Key Engineering Materials Vol. 250 (2003) pp. 60-67
online at http://www.scientific.net

Improvement on the Performance of Diamond Segments for Rock Sawing, Part 3: Factors Influencing the Use of Rare Earth

Y. Q. Yu and X. P. Xu

College of Mechanical Engineering and Automation, Huaqiao University,
Quanzhou, Fujian Province 362011, P.R. China

Keywords: Segment, Additives, Diamond, Sawing, Rare Earth, Granite

Abstract. This is the third in a series of three papers concerned with the improvement of the performance of diamond-impregnated segments for the circular sawing of natural rock materials. In Part 1, the influences of segment components on the performance of segments were studied through relating segment working state with its service performance. The second part studied the factors influencing the use of coated diamond grits. This third part is devoted to evaluate the influences of sintering parameters, the amount of rare earth additive, and the modes of diamond failure on the use of rare earth elements, which have been extensively used to improve the performance of metal bonded diamond tools. A kind of rare-earth element was used to fabricate diamond segments in the form of misch-metal. The effects of the rare-earth were evaluated in terms of segment bending strength, segment hardness, and diamond protrusion height, quality changes of recovered diamonds, consumed power and segment wear performance. It was found that an addition of only 1.5 per cent of the rare-earth metal to the mixture of bond base metals could considerably increase the segment performance. However, the effect of the rare-earth metal might be offset by the different mechanisms of diamond failure on same segment surface.

Introduction

Segments used for circular sawing of rock materials are composed of diamonds and a metal bond matrix. As well discussed in the first part of these serial papers and other previous papers [1-4], the type of the metal matrix used is crucial in determining the performance of diamond-impregnated tools. The typical base metals used in the formulation of a matrix are generally elemental metals, e.g. iron, copper, tungsten, nickel, cobalt, or their alloys. In spite of the lowest price of iron among the above metals, the use of iron in diamond tool manufacture is limited by its tendency to react with diamond at elevated temperatures during sintering. Furthermore, the main constituents of the metal bond matrix for diamond segments, such as iron, copper, and tin, all have a tendency to react with the atmospheric O_2 even at room temperatures. As a result of the oxidation, a certain level of porosity would be left in the final product due to insufficient sintering. As already indicated in Part 1, a porous microstructure of bond can result in a weak bonding of diamond to the bond matrix.

As de-oxidizing agents rare-earth (RE) metals are widely used for de-oxidation of copper and its alloys [5]. Rare-earth elements and their alloys are also extensively applied to ameliorate the performance of cast iron [6]. Therefore, rare-earth elements were applied in a form of what is known as misch-metal in order to ameliorate sintering quality of segments containing micro diamond powders in our previous work [7]. Some other researchers also found that the addition of La and Nd to iron-based diamond composites have a very positive effect on the microstructure and the mechanical properties of the composite material [8]. A preliminary study done in our lab also indicated a promising result of the use of RE in raising the wear performance of diamond segments [9].

Recently, increasing numbers of papers are concerned with the use of rare earth elements in the manufacture of diamond impregnated tools. However, most of them focus mainly on revealing the modification effects of the elements. The prevailing mechanisms of RE as active agents and especially the factors influencing the effects of RE have not been understood clearly. Coupled with the findings of previous studies, this third part is devoted to evaluate the influences of such factors as sintering parameters, the amount of rare earth additive, and diamond failure modes on the use of RE.

Experimental

As the main constituent metals for fabricating sawblade segments, the grain size of iron, copper, tin and nickel powders was less than 53 μm. A kind of misch-metal (RE-Si-Fe) with grain size less than 10μm was used as RE additives. Diamond of 40/50 US mesh was used at a concentration of 40 (1.76 carat/cm^3). Metal powders were blended together with diamond grains and RE additive for 1 hour in an ∞ shape rotary mixer. The mixed powders were hot-pressed in graphite molds on an automatic hot pressing machine installed with an infrared device for monitoring temperature. The hot pressing process consists in heating a diamond impregnated metal bond mixture accompanied by pressing. The time and temperature sintering parameters are automatically controlled. The typical temperature-time curve used in the present work is shown in Fig.1.

