ANALYSIS OF A TECHNIQUE TO COMPARE THE ADHESION OF COATINGS ON WC-CO CUTTING TOOL INSERTS

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INTRODUCTION

WC-Co cutting tool inserts used for cutting ferrous materials are typically coated with varying combinations of TiCN, TiN, Al_2O_3 and/or other coatings of varying thickness. The main function of the coatings is to prevent the diffusion of W (from the cutting tool insert) into the ferrous workpiece, which, obviously, leads to the wear of the insert[1]. The insert is discarded when the coating is removed and the substrate is exposed, which should occur through the progressive wear of the coating, but often occurs through the flaking of the coating, due to inadequate adhesion to the substrate. For this reason, the adhesion of the coating to the substrate plays a major role in the performance of coated inserts.

The quantitative measurement of adhesion, defined as the force required to separate a coating from the substrate (and therefore called "adhesion strength"), is practically impossible[2] because it requires the knowledge of the distribution of the stresses exerted by the tool used for the measurement and the knowledge of the residual stresses in the coating and the substrate and of the mechanical properties of all materials involved. Therefore all the methods used to assess adhesion give only relative results. In industry, the preferred methods are those which, besides giving reproducible results, utilize equipment which is generally available and are not time consuming. For this reason, a method which is based on the assessment of damage induced by Rockwell indentations[3] is used more and more frequently[4],

The damage consists of the flaking and/or cracking of the coating and on the basis of the damage pattern Su *et al.*[5] classified the adhesion of coatings into "good", "fair" or "poor".

This paper presents the application of the method based on Rockwell indentations to compare the adhesion of coatings in WC-Co cutting tool inserts. In order to apply the method to these coatings it was necessary to identify how much of the damage caused by Rockwell indentations was due to poor adhesion and how much to properties of the substrate or the coating. Besides, the comparison of coatings had to be based on their effectiveness in preventing the diffusion of W into the workpiece.

METHOD

The method to assess adhesion on the basis of damage induced in a coating by Rockwell indentations consists of indenting coated surfaces by means of the conical diamond of a Rockwell hardness tester. In the present case a Wilson Rockwell hardness tester 5 JR was used and the indenting load was 60 kg. The tip radius of the conical indenter was 200 μm and the cone angle 120°.

The samples tested were CVD coated commercial WC-Co cutting tool inserts from five different manufacturers (who will be identified as Suppliers 1 to 5). The tools were all meant to be used for turning steel. In all cases the substrate was WC-Co (with TiC and TaC as minor components). Table 1 gives the composition of the coatings' layers, their thickness, the Vickers hardness of the substrate and the Vickers hardness measured on the coatings (which is a combination of the hardness of the coating and the hardness of the substrate).

Table 1: Composition, thickness and hardness of the coatings tested. The "coating hardness" is a combination of the hardness of the coating and of the substrate

Cutting tool insert	Layer	Composition	Thickness [μm]
Supplier 1	1	TiC	5.0 ± 0.3
	2	TiCN	7.1 ± 0.5
Supplier 2	1	TiCN	0.5 ± 0.2
	2	TiCN	8.6 ± 0.3
	3	Al_2O_3	2.9 ± 0.5
	4	TiCN	0.8 ± 0.2
Supplier 3	1	TiCN	0.3 ± 0.1
	2	TiCN	7.8 ± 0.2
	3	Al_2O_3	4.6 ± 0.5
	4	TiCN	1.7 ± 0.3
Supplier 4	1	TiCN	9.0 ± 0.3
	2	Al_2O_3	2.1 ± 0.2
	3	TiCN	0.9 ± 0.4
Supplier 5	1	TiCN	5.6 ± 0.4
	2	TiC	2.0 ± 0.1
	3	TiCN	0.9 ± 0.05
	4	Al_2O_3	1.7 ± 0.1
	5	TiCN	0.7 ± 0.1

Table 1: (cont.)

