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Factors Affecting Diamond Retention in Stone Sawblade Segments

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Abstract. An important requirement of the matrix in diamond impregnated segments is to retain the diamond grits for as long as possible. The existing theoretical knowledge on diamond retention is based on fairly simplified models and, therefore, does not provide satisfactory explanation of the complexity of individual diamond pullout events observed in application. Neglecting chemical bonding between the diamond and the matrix, which is outside the scope of this study, the relevance of potential retention indicators, such as yield strength, hardness and impact strength of the matrix, to field conditions has been assessed theoretically. Furthermore, a novel dynamic hardness test has been proposed to assist in predicting the matrix behaviour under multiple short-loading-time conditions. Additionally, three hot pressed materials, used as matrices in diamond impregnated sawblade segments, have been examined in-lab and in-the-field on their retention characteristics.

Theoretical Background

The role of the matrix in a diamond tool is to hold the diamond grits tight and to wear at a rate compatible with the diamond particle breakdown. In that case the tool attains an optimum balance between its in-service life and free-cutting ability.

A reliable assessment of diamond retentive properties of the matrix is difficult. During application the diamond-matrix interactions occur in a variety of forms depending on the size and shape of a diamond particle, its orientation and loading conditions, residual stresses in the matrix, diamond-matrix friction, etc. The existing theoretical knowledge of diamond retention has evolved from fairly simplistic models and, therefore, it does not give satisfactory explanation of the complexity of individual diamond pullout events observed in use. Diverse opinions have been expressed to date on practical relevance of some routinely used retention indicators, such as yield strength, hardness and impact strength, to various field conditions. The dispute over retention is hardly expected to conclude since reliable evidence to support individual viewpoints is insufficient and, if exists, confines to extreme situations.

The actual mechanical response of the matrix subjected to an application of a pulsing force of varying intensity is apparently affected by its fatigue properties under complex loading conditions and at moderately elevated temperature. As a further complication a contribution from the internal stresses set up around each diamond particle during the manufacturing process, due to mismatched thermal expansion coefficients, is anticipated in the system. Such stresses are believed to enhance retention but direct quantification of their effect still presents difficulty.

It is important that this pre-stressed state is not annihilated by plastic deformation or brittle failure of the matrix caused by external forces applied through the working diamonds. Since the temperature in the cutting zone attains 200℃ [1], diamond grits may tend to get loose and fall off when loaded, due to reverse thermal expansion of the matrix.

As it has already been mentioned, there are several mechanical properties of the matrix material which are believed to control its retention capacity. The most important are:

- yield strength,
- hardness,
- impact strength.

Yield Strength. As shown in Fig.1, each working diamond is subjected to the application of a cyclic stress, which is transmitted directly to the matrix. It is postulated [2] that the best retention of diamonds is achieved when there is only reversible, elastic deformation of the matrix (see path A in Fig.1). Each time the yield strength of the material is exceeded, the seat of the diamond slightly opens (see path B in Fig.1) and thereby the hold on the grit is being gradually destroyed.

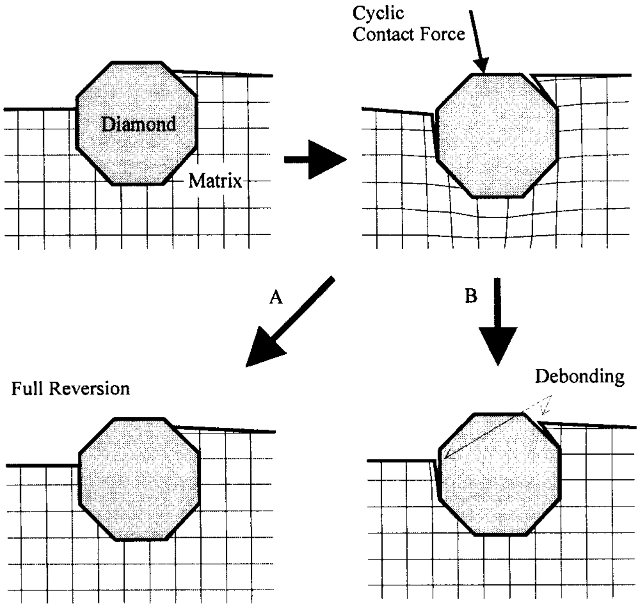


Fig.1 Schematic view of mechanical locking of a working diamond in the matrix [3]

Even better retention indicator would presumably be the energy required by various matrices to yield and hence, besides the yield strength, allowance for the *modulus of elasticity* should also be made [3]. Fig.2 explains this in a simple manner.