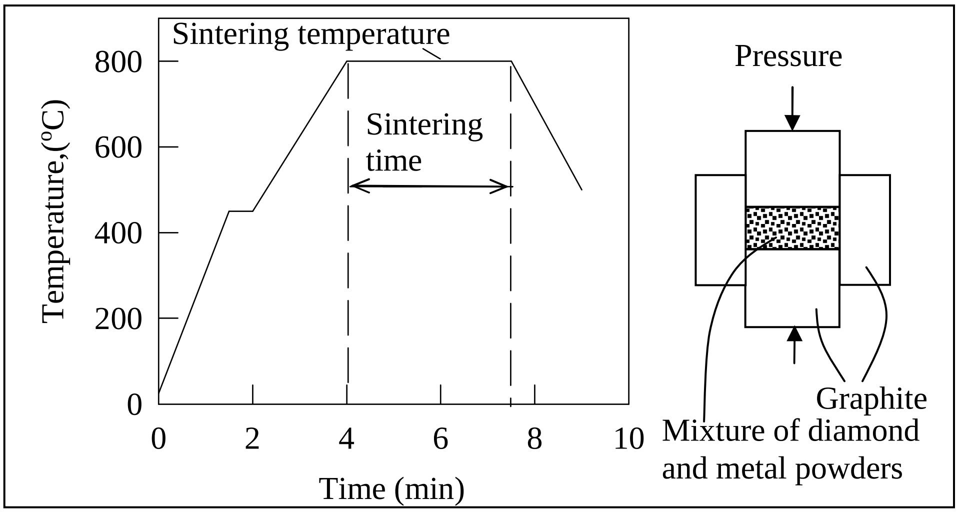


Fig.1 Curve of temperature versus time during sintering

The influence of the RE additive on the properties of diamond segments were quantitatively evaluated in terms of traverse rupture strength (TRS), hardness, and diamond protrusion together with practical sawing tests. The hardness of the segments was measured with a Rockwell B hardenss tester. The TRS values were determined by using a three point bending test. Each hardness value was obtained by averaging nine hardness values measured on nine different areas of three segments sintered under same conditions. Protrusion height of a diamond grit beyond the bond matrix in a worn segment was measured by an optical microscope after the segments was used for sawing a specified period of time.

In order to evaluate the changes of diamond particle quality under the conditions of different sintering temperatures and different additions of RE, reclamation of diamond grits were carried out through electrochemical dissolution [8], in which case diamond segments were dissolved electrochemically in an HCl solution. The compressive strength of diamond grits was evaluated by the static method as already indicated in Part 2.

The sawing experiments were conducted on a bridge-type sawing machine as already shown in Part 1. Same as Part 1, the service performance of the saw blade was evaluated in terms of the consumed spindle power (P) and the wear performance factor (W). The radial wear was measured on four segments equally spaced around the sawblade for an average. Details of the worn segment surfaces were analyzed by SEM.

The workpiece materials for the sawing experiments included three kinds of typical granite rock whose sawabilities were classified 1 to 3 from easy to difficult based on factory records.

Results

Mechanical Properties. Fig.2 shows the relationship between the bending strength of diamond segments and the contents of RE under two different sintering tempearatures. The curves showing the variation of segment hardness versus the contents of RE is plotted in Fig.3. It can be found that both bending strength and hardness increase with increasing RE contents. However, the bending strength and hardness become nearly constant when the content of RE is up to 1.5%. Compared to the segments without an addition of RE, the bending strength is raised by 17% at 800^{o}C and 23% at 750 ^{o}C for the 1.5% addition of RE. For the 1.5% addition of RE, the hardness values for both temperatures are also raised to higher levels, which will be very important to the wear resistance of the segment bond matrix in sawing as already shown in Part 1. Allowing for the cost of RE metals, it is reasonable to choose 1.5% as the optimum content of RE addition.

