ELECTRICAL DISCHARGED MACHINING USING ELECTRODES OF ZrB_2 INFILTRATED WITH COPPER

Eugene T. Kim
University Undergraduate Fellow, 1995-1996
Texas A&M University
Department of Mechanical Engineering

APPROVED
Fellows Advisor W L Bradley
Honors Director Susanna Finnell

ELECTRICAL DISCHARGED MACHINING USING ELECTRODES OF ZrB_2 INFILTRATED WITH COPPER. Eugene T. Kim (Walter L. Bradley), Mechanical Engineering, Texas A&M University.

The objective of this research is to evaluate the performance of ZrB_2 infiltrated with copper as an alternative material system to the standard electrodes of copper and graphite used in electrical discharged machining (EDM). ZrB_2 powder particles are coated with a polymer binder and then cold pressed in a square die. The cold pressed electrodes are then annealed in a furnace to burn off the polymer binder coating and to sinter the ZrB_2 particles together. The 50-60% dense part is then infiltrated with a doped copper using capillary action, producing a 100% dense electrode. The electrode is then milled to produce the final 3/8" x 3/8" cross sectional square electrode. The anode, ZrB_2/Cu is tested at a constant current and constant off-time with different on-times. The steel workpiece is the cathode. The results clearly show that ZrB_2/Cu displays a higher workpiece removal rate, lower tool removal rates, and a lower wear ratio. Further research on infiltrating ZrB_2 with pure copper and finding the on-time for maximum removal rates will define even more optimal performance characteristics. Therefore, one may conclude that the production of ZrB_2/Cu electrodes using selective laser sintering will produce superior electrodes relative to the industry standard electrodes of graphite and copper.

INTRODUCTION

From antiquity to the present, the competition between different companies instigates the need for advances in technology. New technology allows a company to have an advantage over their competitors by bringing better products to market more quickly. In the past, printers and plotters were developed to output two dimensional drawings and schematics, but within the past ten years the emergence of rapid prototyping has changed the design process. Computer software allows the designer to generate a 3-D model from a CAD system and rapid prototyping allow such solid models to be produced directly, including complex shapes that could not be manufactured by standard machining processes. Quick turn-around times can be established from the design stage to parts, thereby allowing the companies to be more competitive. In addition, another emerging technology utilized throughout the tool and die industry is electric discharge machining. This accounts for 2% of worldwide machining, with a substantially greater concentration in the tool making industry[1]. Electric discharge machining utilizes electro-thermal energy to remove material. The industry standard for electrodes, copper or graphite, exhibit high wear ratios due to the high temperatures of spark erosion involved in the EDM process. The ceramic composite ZrB_2 infiltrated with copper, exhibiting high thermal and electrical conductivity and high melting point, is proposed as an alternative material for EDM electrodes. By taking advantage of rapid prototyping technology to create ZrB_2/Cu electrodes that cannot be machined, the superior wear ratios of the new electrodes relative to copper and graphite can be exploited.

LITERATURE REVIEW

RAPID PROTOTYPING

Rapid prototyping or solid freeform fabrication, SFF, which has been developed in the last ten years, is a tool-less technology that allows the designer to create solid objects. Different methods of rapid prototyping include the laser cutting of adhesive powder layers using an adhesive deposited in an ink-jet type device[2], deposition of material by extrusion through a nozzle[3], or the sintering of powder layers using a CO_2 laser[4].

Rapid prototyping by the sintering of powder layers using a CO_2 laser is done at Texas A&M by a selective laser sintering, SLS, machine called the Sinterstation 2000™ created by the DTM Corporation of Austin, Texas. The SLS machine consists of hardware and software components. The hardware components include the process chamber and powder engine, the controls cabinet, and the atmospheric control unit. The process chamber incorporates the laser, pre-heater, and the powder handling equipment. The controls cabinet interprets the CAD drawing and controls and monitors the SLS process. The atmospheric control unit regulates the temperature and amount of N_2 flowing through the air in the chamber. It also filters the air that flows through the process chamber. The software components utilize the UNIX operating system and other DTM proprietary applications.

Three dimensional models designed using a CAD system are transferred in a .STL format to the selective laser sintering machine. The controls cabinet modifies the .STL file to correct for shrinkage that occurs when the part is built. The drawing is then geometrically modified to horizontally divide the .STL file into thin layers. These layers can be adjusted in thickness, but are typically 0.005". The thin layers represent the sintering planes to be traced by the CO_2 laser. The two dimensional thin layers are then transmitted to the optics system that directs the CO_2 laser. The temperature of the powder is kept just below the fusion temperature of the powder. When the cross section of the layer is traced out by a CO_2 laser, the powder particles sinter together by the increase in temperature of the laser. The part is then lowered in the part cylinder by 0.005", and new layers are added to form the solid mass. The SLS machine builds the part one layer at a time by creating the bottom layer first, and then adding layers until the part is finished. The final solid mass product composed of the thousands of thin layers is then complete.

Presently, rapid prototyping can only create solid models out of polymers or thin layers of paper. Early attempts to SLS single phase metals were unsuccessful[4]. However, polymer coated metals or ceramic powders can be utilized in a SLS machine like polymer particles. A polymer coating of equal to or greater than 3% of the particle diameter will react similarly to pure polymer particles in SLS processing[5]. The metal or ceramic powders are coated with a thin layer of polymer to facilitate the sintering done by the SLS machine. The SLS machine sinters the polymer coated powders together like conventional polymer powders. After rapid prototyping of the polymer coated powders, the solid mass is then subjected to a heat treatment that causes the polymer coating to be burned out and the metal or intermetallic powder to be sintered together.

ELECTRICAL DISCHARGE MACHINING

Electrical discharge machining removes material by employing electrical discharges between the workpiece and tool electrodes in a dielectric fluid. The three basic components of EDM are the workpiece electrode, the tool electrode, and the dielectric fluid. After an electric discharge imparts material breakdown, the dielectric fluid flows between the workpiece and tool electrodes. This process is known as flushing which provides several purposes such as introducing "fresh" dielectric to the cut, removing the “chips” and debris away from the spark gap, and cooling the electrode and workpiece[6]. Proper flushing is pertinent in order to minimize off-time, thereby increasing efficiency[6].

Electrical discharge machining is used to manufacture parts for the tool and die industry with many positive attributes over conventional machining. The advantage to allowing the tool parts to be heat treated to its full hardness before the cavity is produced eliminates the need for heat treatment after milling. Thus, there will be no distortion in the final part due to the heat treatment. Also, the EDM process imparts no work-hardening or mechanical stresses since there is no contact between the workpiece and the tool. Any material with less than 1 $\Omega\cdot$m of electrical resistivity, regardless of hardness, can be machined using EDM[5]. EDM offers higher dimensional accuracy and ease of production of complex shapes in the tool cavity compared to conventional machining.

The EDM process works in the following manner. A voltage is initially applied across the electrodes causing an increase in electric field. At this initial temporary state, the current does not flow since the electrodes are insulated by the dielectric. At a certain voltage level, the electrons break loose from the workpiece and collide with the dielectric particles causing ionization, thus producing positive ions and electrons. The dielectric strength of the liquid in the gap is exceeded and breakdown occurs initiating a plasma channel that develops and expands during the following spark on-time[7].

