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ELECTROLYTIC IN PROGRESS DRESSING (ELID) FOR HIGH-EFFICIENCY, PRECISION GRINDING OF CERAMIC PARTS: An Experiment Study

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CERAMIC TECHNOLOGY FOR ADVANCED HEAT ENGINES

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ELECTROLYTIC IN PROGRESS DRESSING (ELID) FOR HIGH-EFFICIENCY, PRECISION GRINDING OF CERAMIC PARTS: An Experimental Study

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Prepared for the
U.S. Department of Energy
Assistant Secretary for Energy Efficiency and Renewable Energy
Office of Transportation Technologies

for
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract DE-AC05-84OR21400

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SUMMARY

This report describes Electrolytic In-process Dressing (ELID) as applied to the efficient, high-precision grinding of structural ceramics, and describes work performed jointly by Dr. B. P. Bandyopadhyay, University of North Dakota, and Dr. H. Ohmori, of the Institute of Physical and Chemical Research (RIKEN), Tokyo, Japan, from June through August, 1994. Dr. Ohmori pioneered the novel ELID grinding technology which incorporates electrolytically-enhanced, in-process dressing of metal bonded superabrasive wheels. The principle of ELID grinding technology will be discussed in the report as will its application for rough grinding and precision grinding. Two types of silicon nitride based ceramics (Kyocera's Si_3N_4, and Eaton's SRBSN) were ground under various conditions with ELID methods. Mirror surface finishes were obtained with # 4000 mesh size wheel (average grain size = 4 μm). The results of these investigations will be presented in this report. These include the effects of wheel bond type, type of power supply, abrasive grit friability, and cooling fluid composition. The effects of various parameters are discussed in terms of the mechanisms of ELID grinding, and in particular, the manner of boundary layer formation on the wheels and abrasive grit protrusion.

1. INTRODUCTION

Interest in advanced ceramics has increased significantly in recent years due to their unique physical properties and to significant improvements in their mechanical properties and reliability [1]. The advantages of ceramics over other materials include high hardness and its retention at elevated temperatures, light weight, chemical stability, and superior wear resistance. Despite these advantages, use of structural ceramics in various applications has not increased rapidly owing in part to the high cost of machining these materials.

The cost of grinding may account for up to 75% of the component costs for structural ceramics compared to 5% to 15% for metallic components [2]. The primary cost drivers in grinding structural ceramics are low efficiency due to low removal rates, high superabrasive wheel wear rates, and long wheel dressing time. Manufacturing engineers tried to solve the problem in the traditional way utilizing highly rigid grinding machines and tough metal bonded superabrasive wheels. That research led to the successful development of cast iron-bonded diamond grinding wheels [3,4]. These wheels are manufactured by mixing diamond abrasive, cast iron powder or fibers, and a small amount of carbonyl iron powder, by compacting it to the desired form under the pressure of 6-8 ton/cm^2 and then by sintering it in an atmosphere of ammonia [5]. Higher material removal rates have been reported for grinding with these wheels; however, that type of wheel is not suitable for long-term, continuous grinding for the following reasons:

1) Tougher metal-bonded wheels will exhibit poor dressing ability. Therefore, efficient and stable grinding will be difficult to achieve simultaneously.

2) High material removal rate grinding will promote wear of the abrasive grains. Therefore, more frequent redressing of the wheel will be required.

3) While machining metals such as steel, wheel loading (embedment of swarf) will be caused.

Considerable research on ceramic machining has been conducted at the Institute of Physical and Chemical Research (RIKEN), Tokyo, Japan. RIKEN was established in 1917. It is a nonprofit institute supported by the government's Science and Technology Agency. The institute is a research complex consisting of about fifty laboratories of various deciplines. Research is conducted under active collaborations with universities, other research institutions, and industries.

In 1988, Dr. Hitoshi Ohmori of RIKEN pioneered the novel grinding technology known as Electrolytic In-process Dressing (ELID) and is now senior scientist for the ELID project. The ELID technique can provide in-process dressing of tough, metal-bonded superabrasive grinding wheel by the electrolytic action. In-process dressing controls the effectiveness of abrasive protrusions before and during the grinding of ceramic materials.

ELID grinding research is performed at one of the Materials Fabrication Laboratories in RIKEN. Cast Iron Fiber Bonded Diamond (CIFB-D) wheels were also developed at this laboratory. ELID grinding research is performed in two branches of RIKEN. One branch is at Wako city, which is the main campus of RIKEN, and the other branch is at Itabashi. The funding for this research project is obtained from various industries and there is no contribution from any government agency. However, the salaries of the researchers are paid by RIKEN. 40 (forty) companies are currently participating in this research project. The contribution from each company is 500,000 yen ($5000.00, with the present exchange rate $1 = 100 yen). Therefore, the annual budget for the project is 2 million yen or $200,000.00. The ELID research group organizes seminars three times a year and to which it invites representatives from various industries.

Dr. Bandyopadhyay participated in the ELID grinding research program at RIKEN, Japan, from June until August 1994. During this time he was mainly involved in the ultra precision ELID grinding of two types of silicon nitride specimens on a rotary surface grinder. He also worked with ELID systems on a horizontal surface grinder and a horizontal spindle in-feed grinder. These grinding machines were available at the Itabashi Campus (the experiments were conducted mainly at the WAKO campus) of RIKEN. Dr. Bandyopadhyay carried with him two types of silicon nitride specimens for study. One of them was Kyocera's Si_3N_4 and the other one was Eaton's SRBSN. Specimens were in the form of modulus of rupture specimens of rectangular cross section. These two types of silicon nitride based ceramics were ground with the ELID grinding technology under various grinding conditions.

This rest of this report will discuss the principle and mechanisms of ELID grinding, various applications of ELID grinding technology, and the results of the ELID grinding experiments on silicon nitride specimens.

2. THE ELID GRINDING PRINCIPLE

The concept of in-process dressing in a crude form was proposed by Nakagawa and Suzuki [4]. Those authors studied the effects of in-process dressing with a dressing stick. The grinding wheel was dressed at the beginning of each stroke. The authors reported higher material rates and steady state grinding with the in-process dressing.

Dressing methods which use electric power are not new. The principle is based on "electro-chemical grinding" [6]. The electrolytically-conductive or metal-bonded wheel is made the anode. The grinding wheel is dressed because an electrolysis process occurs between the anode and a fixed graphite cathode. A bronze-bonded diamond grinding wheel was dressed using this technology [7]. However, the authors used a sodium chloride solution as an electrolyte and this solution is harmful to machine tools.

A commercial in-process dressing grinding machine, based on the electro-discharge principle, is currently available. The machine is sold under the trade name COMMEC system. The system uses an electro-conductive grinding wheel which is energized with a relatively small amount of pulse current. Current flows from the wheel to the chuck through the coolant. The flow of ions creates hydrogen bubbles in the coolant creating an electric potential across them. When the potential becomes critical, a spark jumps across the bubble. These sparks will melt the material as it begins to clog the wheel and thus provides in-process dressing [8]. Expensive COMMEC systems do not provide continuous protrudent grains from the superabrasive wheels. Therefore, the method is not suitable for ultrafine grinding of materials; especially, with a micro-grain sized grinding wheel.

The ELID grinding method was first proposed by Dr. Ohmori in 1988. A number of papers describing the advantages of ELID grinding have been published [9-13]. The ELID system's essential elements are metal bonded grinding wheel, electrolytic power source, and electrolytic coolant. The most important feature of this system is that no special machine is required. Power sources from conventional electro-discharge or electro-chemical machines can be used for this method. Also, conventional grinding machines can be used for this method.

Figure 1 shows the principle of the ELID grinding process. The grinding wheel is connected to the positive terminal of a power supply with a smooth brush contact, and a fixed electrode is made negative. The electrode is made from copper having 1/6 of the wheel periphery length and width of 2 mm more than the wheel rim thickness. The gap between the wheel and the electrode can be adjusted by a mechanical means. A clearance of approximately 0.1 mm is kept between the positive and negative poles. The electrolysis occurs upon the supply of a suitable grinding fluid and an electric current. The experimental set up is shown in Fig. 2.

2.1 Steps Involved in Electrolytic Dressing:

The ELID grinding consists of the following three steps:

i) Precision truing of the micro-grain grinding wheel.

ii) Pre-Dressing process of the wheel by electrolysis.

iii) Grinding process with electrolytic in-process dressing.

Precision truing is carried out so that the initial eccentricity is reduced to a level comparable or less than that of the average grain size of the wheel. Therefore, truing is very important when ultraprecision grinding is performed with a micro-grit-size wheel.

The second step is pre-dressing to achieve protrusion of the grains. This step is essential for proper grinding operation. Pre-dressing is performed at a slower speed and typically takes about 10-15 minutes.

The in-process dressing (third process) occurs whilst grinding. The conditions of electrolysis of the last two processes differ due to the changing wheel surface condition during electrolysis.

2.2 Electrical Behavior during Electrolytic Dressing:

The relationship between electric current, voltage, and time during electrical dressing is shown in Fig. 3. When the predressing starts (point 1), the surface of the trued wheel has good electrical conductivity. Therefore, the current is as high as that set on the power source, and the voltage between the wheel and the electrode is low. After several minutes, the cast iron bond material, which is mostly ionized into Fe^{+2}, is removed by electrolysis. The ionized Fe reacts to form either $Fe(OH)_2$ or $Fe(OH)_3$ according to the following:

$$Fe \rightarrow Fe^{+2} + 2e^- \qquad (1)$$

$$Fe^{+2} \rightarrow Fe^{+3} + e^- \qquad (2)$$

$$H_2O \rightarrow H^+ + OH^- \qquad (3)$$

$$Fe^{+2} + 2OH- \rightarrow Fe(OH)_2 \qquad (4)$$

$$Fe^{+3} + 3OH- \rightarrow Fe(OH)_3 \qquad (5)$$

These hydroxides further change into oxides (e.g., Fe_2O_3) during electrolysis. After these reactions have occurred and insulating substances grow on the wheel surface, its the electrical conductivity will be reduced. The current decreases and the working voltage becomes as high as that which was originally set as the open circuit voltage (denoted by 2).

2.3 The ELID Grinding Mechanism

The various stages of ELID are shown in Fig. 4. At the beginning, grinding is performed with the pre-dressed wheel and the protrudent grains grind the workpiece. With time, the grains and the oxide layer begin to wear. The wear of the oxide layer causes an increase in electro-conductivity of the wheel's surface. Thus, the electrolysis increases (denoted by 3 in Fig. 3) and the oxide layer is recovered. The protrusion of the grains remains constant. For high-efficiency ELID grinding (rough grinding) no isolating layer is required. However, for mirror finish ELID grinding a relatively thick oxide layer seems to work better.

3. EXPERIMENTAL SET UP

3.1 The Grinding Machine

An ELID system can easily be adapted to work on a conventional grinding machine. The following items are required to develop the system: a negative electrode, a brush, a specific type of metal-bonded wheel, and a specific type of grinding fluid.

The current experiments were conducted on a vertical rotary surface grinder. The spindle was direct belt-driven by a 5.5 kW motor. Spindle speed was regulated with an invertor. The spindle of the machine was mounted on hydrostatic oil bearings. The table feed was controlled by a DC tachometer-generator connected to a reduction motor. Such a system allowed continuous feed adjustment. The workpiece was mounted on a plate which was in turn clamped in the fixture on the table. A copper cathode which had 1/6 the area of the entire wheel surface was used for the electrical dressing.

3.2 Grinding Wheels

Cup-type Cast Iron Fiber Bonded (CIFB) diamond wheels with various grit sizes were used to study grit size effects on surface finish. The diameter of the wheels was 200 mm. The wheel grit sizes we used are given in Table I.

Table I: Grain Size of Used Diamond Grinding Wheels.

Mesh Size	Grain Size μm	Average Grain Size μm
#325	40 ~ 90	63.0
#600	20 ~ 30	25.5
#1200	8 ~ 16	11.6
#2000	5 ~ 10	6.88
#4000	2 ~ 6	4.06
#6000	1.5 ~ 4	3.15
#8000	.5 ~ 3	1.76

3.3 Grinding Fluid

Noritake AFG-M Grinding fluid was used diluted to 1:50 in these experiments. The pumping rate of the fluid was 20-30 lit/min.

3.4 Power Supply

A direct current pulse generator was used as a power supply. The power supply has a open voltage of 60 V (square wave) with a peak current of 10 A. The pulse width can be adjusted, and in the experiment 5 μs on-time and off-time was used.

