas the wear behavior of tungsten carbide cobalt coatings is noted considerably understood. Particularly the erosion wear of these tungsten carbide cobalt materials is not understood.

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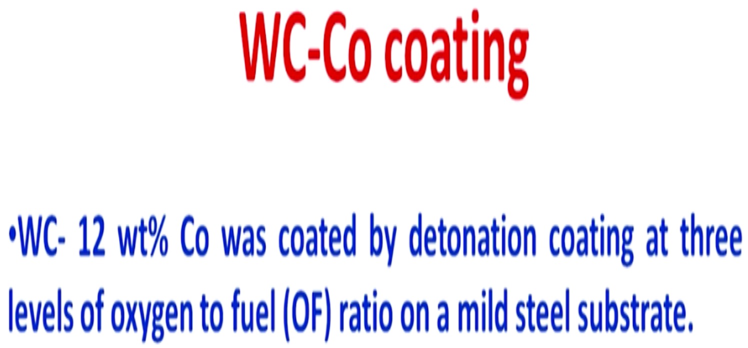

WC-Co coating

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

Tungsten carbide cobalt was coated by a detonation coating method using 3 levels of oxygen to fuel ratios and a mild steel substrate and the feed stock of tungsten carbide and 12% cobalt was used for the coating and all this coatings gave a uniform thickness of around 350 micron meter.

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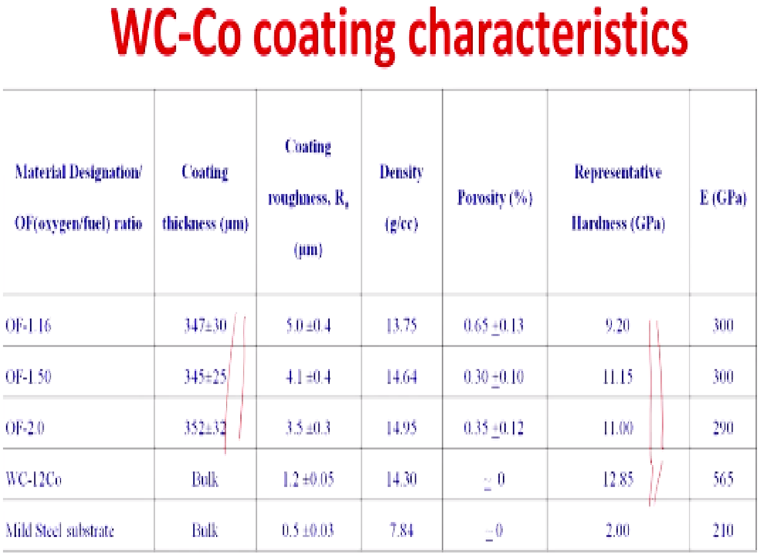

WC-Co coating characteristics

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 in this study we have 3 different coatings designated by the difference in their oxygen to fuel ratio. The oxygen to fuel ratio was 1.16 in one case, 1.50 in another case and 2.0 in the other case. So these coatings were done to obtain a uniform thickness of around 350 micron meter and the representative hardness showed the hardness varied between 9 to 11 gigapascal and then the elastic modulus varied between 290 to 300 gigapascal.

And for the comparison a tungsten carbide 12% cobalt bulk material is also taken for the study and you can see this hardness of this bulk material is around 12.85 gigapascal and the mild steel substrate of course has a very less hardness of around 2 gigapascal.

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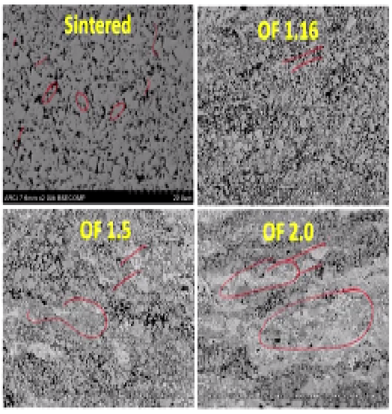
Microstructures



- Number density of cuboids are lower in OF 1.5 and OF 2.0 coatings, compared to the OF-1.16 coating
- Brighter decarburization zones in OF 1.5 and OF 2.0 coating

So the microstructures reveal very important information. We can see the sintered material has the tungsten carbide grains and then this black one is this binder phase and when the tungsten carbide cobalt coated material was studied for their microstructural characteristics there is a difference in the number of these density of this tungsten carbide cuboids with change in the ratio of this oxygen to fuel.

And you can see the number of density of cuboids are lower relatively in case of the oxygen to fuel ratio of 1.5 and 2.0 coatings compared to that for the oxygen to fuel ratio of 1.16 and you can also see there is certain bright contrast regions. These bright contrast regions or decarburization regions. So brighter decarburization regions are significant in case of the coatings obtained using oxygen to fuel ratio of 1.5 and 2.0.

In another study it was found the maximum decarburization of around 45% in case of oxygen to fuel ratio of 2.0 and 34% in case of the coating obtained using oxygen to fuel ratio 1.5 and very less decarburization of around 4% in the other coating you obtained using oxygen to fuel ratio 1.16.

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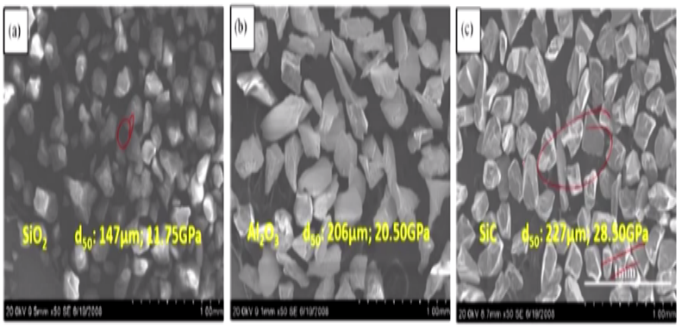
Abrasives



In this study the abrasives that we call erodents are 3 silicon oxide, aluminum oxide and silicon carbide. So these were considered because of their differences in their hardness. Silicon oxide is less harder material out of this 3 and silicon carbide is the material with highest hardness of around 28.5 gigapascal and silicon oxide having a hardness of around 11.75 gigapascal and aluminum oxide is in between in the hardness and the particle size of these erodents were between 147 to 227 micron meter.

You can see all the particles are of angular shape and aluminum oxide is a bit flaky shape and these 2 silicon oxide and then silicon carbide are angular and block type whereas aluminum oxide erodent is of angular and flaky type.