EDM machining is not viable for many market areas due to the cost in the replacement of the electrodes that accounts for 50 - 80% of the total cost of fabricating a die[8]. Presently, copper and graphite electrodes require multiple electrodes to produce the finished part due to the high wear ratio inherent with the material systems.

Therefore, the production of an electrode with a lower wear ratio would be highly beneficial in cutting the costs of the EDM industry.

Copper and graphite are the industry standard electrode in EDM due to their high electrical and thermal conductivity and ease of machining the desired final electrode shape. Materials that have the proper material properties for EDM but are too hard to machine are not feasible for electrode production using conventional CNC machining. However, superior material systems, which are not easily machined, may be produced by rapid prototyping to create the electrodes. Therefore, the use of rapid prototyping opens the door to previously unconsidered systems.

The degradation of the electrode by the plasma channel depends upon the material properties of the system. Three mechanisms cause the degradation of the electrodes: melting, evaporation, and thermal spalling[9]. Melting and evaporation commonly occurs when the plasma arc melts both electrodes in metal and ceramic systems. During the initiation of the off-time, the violent collapse of the plasma channel and the vapor bubble causes superheated, molten liquid on the surface of both electrodes to explode into the gap, where the dielectric resolidifies the molten material[9]. Evaporation also adds to the degradation of the electrode at high temperatures when the plasma arc vaporizes the material. Thermal spalling is a mechanical failure of the material without melting due to the created internal stresses that overcome the bond strength. This phenomenon occurs during sudden changes in temperature causing the expansion and contraction of the material.

CANDIDATE INTERMETALLIC/METAL ELECTRODE SYSTEMS

Due to the phenomena of the degradation of EDM electrodes, a candidate intermetallic ceramic with a metal appears to have superior characteristics. The characteristics of the performance of EDM electrodes are based upon these criteria: the sink rate, the wear ratio, and the surface finish produced. Since each material system has its own mechanical properties, the testing of the electrodes must be done at the optimum conditions for each respective material system to produce comparable results. An intermetallic ceramic or cermet with a high melting point, high thermal and electrical conductivity, and low isotropic thermal expansion combined with a metal with a lower melting point and high electrical and thermal conductivity will produce the ideal electrode.

Zirconium diboride is a refractory compound originally developed by NASA for a high strength refractory coating for space ships subject to hostile laser bombardment as well as for protection upon re-entry into the earth's atmosphere. ZrB_2 has excellent material properties such as high wear and abrasion resistance, a high melting point, and extreme hardness. Due to the low thermal shock resistance and room temperature brittleness, ZrB_2 has found limited uses in high temperature environments[10]. With the addition of copper to the ZrB_2 matrix, the performance characteristics are greatly improved. The electrical conductivity is near copper, and the thermal shock resistance of the matrix is also improved. ZrB_2/Cu is reported to have low wear ratios and high resistance to spark erosion making it an ideal candidate for EDM electrodes. However, it has not been used for EDM electrodes because of the difficulty in machining ZrB_2/Cu since it is an extremely hard and wear resistant material. However, ZrB_2/Cu can now be easily produced in any shape needed using rapid prototyping and subsequent annealing steps.

METHOD OF EXPERIMENTATION

The ZrB_2 and copper powder particles were obtained from CERAC incorporated. The specifications for the raw materials can be viewed in Table 1.

	Purity (%)	**Grain Size (μm)**	**Melting Point (°C)**	**Density (g cm^{-3})**
ZrB_2	**99.5**	**1-10**	**3027**	**6.09**
Copper	**99.9**	**<46**	**1083**	**8.93**

Table 1: Specification for Raw Materials

COMPOSITE PREPARATION

The ZrB_2 powder was then sent to ART to be coated with a thin layer of polymer binder by the following process. The polymer binder obtained from Petrolyte was the Ceramer 1608. This was mixed with acetone to achieve a 25% by weight of Ceramer binder in acetone. Three percent by weight of the Ceramer binder from the solution was then added to the ZrB_2 powder. This mixture was mixed using a stir bar while adding a small amount of acetone. After the acetone evaporated from the ZrB_2 mixture, the material was placed in a rock tumbler to break up the dried powder. The dried powder was then sieved through a 60 micron sieve to break the agglomerates.

ELECTRODE FORMATION

The ZrB_2 coated with the polymer binder particles was then isostatically cold pressed at 10,000 psi in a square 1" x 1" die to form a square electrode with a finished height of approximately 1.4". Lecithin mold release was used on the die to facilitate in the removal of the rectangular electrode.

The rectangular electrode was then placed in the Thermal Technology's Inc. "Group 1000" graphite furnace. The furnace was then raised to 600°C for ½ an hour to burn out the polymer binder, and then subsequently heated to 1600°C for one electrode and 1700°C for the other electrode to sinter the ZrB_2 particles together. Argon was used as an inert operating gas to avoid the formation of nitride and to flush away the impurities in the furnace. This process resulted in approximately a 50% dense part. Next, doped copper powder was added to a crucible and fired at 1200°C to infiltrate the copper via capillary action. In order to enable the capillary action to take place, the copper powder was doped with an additive to increase the wettability with ZrB_2. The final part resulted in a 100% dense part. Each part was then cut into and milled into two 3/8" x 3/8" electrodes. Figure 1 shows the procedure for obtaining the finished electrode used in the preparation of the ZrB_2/Cu electrode.

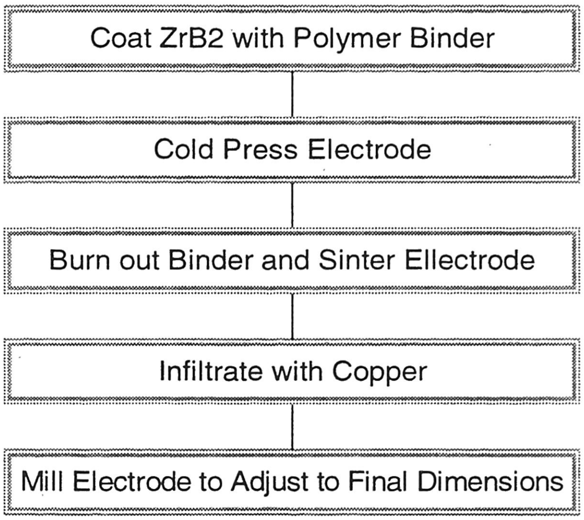
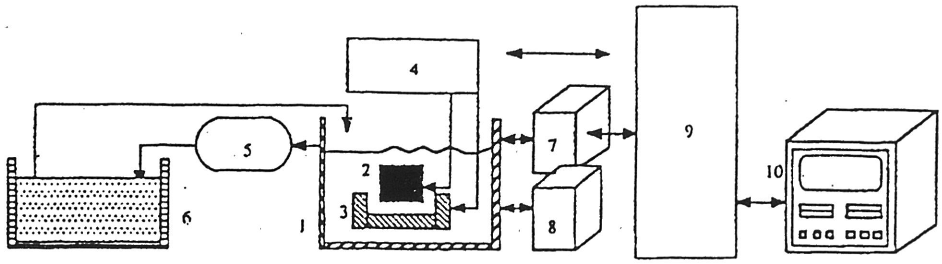


Figure 1: Flow chart for production of ZrB_2/Cu electrodes.