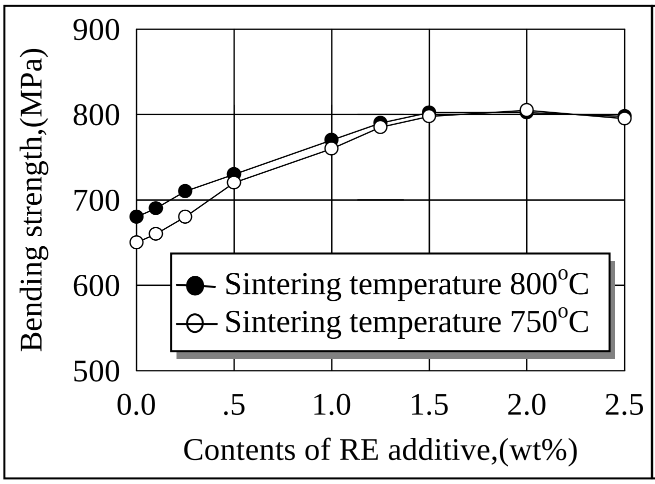


Fig.2 Bending strength versus RE contents

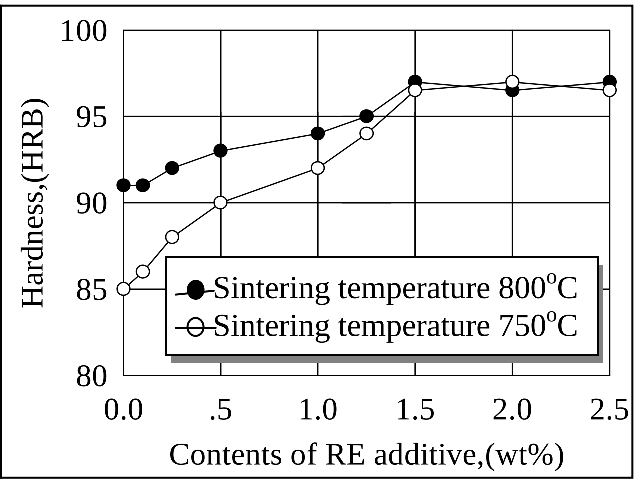


Fig.3 Hardness versus RE contents

Fig.4 illustrates how the hardness of the segments changes with the sintering time. As can be seen from Fig.4, for the segments with the addition of 1.5% RE, only 3 minutes are required to reach an expected hardness value. For the segments without the addition of RE, the expected value cannot be reached even the sintering time is up to 4 minutes.