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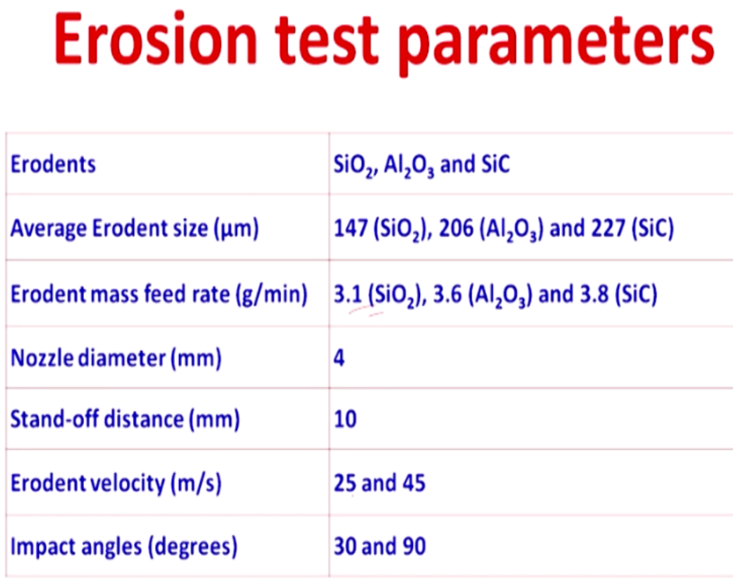

Erosion test parameters

Erodents	SiO_2, Al_2O_3 and SiC
Average Erodent size (µm)	147 (SiO_2), 206 (Al_2O_3) and 227 (SiC)
Erodent mass feed rate (g/min)	3.1 (SiO_2), 3.6 (Al_2O_3) and 3.8 (SiC)
Nozzle diameter (mm)	4
Stand-off distance (mm)	10
Erodent velocity (m/s)	25 and 45
Impact angles (degrees)	30 and 90

The erosion was conducted in a solid particle erosion tester where these solid particles of erodent were impinged on the sample in this case the coating or this mid steel or the tungsten carbide cobalt bulk material. So the erodent are silicon oxide, aluminum oxide and silicon carbide particles and erosion was conducted with erodent mass feed rate of around 3 for silicon oxide, 3.6 for aluminum oxide, 3.6 for aluminum oxide and 3.8 for the silicon carbide.

This mass feed rate is in gram per minute and erodent velocities were changed from 25 meters per second to 45 meters per second. So the impact angles were changed from 30 to 90. So the study was conducted to understand the behavior of the tungsten carbide cobalt coatings with change in the erodents, impact velocity and impact angles.

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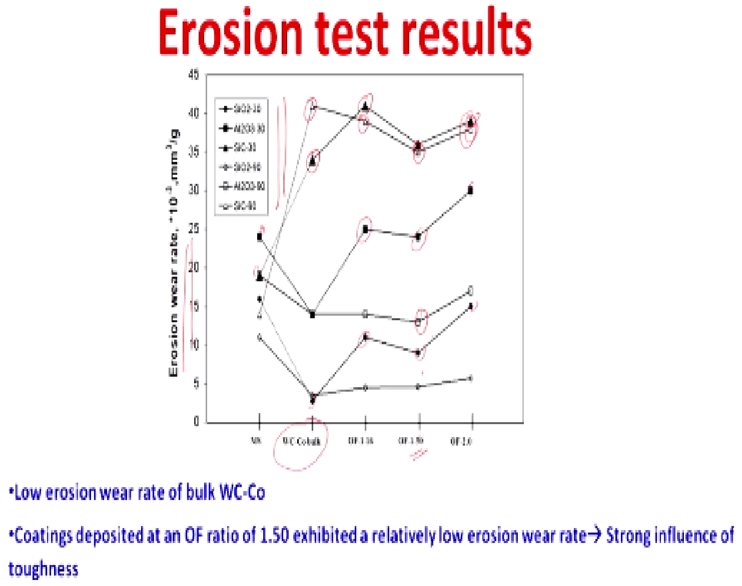

Erosion test results

- Low erosion wear rate of bulk WC-Co
- Coatings deposited at an OF ratio of 1.50 exhibited a relatively low erosion wear rate→ Strong influence of toughness

So again the erosion wear rate was determined by measuring the weight loss then converted into volume loss. The volume loss per unit mass of the erodents used that will give the erosion rate. So erosion rate as a function of different materials and the different erodents and the angles of impact. So you can see this solid triangles or data for the silicon carbide and at 30 degrees angle of impact whereas this hollow triangles or of silicon carbide data of silicon carbide at 90 degree angles.

Similarly, this square is of for the aluminum oxide and this diamond shapes indicates the data for the silicon oxide. Now let us understand this behavior. There is a low erosion wear rate of the bulk tungsten carbide cobalt right. The coatings deposited at an oxygen to fuel ratio of 1.50 show relatively lesser wear, lesser erosion wear rate. So we can see in each condition the 1.50 case showed a lesser wear rate right and compared to those obtained for an oxygen the coatings used the coatings obtained with oxygen to fuel ratio of 2.0 or 1.16.

You have lower erosion wear rates for the coatings obtained using 1.50 oxygen to fuel ratio right.

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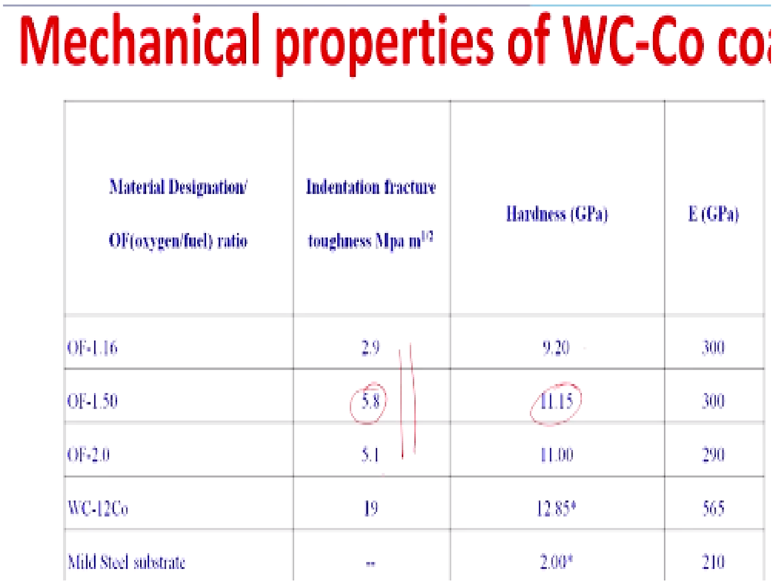

Mechanical properties of WC-Co co

Material Designation/ OF(oxygen/fuel) ratio	Indentation fracture toughness Mpa m$^{1/2}$	Hardness (GPa)	E (GPa)
OF-1.16	2.9	9.20	300
OF-1.50	5.8	11.15	300
OF-2.0	5.1	11.00	290
WC-12Co	19	12.85*	565
Mild Steel substrate	--	2.00*	210

So this type of behavior can be understood on the basis of their mechanical properties. So generally when ceramics are any brittle materials are subjected to erosion by a sharper object. So there is a crack formation and then material will be removed by the fracture. So indentation fracture toughness is measured to understand the resistance against the propagation of cracks.