ELECTRODE TESTING

An AGIETRON 1U die-sinking machine was used to compare the performance of the ZrB_2/Cu electrodes relative to the copper and graphite at different on-times. The schematic of the machine may be seen in Figure 2.



1. Working Tank
2. Tool
3. Workpiece
4. Generator
5. Filter
6. Dielectric tank
7. Flushing unit
8. Level Controller
9. CNC
10. Control Console

Figure 2: Schematic diagram of the AGIETRON 1U die-sinking machine.

The materials were tested under a constant current of 24.8A, off-time of 100 μs and varying on-times ranging from 560 - 3.2 μs. The dielectric fluid used was BP cutting oil and flushing was achieved from the vertical movement of the electrode. Higher flushing efficiencies could be achieved by pressure flushing using a circulation pump. The material removal rate was calculated as the volumetric removal rate divided by the total time as shown in Equation 1.

$$\text{Removal Rate} = \frac{Area}{9 \cdot Time} \sum_{i=1}^{3} \sum_{j=1}^{3} (Zf_{ij} - Zi_{ij})$$

Area = cross sectional area of workpiece
Time = total time = on-time + off-time
Z_f = Final height of electrode
Z_i = Initial height of electrode

Equation 1: The removal rate equation for the tool and workpiece electrodes.

The removal height was calculated as the average of the difference in the height of the electrode as shown in Figure 1. All data may be viewed in Appendix B, and sample calculations may be seen in Appendix A.

RESULTS

On-time	ZrB2/Cu 1600C				ZrB2/Cu 1700C			
(μs)	WRR (m^3/hr)	TRR (m^3/hr)	Wear Ratio	Surface Roughness	WRR (m^3/hr)	TRR (m^3/hr)	Wear Ratio	Surface Roughness
560	5.71E-02	0.00E+00	0.000	>45	5.44E-02	0.00E+00	0.000	45
180	6.88E-02	1.42E-04	0.002	45	6.25E-02	0.00E+00	0.000	42-45
75	4.46E-02	0.00E+00	0.000	39-42	4.19E-02	5.24E-04	0.012	39
56	3.23E-02	9.87E-04	0.031	39	3.68E-02	9.56E-04	0.026	39
32	2.34E-02	5.49E-04	0.023	36	2.27E-02	6.45E-04	0.028	36
13	9.73E-03	2.46E-04	0.025		1.01E-02	2.19E-04	0.022	33
7.5	5.12E-03	2.33E-04	0.046	33	5.11E-03	2.52E-04	0.049	33
3.2	1.44E-03	1.75E-04	0.121	27	1.50E-03	1.70E-04	0.113	27

On-time	Copper			Graphite		
(μs)	WRR (m^3/hr)	TRR (m^3/hr)	Wear Ratio	WRR (m^3/hr)	TRR (m^3/hr)	Wear Ratio
560	5.82E-02	0.00E+00	0.000	4.54E-02	0.00E+00	0.000
180	5.09E-02	0.00E+00	0.000	3.91E-02	0.00E+00	0.000
75				3.48E-02	0.00E+00	0.000
56	2.19E-02	2.00E-03	0.091	3.14E-02	0.00E+00	0.000
32	1.41E-02	6.50E-03	0.461	2.31E-02	4.70E-04	0.020
13	5.60E-03	4.50E-03	0.804	9.20E-03	1.20E-03	0.130
7.5	2.90E-03	2.40E-03	0.828	4.70E-03	1.10E-03	0.234
3.2	9.00E-04	8.00E-04	0.889	4.40E-04	6.30E-04	1.430

Current = 24.8A
Off-time = 100μs

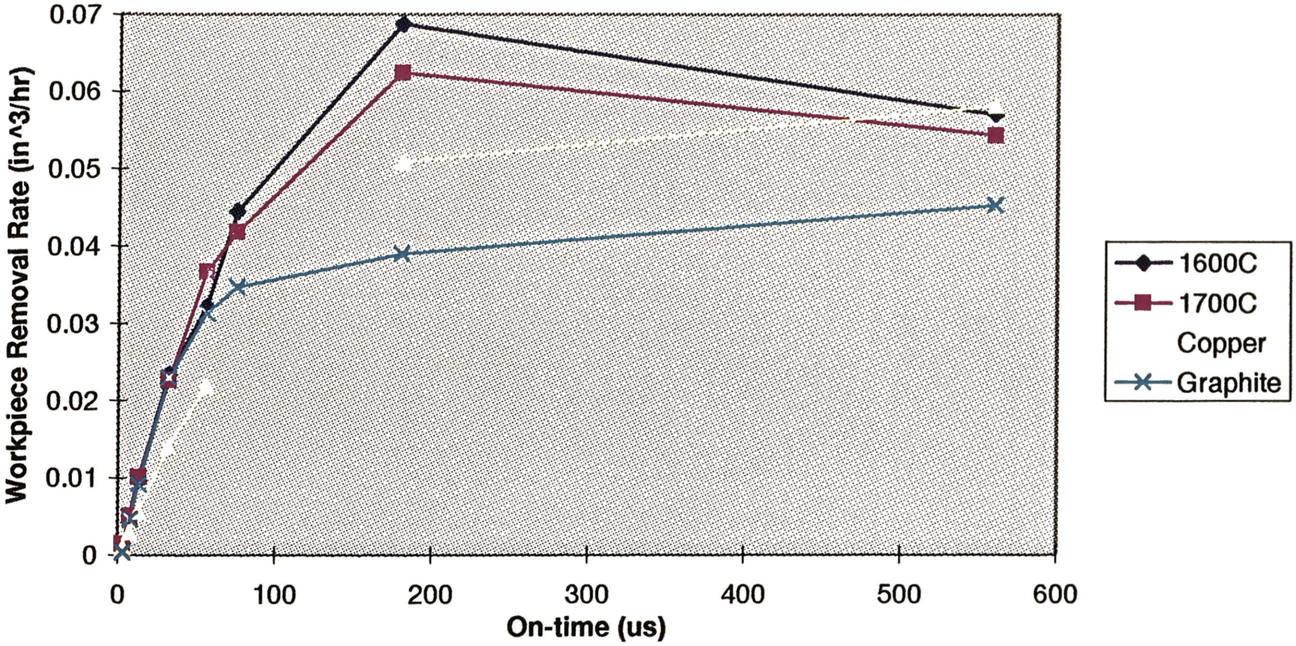
Table 2: Removal Rates and Wear Ratios of Copper, Graphite, and ZrB_2/Cu.