3.5 Surface Finish Measurements

The surface finish was measured by the Mitutoyo 501 surface roughness measuring instrument using a 5 micron diamond stylus. For surface characterization of the ground specimens video microscope was used. The system consists of a Olympus microscope model OVM 1000 NM (along with OVM-SAD), Ikegami Monitor and a video printer from Mitsubishi color video copy processor SCT-CP 120.The total cost of the system is 1 million yen ($10,000.00) with two lenses magnification 100 and 1000. Lenses each cost about 100,000 yen ($1000.00). The operating cost is nominal, cost of one picture is 40 yen (40 cents). Some representative pictures are provided later in the report. Because of limited lens quality the images were not clear.*

[* Note: In previous investigations of ground ceramic surfaces, conducted with a Hitachi S-800 scanning electron microscope at Oak Ridge National Laboratory, we found that a magnification of 300X to 700X was optimum.]

The ground specimens (a small section from each sample) were sent to another institute for Scanning Electron Microscopy (SEM) and Atomic Force Microscope (AFM) studies. The results of that work were not available at this time of this report.]

4. MATERIALS

Two silicon nitride materials, a sintered reaction bonded silicon nitride (Eaton's SRBSN), and a cast and sintered silicon nitride (Kyocera's Si_3N_4) obtained from a commercial vendor were ground. Specimens were in the form modulus of rupture specimens of rectangular cross-section. Their nominal dimensions were as follows:

Kyocera's silicon nitride: 60 mm * 5 mm * 5 mm.
EATON's SRBSN: 100 mm * 10 mm * 10 mm.

5. RESULTS - PART I: Effects of Process Variables on ELID Grinding

The results of our ELID grinding tests are presented in two parts. Part I describes the effects on grinding properties such as efficiency, accuracy and quality due to the different types of metal bonded wheels, electrolytic power source, grinding fluid, and abrasive friability. Part 2 describes various applications of ELID grinding.

5.1 Influence of Bond Materials.

The effects of three kinds of metal bonded wheels, cast iron fiber bonded (CIFB), cobalt bonded (CB), and bronze bonded (BB), were studied [12]. Figure 5 shows the effect of bond materials on the dressing current. A CIFB wheel has the type of electric behavior which indicates easy isolation of the wheel surface, i.e.

the working current can easily decrease. In contrast, a CB wheel showed relatively constant current during dressing, and a BB wheel showed an almost constant current. Figure 6 shows the change in the wheel diameter before and after the dressing. A CIFB wheel has a thick isolating layer consisting of the oxides and hydroxides generated on the wheel surface. The thickness is checked by measuring the wheel diameter with a micrometer before and after dressing. A BB wheel has a thin isolating layer, and a CB wheel has an isolating layer between those extremes.

For high-efficiency grinding no isolating layer is required. This condition will provide a high dressing rate and high abrasive protrusion. For ELID mirror-surface grinding a relatively thick oxide layer is required. Therefore, BB bonded wheels are recommended for rough grinding and CIFB wheels should be used for mirror-finish grinding. However, our investigations have shown that a CIFB wheel can be used both for rough and mirror finish grinding.

After 30 minutes of pre-dressing, each wheel (#140 metal bonded CBN wheel) was tested for efficient grinding. Figure 7 shows the difference in the normal component of the grinding force for the three bond materials. It is clear from the figure that a wheel having a thinner isolating layer has a lower grinding resistance (e.g., the BB wheel). The grinding force was maximum for the CIFB wheel.

5.2 Influence of Power Source

The effects of using three types of power sources were studied: one using a DC (direct current)- pulse, one using DC - plain (constant voltage), and one using AC (alternate voltage) [12]. Figure 8 shows the difference in dressing current due to the type of power source. The DC-plain produced the sharpest decrease in the dressing current. On the other hand, AC caused the smallest decrease in current.

Figure 9 shows the difference in the isolating layer and the etched layer thickness during the initial 20 minutes of dressing. The DC-plain caused the greatest thickness, the AC the least. The etched layer was obtained by measuring the change in wheel diameter after the dressing and scrapping the isolating layer. Figure 10 shows the effects of the power source on the normal component of the force. The DC-plain source exhibited the highest grinding force because the thick isolating layer reduced the effectiveness of the abrasive action. If a DC-plain source is applied to a CB or BB wheel, it should be effective because those wheels do not generate much of an isolating layer (see Fig. 6).

Differences in the dressed wheel surface produce differences in the surface roughness of the ground specimens. When ELID grinding was performed using a #4000 mesh size wheel, the AC source provided the worst surface finish and the DC-pulse provided the best.

Figure 11 shows the changes in the isolating layer thickness which occur with time and pulse width. A pulse width of 2 μs generated the thickest isolating layer during an electrical dressing of 20 min. No significant differences were produced by pulse widths of 8 micro seconds and 4 micro seconds. In both the cases tap water was used. A thick isolating layer of approximately 24 μm was generated under 2 μs pulses, but when 4 or 8 μs were applied, an isolating layer of 5 micron was generated.

5.3 Influence of Abrasive Friability

Influence of abrasive friability was investigated by using four steel-bonded wheels having four kinds of #140 diamond abrasives: MBG-660, MBG II, MBG-600, and RVG.

The changes in normal grinding force, under conventional grinding conditions, which are produced by grinding wheels having different abrasive friabilities are shown in Fig. 12. The lowest grinding force was obtained with the RVG wheel, which has the highest friability. After a stock removal of 5000 mm^3, MBG 660 wheel, which had the lowest friability, exhibited the highest force. Thus, the grinding force corresponded to relative friability. Figure 13 shows the changes in the normal grinding force using the same wheels with ELID grinding. With the application of ELID, all the grinding forces were reduced, although the order of the grinding force remained same as under the conventional grinding. This is because ELID can provide protrusions of any kind of diamond abrasives, thereby reducing the grinding force.

5.4 Influence of Grinding Fluid on ELID Finish Grinding

The influence of grinding fluids was investigated while finish ELID grinding. Figure 14 shows the change in the dressing current while using two different types of grinding fluids. Fluid 1 was diluted with tap water with a lower percentage of Cl- ion than fluid 2. The properties of these two fluids are given in table 2.

Table 2 Properties of the grinding fluids used.

Properties	Ion % ppm		pH	Electrical Conductivity $\mu S/cm$
	Cl^-	SO_4^{2-}		
Fluid 1 with tap water	8.1	16.8	8.1	130
Fluid 2 with ground water	26.6	44.0	7.4	257

With fluid 1, the current decreased more rapidly than with fluid 2. The isolating layer thickness resulting from fluid 1 was approximately 12 μm and that from fluid 2 was 2 μm. Better surface finish was obtained with the application of fluid 1.

5.5 Conclusions (Section I)

The influence of the wheel bond materials, power supplies, abrasive friability, and grinding fluid on ELID grinding performance has been discussed. Proper selection of wheel, power supply, grinding fluid improves the efficiency and precision of the ELID grinding process.

The ideal wheel surface condition required is illustrated in Fig. 15. For high efficiency grinding a thinner isolating layer is required whereas for mirror finish ELID grinding a relatively thick oxide layer is preferred.

A thinner isolating layer is formed when grinding is performed with a bronze bonded diamond grinding wheel. Therefore such a wheel will be suitable for rough grinding. The grinding force will also be less.

CIFB-D wheels are recommended for both rough and mirror finish grinding. The grinding performance can be optimized by controlling the current, pulse width of the electric supply, and the grinding fluid. Currently optimized ELID grinding parameters are not available. More research is to done especially in the area of rough grinding to optimize the ELID grinding performance.

6.0 RESULTS - PART II: Applications of ELID Grinding

6.1 Rough and Efficient Grinding

Rough and efficient ELID grinding was performed on a reciprocal surface grinder and coarse grit CIFB-D wheels (#140 and #170). A specialized power generator was used as the ELID power supply. The following ceramic materials were ground: SiC, Si_3N_4, Sialon, and WC. Figure 16 shows the normal grinding force in grinding Si_3N_4 ceramics with and without ELID. When ELID was not applied, the normal grinding force increased gradually to approximately to 450 N. On the other hand, with the application of ELID the grinding force was reduced to 200N.

Table 3 summarizes the grinding conditions used in these experiments [11]. In traverse grinding, as shown in Fig. 16, a material removal rate (MRR) of 1800 mm^3/min was obtained. This is not high compared to conventional grinding. In plunge grinding, however, MRRs as high as 6000 mm^3/min could be achieved with the ELID technique. Figure 17 shows the influence of ELID current on the grinding force. Higher current reduces the grinding force. But the data in Fig. 17 suggest that the difference between grinding forces will be smaller after a large amount of stock removal.

Table 3 Plunge Grinding Conditions

Work Material	SiC	Si3N4	SiAlON	WC
Wheel Velocity: m/min	1200	1200	1200	1200
Feed Rate: m/min	20	20	20	20
Grinding Width: mm	10	10	10	10
Depth of cut: μm	30	30	30	10
Removal rate: mm3/min	6000	6000	6000	2000
Open Voltage: Volt	90	90	90	90
Peak Current: Amp	10	10	10	10
On-time: μs Off-time: μs	2 2	2 2	2 2	2 2

Table 4 shows the normal grinding force obtained in ELID grinding of different work materials. WC tends to load the wheel surface with chips. Even when ELID was applied, the grinding force was higher than that of the other ceramics. The grinding force for machining SiC was found to be the lowest. This is because SiC was the most brittle material of the four ceramics we machined.

Table 4 Normal grinding force and working current for ELID grinding of different work materials

Removal Rate mm^3/min	SiC		Si3N4		SiAlON		WC	
	Fn N	Iw A	Fn N	Iw A	Fn N	Iw A	Fn N	Iw A
2000	170	2.2	280	2.2	300	2.2	450	6.0
4000	250	3.0	500	6.0	500	4.2	-	-
6000	350	4.0	650	7.5	650	5.0	-	-

6.2 Mirror Finish Grinding

Experiments were conducted to study the effects of mesh size on the surface finish of the workpiece. The cutting conditions for this part of the experiment were: cutting speed = 21.5 m/sec, workpiece feed rate = 80 mm/min, and the depth of cut = 1 μm/pass. The results of the investigation are presented in Figs. 18 and 19. Three surface finish parameters, Ra, Rz, and Rmax [where Ra is the arithmetic mean of the departures of the roughness profile from the mean line, Rz is the ten point height of the roughness profile, and Rmax is the maximum peak to valley height of the profile] were monitored [14] during this investigation. A mirror finish surface was obtained when ELID grinding was performed with a 4000 mesh size grinding wheel. Typical surface roughness profiles are shown in Fig. 20.

In the second series of experiments, the effect of cutting speeds on the surface finish (Ra) was studied. The experiments were conducted at a workpiece feed rate of 80 mm/min, and depth of cut of 1 μm/pass. The results are presented in Fig. 21 and 22. In ELID grinding, the cutting speed has no significant effect on the surface finish of the workpiece. Better surface finish was obtained with the SRBSN material than Si_3N_4 especially with rougher wheels (#325, and #600). However, with finer wheels (#4000), almost the same surface finish was obtained with both the materials. This behavior is shown in the Fig. 23.

In the third series of experiments, the effect of feed rate on the surface finish was studied. The grinding conditions for this series of experiments were cutting speed = 21.5 m/sec and the depth of cut = 1 μm/pass. The results are shown in Figs. 24 and 25. Except for the higher feed rate with the rougher wheel (#325), in ELID grinding, the feed rate had no significant effect on the surface finish. As observed previously, better surface finish was obtained with the SRBSN material than Si_3N_4 when grinding was performed with rougher wheels. However, with finer wheels (#4000) almost same surface finish was obtained with both the materials.

In the last series of experiments, the effect of diamond concentration was studied on the three surface finish parameters. The results are presented in Figs. 26, and 27. When grinding with lower diamond concentration (10 in the experiment), chatter marks were observed on the ground surface. There was a wide variation of Rmax parameter along the specimen. During grinding, the ELID current was not stable, indicating that the grinding process itself was not stable. We concluded that more burnishing was taking place instead of grinding under this condition. We therefore do not recommend using a 10 concentration wheel in this process.