And you can see the indentation fracture toughness for these 3 coating materials vary between 2.9 to 5.1 MPa root meter. So maximum fracture toughness is obtained for the oxygen to fuel ratio of 1.50. So you can see the hardness is again maximum for the coating obtained with oxygen to fuel ratio of 1.50, but if you can see the mechanical property influence generally for a brittle materials there is a combination of this hardness and fracture toughness and the elastic modulus that actually determines the erosion wear.

So here also we can see the combination of improved properties of indentation fracture toughness of 5.8 MPa root meter and hardness of 11.15 gigapascal showed a lesser erosion wear rate compared to other two. In other words, we can see the strong influence of indentation fracture toughness than the hardness. Hardness does not change from 11.15 to 11.00 with changing oxygen to fuel ratio from 1.50 to 2.0.

But the fracture toughness is maximum for the around 5.8 MPa root meter for the oxygen to fuel ratio of 1.50 that means there is a strong influence of the fracture toughness on the erosion wear rate of this material coating material.

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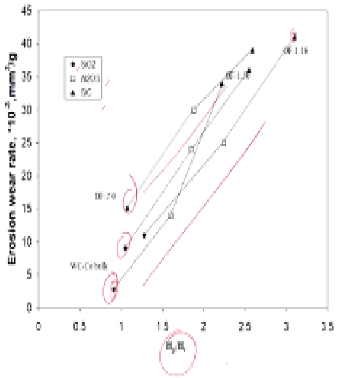
Erosion wear rate as a function of erodent- target hardness ratio



- The erosion wear rate of coatings increased with increasing hardness of the erodent.
- An increase in Hp/Ht ratio from 1.0 to 2.5 results in an increase of wear rate by 3.5–4.0 times.

Let us understand the behavior more in detail. Erosion wear rate as a function of erodent target hardness ratio so this ratio is of the hardness of the particle used to the hardness of the target. So we can see these erosion wear rate of coatings generally increased with the hardness of the indent right. You can see this is a silicon oxide, aluminum oxide and silicon carbide. So again this diamond data represented by the diamond (()) (13:12) is very low right.

So we have lesser erosion rate when the silicon oxide was used whereas highest erosion wear rate was obtained when silicon carbide was used right and with respect to the oxygen to fuel ratio again the erosion wear rate was less for the coating obtained using oxygen to fuel ratio 1.50 for any erodent. So you can see then the increase in the ratio from 1.0 to 2.5 results in an increasing wear rate of almost 3.5 to 4 times. This hardness influences the erosion considerably.

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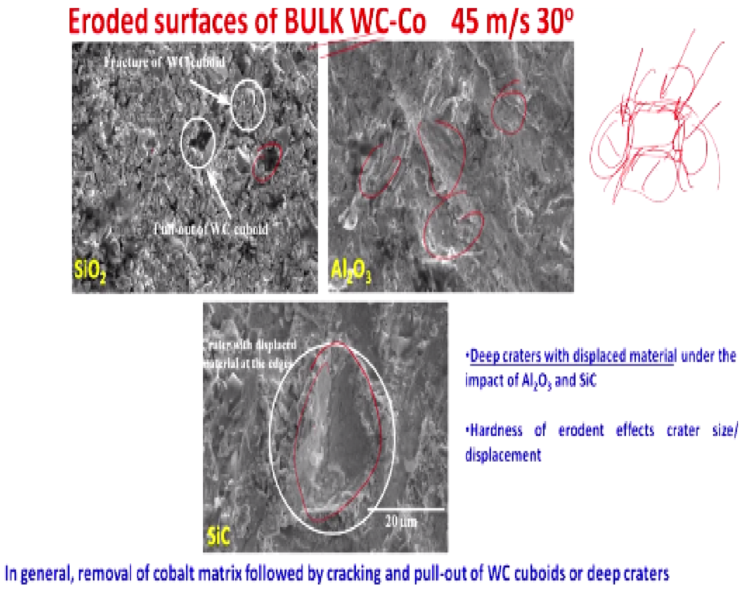

Eroded surfaces of BULK WC-Co 45 m/s 30°

- Deep craters with displaced material under the impact of Al_2O_3 and SiC
- Hardness of erodent effects crater size/ displacement

In general, removal of cobalt matrix followed by cracking and pull-out of WC cuboids or deep craters

To understand the erosion wear behavior it is very important, very much required to understand the dominant material removal mechanism. So these are the worn surfaces after erosion of a bulk tungsten carbide cobalt eroded at 30 degrees impact angle and 45 meters per second impact velocity with different erodent. Now you can see in general the material is removed by removing first this material of cobalt followed by the cracking.

And then pull out of this tungsten carbide. So if you understand the microstructure in such a way that you have certain tungsten carbide grains and these are actually attached through this cobalt phase right. So when the erodent attacks the surface of this material first the deformable softer material will be easily removed. When the softer material cobalt binder material is removed these materials of tungsten carbide grains they will be subjected to further attack by the erodents.

Now when these are not intact with the cobalt binder because it is smeared away or removed away. So these tungsten carbide cobalt can be removed as such as so you get a pull out or there can be some fracture of this grains a tungsten carbide cobalt. So in this particular bulk tungsten carbide cobalt material the tungsten carbide cuboids are mostly pulled out right. So particularly if you see this one surfaced after erosion by the silicon oxide.

You can see lot of these material removal by the pull of this tungsten carbide cuboids, but when the aluminum oxide or silicon carbide were used the craters are more deeper and then material is displace away right. So you can see such a large area of this crater so the crater is deeper and the area is also larger which is the material is displaced from the edges. So we can say again if you consider the hardness of this materials of erodent silicon oxide is less harder erodent.