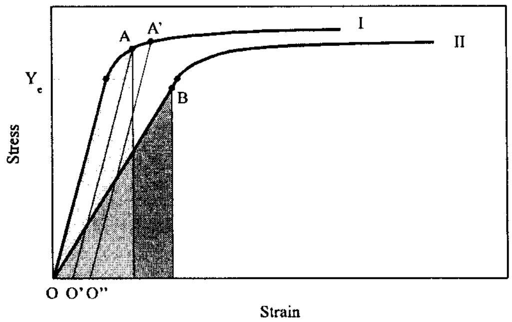


Fig.2 Mechanical response of materials having different stress-strain characteristics to the same amount of energy expended on tension

To deform the materials I and II by the amount OA and OB respectively, would require expending the same amount of energy which is represented by the shaded areas in Fig.2. The material I yields plastically beyond the elastic limit, estimated by its yield strength Y_e, and follows the path AO' when the stress is being removed. On applying the stress again, the deformation will proceed elastically along O'A and then plastically along AA' to additionally increase the permanent plastic deformation by amount O'O''. On the other hand, the material II is stretched within the elastic range and therefore it contracts to its original size after removing the tension.

It should be noted that, besides the magnitude of stress and number of loading cycles, the amount of permanent deformation will also depend on the material's strain-hardening characteristics. Once the load has been re-applied the stress required to produce further plastic flow is no longer the initial yield strength (Y_e in Fig.2) but it attains a higher level (A in Fig.2). For most metallic materials the response of yield stress to plastic deformation is proportional to the true strain to the power of *n*, where *n* is a strain-hardening coefficient which exhibits the slope of the plastic portion of the true stress v true stain curve.

As exemplified in Fig.3, some cobalt containing alloys may widely differ in this respect.

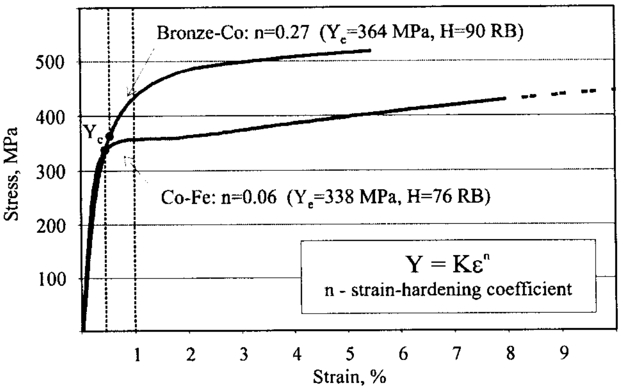


Fig.3 The stress-strain behaviour for bronze-cobalt and cobalt-iron materials.

Therefore, there is only negligible difference between the alloys in permanent deformation recorded after a single application of stress, which slightly exceeds the yield strengths; and there is marked variation in results obtained from multiple-loading experiments.

As forces exerted on each individual working diamond, and consequently stresses generated within the matrix, may attain very high levels, it is theoretically justified to anticipate superior retention potential in matrices which exhibit a combination of high yield strength, high strain-hardening coefficient, and low modulus of elasticity.

Hardness. A properly densified diamond impregnated segment acquires a narrow hardness range. Thus the hardness test is primarily used as a convenient quality check but, due to its ease and versatility, it has also extensively been utilised to indicate the diamond-holding power of the matrix.

Hardness readings are to a large extent affected by the strain hardening characteristics of the tested material and cannot be simply correlated with its yield strength. As shown in Fig.3, the bronze-cobalt specimen work-hardens as a result of deformation, whereas the cobalt-iron alloy displays almost ideally plastic behaviour. Therefore, the materials are characterised by nearly the same yield strength and widely differ in hardness.

As speculated in the preceding section, the combination of yield strength and strain-hardening coefficient of the matrix material should have some bearing on its diamond retention capacity. Hardness measurements, however, involve fairly large plastic strains of between 5 to 12%, attained under quasi-static conditions, as is also the case with the estimation of yield strength and strain-hardening coefficient, whereas an operating diamond-matrix set-up is subjected to a cyclic, low strain dynamic loading. Experimental results obtained in sawing hard granite at a rate of 300 cm^2/min indicate an average contact load of around 190 N per cutting crystal with a strain period of about 300 kHz oriented 80-85^0 normal to the stone surface [4]. Hence, in contrast with testing hardness, in sawing stone the loading time is very short (~3.3 μs) which may affect the yielding behaviour of the matrix, thus making the hardness numbers obtained from the standardised static tests irrelevant to the actual diamond holding ability.