6.3 Part II Conclusions

This section describes a mirror finish surface grinding technique with electrolytic-in-process (ELID) dressing using micro-grit cast iron fiber bonded wheels. Experiments were conducted on a rotary surface grinder. The influence of mesh size, grinding speeds, feed rate, and diamond wheel concentration on surface finish were also studied in this investigation. We concluded:

1. Employment of the ELID system produced a mirror finish workpiece.

2. This technology will find wide application in the optical and semiconductor industry, such as mirror finishing of silicon wafers, many kinds of fine ceramics, ferrite and glass.

3. The ELID grinding system has been successfully applied to the following grinding operations: machining center, surface grinder, in-feed grinder, lap grinder, and internal grinder.

ACKNOWLEDGEMENTS

Research sponsored by the United States Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies, as part of the Ceramic Technology Project of the Propulsion system Materials Program, under contact DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

REFERENCES

1. Spriggs, R. M., "Advanced Ceramic Materials; Applications and Opportunities," Intersociety Symposium on Machining of Advanced Ceramic Materials and Components, American Ceramic Society, April 1987, pp 1-9.

2. Jahanmir, S., et. al., "Ceramic Machining: Assessment of Current Practice and Research Needed in the United States," NIST Special Publication 834, June 1992.

3. Nakagawa, T., Suzuki, K., Uematsu, T., "Three Dimensional Creep Feed Grinding of Ceramics by Machining Center," Proceedings ASME WAM, PED 17, 1985, pp 1-7.

4. Nakagawa, T. and Suzuki, K., "Highly Efficient Grinding of Ceramics and Hard Metals on Grinding Center," CIRP annals, Vol. 35, No.1, 1986, pp 205-210.

5. Nakagawa, T., Sharma, C. S., "Modern Developments in Powder Metallurgy," Vol. 9, 1977, pp 347-388.

6. McGeough, J. A., "Principles of Electro Chemical Machining," Chapman and Hall, 1974.

7. Welch, E., Yi, Y., and Bifano, T., "Electro Chemical Dressing of Bronze Bonded Diamond Grinding Wheels," Proceedings of the International Conference on Machining of Advanced Materials, NIST publication 847, July 1993, pp 333-340.

8. NICCO Creep Feed Grinders: Catalog from Carl Citron Inc., NJ.

9. Ohmori, H., Nakagawa, T., "Mirror Surface Grinding of Silicon Wafers with Electrolytic In-Process Dressing," Annals of CIRP, Vol. 39, No. 1, 1990, pp 329-332.

10. Ohmori, H., "Electrolytic In-Process Dressing (ELID) Grinding Technique for Ultraprecision Mirror Surface Machining," International Journal of JSPE, Vol. 26, No. 4, Dec. 1992, pp 273-278.

11. Ohmori, H., " Efficient and Precision Grinding Technique for Ceramics with Electrolytic In-Process Dressing (ELID)," Proceedings of the International Conference on Machining of Advanced Materials, NIST publication 847, July 1993, pp 359-382.

12. Ohmori, H., Takahashi, I., "Efficient Grinding Technique Utilizing Electrolytic In-Process Dressing for Precision Machining of Hard Materials," Proceedings 7th International Conference on Production/Precision Engineering, Sept 1994, Chiba, Japan.

13. Walter, M., "ELID Dressing of Grinding Wheels," Poster paper presented at the ASPE Annual Conference, Seattle, WA, 1993.

14.ANSI Standard B46.1, "Surface Texture (Roughness, Waviness, and Lay)," ASME, NY, 1985.

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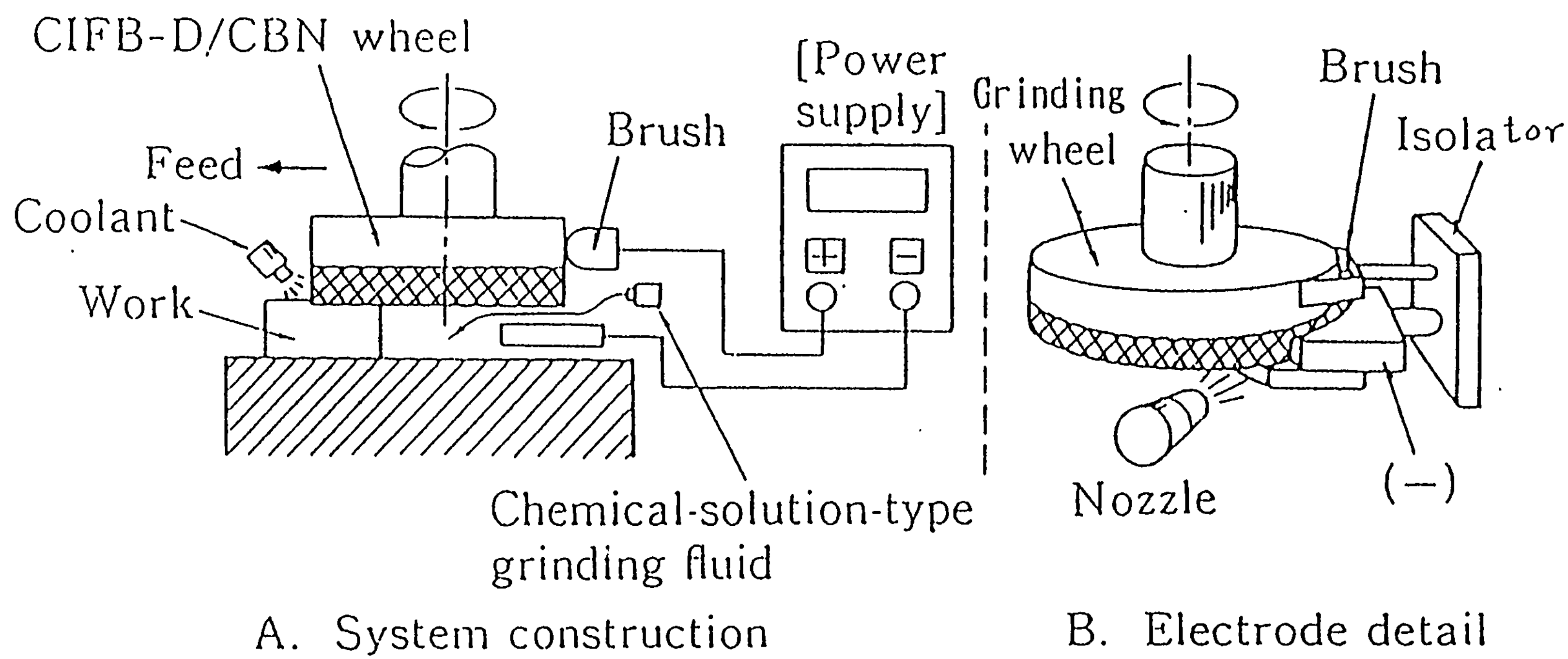