Whereas silicon carbide is of high hardness. So you can say the hardness of this erodents affects the size of the crater or the displacement. So when the silicon oxide of which is less in the hardness is used as an erodent. The crater size is less or in other words when harder materials like aluminum oxide or silicon carbide were used the crater sizes were more right. So particularly this crater is maximum when silicon carbide was used.

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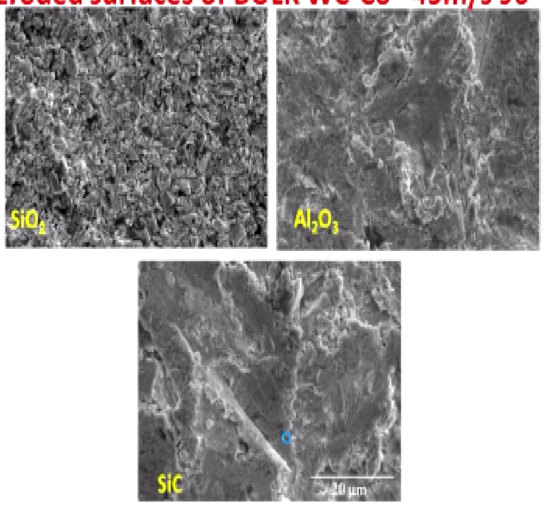
Eroded surfaces of BULK WC-Co 45m/s 90°



No appreciable difference in the wear mechanism at two widely different impact angles

So these are the eroded surfaces of the bulk tungsten carbide cobalt after eroding at 45 meters per second and 90 degrees angle again there is no much difference in the dominant mechanism of material removal with respect to the impact angle there is only difference in the severity.

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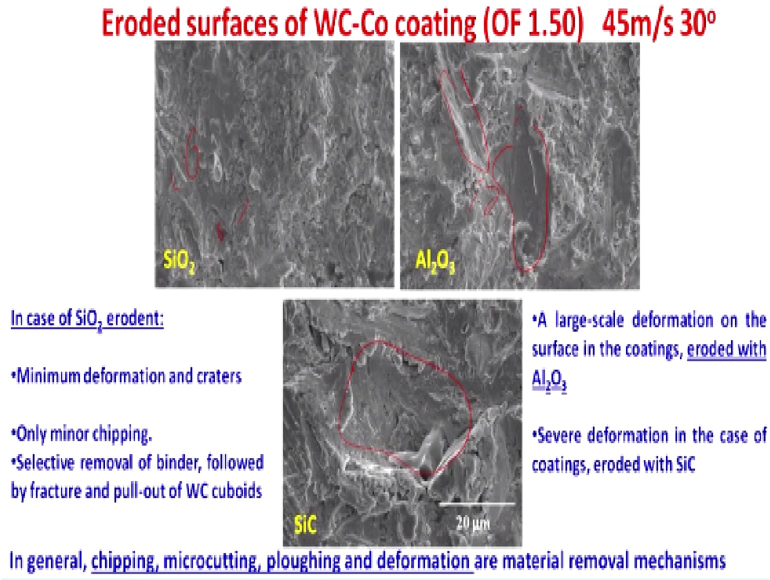

Eroded surfaces of WC-Co coating (OF 1.50) 45m/s 30°

In case of SiO_2 erodent:

- Minimum deformation and craters
- Only minor chipping.
- Selective removal of binder, followed by fracture and pull-out of WC cuboids

- A large-scale deformation on the surface in the coatings, eroded with Al_2O_3
- Severe deformation in the case of coatings, eroded with SiC

In general, chipping, microcutting, ploughing and deformation are material removal mechanisms

Now let us understand with the tungsten carbide cobalt coating. The tungsten carbide cobalt coating eroded surface. Now this particular eroded surface of a coating which was done at oxygen to fuel ratio 1.50. Now you see in case of silicon oxide erodent comparatively minimum craters and the deformation is observed. So material is removed mainly by the chipping by the minor chipping.

So again in this case the first of all the material which is softer in nature which is cobalt binder is removed followed by the fracture as well as the pull out of this tungsten carbide cuboids then in case of aluminum oxide a large scale deformation on the surface is observed right. So there is a large scale deformation you can see large scale deformation and severe deformation is observed when silicon carbide was used.

So in general the coatings were worn away by chipping or the microcutting or the deformation.

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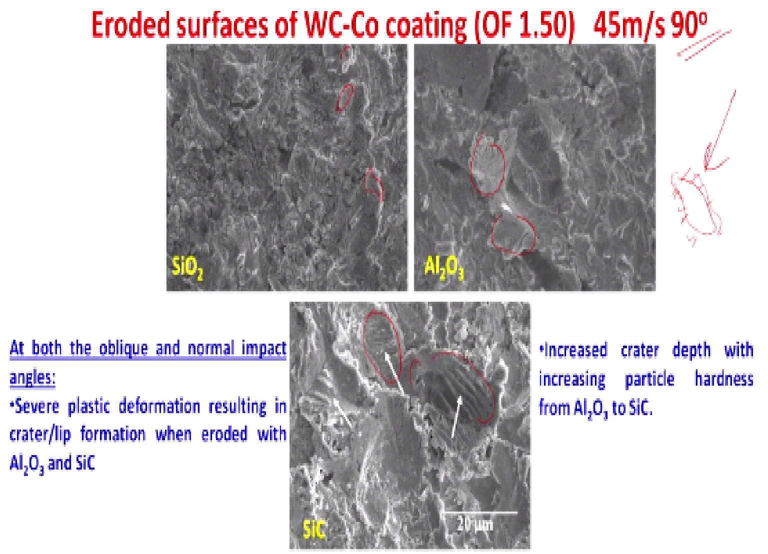

Eroded surfaces of WC-Co coating (OF 1.50) 45m/s 90°

At both the oblique and normal impact angles:

- Severe plastic deformation resulting in crater/lip formation when eroded with Al_2O_3 and SiC

- Increased crater depth with increasing particle hardness from Al_2O_3 to SiC.

With change in angle of impact. So the severe plastic deformation resulting in the crater or lip formation you can see lot of lips. So when this particles erodes the material is removed and then at the edges there is a material ejected from the edges and which forms as a lip. So you can see lot of lip formation when eroded with the aluminum oxide right and then silicon carbide.

So this type of deformation signatures are more when the surface is eroded by harder erodents of aluminum oxide or silicon carbide compared to silicon oxide. You can see certain creations this creations are nothing but the deformation signature. So increased crater depth with increased particle hardness is observed when we use the aluminum oxide to silicon carbide.

So these kinds of surfaces show lot of crater forming when you use the erodent of high hardness. So this material is removed by the cutting that is the crack formation.