When a hard spherical indentor is dropped on to a flat surface of a softer metal it strikes the surface and rebounds. The collision lasts for a very short time which depends on the diameter and impact velocity of the indentor [5]. A complicated analytical treatment of this simple experiment enables evaluation of hardness at high rates of strain.

To this end a purpose-build apparatus was used to examine the material's resistance to plastic flow during its repeated indentation by a hard spherical object at high rates of strain. The measurement consisted in impacting a flat specimen, positioned at one end of a cylindrical test capsule, with a bearing steel ball 3 mm in diameter. The capsule was put into oscillation at a frequency of 40 Hz and stopped after predetermined numbers of cycles to measure the diameter of permanent indentation produced by the ball in the examined material. The test parameters were tuned to achieve the contact time (at first impact) of between 3-4 μs, which corresponds to the diamond-loading period in sawing granite [4] and yields strain rates in excess of 10^3 s^{-1} [3].

Neither the force at impact nor its energy was directly measured but the testing conditions remained unaltered for all tested specimens. Therefore the inverse of the projected area of the impression was chosen as the measure of hardness evaluated under the multiple-impact conditions. The Brinell hardness was also measured, in the vicinity of the impact trace, so as to assess the effect of strain rate on the susceptibility of the tested material to plastic flow.

The results are presented in Table 1 and in Fig.4.

Table 1 Brinell hardness and multiple-impact hardness (MIH) of the tested materials [3]

Material	Brinell hardness	MIH (1) [mm^{-2}]	MIH/HB ratio (2)
Cobalt	305	3.11	100
Bronze-Cobalt	153	1.42	91
Cobalt-Iron	142	0.86	59

(1) obtained after 32 000 impacts

(2) results are relative to unalloyed cobalt (=100)

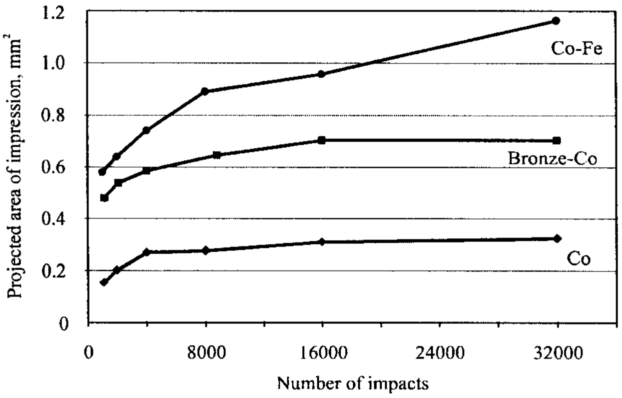


Fig.4 Variation in the projected area of impression with the number of impacts

As demonstrated in Fig.4, the crater may grow steadily with increasing the number of impacts (Co-Fe) or its size may reach a quasi-plateau (Co and Bronze-Co).

It can be deduced from Fig.4 that, under the applied experimental conditions, cobalt requires around 4000 impacts so as to work-harden to such an extent that the following collisions are predominantly elastic and produce negligible permanent deformation. The bronze-cobalt material attains such a state after about 16000 impacts and at lower stress generated at impact due to the greater area of contact (impression). Interestingly, the cobalt-iron alloy deforms plastically throughout the entire test. This indicates poor response to cold working, i.e. low strain hardening coefficient.