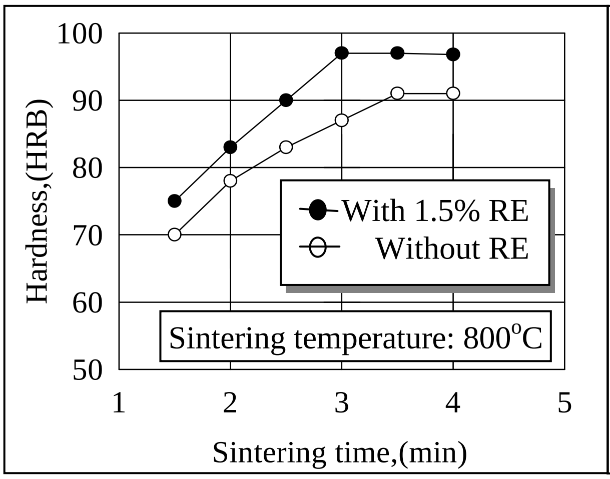


Fig.4 Hardness versus sintering time

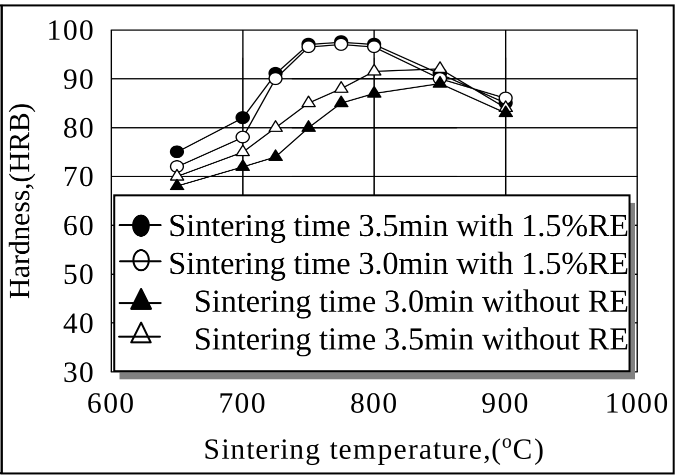


Fig.5 Hardness versus sintering temperature

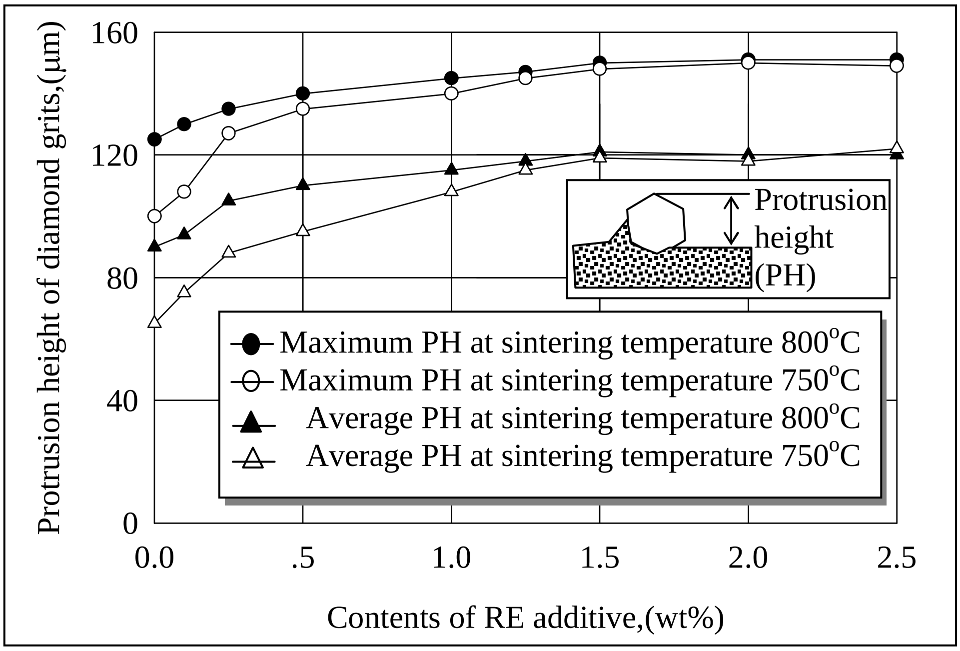
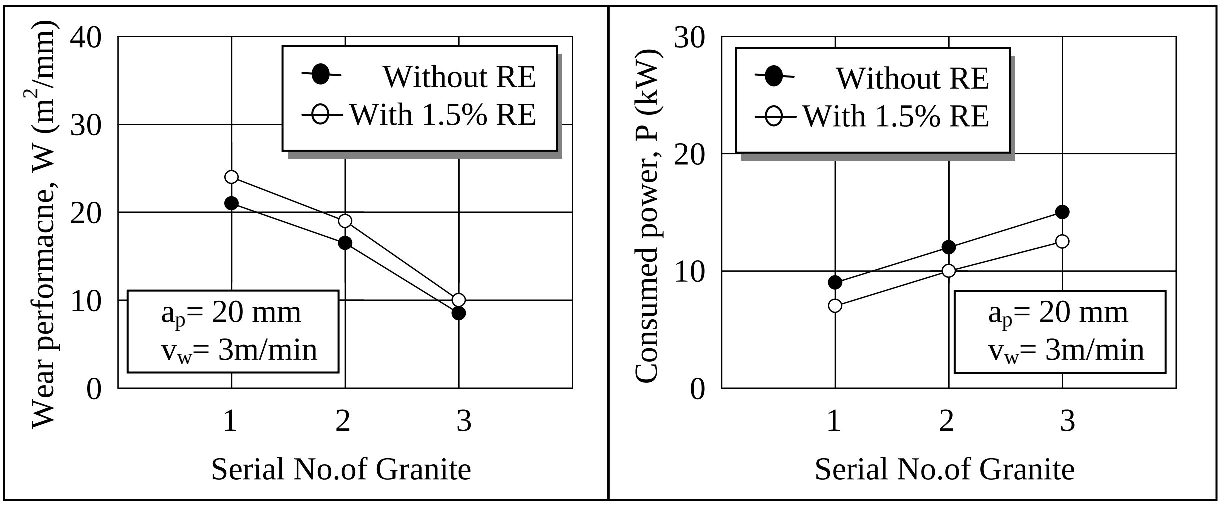