Cutting tool insert	Overall thickness [µm]	Hardness Substrate HV30	Hardness Coating HV30
Supplier 1	12.1	1591 ± 19	1672 ± 25
Supplier 2	12.8	1563 ± 4	1660 ± 41
Supplier 3	14.7	1488 ± 5	1509 ± 34
Supplier 4	12.0	1463 ± 3	1526 ± 35
Supplier 5	10.9	1350 ± 5	1410 ± 47

The coated surfaces of the inserts were tested as received. The damage caused by the indentations (consisting of flaking and/or cracking) was examined by optical and scanning electron microscopy (SEM). Energy dispersive spectroscopy (EDS) was used to establish whether the flaking and chipping exposed the substrate.

In order to determine which part of the damage caused by the indentations was related to adhesion problems and which part was related to the properties of the substrate or the coating, an insert from each manufacturer was sectioned, ground and polished to produce a flat substrate surface without coating. This surface was indented under the same conditions as the coated surfaces and the damage patterns on the uncoated and coated surfaces were compared.

RESULTS AND DISCUSSION

Figures 1 to 5 show Rockwell indentations on the substrates and the coatings of the cutting tool inserts from the five different suppliers. The pictures of the indentations on the substrates are optical micrographs while the pictures of the indentations on the coatings are SE micrographs. The imperfect symmetry of some indentations is due to the indented surface not having been perfectly normal to the loading direction.

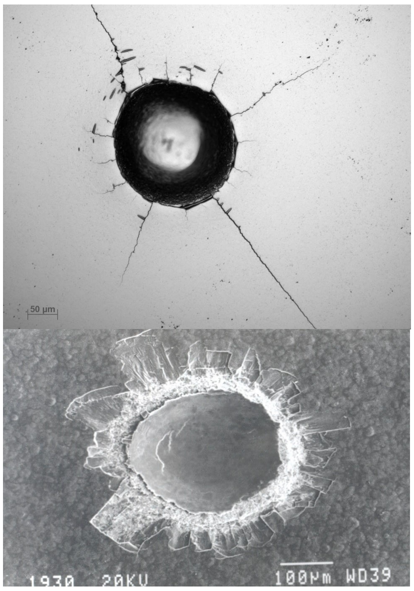

Fig. 1: Typical indentations on substrate (above) and coating (below) of an insert from Supplier 1

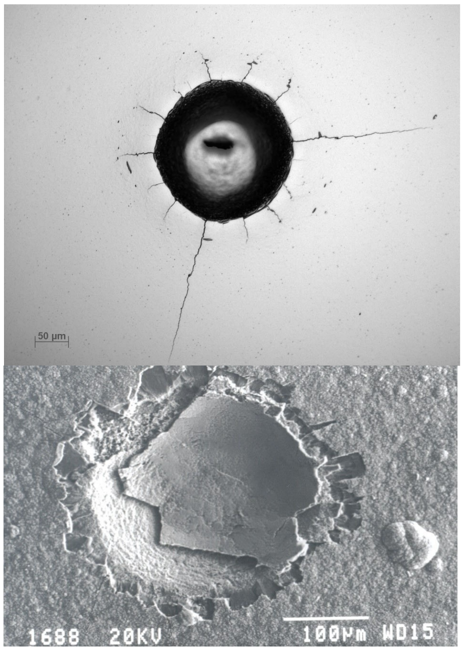

Fig. 2: Typical indentations on substrate (above) and coating (below) of an insert from Supplier 2

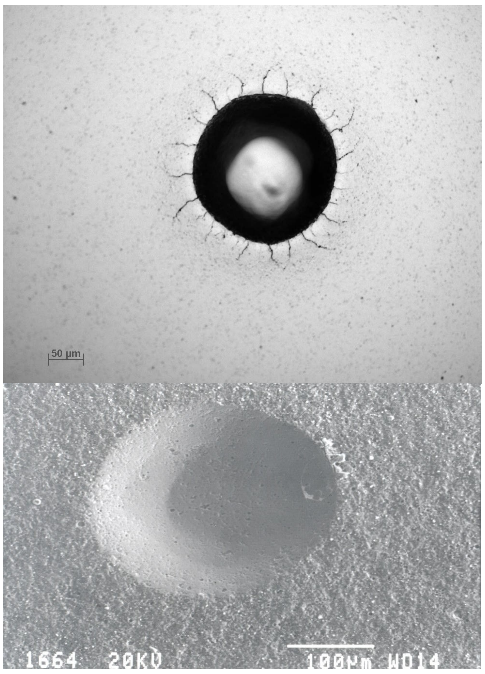

Fig. 3: Typical indentations on substrate (above) and coating (below) of an insert from Supplier 3