Comparison Ratios

On-time	Copper/1600			Copper/1700		
(μs)	WRR	TRR	Wear Ratio	WRR	TRR	Wear Ratio
560	1.02	0.00	0.00	1.07	0.00	0.00
180	0.74	0.00	0.00	0.81	0.00	0.00
75	0.00	0.00	0.00	0.00	0.00	0.00
56	0.68	2.03	2.98	0.60	2.09	3.52
32	0.60	11.84	19.69	0.62	10.08	16.23
13	0.58	18.33	31.83	0.55	20.51	37.12
7.5	0.57	10.28	18.17	0.57	9.52	16.79
3.2	0.62	4.58	7.34	0.60	4.70	7.84

On-time	Graphite/1600			Graphite/1700		
(μs)	WRR	TRR	Wear Ratio	WRR	TRR	Wear Ratio
560	0.80	0.00	0.00	0.83	0.00	0.00
180	0.57	0.00	0.00	0.63	0.00	0.00
75	0.78	0.00	0.00	0.83	0.00	0.00
56	0.97	0.00	0.00	0.85	0.00	0.00
32	0.99	0.86	0.87	1.02	0.73	0.72
13	0.95	4.89	5.17	0.91	5.47	6.03
7.5	0.92	4.71	5.14	0.92	4.36	4.75
3.2	0.31	3.61	11.80	0.29	3.70	12.61

Table 3: Comparison Ratios of Copper and Graphite to ZrB_2/Cu.



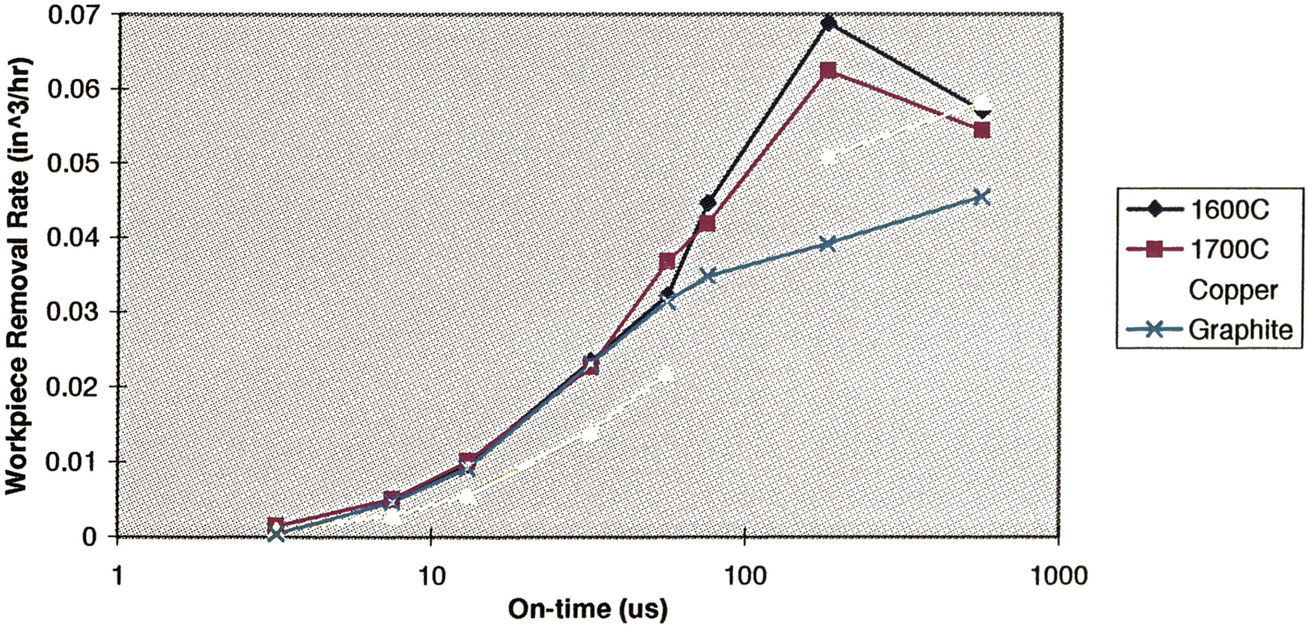


Figure 4: Workpiece removal rate vs. on-time for copper, graphite, and ZrB_2/Cu sintered at 1600°C and 1700°C on regular and semi-log graphs.

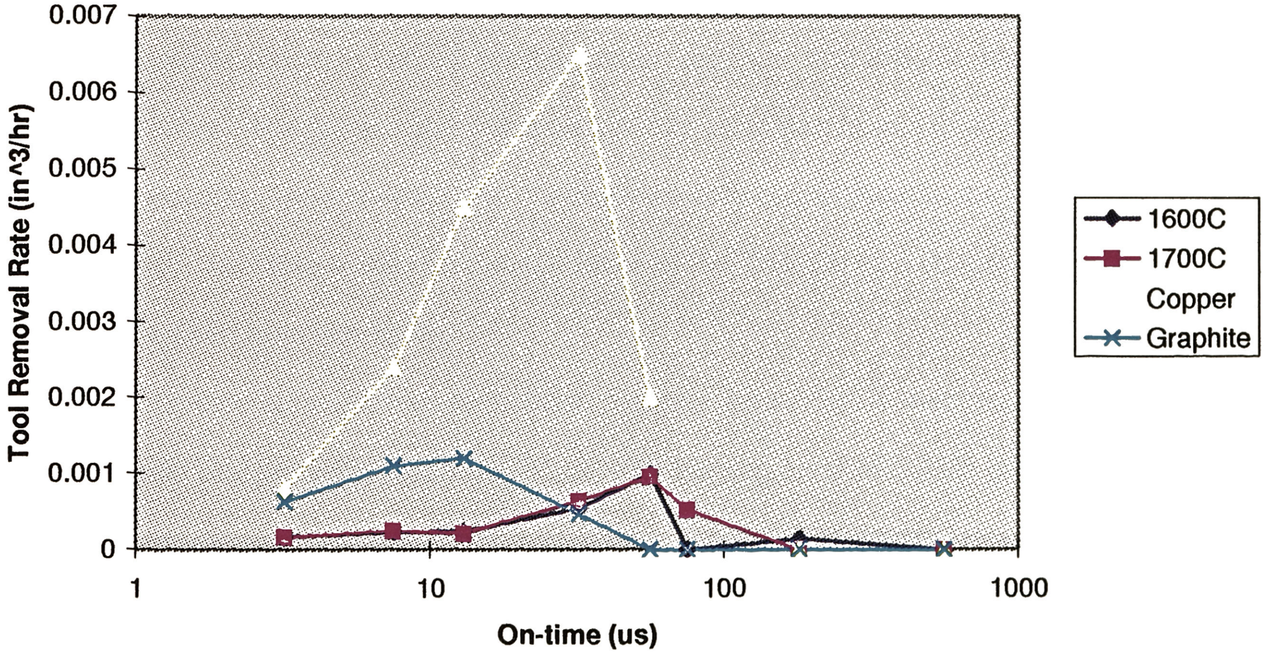


Figure 5: Tool removal rate vs. on-time for copper, graphite and ZrB_2/Cu sintered at 1600°C and 1700°C.