Figure 1. Principle of ELID Grinding

Figure 2. Experimental Set Up

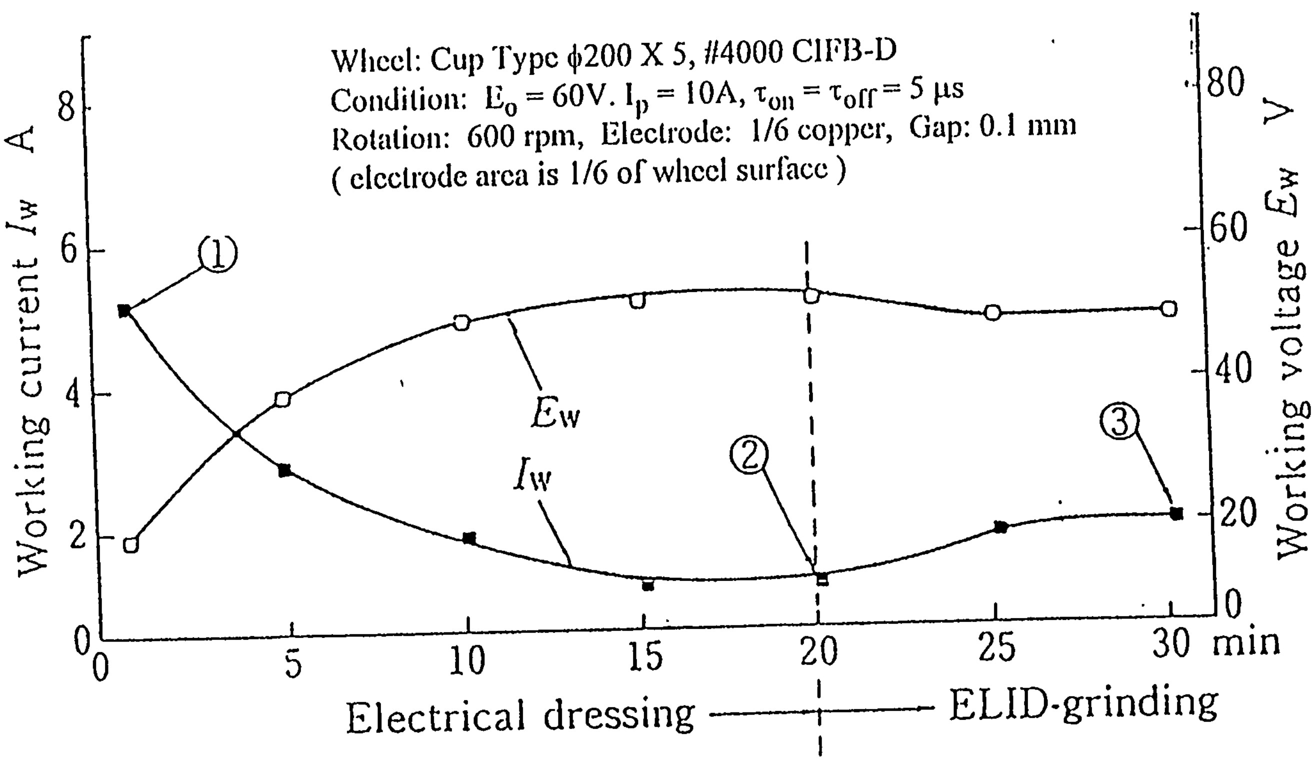


Figure 3. Behavior of Electrolytic Dressing

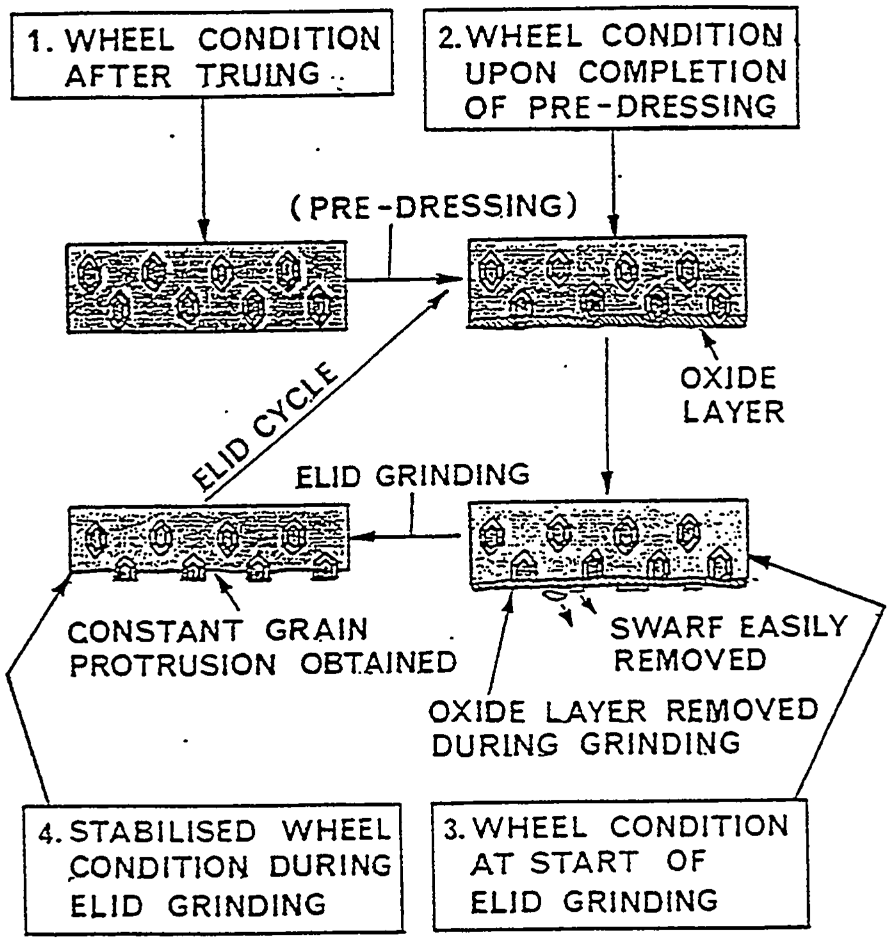


Figure 4. Stages of In-Process Electrolytic Dressing

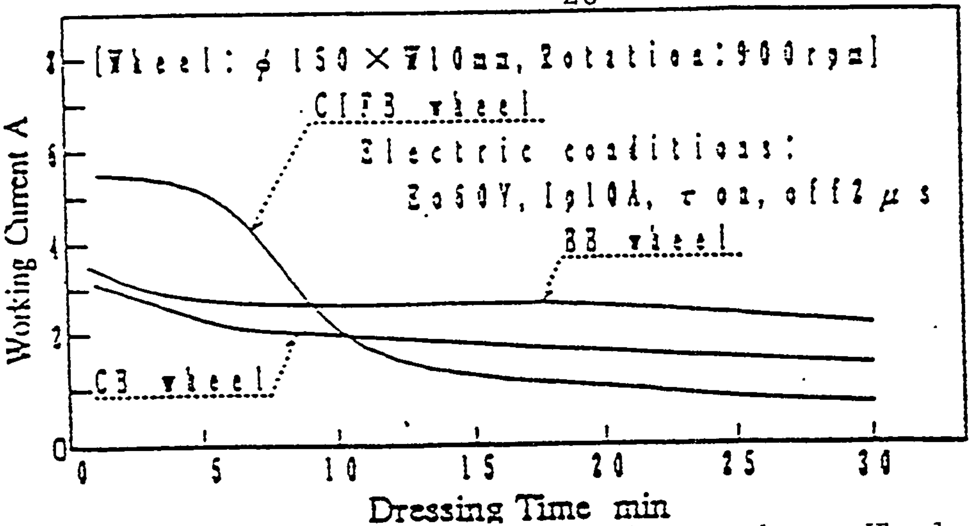


Figure 5. Difference in Dressing Current due to Wheel Bond Material

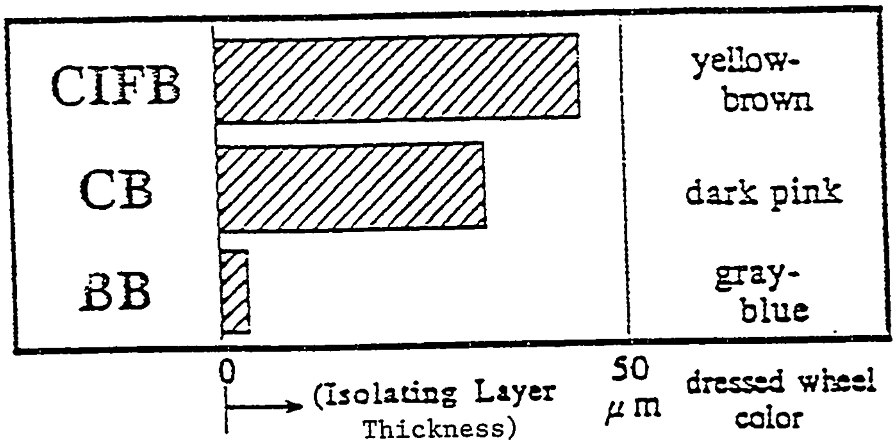


Figure 6. Difference in Wheel Diameter Before and After Pre-Dressing

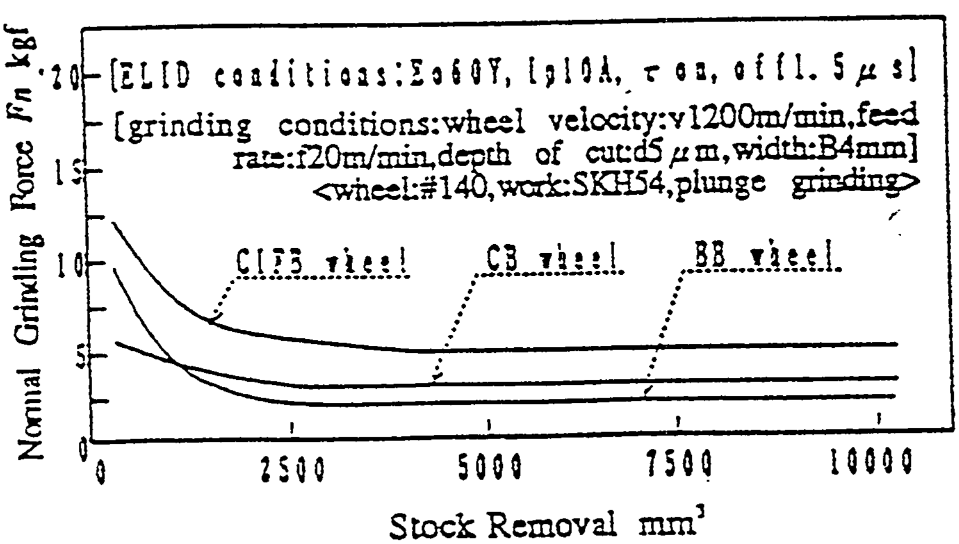


Figure 7. Difference in Grinding Force Due to Wheel Bond Material

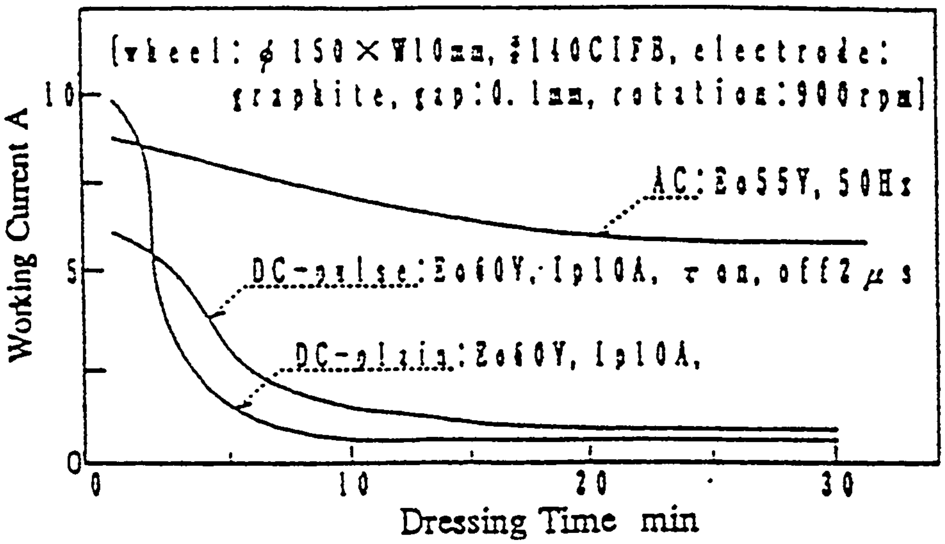


Figure 8. Difference in Dressing Current due to Power Source

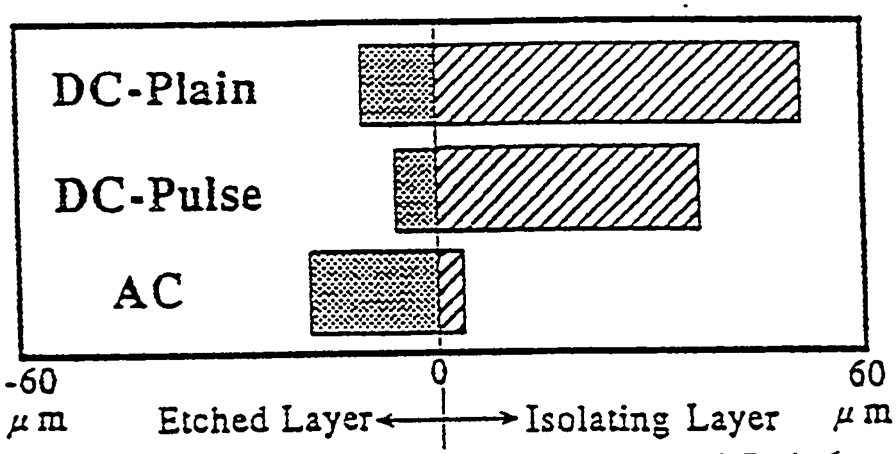


Figure 9. Difference in Isolating Layer and Etched Layer Thickness due to Power Source

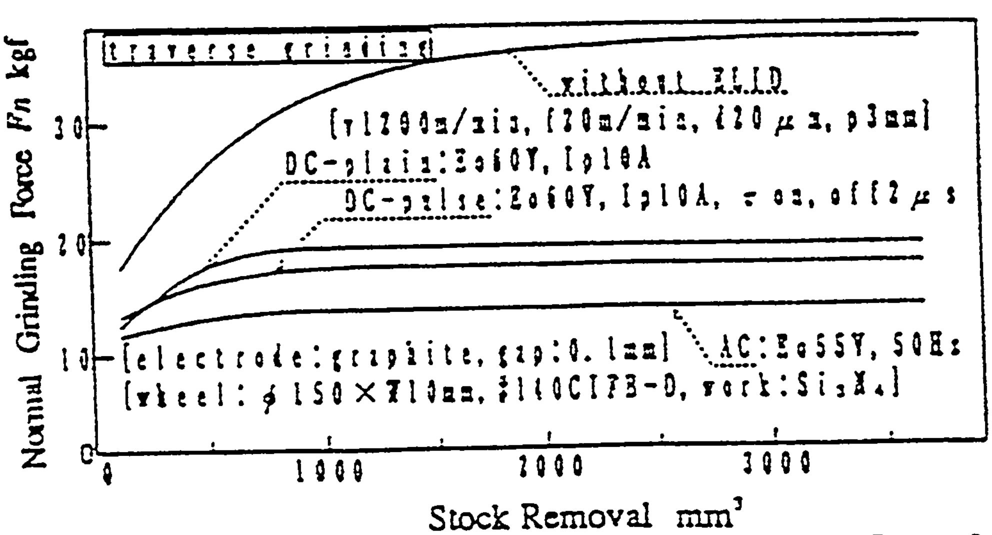


Figure 10. Difference in Grinding Force due to Power Source

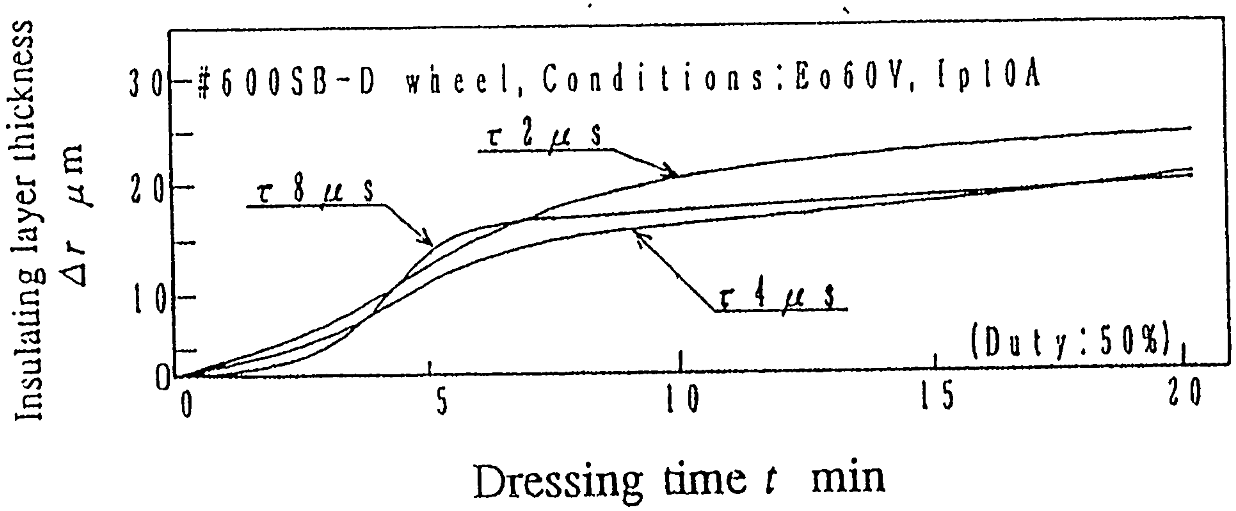


Figure 11. Change in Insulating Layer Thickness according to Time and Pulse Width