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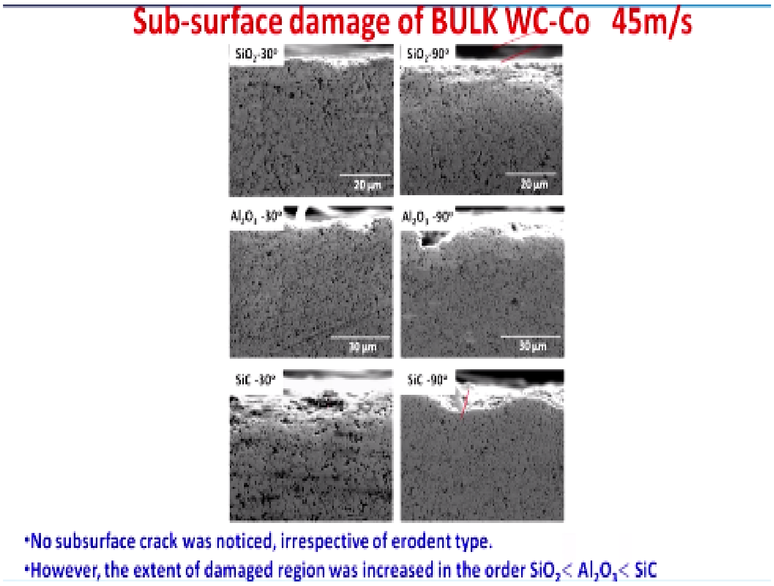

Sub-surface damage of BULK WC-Co 45m/s

- No subsurface crack was noticed, irrespective of erodent type.
- However, the extent of damaged region was increased in the order $SiO_2 < Al_2O_3 < SiC$

If you look at the subsurface damage of this materials first of all this bulk material so you do not see much subsurface irrespective of this erodent used. However, the extent of damage region was actually increased in the order of silicon oxide more than aluminum oxide more than the silicon carbide. So when silicon carbide was used larger extent of the damage region was observed compared to aluminum oxide or to silicon oxide erodent.

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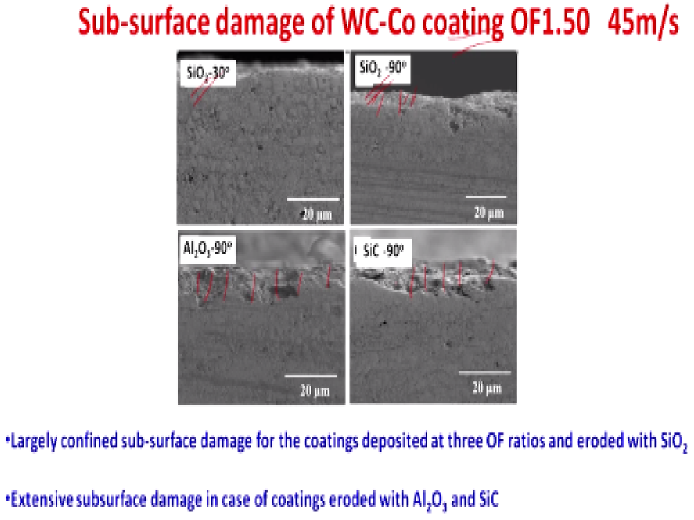

Sub-surface damage of WC-Co coating OF1.50 45m/s

- Largely confined sub-surface damage for the coatings deposited at three OF ratios and eroded with SiO_2
- Extensive subsurface damage in case of coatings eroded with Al_2O_3 and SiC

So for the coating for the coating you can see largely confined zone confined subsurface damage for the coatings deposited at any oxygen to fuel ratio when silicon oxide erodent was used whereas extensive damage you can see the damage is only here right very few microns. So here there are tens of micron meters subsurface damage is observed when we use the aluminum oxide or silicon carbide erodent.

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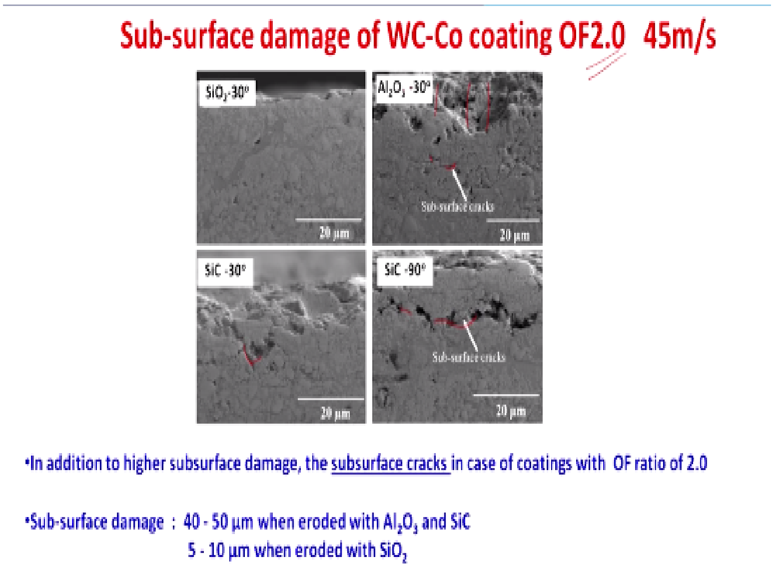

Sub-surface damage of WC-Co coating OF2.0 45m/s

- In addition to higher subsurface damage, the subsurface cracks in case of coatings with OF ratio of 2.0

- Sub-surface damage : 40 - 50 μm when eroded with Al$_2$O$_3$ and SiC
  5 - 10 μm when eroded with SiO$_2$

So even with the increased oxygen to fuel ratio similar trend is observed. So in addition to the subsurface damage there is a subsurface cracking in addition to the subsurface you can see subsurface cracking. When the oxygen to fuel ratio is higher at around 2.0 oxygen to fuel ratio of 2.0. So if you roughly estimate the subsurface damage it is around 40 to 50 micron meter when aluminum oxide or silicon carbide was used whereas only less than 10 micron meter when the erodent of silicon oxide was used.