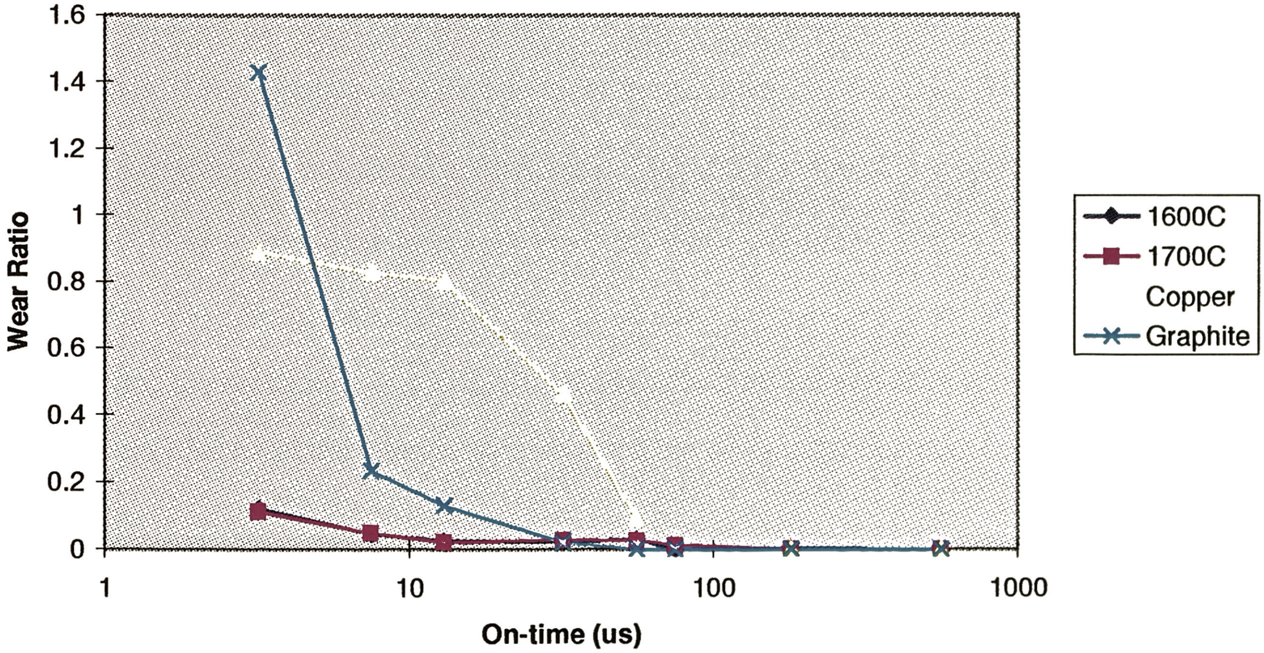


Figure 6: Wear Ratio vs. on-time for copper, graphite, and ZrB_2/Cu sintered at 1600°C and 1700°C.

DATA ANALYSIS

The workpiece removal rates, tool removal rates, wear ratios, and estimated surface roughness is shown in Table 2 for the copper, graphite, and ZrB_2/Cu electrodes at different on-times. The surface roughness is visually estimated from a Charmilles Technologies indicator. As expected, the on-time is directly proportional to the quality of the surface finish. In Table 3, the comparison ratios of the ZrB_2/Cu with copper and graphite can be seen for all on-times.

The workpiece removal rates for copper, graphite, and ZrB_2/Cu electrodes are plotted on regular and semi-log graphs in Figure 4 for varying on-times. This graph clearly shows the superior workpiece removal rates of the ZrB_2/Cu material relative to copper and graphite. At 180µs, the workpiece removal rates of the ZrB_2/Cu electrode is 1.7 times better than graphite and 1.3 times better than copper. The data shows that ZrB_2/Cu has a peak workpiece removal rate of 5.71E-2 in^3/hr. However, looking at the trend of the data, the optimum workpiece removal rate is expected to occur between 180 and 560µs. Unfortunately no data was taken in this range of on-times. The decrease in workpiece removal rate at 560µs is probably due to the binary system involved here. The long on-time increases the local heating, thereby causing thermal spalling of the ZrB_2. At a shorter on-time, the copper can carry away the excess heat, thus preserving the electrode. The ZrB_2/Cu results should be conservative estimates of the actual performance of the material system since the on-time for optimum conditions was not found.

The tool removal rates for copper, graphite, and ZrB_2/Cu electrodes are plotted for varying on-times. This graph also shows the superior performance of the ZrB_2/Cu material system. At low on-times where surface finishing is performed, the highest degradation of the tool occurs. The plasma spark is concentrated at a small point at low on-times. However, at longer on-times the plasma spark spreads over a larger area, resulting in a lower energy density, thus reducing the tool wear. Also, the material floating around in the dielectric can resolidify onto the tool, causing an increase in height of the tool. This phenomenon is observed in the data at higher on-times. At an on-time of 3.2μs, the ZrB_2/Cu is 4.7 times better than copper and 3.7 times better than graphite. At these an on time of 7.5μs, ZrB_2/Cu is 10 times better than copper and 4.7 times better than graphite. At an on time of 13μs, the ZrB_2/Cu is 20 times better than copper and 6 times better than graphite. Thus at low on-times where surface finishing is performed, ZrB_2/Cu is a superior electrode.

The wear ratios of copper, graphite, and ZrB_2/Cu for different on-times are plotted in Figure 6. Once again, this clearly demonstrates the superior performance of the ZrB_2/Cu electrode. According to the wear ratio at an on-time of 3.2μs, ZrB_2/Cu is 7.8 times better than copper and 12.6 times better than graphite. At an on-time of 13 μs, ZrB_2/Cu is 37 times better than copper and 6 times better than graphite.

CONCLUDING REMARKS

The performance of ZrB_2/Cu relative to electrodes of copper and graphite according to workpiece removal rate, tool removal rate, and wear ratio is finished. According to these attributes, ZrB_2/Cu is superior to copper and graphite for surface finishing and high speed cutting. Although this research indicates that the ZrB_2/Cu material system is superior to copper and graphite, the evaluation is considered to be conservative. Performance gains are expected with infiltration of pure copper in ZrB_2, and the finding of the on-time for peak performance of workpiece removal rates. ZrB_2/Cu as an alternative material to the industry standard copper and graphite for electrical discharge machining will considerably cut the cost of fabricating a part by EDM.

ACKNOWLEDGMENTS

This material is based upon work supported under National Science Foundation grant # DMR-94203896. Special thanks to Dr. Bradley for his direction, encouragement, compassion, patience and advice, to Brent Stucker for his concern, teaching, and constant help throughout the project, to Jiab Norasetthekul for training and assistance with the EDM machine and long days testing the electrodes, to Gwo Ping for spending late nights grinding the ZrB_2/Cu; to my mom for her love, concern, and sacrificing heart, to Bethany Trulock for being a faithful friend with an abundance of encouragement, and to Christ Jesus who gave me life.