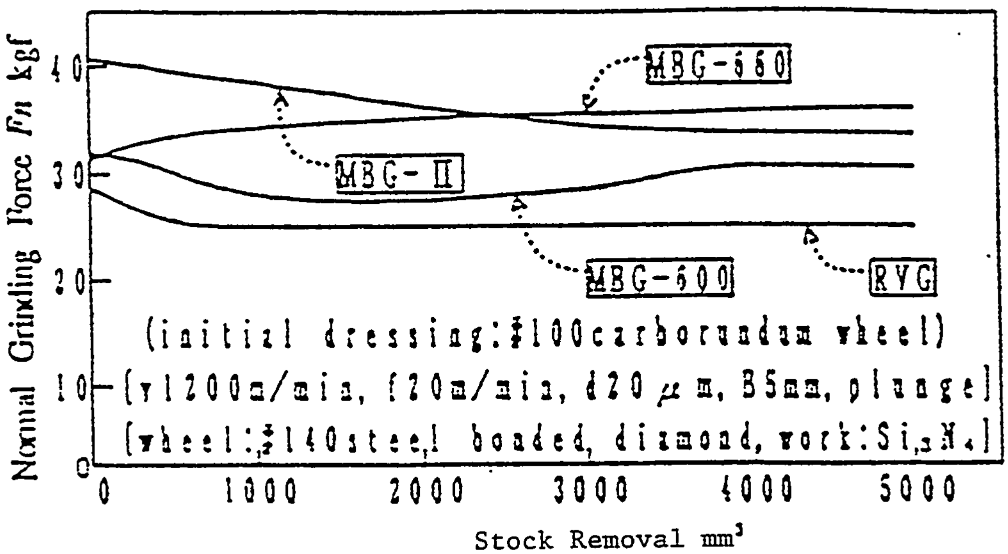


Figure 12. Difference in Grinding Force due to Abrasive Friability under Ordinary Grinding

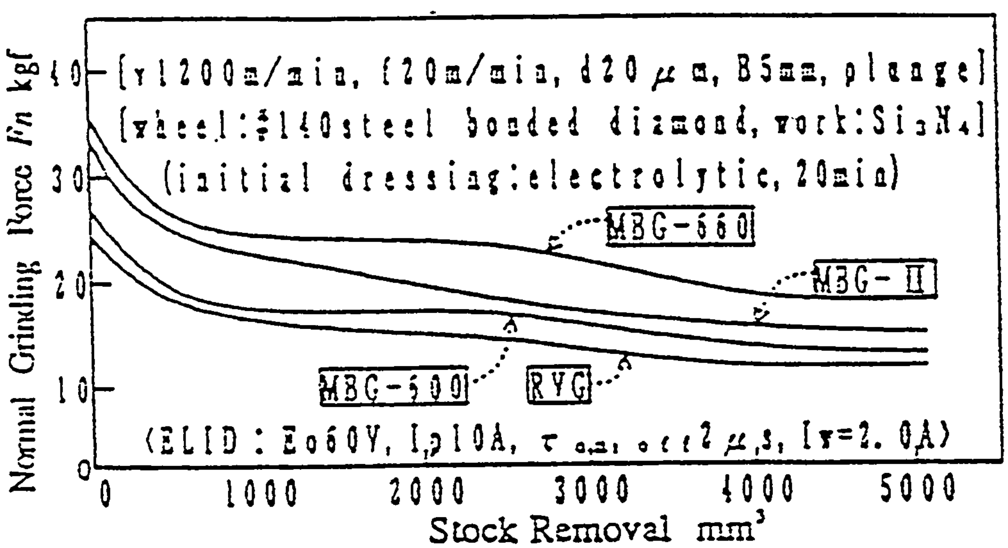


Figure 13. Difference in Grinding Force due to Abrasive Friability under ELID Grinding

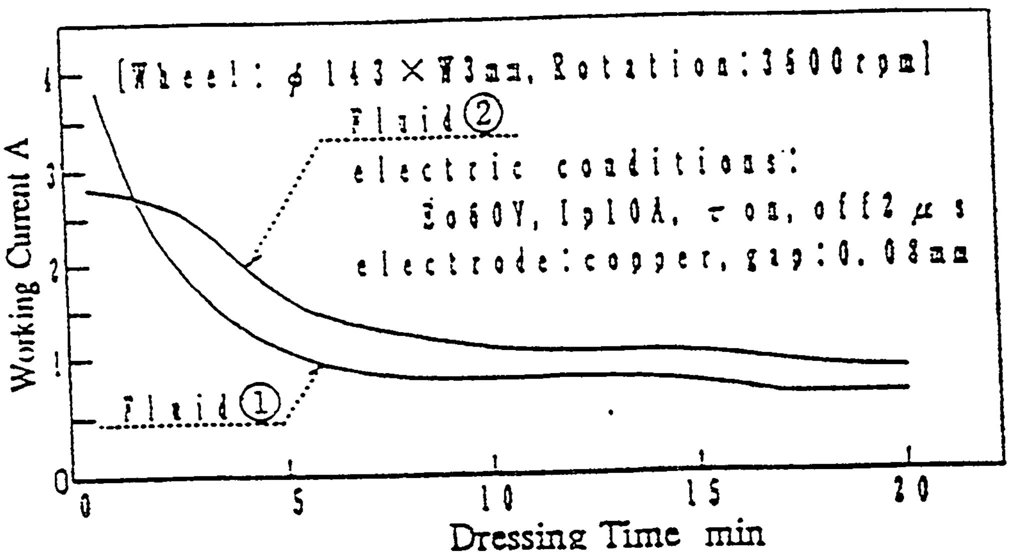


Figure 14. Difference in Working Current due to Grinding Fluid

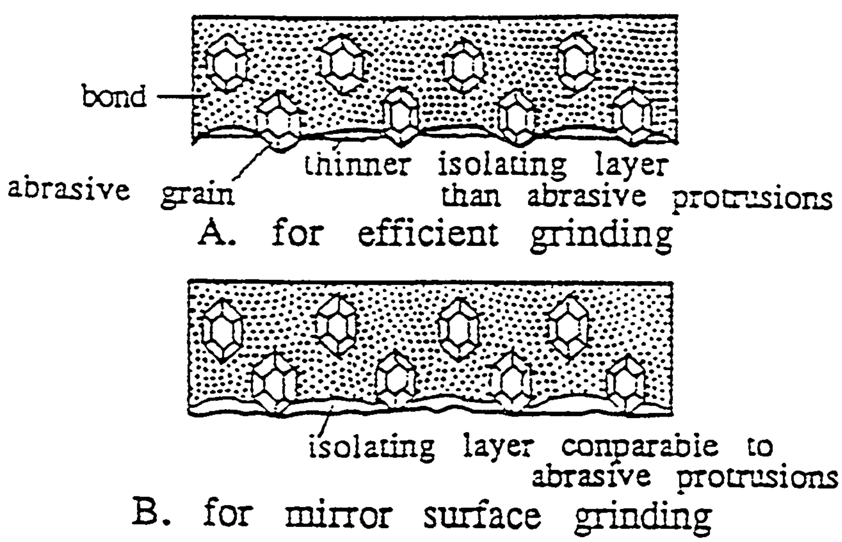


Fig. 15 Ideal Wheel Conditions

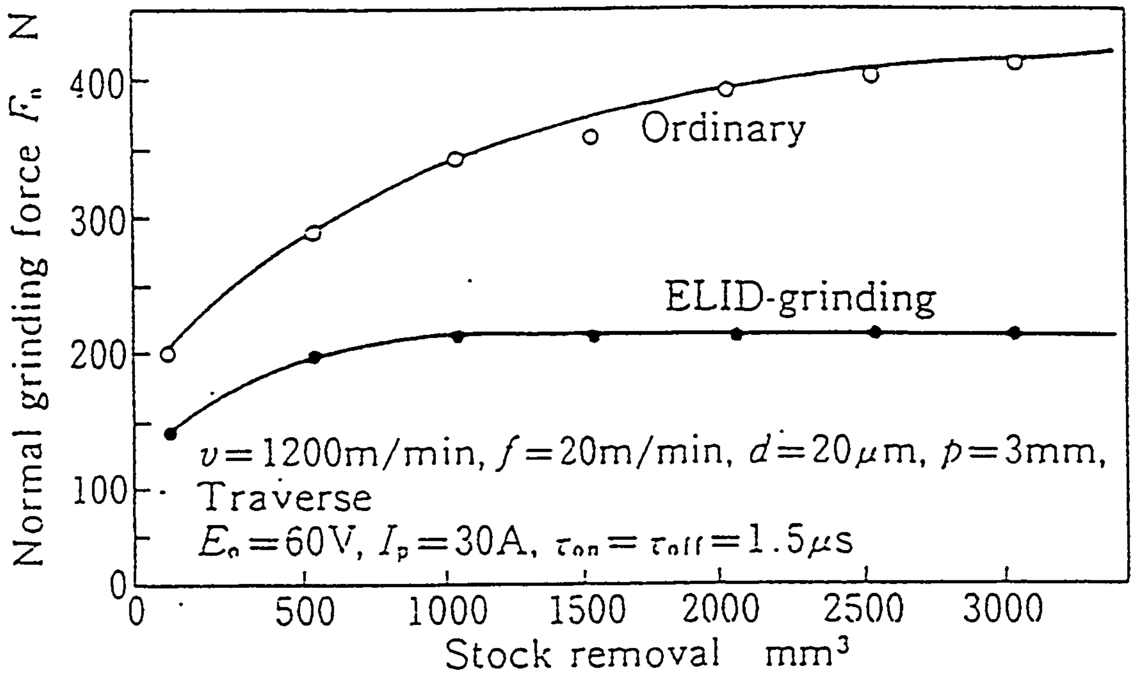


Figure 16. Changes in Normal Grinding Force Wheel: #170 CIFB-D, Work: Si3N4 (50*50)