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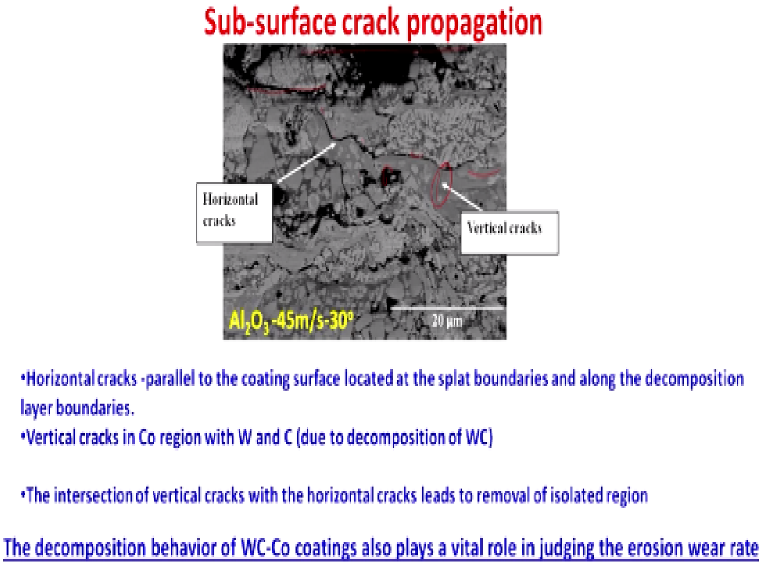

Sub-surface crack propagation

- Horizontal cracks -parallel to the coating surface located at the splat boundaries and along the decomposition layer boundaries.
- Vertical cracks in Co region with W and C (due to decomposition of WC)

- The intersection of vertical cracks with the horizontal cracks leads to removal of isolated region

The decomposition behavior of WC-Co coatings also plays a vital role in judging the erosion wear rate

So subsurface crack is very important because these subsurface cracks they coalesce each other and then form a bigger crack and then the material is removed by the fracture. So further investigation was also done to understand the crack propagation in the subsurface region. So very interestingly there are 2 types of cracks one is that crack which is almost parallel to the surface coating surface right.

And also there are certain cracks which are perpendicular to the surface coating surface. So there are actually horizontal cracks as well as vertical cracks found. So horizontal cracks located at almost to the splat boundaries right and along the decomposition boundaries. So vertical cracks are generally found in the cobalt binder region actually this cobalt binder region is also having the tungsten and carbon as a result of a decomposition of this tungsten carbide.

Because of the decarburization these tungsten and carbide go into the cobalt region and make it more brittle because of such brittleness they crack. So there are 2 different horizontal and vertical cracks and the intersection of these cracks lead to the isolation of the material and then material is removed as we say the wear. So the decomposition behavior of this coatings also plays a vital role in judging the erosion wear rate.

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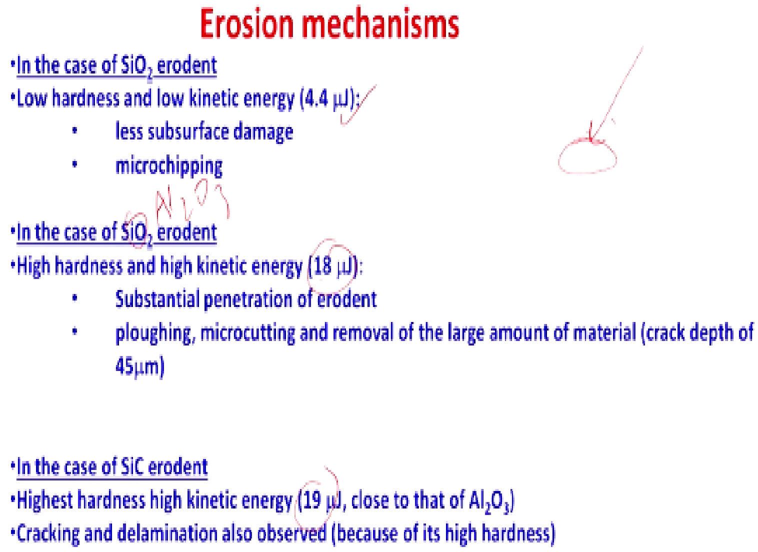

Erosion mechanisms

- In the case of SiO_2 erodent
- Low hardness and low kinetic energy (4.4 μJ):
  - less subsurface damage
  - microchipping

Al_2O_3

- In the case of SiO_2 erodent
- High hardness and high kinetic energy (18 μJ):
  - Substantial penetration of erodent
  - ploughing, microcutting and removal of the large amount of material (crack depth of 45μm)

- In the case of SiC erodent
- Highest hardness high kinetic energy (19 μJ, close to that of Al_2O_3)
- Cracking and delamination also observed (because of its high hardness)

So erosion mechanism can also be understood with respect to the erodents used. In case of silicon oxide erodent low hardness and as well as the low kinetic energy this kinetic energy was estimated because we know the particles which is coming. So it is indent on the surface with a certain velocity so the kinetic energy can be estimated. So low hardness and low kinetic energy in case of silicon oxide that leads to very less subsurface damage as we found.

And the main mechanism of the material was by micro chipping whereas in case of aluminum oxide this is actually aluminum oxide erodents a high hardness of this particles and high kinetic energy that gave the substantial penetration of this erodent and the material is removed mainly by the ploughing and then the microcutting mechanism. The crack depth is almost more than around 40 micron meter.

Whereas in case of silicon carbide erodent because of the highest hardness out of this 3 materials of erodents and high kinetic energy. Kinetic energy if you see it is almost close to that of the aluminum oxide, but a combination of the hardness and kinetic energy which is highest hardness and high kinetic energy that leads to more cracking. So more cracking and delamination are observed are observed in case of the silicon carbide erodent.

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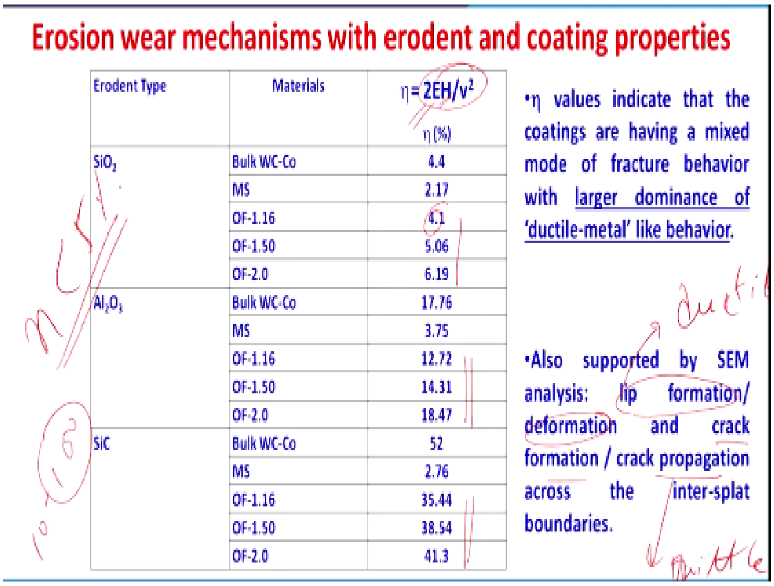