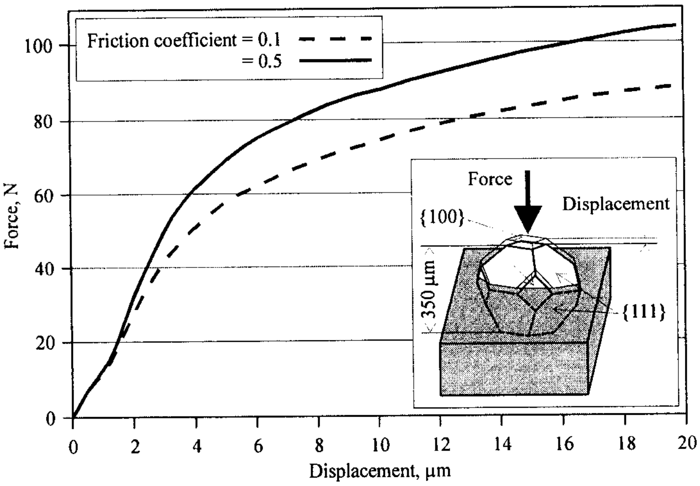


Fig.5 Effect of friction on displacement under load of a perfectly shaped diamond crystal (Tau=0.25 [7]) partially embedded in a metallic matrix

It may be assumed that in the hardness tests the friction between the face of the indentor and the tested metal has negligible effect on its resistance to penetration. In a diamond impregnated segment, however, the slip of the matrix material along the faces of each loaded diamond may not occur in a similar way as in hardness measurements. By increasing the coefficient of friction at the diamond-matrix interface it is possible to increase the pressure necessary to produce plastic yielding. Fig.5 illustrates the effect of friction on the force v displacement curve obtained from computer simulation experiments [6].

The static coefficient of friction for diamond on metals is very small and ranges between 0.1-0.15 [8]. Therefore the metal is nearly free to slip laterally at the interface. The situation changes when the coefficient of friction is increased due to diamond surface imperfections brought about either by the diamond manufacturing conditions or by a chemical attack exerted by the matrix during the hot pressing cycle. From Fig.5 it is evident that by increasing the coefficient of friction from 0.1 to 0.5 it becomes possible to markedly strengthen the matrix under the diamond.

Impact Strength. During operation the matrix periodically experiences impact stresses. Additionally, in the actual industrial environment the tool is fairly open to abuse and hence undesirable vibrations may prove detrimental to its performance. Such incidents are occasionally encountered with diamonds embedded in a too brittle matrix, which starts to break away rather than wear away. Therefore another important property of the matrix is its impact strength, i.e. the ability to withstand a sudden intense blow.

Taking all the discussed mechanical characteristics into account, the perfect hold on the diamond is anticipated in matrices which display high mechanical strength combined with excellent ductility. In the real materials, however, the increase in hardness, or yield strength, is usually accompanied by a loss of impact strength. Therefore, having analysed the tool application conditions, the toolmaker must always compromise on an optimum balance between strength and ductility of the matrix.

Field Behaviour

The actual diamond retention capacity of the tested materials was evaluated in sawing granite. To this end a batch of four sawblades, nominally 250 mm in diameter, was manufactured. All the blades contained a high quality synthetic diamond grit SDA85+ at 20 concentration.

The stone sawing tests were conducted on a traversing head saw fitted with a digital data acquisition system capable of monitoring the power consumption, sawblade position and its rotary speed. A hard Strzelin granite was chosen for the tests. The cutting rate, depth-of-cut and blade peripheral speed were 240 cm^2/min, 2 cm and 32 m/s, respectively.

The mechanical properties of the matrices and stone sawing results are given in Tables 2 and 3, respectively.

Table 2 Mechanical properties of matrix materials

Matrix	Offset yield strength [MPa]	Impact strength [J/cm^2]	Rockwell B Hardness
Cobalt	680	4.6	106
Bronze-Cobalt	364	1.2	89
Cobalt-Iron	346	> 80 (1)	78

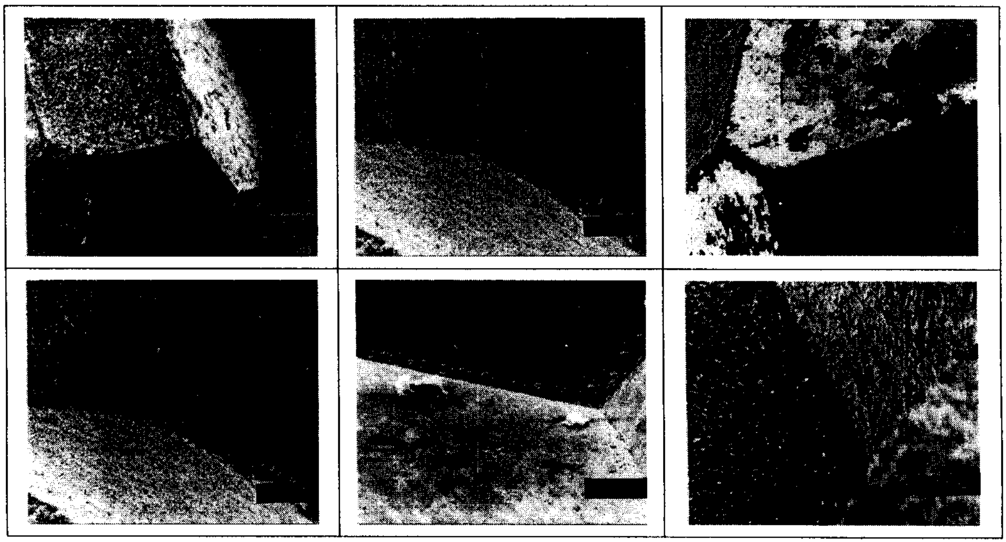
(1) the tested specimens were not broken