Fig.6 Relationship between diamond protrusion height and RE content

The hardness values of the segments are plotted in Fig.5 versus sintering temperatures. It can be seen that the optimum sintering temperature is reduced by 50 °C with the addition of 1.5% RE.

Change of Diamond Protrusion. Fig.6 shows the relationship between the protrusion height values of diamond grains and the contents of RE. Analogous to bending strength and hardness, protrusion height of diamond grits beyond the worn matrix surfaces increases with the increasing contents of RE and keeps basically stable when the content of RE is up to 1.5%.

The Results of Sawing Experiments. Fig.7 gives the wear performance of the segments and the power consumed by the saw machine spindle. It can be seen that the addition of 1.5% RE reduced the consumed power and enhanced the wear performance of the segments, in which case the consumed power reduced by 16-22% and the wear performance increased by 12.5-15% as compared with the segments without RE. Micro observations of the worn segment surfaces further indicated that the pull-outs of diamond grits were decreased by the addition of 1.5% RE.

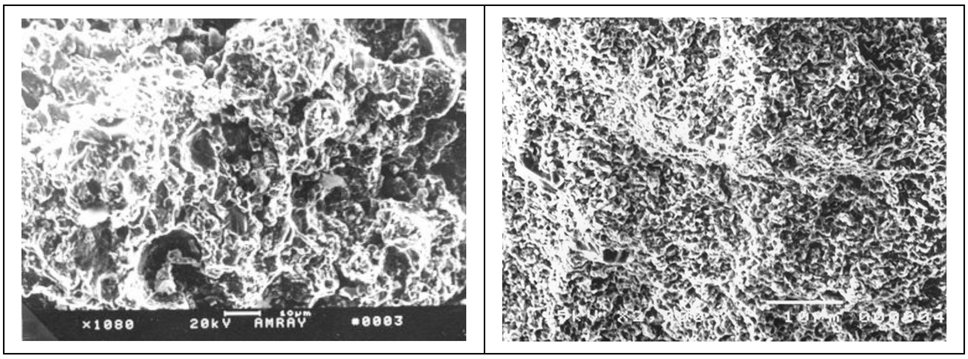


(a) wear performance (b) consumed power

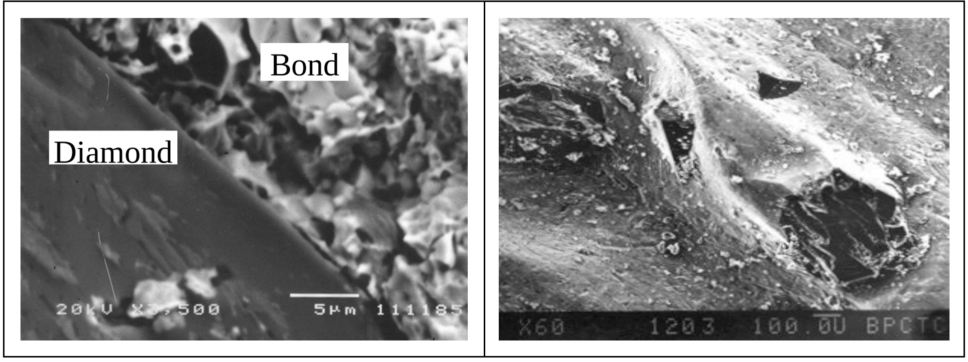
Fig.7 Wear performance and consumed power in sawing with different segments