Erosion wear mechanisms with erodent and coating properties

Erodent Type	Materials	$\eta = 2EH/v^2$ η (%)
SiO_2	Bulk WC-Co	4.4
	MS	2.17
	OF-1.16	4.1
	OF-1.50	5.06
	OF-2.0	6.19
Al_2O_3	Bulk WC-Co	17.76
	MS	3.75
	OF-1.16	12.72
	OF-1.50	14.31
	OF-2.0	18.47
SiC	Bulk WC-Co	52
	MS	2.76
	OF-1.16	35.44
	OF-1.50	38.54
	OF-2.0	41.3

- η values indicate that the coatings are having a mixed mode of fracture behavior with larger dominance of 'ductile-metal' like behavior.
- Also supported by SEM analysis: lip formation/ deformation and crack formation / crack propagation across the inter-splat boundaries.

So erosion wear mechanisms can also be understood with respect to the efficiency of this erosion. Efficiency of the erosion can be determined by the material removed from the surface to the material indented because of this erosion right. So you know this elastic modulus hardness of the target material the velocity. So you can know the efficiency values for the investigated material when different erodents were used.

You can see the coatings efficiency varied 4% to 6% when the silicon oxide was used whereas around 13% to 18% in case of aluminum oxide whereas high efficiency of around 35% to 41% is observed when silicon carbide was used. So generally speaking the efficiency if it is of < 5% the material is removed by a ductile fashion that means by mainly by ploughing and lip formation.

If it is> 5% generally around 100 10% to 100% it is mostly by the brittle fashion that is by cracking and then material removed. So this cracking this crack coalesce and the material is removed. So it indicates actually these value these efficiency values indicate that the coatings have or having a mixed mode of fracture right. You have certain coatings which are< 5% and more or less> this one.

So you do not have exactly the brittle fracture. This is a mixed mode of fracture, but with larger dominance of the ductile metal behavior it is not much higher than usually what we observe for the brittle materials. So this kind of wear mechanisms of largely ductile metal type like behavior is also supported by our (()) (28:34) analysis where we have seen the lip formation and deformation as well as crack formation and crack propagation.

So lip formation and deformation is representation of ductile behavior whereas this is representation of the brittle behavior.

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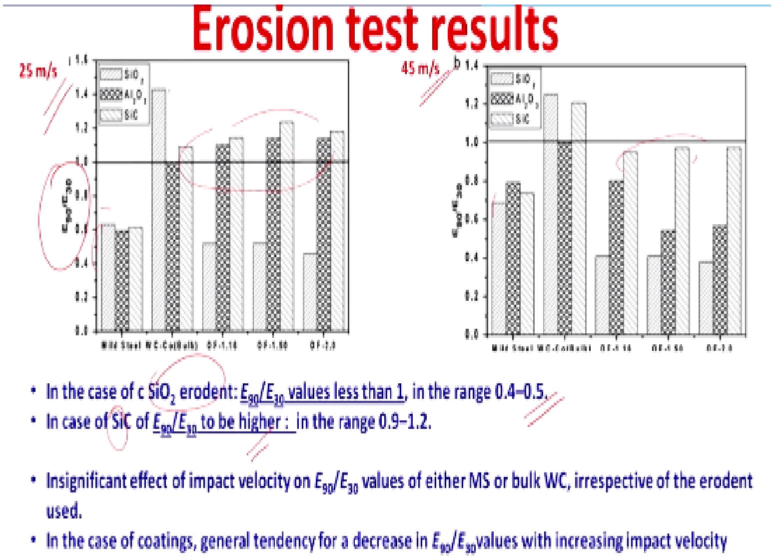

Erosion test results

- In the case of c SiO_2 erodent: E_{90}/E_{30} values less than 1, in the range 0.4–0.5.
- In case of SiC of E_{90}/E_{30} to be higher : in the range 0.9–1.2.

- Insignificant effect of impact velocity on E_{90}/E_{30} values of either MS or bulk WC, irrespective of the erodent used.
- In the case of coatings, general tendency for a decrease in E_{90}/E_{30}values with increasing impact velocity

So you have a simultaneous occurrence of both. So generally we understand the wear by domination of these ductile or brittle behavior. Erosion test results can also be understood by the ratio of the erosion rate obtained at 90 degrees to the erosion rate obtained at 30 degrees. So this is the data for the erosion done at 25 meters per second this is the data for erosion done at 45 meters per second.

Now in case of the softer silicon oxide erodent the value is<1 right so generally in the 0.4 to 0.5. If the value is<1 that means generally at higher angles the cutting is more dominant. So at lower angles it is ploughing more dominant right the deformation. So in case of the softer erodent the value is<1 again indicating the deformation dominated wear mechanism whereas in case of silicon carbide.

It is higher but it is if you see it is around 0/9 to 1.2 if you consider all this things it is around 0.9 to 1.2 it is not as expected for the brittle materials it is always> 1, but you have certain cases where it is<1 also but it is still higher than the values obtained when silicon oxide was used. So the values obtained were higher for the silicon carbide erodent compared to silicon oxide erodent and aluminum oxide erodent the values are in between.

So if you see the velocity effect there is a significant effect of this impact velocity of either this mild steel or the bulk tungsten carbide cobalt irrespective of the erodent, but if you see the coatings generally the tendency is decreasing the values is observed with increase in the impact velocity.

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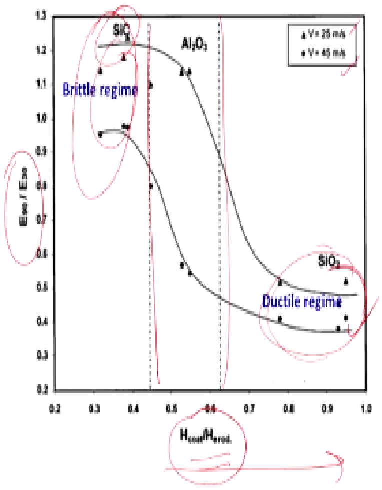
Erosion ratio-erodent-erosion mechanism



So if you consider this ratio versus the hardness of the coating to the hardness of the erodent used. Now you can see a very distinct zones when silicon carbide was used it is giving very larger higher ratios whereas silicon oxide was used it is giving very lesser ratios and aluminum oxide is in between. So you can actually divide the erosion behavior with respect to the mechanisms or the dominant mechanisms.