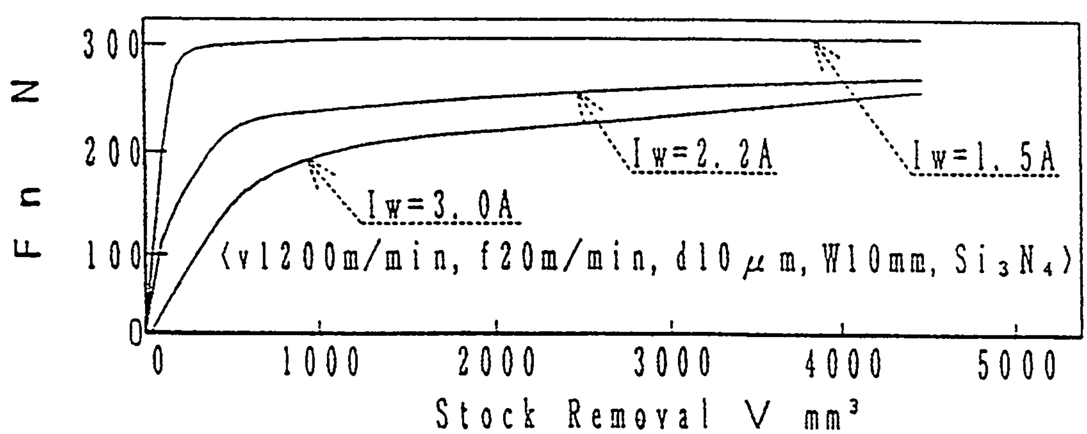


Figure 17. Influence of Current on Grinding Force for Si3N4

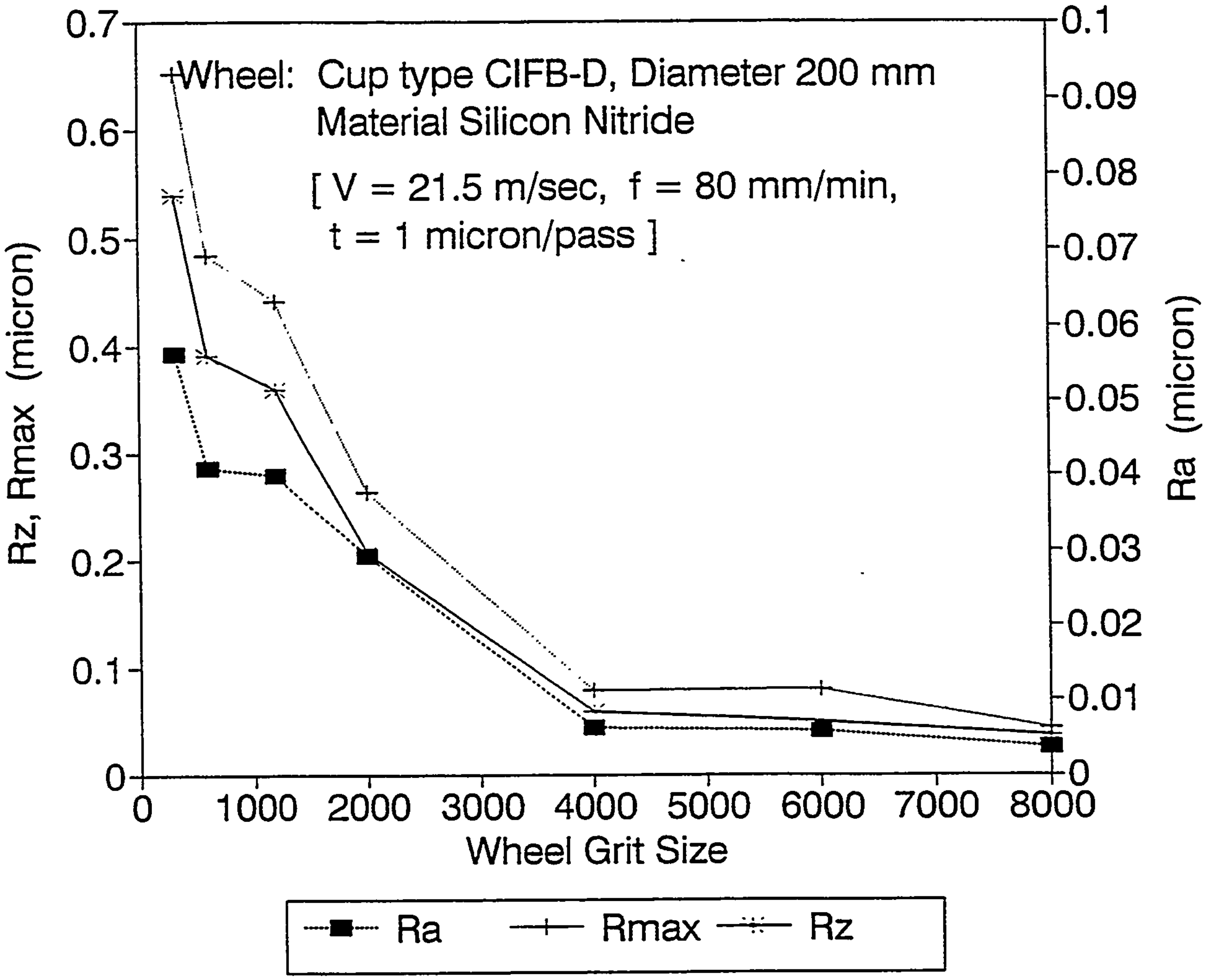


Figure 18. The Effect of Wheel Grit Size on Surface Finish

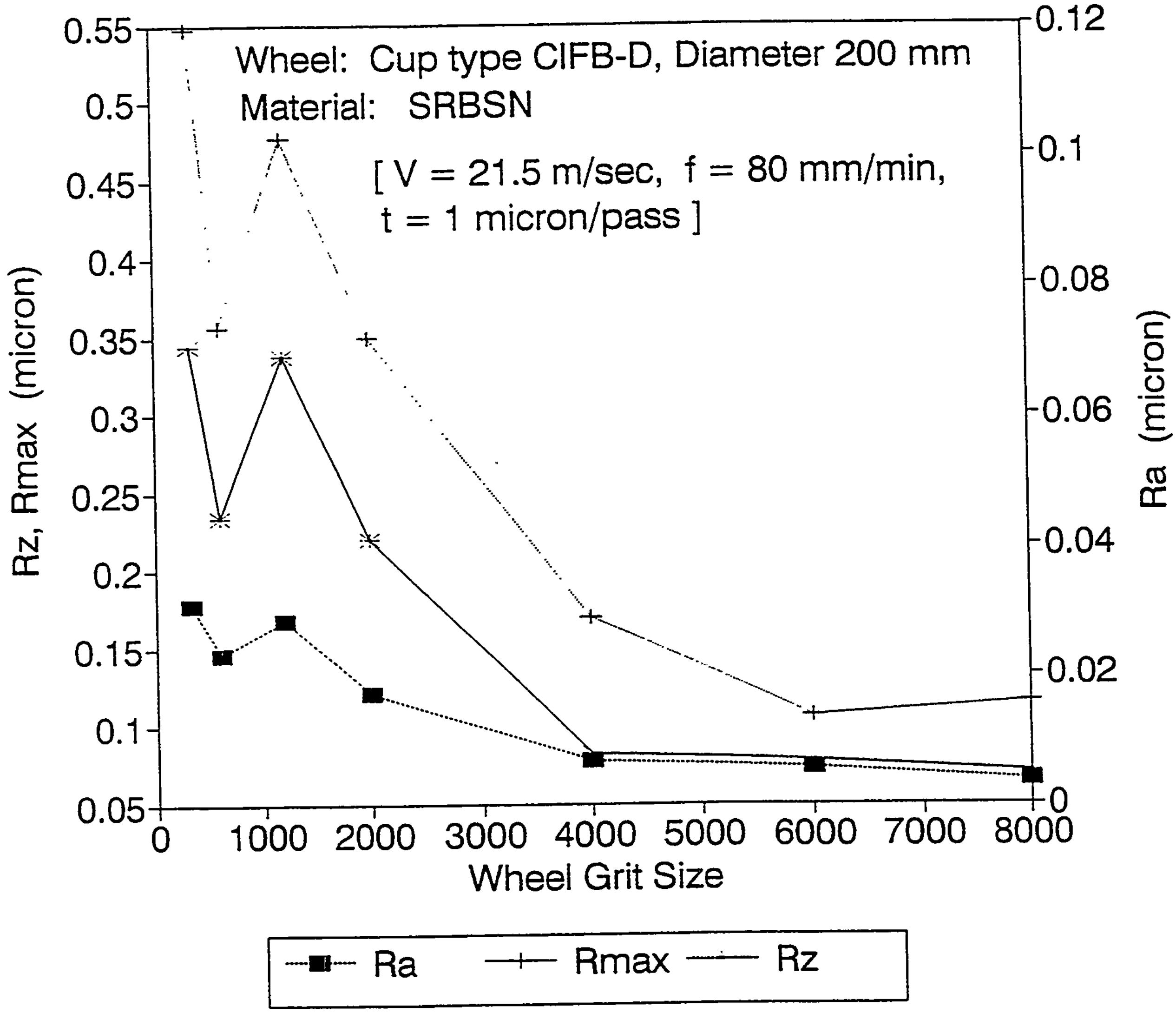
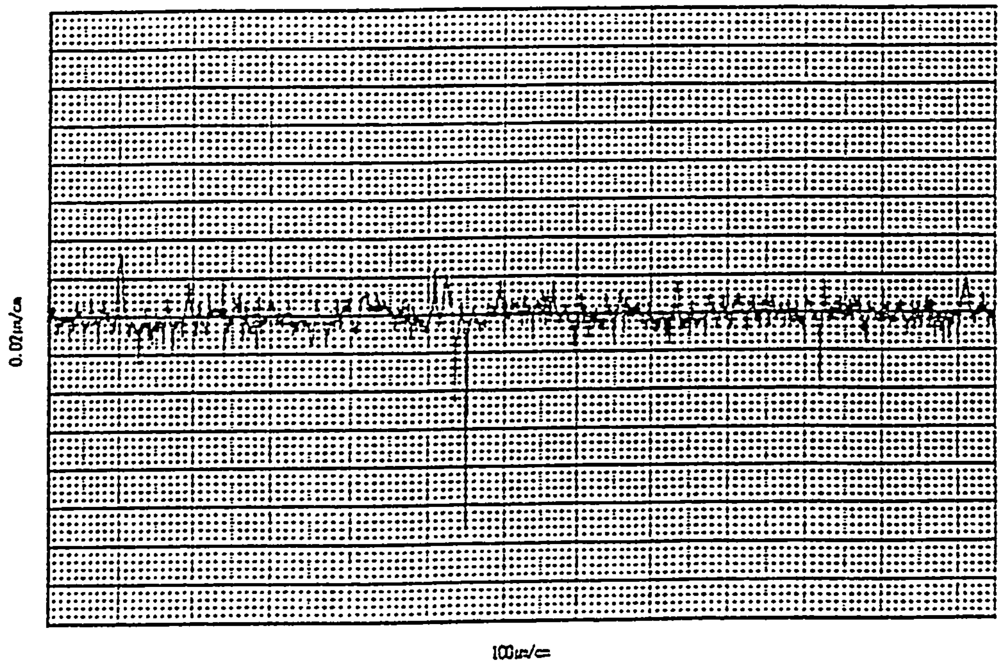
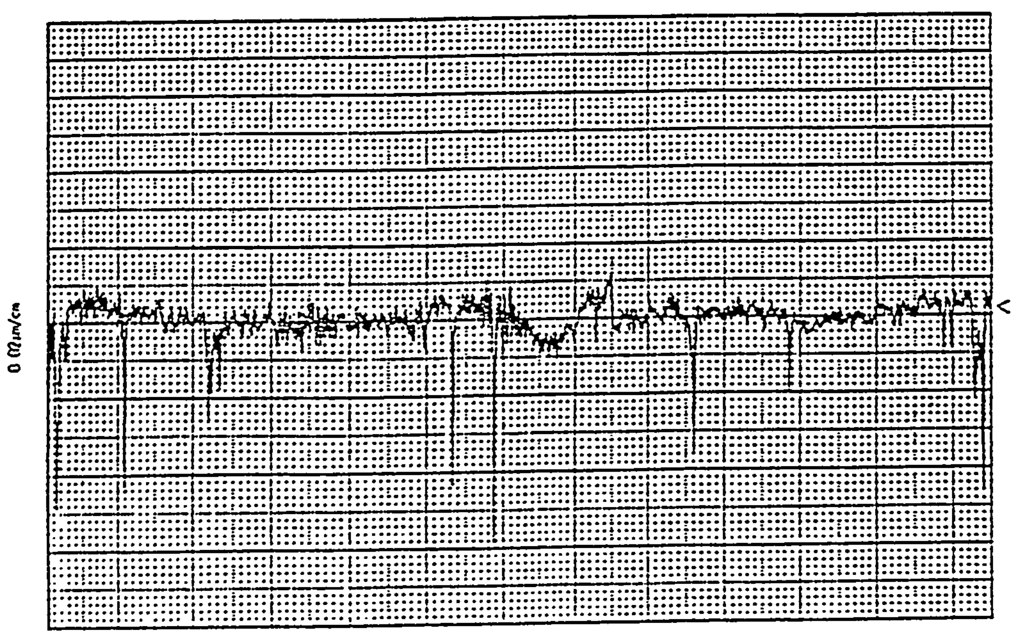