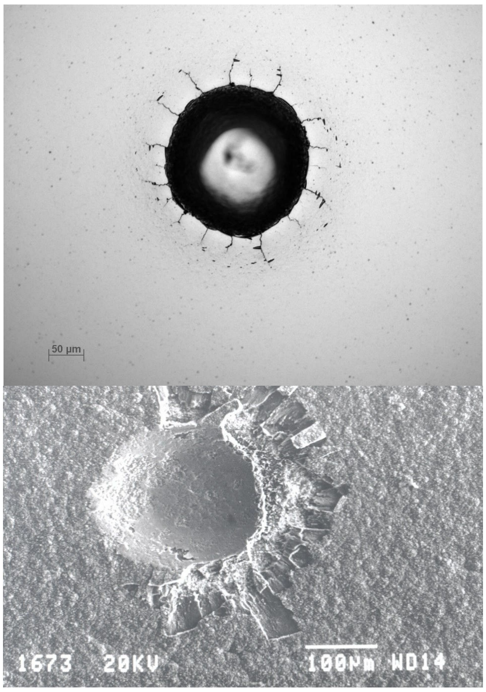

Fig. 4: Typical indentations on substrate (above) and coating (below) of an insert from Supplier 4

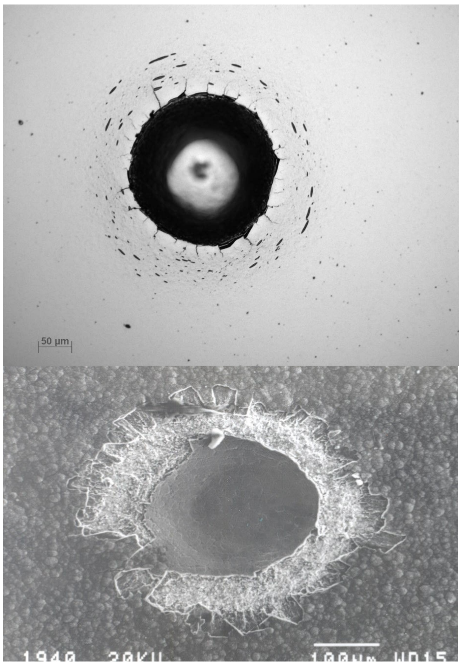

Fig. 5: Typical indentations on substrate (above) and coating (below) of an insert from Supplier 5

Radial cracks were visible around the indentations on all substrates, but in the case of the substrates from Suppliers 1 and 2 the length of the cracks was not as uniform as in the case of Suppliers 3, 4 and 5. The substrates from Suppliers 1 and 2 were the hardest (Table 1), thus they were the most sensitive to microscopic flaws which promoted the propagation of some of the cracks induced by the indentations. All indentations on the substrates were surrounded by a region of piled-up material (i.e. material above the original level of the indented surface), as it is occurs around all indentations[6]. An unusual feature, which was most pronounced around the indentation on the substrate from Supplier 5 (which was the softest substrate) were corrugations parallel to the perimeter of the indentation. Fig 6 shows the geometry of the corrugations in detail, i.e. it shows that they were ridges and not grooves. The corrugations were within the piled-up regions, i.e. they were part of the plastic deformation process.