Discussion

Mechanisms. As mentioned by many previous studies [5-6], additions of rare earth elements can improve the quality of iron and steel through de-oxidizing and de-sulphurizing. As the main constituents of the metal bond matrix for the segments, metal powders of iron, copper, and tin have a tendency to react with the atmopheric O_2 even at room temperatures. From the point of view of sintering theory and powder metallurgy, the sintering of compacts from the mixtures of these metal powders and diamonds is featured with a mechanism of interdiffusion between two constituents of a diffusion couple. However, for the mixtures of oxided metal powders, which are popularly encountered in the sintering of diamond segments, this diffusion is comparatively difficult to take place due to the barrier between two diffusion couple, thereby resulting in a relatively porous compact.



(a) bond matrix without RE (b) densified bond matrix with RE



(c) interface on fracture surface (d) worn segment surface

Fig.8 SEM pictures of fracture segment surfaces and a worn segment surface

When rare earth elements are added into the mixtures of the metal powders, as de-oxidizing agents the rare earth elements can vigorously absorb O in the hot state by interacting with them. As a result of the de-oxidation, the interdiffusion process could be greatly enhanced by the absence of oxides between the diffusion atoms. Fig.8 gives SEM pictures of fracture surfaces of a segment compact and its worn surface after sawing experiments. It can be seen that the microstructure of the fracture surface with the addition of 1.5% RE reveals more ductile cup and cone behavior (Fig.8b) than the surface without RE (Fig.8a), indicating that the desification of the metal bond can be greatly accelerated by the addition of 1.5% RE during the sintering. The effect of the RE on the densification of the metal matrix was also supported by the difference between the bending strength and hardness for the segment compacts without and with RE as indicated in Figs.2,3,4 and 5. The enhanced bonding among bond metal particles further shows that the sintering quality was really improved by the addition of 1.5 % RE, thereby leading to an improved bonding between the diamond and metal matrix as shown in Fig.8c. Therefore, an excellent retention of the metal matrix to diamond can also be observed on the worn segment surface as shown in Fig.8d. The increased protrusion height of diamond grits beyond worn matrix surfaces (see Fig.6), the reduced consumed power, and the improved wear performacne of the segments (see Fig.7) might be directly related to the enhanced retention of diamond grits by the addition of RE.

As can be seen from Figs.8a and 8b, the bond matrix with RE looks finer than the matrix without RE, which might be attributed to the formation of compounds resulting from the reactions between RE and S and/or C.

Due to the enhancement of grain boundary diffusion during the sintering having the de-oxidation of RE, the sintering time can be shortened and the sintering temperature can be lowered under th premise of gaining the expected sintering quality as compared to the sintering without RE (see Figs.2 to 6), which should be good to reduce thermal damages to diamond grits. The compressive strength of the recovered diamonds is plotted versus sintering time in Fig.9. As compared with the sintering without RE, the loss of compressive strength is relatively less. The reduced thermal damage to diamonds during the sintering process should be another contribution to the high wear performance as indicated in Fig.7a.