Figure 19. The Effect of Wheel Grit Size on Surface Finish



Material:
Si_3N_4,
#4000 mesh
Grinding wheel

Figure 20. Typical Surface Roughness Pattern



Material:
SRBSN,
#4000 mesh
Grinding wheel

Figure 20. Typical Surface Roughness Pattern

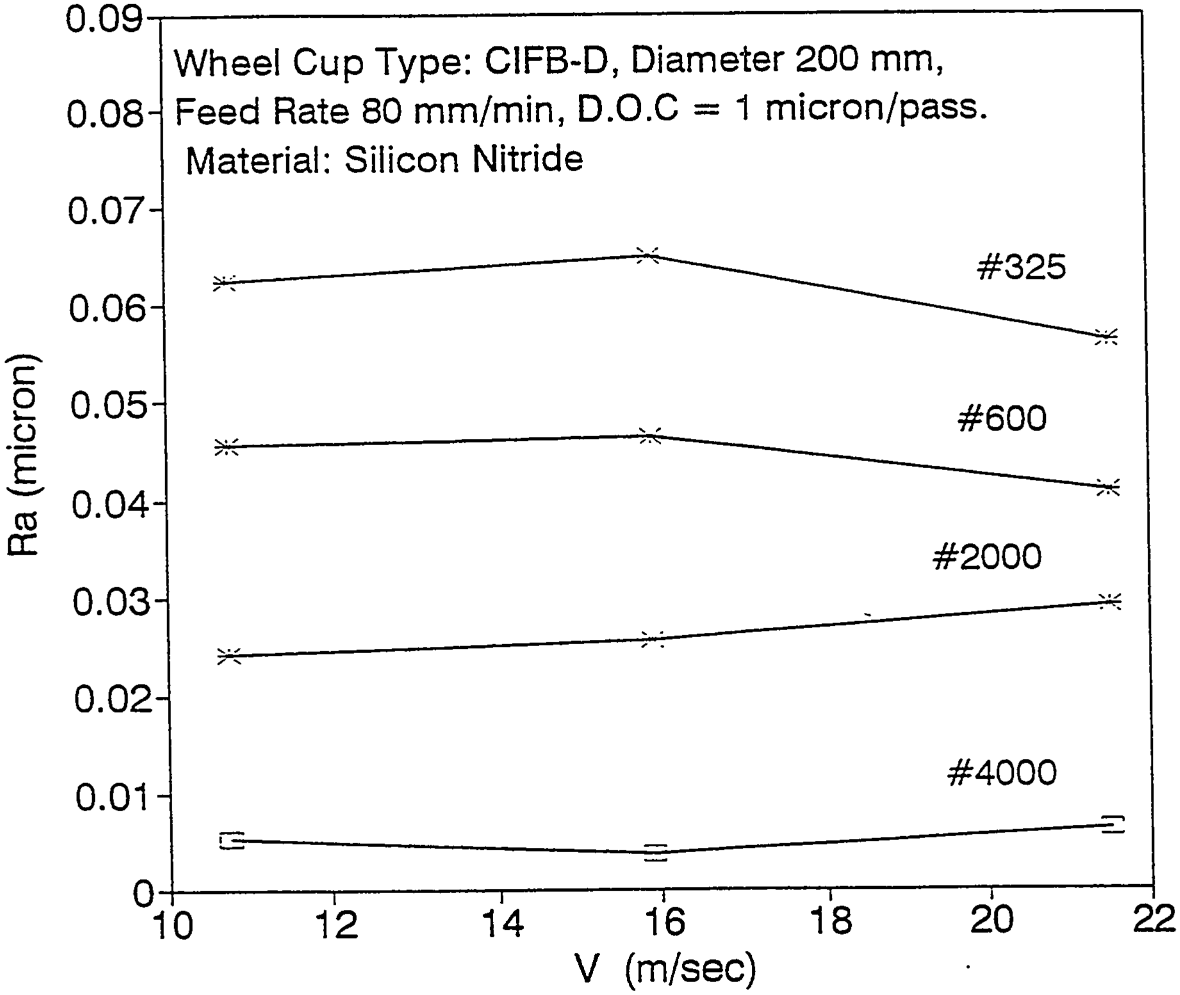


Figure 21. The Effect of Cutting Speed on Surface Finish

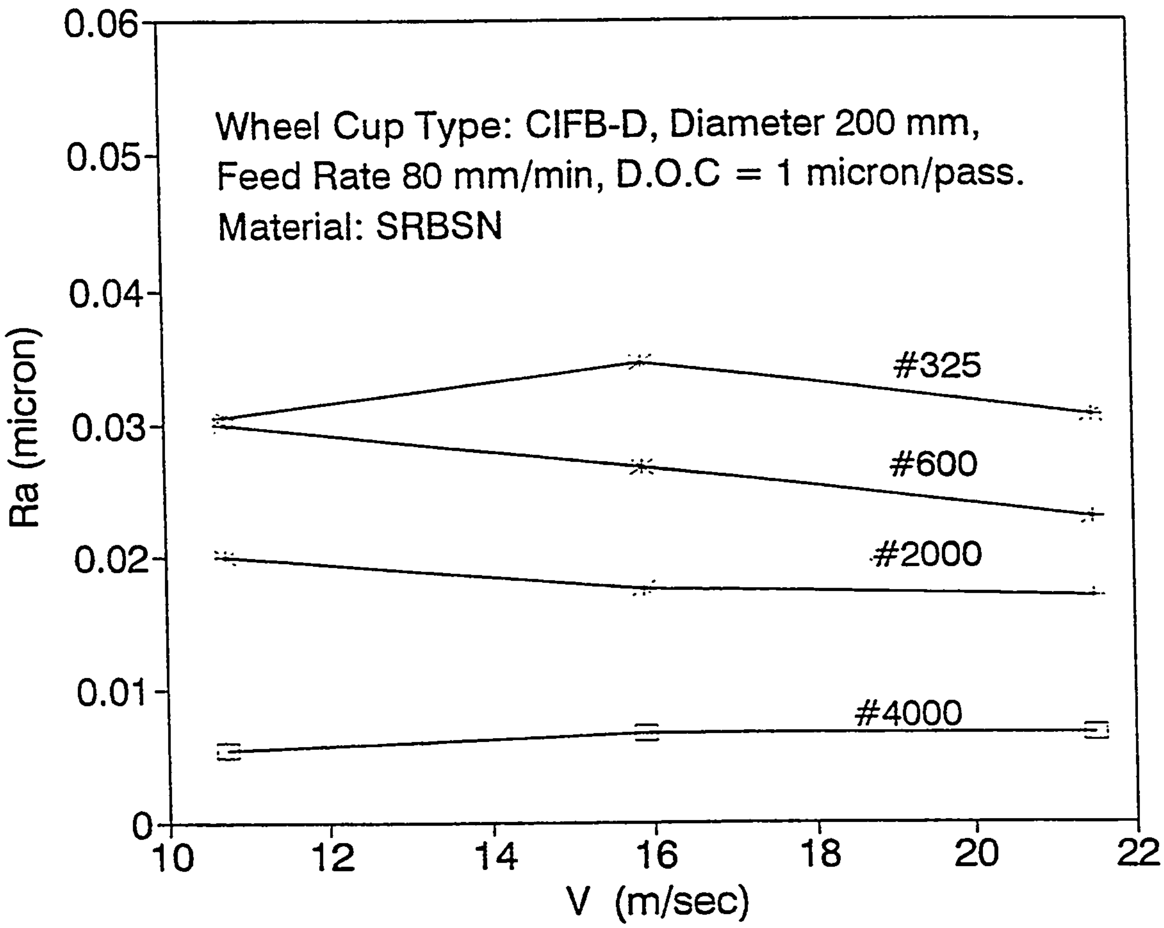


Figure 22. The Effect of Cutting Speed on Surface Finish

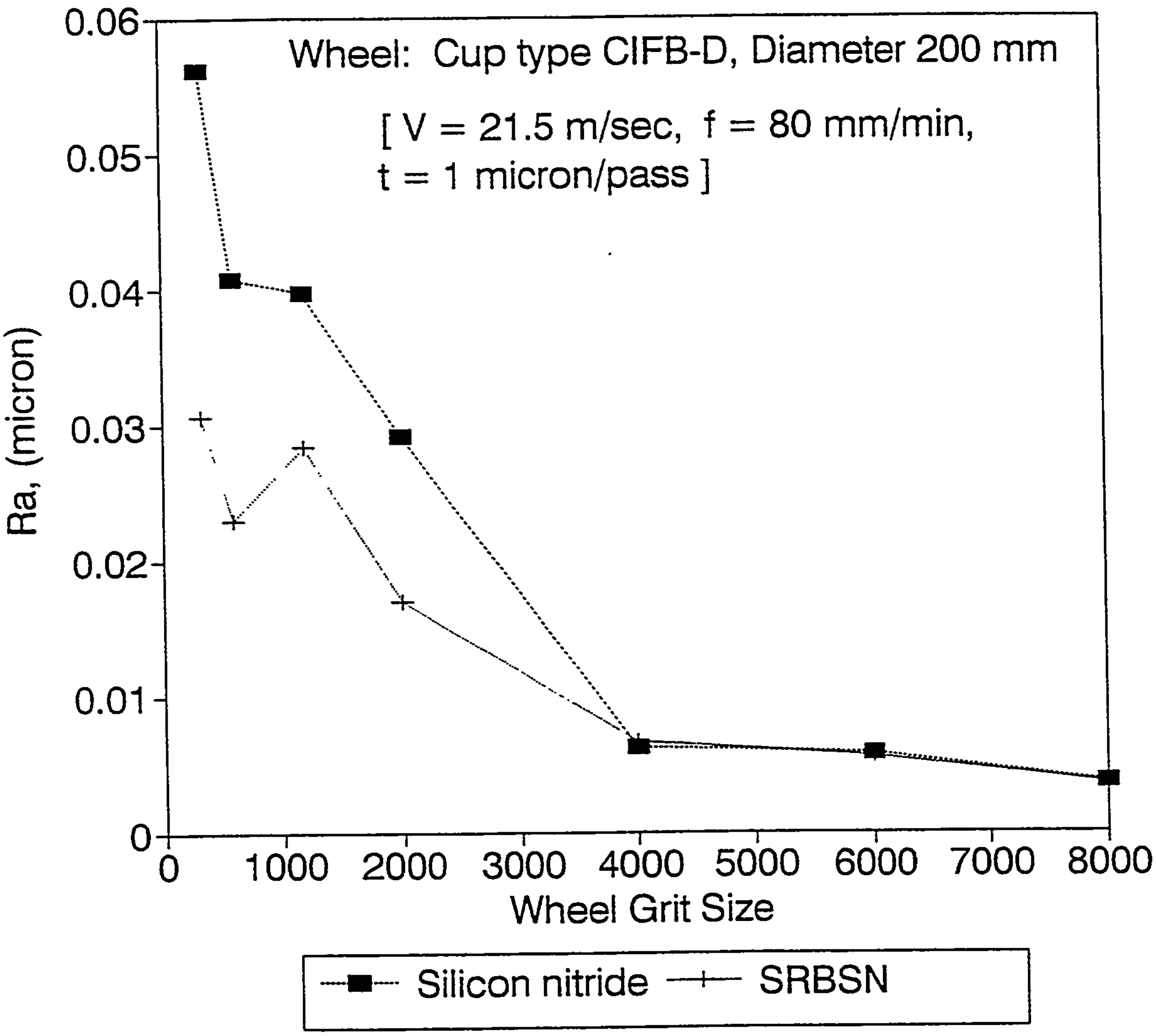