BIBLIOGRAPHY

1. Eubank, P.T. and B. Bozkrut, "Recent Developments in Understanding the Fundamentals of Spark Erosion for Composite Materials in Machining of Composite Materials," T.S. Srivatsan, D.M. Bowden, eds., Am. Soc. Materials, Materials Park, OH, 159-166, 1992.
2. Michaels, S., E.M. Sachs, and J.M. Cima, "Metal Parts Generation by Three Dimensional Printing," The Fourth International Conference on Rapid Prototyping, The University of Dayton, OH, 25-31, 1993.
3. Lightman, A.J., "Tool-Less Rapid Prototyping Technologies – An Overview," SAE Technical Paper Series, Society of Automotive Engineers, Inc., Salem, MA, 91115, 1991.
4. "DTM Sinterstation 2000^{TM}," technical brochure for DTM, Inc. (DTM, Inc., 1611 Headway Circle, Building 2, Austin, TX 78754), 1993.
5. Bourell D. L., Marcus H. L., Barlow J. W., Beamer J. J., "Selective Laser Sintering of Metals and Ceramics," *The International Journal of Powder Metallurgy,* Vol. 28, No. 4, 1992.
6. Electrical Discharge Machining Conference Proceedings 1995, Rosemont Expo Center, Chicago, Il., 1995.
7. Eubank, P.T., M.R. Patel, M.A. Barrufet and B. Bozkurt, "Theoretical Models of the EDM Process. Part III: The Variable Mass, Cylindrical Plasma Model," J. Appl. Phys.73(11), 7901, 1993.
8. Walter L. Bradley and Brent Stucker, "Producing EDM Electrodes With Rapid Prototyping Techniques," Electrical Discharge Machining Conference Proceedings 1995, Rosemont Expo Center, Chicago, Il., 1995.
9. Petrofes N. F.,, Gadall A. M., "Electrical Discharge Machining of Advanced Ceramics," *Ceramic Bullitin,* Vol. 67, No. 6, 1988.
10. Cheng, Y. M., "Synthesis and Electrical Discharge Machining of Advanced Ceramics Containing Zirconium Diboride," Texas A&M University dissertation, May 1994.

APPENDIX A

SAMPLE CALCULATIONS

ZrB_2/Cu - Steel Test 1

On-time	7.5μs
Off-time	100μs
Current	24.8A

Time = 3:05.48 = 3 + 5/60 + 48/3600 = 3.097 hours

Area of electrode = $(3/8)^2$ in^2 = 0.140625 in^2

Depth of tool = $(Zf_{ij} - Zi_{ij})$ = [(-0.080 - 0.024) + (-0.104 - 0.017) + (-0.109 - 0.000) +
(-0.146 + 0.019) + (-0.245 + 0.036) + (-0.175 + 0.049) +
(-0.233 + 0.100) + (-0.252 + 0.115) + (-0.237 + 0.128)]

= -0.131 in.

Depth of Workpiece = 2.997 - 0.131 = 2.866 in.

$$\mathrm{Re}moval\ Rate = \frac{Area}{9 \cdot Time} \sum_{i=1}^{3} \sum_{j=1}^{3} (Zf_{ij} - Zi_{ij})$$

$$Workpiece\ \mathrm{Re}moval\ Rate = \frac{0.140625\ in^2}{3.097\ hr} * 2.866\ mm * \frac{1\ cm}{10\ mm} * \frac{1\ in}{2.54\ cm} = 5.12E-3\frac{in^3}{hr}$$

$$Tool\ \mathrm{Re}moval\ Rate = \frac{0.140625\ in^2}{3.097\ hr} * 0.131\ mm * \frac{1\ cm}{10\ mm} * \frac{1\ in}{2.54\ cm} = 2.33E-4\frac{in^3}{hr}$$

Wear Ratio = TRR/WRR = 2.33E-4/5.12E-3 = 0.046

APPENDIX B

RAW DATA

- ZrB_2/Cu 1600°C

- ZrB_2/Cu 1700°C

ZrB2/Cu -Steel

Test 1

(u = 6)

Temp	1600 C	
Program Code		9
Program Control		4

z = -3.000
Polarity +

Area of Electrode (3/8)^2 in^2

On-time	7.5 uS	**Code**	7
Off-time	100 uS	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*	
0.059	0.133	0.220	-2.781	-2.732
0.025	0.098	0.184	-2.765	
0.000	0.073	0.161	-2.756	

Reference 3

Initial z height			*Final Z height*		
0.024	-0.019	-0.100	-0.080	-0.146	-0.233
0.017	-0.036	-0.115	-0.104	-0.245	-0.252
0.000	-0.049	-0.128	-0.109	-0.175	-0.237

Time	Hour	3
	Min	5
	Sec	48
Total Time (hr) =		3.097

Depth of Tool = -0.131
Depth of Workpiece = (2.997-Depth Tool) = 2.866

Workpiece Removal Rate(WRR)=	5.12E-03 in^3/hr
Tool Removal Rate (TRR) =	2.33E-04 in^3/hr
Wear Ratio (TRR/WRR) =	0.046
Surface Finish	33

ZrB2/Cu -Steel **Test 2**

(u = 6)

Temp 1600 C

Program Code 9

Program Control 4

z = -3.000

Polarity +

Area of Electrode (3/8)^2 in^2

On-time	13 uS	**Code**	9
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
0.008	-0.002	-0.015	-2.911	-2.911	-2.930
-0.001	-0.010	-0.022	-2.881	-2.818	-2.890
0.000	0.013	-0.022	-2.865	-2.863	-2.910

Reference 3

Initial z height			*Final Z height*		
0.030	0.043	0.053	-0.023	-0.030	-0.013
0.015	0.027	0.037	-0.069	-0.105	-0.035
0.000	0.011	0.015	-0.072	-0.050	-0.034

Time	Hour	1
	Min	39
	Sec	31
Total Time (hr) =		1.659

Depth of Tool = -0.074 -2.881

Depth of Workpiece = (2.987-Depth Tool) = 2.913 2.987-2.881= 0.106

.106-.074 0.032

Workpiece Removal Rate(WRR)=	9.73E-03 in^3/hr
Tool Removal Rate (TRR) =	2.46E-04 in^3/hr
Wear Ratio (TRR/WRR) =	0.025
Surface Finish	~

ZrB2/Cu -Steel

Test 3

(u = 6)

Temp	1600 C	
Program Code		9
Program Control		4

z =	-3.000
Polarity	+

Area of Electrode (3/8)^2 in^2

On-time	3.2 us	**Code**	4
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
-0.004	-0.048	-0.113	-2.649	-2.682	-2.797
-0.003	-0.053	-0.104	-2.578	-2.565	-2.731
0.000	-0.045	-0.094	-2.621	-2.640	-2.764

Reference 3

Initial z height			*Final Z height*		
0.041	0.104	0.155	-0.253	-0.239	-0.143
0.020	0.069	0.126	-0.300	-0.351	-0.204
0.000	0.051	0.112	-0.289	-0.286	-0.172

Time	Hour	10
	Min	16
	Sec	33
Total Time (hr) =		10.276

Depth of Tool =	-0.324		-2.618	
Depth of Workpiece =	(2.994-DepthTool) =	2.673	2.994-2.618=	0.376
			.376-.324	0.052

Workpiece Removal Rate(WRR)=	1.44E-03	in^3/hr
Tool Removal Rate (TRR) =	1.75E-04	in^3/hr
Wear Ratio (TRR/WRR) =	0.121	
Surface Finish =	27	

ZrB2/Cu -Steel

Test 4

(u = 6)

Temp	1600 C
Program Code	9
Program Control	4

z = -3.000

Polarity +

Area of Electrode (3/8)^2 in^2

On-time	560 us	**Code**	22
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
-0.011	0.026	0.071	-3.123	-3.089	-3.094
-0.009	0.028	0.075	-3.082	-3.102	-3.088
0.000	0.037	0.086	-3.100	-3.072	-3.015