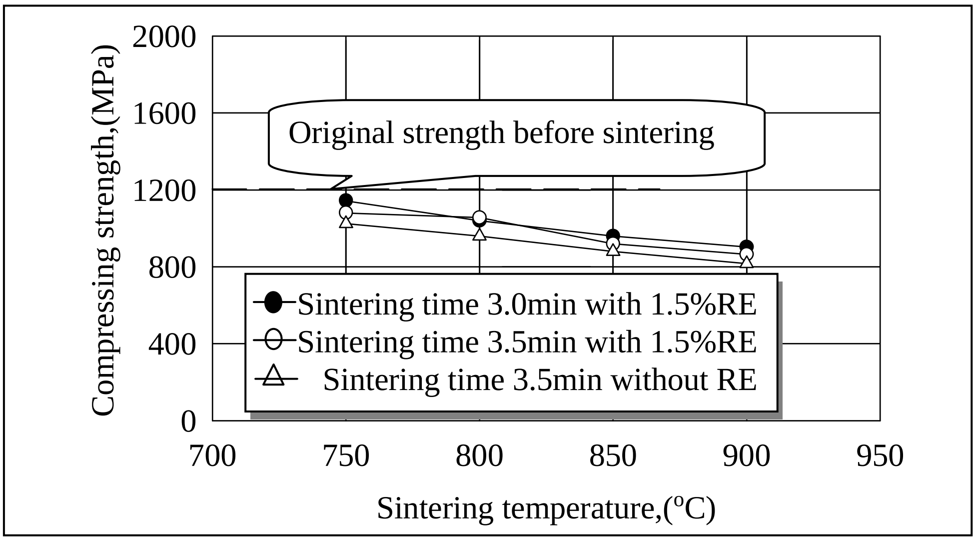


Fig.9 Compressing strength values of recovered diamond grits

Factors Influencing the Effect of RE. It is worthy noting that good retention of metal matrix to diamonds, which really determines the pull-outs of diamonds, is not only associated with good bonding but also with whether the matrix and diamonds wear rates appropriately match. In effect, the mechanical loads acting on segment surfaces are not uniform during the sawing process. Fig.10 illustrates a load distribution along the longitudinal direction of a segment surface. It can be seen that the load on the front section of the segment is heavier than the rear section, which was found to be attributed to the intermittent (segmented) structure of the saw blade. Some calculations revealed that the ratio of the front load to the rear load ranged from 1.8 to 3.0 [11], indicating that the diamond grits on identical segment surface afford different loads. Therefore the diamond grits on same segment surface could not fail in similar ways. Compared with the diamonds on the rear and the middle of the segment, more diamond grits on the front section may fracture and sputter out as shown in Fig.11 due to over loading. Contrarily, polished diamond grits (see Fig.11b) may prevail on the rear section due to much lower loads than the front and middle sections.

In spite of the much lower loads acting on the diamonds on the rear section, more sawing heat might be generated in this case due to the much more sliding and friction between the diamond grits and granite workpiece. Based on a further EDS analysis of the diamond-bond interface, the enhanced bonding between diamond and the RE containing matrix was found to be more likely attributed to the improvement on the wetting of Cu-Sn to the diamond grits. Due to the high thermal conductivity of the diamond grit, heat into the grit at the workpiece surface can arrive quickly at the diamond-matrix interface. The heat at the diamond-matrix interface may induce stresses between the diamond and bond matrix due to their big difference in the coefficients of thermal expansion, thereby resulting in excessive pull-outs of diamonds in their successive sawing [12].