Table 3 Results of sawing tests

Matrix	Grit mesh size	Tool life (1) [%]	Mean power consumption [%]	Total number of diamonds retained on sawblade (2)	Mean dia-mond pro-trusion [μm]
Cobalt	40/50	100	100	757 (71%)	70 ± 5
Cobalt	30/40	131	54	399 (70%)	97 ± 10
Bronze-Cobalt	40/50	94	92	544 (49%)	56 ± 5
Cobalt-Iron	40/50	128	108	834 (66%)	62 ± 3

(1) results are relative to the blade containing 40/50 mesh grit in cobalt (=100%)

(2) values in brackets represent the proportion of the total number of diamonds to the total number of diamonds and pullout sites



(a) cobalt (b) bronze-cobalt (c) cobalt-iron matrix

Fig.6 SEM fractographs showing difference in surface texture of diamond facets and mating matrix planes in fractured segments containing: (a) cobalt, (b) bronze-cobalt, and (c) cobalt-iron matrix.

After the sawing tests several segments were detached from the sawblades and fractured so as to observe the nature and severity of reactions taking place at the diamond-matrix interface. Fig.6 shows diamond particles, embedded in the investigated matrices, and the mating pullout sites.

In the investigated cobalt containing alloys the degree of chemical interaction between the diamond and the surrounding matrix is largely dependent on the matrix composition and hot pressing temperature. High contents of copper and tin, in the bronze-cobalt alloy, in combination with a moderate processing temperature, of 750°C, effectively inhibited etching of the diamond surface leaving it virtually intact. On the other hand, the cobalt and cobalt-iron matrices proved to be fairly reactive at 850 and 950°C, respectively. In these cases the pullout site surfaces are rough and certain amount of the matrix adheres to the diamonds.

Summary

Taken together the results reviewed in the preceding sections show that on hard and dense materials, such as granite, the diamond breakdown and/or pullout is the predominant form of segment's wear. Improved retention yields more diamonds on the working surface of the tool thus aiding its overall resistance to wear. Therefore this is the matrix retention capacity which co-operates with the diamond grit characteristics to control the tool performance.

After the stone sawing tests the overall radial wear recorded on each individual sawblade did not exceed 1.1 mm. Therefore, the relative tool life figures can by no means be regarded as fully representative for the sawblades. Nevertheless, they show evident dependence on the combination of diamond size and its local concentration.

Interestingly, the observed retention characteristics are independent of the diamond grit size and seemingly bear some relation to ductility of the matrix, whereas the other material characteristics, such as hardness and yield strength, do not show any direct effect. However, when resistance to permanent deformation is to be considered as a retention parameter, the topography of the diamond-matrix interface must also be analysed and taken into account.

It seems desirable that the diamond surface is slightly etched during the segment manufacturing process so as to increase friction at the diamond-matrix interface, but, on the other hand, the reaction must be mild enough to leave the sharp crystal edges and corners intact.

The retention capacity of the matrix appears to be a complex, system dependent property, which is affected by the application conditions [3] and material characteristics as well. It seems therefore a risky practice to judge retention by a single controlling property.

The experimental data provides evidence that matrix materials which are characterised by a combination of high yield strength, hardness and resistance to deformation at high rates of strain, good ductility, and moderate reactivity with diamond at the hot pressing temperature, possess unrivalled capability to hold the diamonds tight. It should be emphasised, however, that the knowledge of the actual interactions between the workpiece, the diamond and the matrix is poor and hence there may be other factors affecting diamond retention which still remain unidentified.

Acknowledgements

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