When silicon carbide was used either in case of 25 meters per second or 45 meters per second the material is removed by brittle by the brittle fashion whereas the silicon oxide which is softer so the ratio is going towards 1. So you get lesser erosion ratio so this is actually lesser. So erosion is lesser when it is close to it is going towards 1 the ratio is also lesser. When it is moving away from 1 it is lesser than 1 when it is lesser than 1 the ratio is higher.

So we can actually understand the behavior with respect to mechanisms by this erosion ratios at 90 degrees and 30 degrees with the hardness ratios of coating to erodent. So when the ratio of this hardness going towards worn this E9 to E30 ratio is lesser. When the ratio is less this erosion rate ratio obtained at 90 and 30 degrees angle is actually higher. So we can divide this map into 3 different regions presents brittle regime, ductile regime and aluminum oxide is in between.

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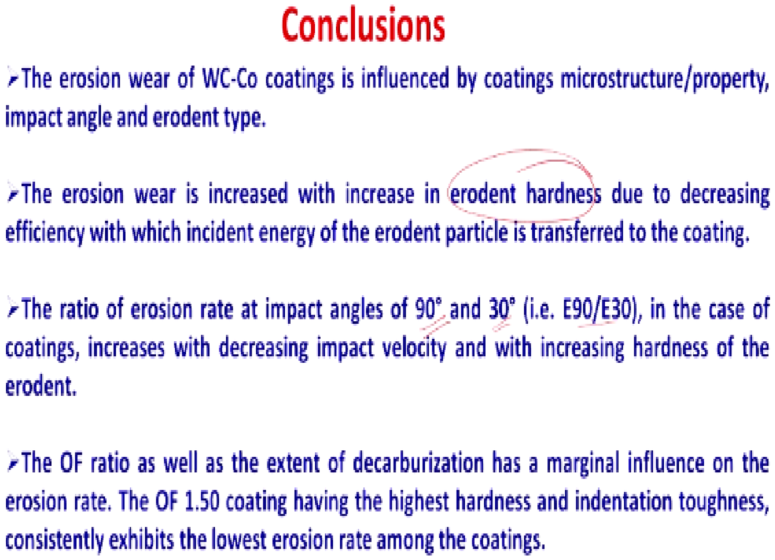

Conclusions

- The erosion wear of WC-Co coatings is influenced by coatings microstructure/property, impact angle and erodent type.
- The erosion wear is increased with increase in erodent hardness due to decreasing efficiency with which incident energy of the erodent particle is transferred to the coating.
- The ratio of erosion rate at impact angles of 90° and 30° (i.e. E90/E30), in the case of coatings, increases with decreasing impact velocity and with increasing hardness of the erodent.
- The OF ratio as well as the extent of decarburization has a marginal influence on the erosion rate. The OF 1.50 coating having the highest hardness and indentation toughness, consistently exhibits the lowest erosion rate among the coatings.

Finally, to conclude this salient results obtained from this study the erosion wear of this coating is influenced by the microstructure of the coating or in other words the properties of the coatings impact angle as well as the type of the erodent used. The erodent wear is increased with increase in erodent hardness mainly because of the decreasing efficiency with which the incident energy of the erodent particle is transferred to the coating.

So when you use the silicon oxide of lesser hardness you have decreased efficiency of this with which the incident energy of the erodent particle is transferred to the coating. So you get a erosion wear is increased with increase in erodent hardness or erosion wear is decreased with the increase in erosion hardness. The ratio of erosion rate at an impact angles of 90 and 30 degrees in case of the coatings increases with decreasing impact velocity with increasing hardness of the erodent.

The oxygen to fuel ratio as well as the extent of the decarburization has a marginal influence on the erosion rate and this study indicates the coating obtained using oxygen to fuel ratio of 1.50 having the highest hardness and indentation fracture toughness combination consistently exhibits the lowest erosion rate among the coatings. So it actually indicates the property influence.

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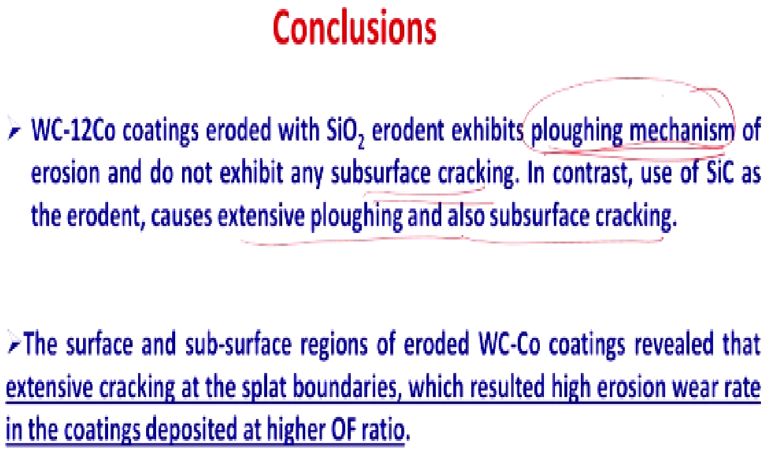

Conclusions

- WC-12Co coatings eroded with SiO_2 erodent exhibits ploughing mechanism of erosion and do not exhibit any subsurface cracking. In contrast, use of SiC as the erodent, causes extensive ploughing and also subsurface cracking.

- The surface and sub-surface regions of eroded WC-Co coatings revealed that extensive cracking at the splat boundaries, which resulted high erosion wear rate in the coatings deposited at higher OF ratio.

With respect to the mechanisms of material removal the tungsten carbide cobalt coatings eroded with silicon oxide erodent exhibits mainly the ploughing mechanisms of erosion and they do not exhibit any subsurface cracking very, very negligible cracking subsurface damage was observed whereas when we use the silicon carbide as erodent we see extensive ploughing as well as the subsurface cracking.

So when softer erodent was used it is mostly ploughing mechanism whereas harder erodent was used in addition to ploughing we also have the subsurface cracking. So the surface and subsurface regions of this eroded tungsten carbide cobalt coatings revealed that extensive cracking at the splat boundaries which are weaker regions that resulted into higher erosion wear rate in the coatings deposited with the higher oxygen to fuel ratio.

So this particular study indicates the complicated influence of the erodent type on the erosion wear behavior of the tungsten carbide cobalt coatings right. So overall this study indicates that erosion resistance is not a material property it is a system property. So involving influence from the erodent type the hardness of the material, coating material as well as the angle of impingement. Thank you.