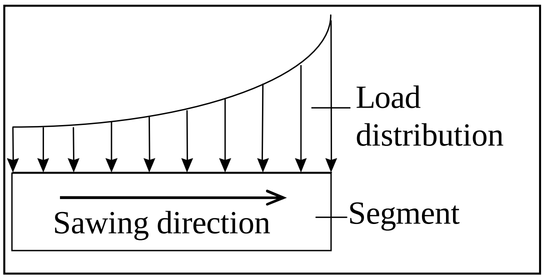


Fig.10 Load distribution on a segment

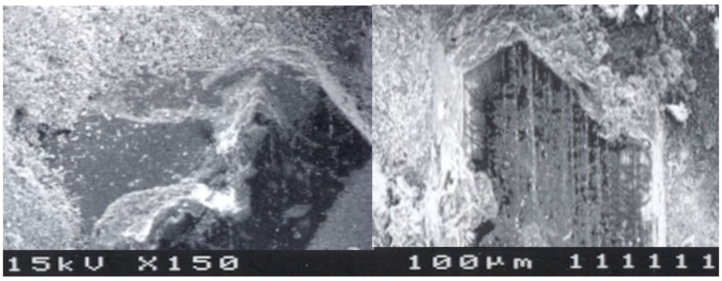


Fig.11 Two modes of diamond failure

In the case of over loading, no matter how excellent bonding was gained between the diamonds and the bond matrix, diamond failure is unavoidable due to diamond fracture. Therefore it can be concluded that the effect of the additions of RE might be offset by the different mechanisms of diamond failure existing on same segment surface.

In order to further improve the retention of metal matrix to diamonds, future work is planned on the incorporation of coated diamonds and rare earth elements into the fabrication of diamond segments together with the optimal distribution of diamonds on the segment surfaces and optimal selection of machining parameters, which will be discussed in future papers.

Summary

The bending strength and hardness of diamond impregnated segment compacts were raised to maximum by the addition of 1.5% RE. By interacting with O, the rare earth elements can vigorously absorb O in the hot state, thereby accelerating the diffusion between bond particles. The accelerated diffusion improves the bonding among the bond particles and hence the sintering quality of the segment compacts. The increased protrusion height of diamond grits beyond worn matrix surfaces, the reduced consumed power, and the improved wear performance of the segments might be directly attributed to the enhanced sintering quality of the segment compacts and thereby the improved retention of diamond grits.

Due to the enhancement of grain boundary diffusion by the de-oxidation of RE, the sintering time can be shortened and the sintering temperature can be lowered in order to gain expected sintering quality. The loss of compressive strength of diamonds recovered from the segments with RE was found to be relatively less than the situation without RE, which should be attributed to the reduced thermal damage to diamonds during the sintering process owing to the shortening of sintering time and the lowering of sintering temperature.

Since the diamond grits on a segment could not fail in similar ways due to the non-uniform load distribution along the segment surface, the effect of the additions of RE might be offset by the different mechanisms of diamond failure existing on same segment surface.

Acknowledgment

The research was supported by the National Natural Science Foundation (NSF) of P. R. China (Grant No.50175030) and the Natural Science Foundation of Fujian Province in China (Grant No.F0110002).

References

[1] B.N. Thakur: *Proceedings of Superabrasive'85* (SME MR85-307, USA, 1985).

[2] J.D. Dwan: Materials Science and Technology Vol. 14 (1998), p. 896

[3] Y.H. Wang, J.B. Zang and M.Z. Wang: J. Mater. Processing Tech. Vol. 129 (2002), p. 371

[4] Y.H. Wang, J.B. Zang and M.Z. Wang: Key Engineering Materials Vol. 202-203 (2001), p. 199

[5] D.N. Trifonv: *The Rare-Earth Elements* (The Maccmillan Company, New York, 1963).

[6] S.J. Li: Journal of Rare Earth Vol.21 (2000), P. 58

[7] X.P. Xu, Y.Q. Yu and J.Y. Shen: Ceramic Transactions Vol.102 (1999), p. 38

[8] Y.K. Wu and Q. Yu: *Proceedings of the 1997 International Conference on Powder Metallurgy and Particulate Materials Part 1*(Metal Powder Industries Federation Princeton, USA, 1997).

[9] X.P. Xu and W.D. Huang: Journal of Rare Earth Vol. 18 (1997), p. 25

[10] Bakon and A. Szymanski: *Practical Uses of Diamond* (Ellis Horwood, England, 1993).

[11] V.A. Aleksandrov: Soviet Journal of Superhard Material (English Translation of Sverkhtverdye Materialy) Vol. 6 (1989), p. 48

[12] X.P. Xu, Y. Li, W.M. Zeng and L.B. Li: J. Mater. Processing Tech. Vol. 129 (2002), p. 50