Figure 23. The Effect of Wheel Grit Size on Surface Finish

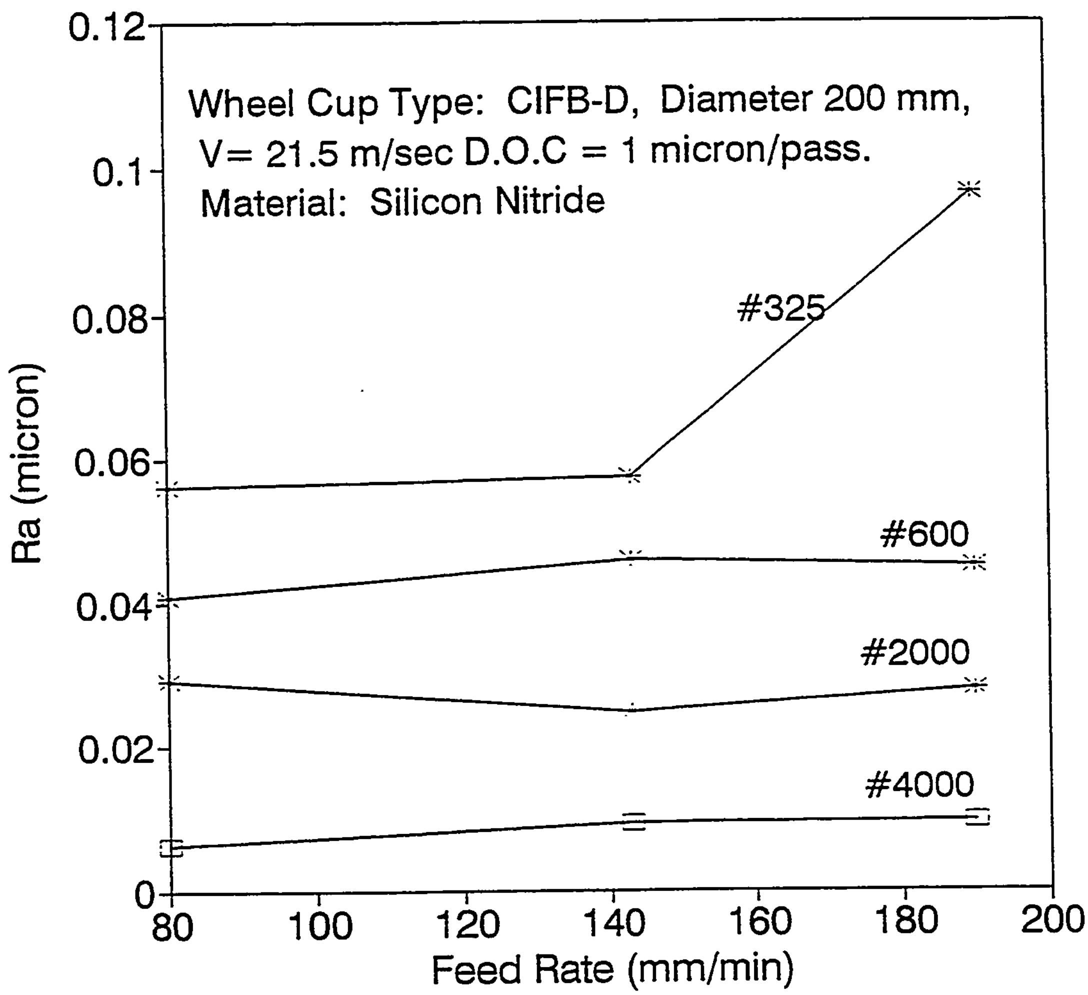


Figure 24. The Effect of Feed Rate on Surface Finish

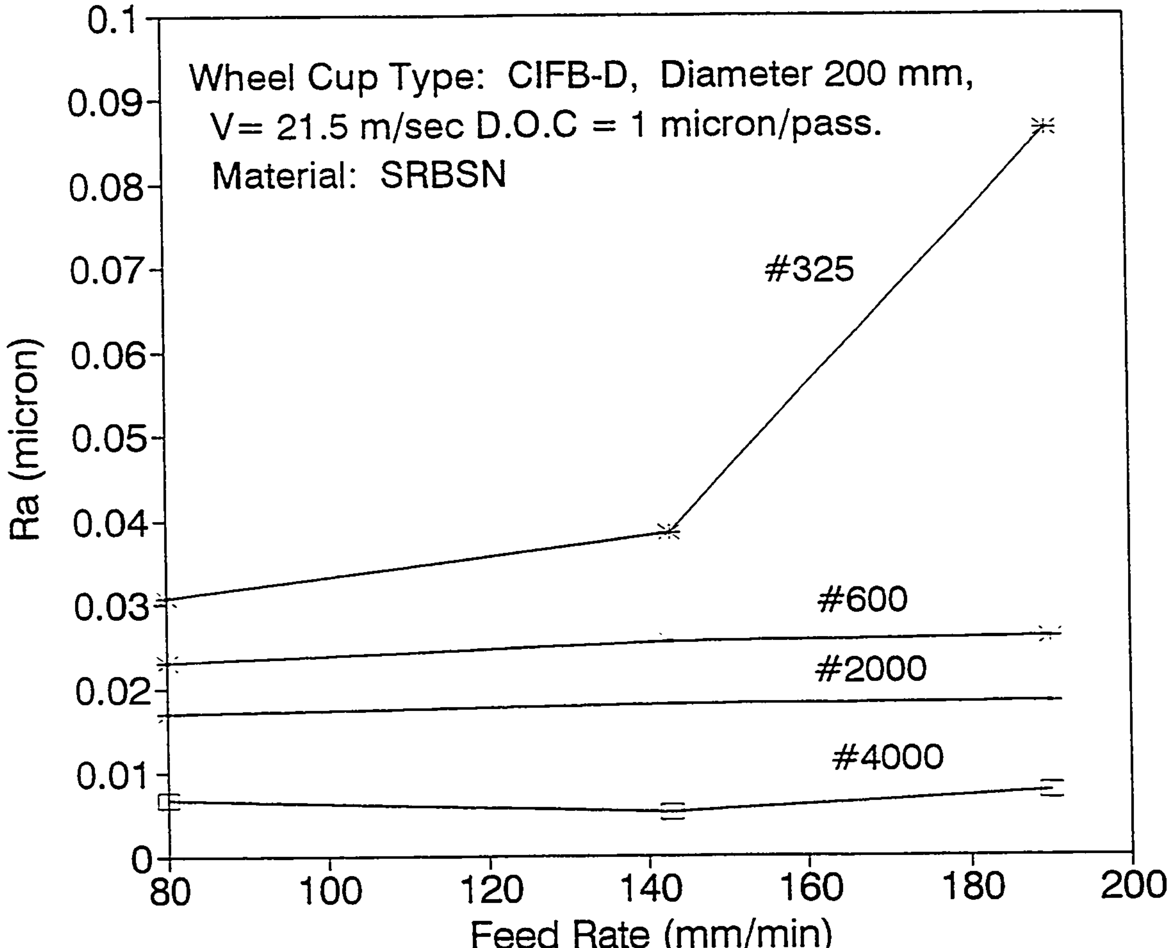


Figure 25. The Effect of Feed Rate on Surface Finish

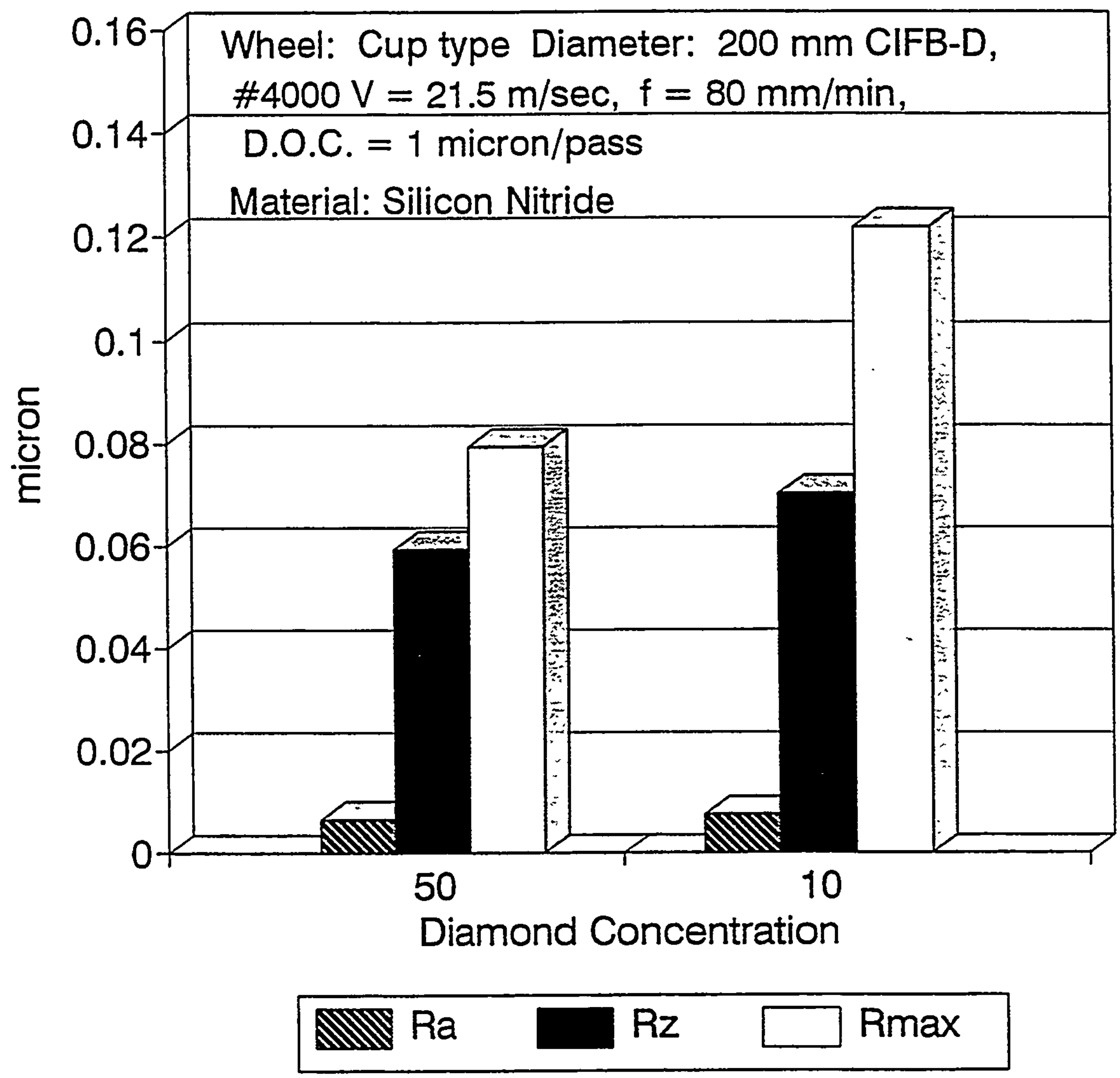


Figure 26. The Effect of Diamond Concentration on Surface Finish

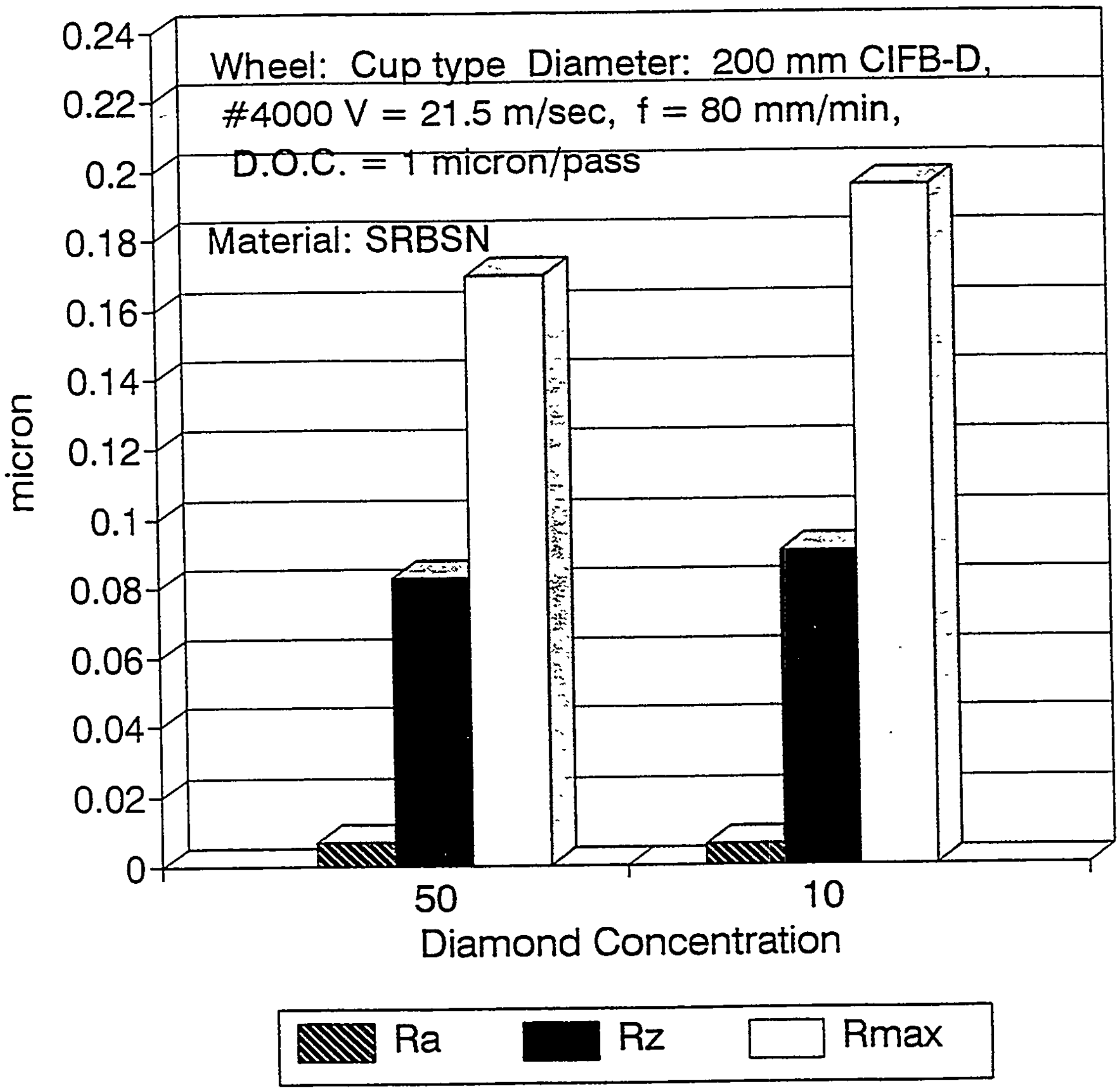


Figure 27. The Effect of Diamond Concentration on Surface Finish

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