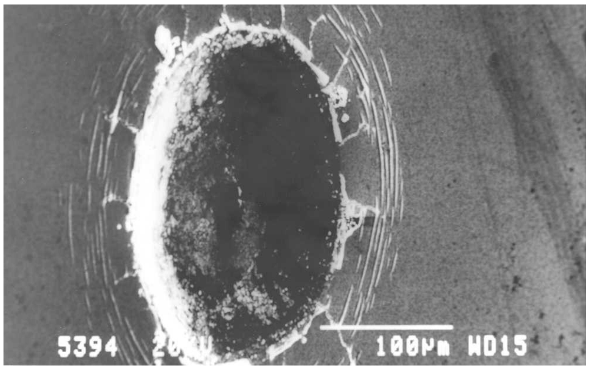

Fig. 6: SE micrograph of corrugation on substrate. The surface was tilted by 45 °

Evidence was found, also in the harder substrates, that the corrugations formed along radial cracks, as shown, for example, by Fig. 7. The mechanism of formation of these corrugations has not yet been explained.

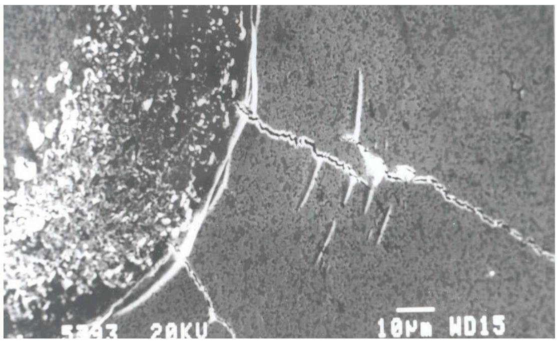

Fig. 7: SE micrograph of corrugations showing their relationship to radial cracks

The SE micrographs of the indentations on the coated surfaces show that the damage on the coated surfaces appeared more complex than on the uncoated ones. In general, the damage on the coated surfaces could be divided into:

i) some cracks inside the indentations;
ii) an inner annular region, outside the perimeter of the indentation, exhibiting extensive fragmentation;
iii) an outer annular region exhibiting radial cracks, mostly joined (at the ends) by cracks roughly normal to the radial cracks (these will be called “circular” cracks).

The above description applies to all indentations except the indentations on the coated surface from Supplier 3. These indentations exhibited only fine radial cracks, which corresponded to the radial cracks in the substrate and were not joined at the ends by circular cracks. These indentations exhibited only minor occasional flaking along their perimeter. It was clear that the coating from Supplier 3, which had undergone the same indenting process as the other coatings, had been able to "follow" the plastic deformation of the substrate with much less damage than the other coatings. This cannot be attributed to less plastic deformation undergone by this substrate because the hardness of the substrate of Supplier 3 is lower than the hardness of two of the other substrates. It must be attributed to the mechanical properties of the coating (e.g. yield and tensile strength) being closer to the mechanical properties of the substrate than in the other four cases. Despite the closer matching of the mechanical properties of coating and substrate, the low damage observed in the coating from Supplier 3 must also be an indication of good adhesion because if the adhesive strength had been low or at least lower than the tensile strength of the coating, delamination would have occurred with subsequent flaking. In fact, the indentation damage on the coating of Supplier 3 is similar to the indentation damage that Su *et al*[5] considered indicative of "good" adhesion.

In the case of the other four coatings, the fine cracks inside the indentations were due to the tensile strength of the coating being exceeded on account of the large strain induced by the indentation (of the order of 5 %). Only the indentation on the coating of Supplier 2 showed that flaking occurred inside the indentation, which gave the impression that the adhesive strength was lower than in the other three cases. However, EDS analysis of the indentation on the coating from Supplier 2 showed that the substrate was not exposed: a lower coating layer was exposed, indicating that the adhesive strength was poor between layers and not between coating (as a whole) and substrate.

As for the finely fragmented annular region adjacent to the indentations on the coatings, its width is related to the width of the piled-up region around the indentations on the substrates. For example, it is widest in the case of Supplier 5, which corresponds to the softest substrate. Therefore the fine fragmentation is related to the plastic deformation that occurred in the piled up region. Besides, the tensile hoop stresses that generated radial cracks in the substrates and the tensile surface stresses (normal to the tensile hoop stresses) due to the material rising above the original surface level, caused the formation of a crack network which is reflected by the fine fragmentation in this region. In the case of Suppliers 1, 2, 4 and 5 the coatings could not "follow" the plastic deformation undergone by the substrates as well as in the case of Supplier 3 because the mechanical properties of substrates and coatings must have not been as well matched. The fragmentation in itself is not an indication of poor adhesion unless the coating fragments flake off exposing the substrate and this was observed only in the case of the coatings from Suppliers 1 and 5.