Reference 3

Initial z height			*Final Z height*		
0.040	0.006	-0.034	0.079	0.040	0.006
0.016	-0.022	-0.062	0.054	0.019	-0.007
0.000	-0.031	-0.073	0.049	-0.005	-0.033

Time	Hour	0
	Min	17
	Sec	48
Total Time (hr) =		0.297

Depth of Tool = 0.040 .=0

Depth of Workpiece = (3.058-DepthTool)= 3.058

Workpiece Removal Rate(WRR)=	5.71E-02 in^3/hr
Tool Removal Rate (TRR) =	0.00E+00 in^3/hr
Wear Ratio (TRR/WRR) =	0.000
Surface Finish	>45

ZrB2/Cu -Steel **Test 5**

(u = 6)

Temp	1600 C	
Program Code		9
Program Control		4

z = -3.000
Polarity +

Area of Electrode (3/8)^2 in^2

On-time	75 us	**Code**	15
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
0.003	-0.009	-0.008	-2.799	-2.896	-2.984
0.000	-0.004	-0.008	-2.805	-2.875	-3.023
0.000	0.005	-0.007	-2.743	-2.865	-2.966

Reference 3

Initial z height			*Final Z height*		
0.019	0.113	0.194	0.098	0.230	0.259
0.033	0.132	0.212	0.124	0.234	0.238
0.000	0.098	0.193	0.092	0.199	0.229

Time	Hour	0
	Min	22
	Sec	26
Total Time (hr) =		0.374

Depth of Tool = 0.079 .=0
Depth of Workpiece = (3.009-DepthTool)= 3.009

Workpiece Removal Rate(WRR)=	4.46E-02 in^3/hr
Tool Removal Rate (TRR) =	0.00E+00 in^3/hr
Wear Ratio (TRR/WRR) =	0.000
Surface Finish	39-42

ZrB2/Cu -Steel **Test 6**

(u = 6)

Temp	1600 C	
Program Code		9
Program Control		4

z = -3.000
Polarity +

Area of Electrode (3/8)^2 in^2

On-time	56 us	**Code**	14
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
-0.004	-0.013	-0.030	-2.849	-2.856	-2.791
0.000	-0.013	-0.035	-2.945	-2.864	-2.816
0.000	-0.004	-0.041	-2.852	-2.852	-2.796

Reference 3

Initial z height			*Final Z height*		
0.037	-0.010	-0.076	-0.059	-0.095	-0.176
0.047	-0.005	-0.062	-0.037	-0.065	-0.147
0.000	-0.021	-0.096	-0.100	-0.124	-0.186

Time	Hour	0
	Min	30
	Sec	2
Total Time (hr) =		0.501

Depth of Tool = -0.089
Depth of Workpiece = (3.005-DepthTool) 2.916

Workpiece Removal Rate(WRR)=	3.23E-02 in^3/hr
Tool Removal Rate (TRR) =	9.87E-04 in^3/hr
Wear Ratio (TRR/WRR) =	0.031
Surface Finish	39

ZrB2/Cu -Steel **Test 7**

(u = 6)

Temp	1600 C	
Program Code		9
Program Control		4

z = -3.000
Polarity +

Area of Electrode (3/8)^2 in^2

On-time	180 us	**Code**	18
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
0.032	-0.042	-0.097	-2.998	-2.999	-2.962
0.022	-0.050	-0.118	-3.048	-3.062	-2.980
0.000	-0.060	-0.136	-3.028	-3.048	-3.011

Reference 3

Initial z height			*Final Z height*		
-0.043	-0.077	-0.136	-0.051	-0.077	-0.136
-0.025	-0.048	-0.098	-0.039	-0.053	-0.106
0.000	-0.038	-0.097	-0.007	-0.049	-0.100

Time	Hour	0
	Min	14
	Sec	35
Total Time (hr) =		0.243

Depth of Tool = -0.006
Depth of Workpiece = (3.028-DepthTool)= 3.022

Workpiece Removal Rate(WRR)=	6.88E-02 in^3/hr
Tool Removal Rate (TRR) =	1.42E-04 in^3/hr
Wear Ratio (TRR/WRR) =	0.002
Surface Finish	45

ZrB2/Cu -Steel

Test 8

(u = 6)
Temp 1600 C
Program Code 9
Program Control 4

z = -3.000
Polarity +

Area of Electrode (3/8)^2 in^2

On-time	32 us	**Code**	12
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
0.036	-0.029	-0.094	-2.906	-2.943	-2.951
0.018	-0.048	-0.113	-2.913	-2.944	-2.969
0.000	-0.064	-0.133	-2.888	-2.927	-2.969

Reference 3

Initial z height			*Final Z height*		
0.027	0.063	0.082	-0.042	-0.005	0.009
0.022	0.075	0.087	-0.051	0.008	0.010
0.000	0.068	0.078	-0.034	-0.019	0.008

Time	Hour	0
	Min	41
	Sec	34
Total Time (hr) =		0.693

Depth of Tool = -0.069
Depth of Workpiece = (3.001-DepthTool)= 2.932

Workpiece Removal Rate(WRR)=	2.34E-02 in^3/hr
Tool Removal Rate (TRR) =	5.49E-04 in^3/hr
Wear Ratio (TRR/WRR) =	0.023
Surface Finish	39

ZrB2/Cu -Steel

Test 1

(u = 6)

Temp	1700 C	
Program Code		9
Program Control		4

z = -3.000
Polarity +

Area of Electrode (3/8)^2 in^2

On-time	13 us	**Code**	9
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
0.005	0.095	0.221	-2.822	-2.750	-2.684
0.007	0.094	0.213	-2.796	-2.691	-2.651
0.000	0.078	0.200	-2.766	-2.723	-2.653

Reference 3

Initial z height			*Final Z height*		
0.013	-0.034	-0.092	-0.033	-0.095	-0.146
0.012	-0.042	-0.108	-0.062	-0.160	-0.167
0.000	-0.067	-0.123	-0.050	-0.120	-0.181

Time	Hour	1
	Min	36
	Sec	24
Total Time (hr) =		1.607

Depth of Tool = -0.064
Depth of Workpiece = (3.005-DepthTool)= 2.941

Workpiece Removal Rate(WRR)=	1.01E-02 in^3/hr
Tool Removal Rate (TRR) =	2.19E-04 in^3/hr
Wear Ratio (TRR/WRR) =	0.022
Surface Finish	33

ZrB2/Cu -Steel

Test 2

(u = 6)

Temp	1700 C	
Program Code		9
Program Control		4

z = -3.000

Polarity +

Area of Electrode (3/8)^2 in^2

On-time	560 us	**Code**	22
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
0.032	-0.049	-0.149	-3.041	-3.146	-3.227
0.014	-0.066	-0.166	-3.015	-3.149	-3.220
0.000	-0.083	-0.181	-3.017	-3.105	-3.171

Reference 3

Initial z height			*Final Z height*		
0.029	0.113	0.212	0.056	0.161	0.238
0.014	0.097	0.197	0.045	0.126	0.227
0.000	0.087	0.187	0.033	0.118	0.219