As for the outer annular regions exhibiting radial cracks joined, at the ends, by circular cracks, the cracks were found to be related to the radial cracks in the substrates, e.g. the coatings from Suppliers 1 and 2 exhibited the same longer-than-average cracks that had been observed in the substrates. The joining of the ends of the radial cracks by circular cracks, however, suggests some delamination of the coatings from the substrate. However, the delamination led to flaking and exposure of the substrate only in the coatings from Suppliers 1 and 5. In the case of the coating from Supplier 2, Fig.2 shows that the annular region around the indentation had totally flaked off, but EDS showed that the substrate was not exposed. Again, what was exposed was a lower coating layer, indicating poor adhesion between layers and not between the overall coating and the substrate. In the classification of Su *et al*.[5] the adhesion of the coating from Supplier 2 would have been considered the worst, because the coating exhibits the largest amount of flaking. However, this coating would still be able to prevent diffusion of W into the workpiece, while the coatings from Suppliers 1 and 5 (where the substrate was exposed) would allow some diffusion to occur. Therefore, as a result of the present analysis, the coatings from Suppliers 1 and 5 would be considered as the ones having the poorest adhesion.

CONCLUSION

By comparing the features of indentations on coated and uncoated surfaces of WC-Co cutting tool inserts it was possible to determine the origin of the damage caused by Rockwell indentations on the coatings of these inserts. The damage observed in these coatings is similar to the damage observed by Arai *et al*.[3] and Su *et al.*[5] in other types of coatings, so it is possible that the origin of the damage established in this case is the general origin of the damage caused by Rockwell indentations in thin coatings.

The damage consists of flaking and/or cracking. The cracking is not related to adhesion but to the cracking and plastic deformation that occurs in the substrate. If the cracks are not due to delamination, when the indenter is removed the cracks close both in the substrate and in the coating, as it appears to be the case particularly in the coating from Supplier 3, where the cracks in the coatings were barely visible. If the cracks are due to delamination they may remain "open" when the indenter is removed and may lead to flaking, as was observed in the coatings from Suppliers 1 and 5. As for cracks related to plastic deformation, in the region adjacent to the indentation, they are an indication of a mismatch between the mechanical properties of the substrate and the coating. Again, if poor adhesion is added to the mismatch between properties, flaking is observed.

Therefore the results of this analysis generally agree with Su *et al*.'s[5] broad classification of adhesion into

- "good", if (almost) no cracking and no flaking are observed;
- "fair" , if only cracking and occasional flaking are observed;
- "poor" if extensive flaking is observed.

However, this analysis has established that cracks are largely unrelated to adhesion and that in WC-Co cutting tool inserts the adhesion of different coatings should be ranked on the basis of the amount of exposed substrate.

In the case of the five coatings analyzed in the present work, according to Su *et al.*'s classification the coatings would rank as follows:

- "good": coating from Supplier 3
- "fair" : coatings from Suppliers 1, 4 and 5
- "poor": coating from Supplier 2.

By contrast, as a result of the present analysis the five coatings can be ranked as follows, in order of decreasing adhesion strength:

Coating from Supplier 3
" " " 4
" " " 2
Coatings from Suppliers 1 and 5.

According to Arai *et al.*[3] the test based on Rockwell indentations can be considered useful only to identify coatings having extremely poor adhesion. On the contrary, this investigation has shown that the test can be useful to recognize differences in the adhesion and properties between coatings on tools that were produced by five of the world's leading manufacturers and were expected to perform effectively. However, in coatings for cutting tool inserts small differences in adhesion can only be detected by the help of characterizing techniques such as SEM and EDS, since it is necessary to establish whether the substrate was exposed.

Acknowledgments
The authors wish to thank the NRF, THRIP and Powder Industries (Pty) Ltd. for financial support.

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