Time	Hour	0
	Min	18
	Sec	35
Total Time (hr) =		0.310

Depth of Tool = 0.032 .=0

Depth of Workpiece = (3.045-Depth Tool) = 3.045

Workpiece Removal Rate(WRR)=	5.44E-02 in^3/hr
Tool Removal Rate (TRR) =	0.00E+00 in^3/hr
Wear Ratio (TRR/WRR) =	0.000
Surface Finish	45

ZrB2/Cu -Steel

Test 3

(u = 6)

Temp	1700 C	
Program Code		9
Program Control		4

z = -3.000

Polarity +

Area of Electrode (3/8)^2 in^2

μμμ

On-time	180 us	**Code**	18
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
-0.009	0.002	0.020	-2.915	-2.966	-2.939
-0.004	0.015	0.021	-2.976	-2.972	-2.988
0.000	0.028	0.029	-2.943	-2.979	-2.982

Reference 3

Initial z height			*Final Z height*		
-0.033	-0.018	-0.001	-0.029	-0.014	0.006
-0.015	0.000	0.017	-0.011	-0.001	0.019
0.000	0.015	0.032	0.004	0.025	0.036

Time	Hour	0
	Min	16
	Sec	6
Total Time (hr) =		0.268

Depth of Tool = 0.004 .=0

Depth of Workpiece = (3.029-DepthTool) = 3.029

Workpiece Removal Rate(WRR)=	6.25E-02 in^3/hr
Tool Removal Rate (TRR) =	0.00E+00 in^3/hr
Wear Ratio (TRR/WRR) =	0.000
Surface Finish =	42-45

ZrB2/Cu -Steel

Test 4

(u = 6)

Temp	1700 C	
Program Code		9
Program Control		4

z =	-3.000
Polarity	+

Area of Electrode (3/8)^2 in^2

On-time	75 us	**Code**	15
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
0.036	0.011	-0.041	-2.921	-2.977	-2.903
0.019	0.004	-0.102	-2.953	-2.934	-2.973
0.000	-0.001	-0.033	-2.928	-2.955	-2.950

Reference 3

Initial z height			*Final Z height*		
0.032	0.049	0.073	-0.064	-0.002	0.021
0.015	0.032	0.056	-0.001	0.016	0.043
0.000	0.017	0.050	-0.033	-0.001	0.011

Time	Hour	0
	Min	23
	Sec	32
Total Time (hr) =		0.392

Depth of Tool = -0.037

Depth of Workpiece = (3.007-DepthTool)= 2.970

Workpiece Removal Rate(WRR)=	4.19E-02 in^3/hr
Tool Removal Rate (TRR) =	5.24E-04 in^3/hr
Wear Ratio (TRR/WRR) =	0.012
Surface Finish	39

ZrB2/Cu -Steel

Test 5

(u = 6)

Temp	1700 C	
Program Code		9
Program Control		4

z =	-3.000
Polarity	+

Area of Electrode (3/8)^2 in^2

On-time	3.2 us	**Code**	4
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
0.160	0.144	0.142	-2.466	-2.452	-2.550
0.080	0.062	0.046	-2.420	-2.350	-2.494
0.000	-0.020	-0.033	-2.429	-2.429	-2.529

Reference 3

Initial z height			*Final Z height*		
0.031	0.093	0.141	-0.247	-0.213	0.091
0.018	0.075	0.136	-0.324	-0.330	-0.278
0.000	0.059	0.119	-0.277	-0.256	-0.238

Time	Hour	9
	Min	54
	Sec	43
Total Time (hr) =		9.912

Depth of Tool = -0.305

Depth of Workpiece = (2.994-DepthTool)= 2.689

Workpiece Removal Rate(WRR)=	1.50E-03 in^3/hr
Tool Removal Rate (TRR) =	1.70E-04 in^3/hr
Wear Ratio (TRR/WRR) =	0.113
Surface Finish	27

ZrB2/Cu -Steel

Test 6

(u = 6)

Temp	1700 C	
Program Code		9
Program Control		4

z = -3.000
Polarity +

Area of Electrode (3/8)^2 in^2

On-time	32 us	**Code**	12
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
-0.044	-0.197	-0.372	-2.974	-3.068	-3.285
-0.021	-0.177	-0.354	-2.924	-3.084	-3.126
0.000	-0.152	-0.329	-2.873	-3.033	-2.975

Reference 3

Initial z height			*Final Z height*		
0.114	0.281	0.466	0.083	0.159	0.432
0.063	0.221	0.410	-0.021	0.146	0.286
0.000	0.179	0.363	-0.068	0.095	0.237

Time	Hour	0
	Min	42
	Sec	49
Total Time (hr) =		0.714

Depth of Tool = -0.083
Depth of Workpiece = (3.010-DepthTool)= 2.927

Workpiece Removal Rate(WRR)=	2.27E-02 in^3/hr
Tool Removal Rate (TRR) =	6.45E-04 in^3/hr
Wear Ratio (TRR/WRR) =	0.028
Surface Finish	39

ZrB2/Cu -Steel

Test 7

(u = 6)

Temp	1700 C	
Program Code		9
Program Control		4

z = -3.000

Polarity +

Area of Electrode (3/8)^2 in^2

On-time	56 us	**Code**	14
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
0.232	0.166	0.098	-2.757	-2.816	-2.876
0.108	0.049	-0.025	-2.818	-2.904	-2.883
0.000	-0.050	-0.131	-2.842	-2.933	-2.922

Reference 3

Initial z height			*Final Z height*		
-0.047	0.020	0.072	-0.116	-0.096	-0.029
-0.019	0.053	0.098	-0.071	-0.008	0.012
0.000	0.062	0.088	-0.061	0.008	0.004

Time	Hour	0
	Min	26
	Sec	25
Total Time (hr) =		0.440

Depth of Tool = -0.076

Depth of Workpiece = (3.002-DepthTool)= 2.926

Workpiece Removal Rate(WRR)=	3.68E-02 in^3/hr
Tool Removal Rate (TRR) =	9.56E-04 in^3/hr
Wear Ratio (TRR/WRR) =	0.026
Surface Finish	36-39

ZrB2/Cu -Steel

Test 8

(u = 6)

Temp	1700 C	
Program Code		9
Program Control		4

z = -3.000

Polarity +

Area of Electrode (3/8)^2 in^2

On-time	7.5 us	**Code**	7
Off-time	100 us	**Code**	16
Current	24.8 A	**Code**	12

Reference 2

Initial z height			*Final Z height*		
0.030	0.036	0.034	-2.743	-2.679	-2.595
0.013	0.022	0.018	-2.793	-2.673	-2.620
0.000	0.008	0.004	-2.865	-2.754	-2.698

Reference 3

Initial z height			*Final Z height*		
-0.108	-0.176	-0.277	-0.240	-0.322	-0.396
-0.047	-0.123	-0.235	-0.197	-0.333	-0.372
0.000	-0.072	-0.187	-0.119	-0.204	-0.302

Time	Hour	3
	Min	4
	Sec	28
Total Time (hr) =		3.074

Depth of Tool = -0.140

Depth of Workpiece = (2.980-DepthTool)= 2.840

Workpiece Removal Rate(WRR)=	5.11E-03 in^3/hr
Tool Removal Rate (TRR) =	2.52E-04 in^3/hr
Wear Ratio (TRR/WRR) =	0.049
Surface Finish	33

This page is not here.